Geologos 21, 1 (2015): 59–69
doi: 10.1515/logos-2015-0003

GEOLOGOS

Cyclic sedimentation pattern in Lake Veetka, southeast Estonia: a case study

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Abstract

A sediment core from Lake Veetka, southeast Estonia, 1077 cm in length and covering 10,500 calibrated years, was examined using loss-on-ignition, grain-size distribution and AMS ^{14}C dating to reconstruct depositional dynamics. The studied core, recovered from the northern part of the lake, shows a cyclic pattern of organic and mineral matter concentration with cycle durations of 100-400 years. Cyclicity is displayed better in sediments laid down between 9,200 and 5,600 cal BP. Within two time windows (5,600–5,100 cal BP and from 1,200 cal BP to the present), sediment composition changed drastically on account of a high and fluctuating mineral matter content, obviously driven by different factors. Little Ice Age cooling is characterised by the highest proportion of mineral matter, and the Medieval Warm Period is typified by high organic matter content. The cyclic change of organic and mineral matter has been related to climate dynamics, most likely an alternation of wet and dry conditions, changes in the water level of the lake and differences in bioproduction.

Keywords: cyclicity, granulometry, radiocarbon dates, loss-on-ignition, lake sediments, climate, Holocene

1. Introduction

A cyclic pattern in lacustrine sediments has been found at different localities, and its formation has been explained by various factors (Yu & Ito, 1999, 2003; Battarbee et al., 2001; Skilbeck et al., 2005; Wu et al., 2009). Studying loss-on-ignition (LOI), magnetic susceptibility (MS), diatoms, $\delta\ ^{13}C$ and chironomid head capsule abundance in a loch sequence from the Scottish Mountains, Battarbee et al. (2001) identified a quasi-periodicity of *c.* 200–225 years in organic matter (OM) content and attributed this to changes in lake productivity driven by climate variability. Yu & Ito (1999, 2003) described a 400-year wet-dry cycle in six Great Plain Lake sediment cores (roughly between 45° and 52°N, USA) and related dry events to decreased solar activity because cosmogenic isotopes (^{14}C, ^{10}Be) also revealed a periodicity of nearly 400 years (Stuiver & Braziunas, 1989). The sediment record from a Chinese lake provided evidence of deposition of coarse-grained beds during wet and fine-grained beds during dry climatic conditions, with an approximate 400-year periodicity. This was also related to solar activity (Wu et al., 2009).

Several mires in northwest Europe showed cyclic humification ranging in time from a century to a millennium, triggered by changes in hydrological and climatic conditions (Chambers & Blackford, 2001; Väliranta et al., 2007), precipitation being the prime controlling factor (Charman et al., 2009). Biological and palaeohydrological records from the Central Estonian Männikjärve bog (58°52´N, 26°15´E) also documented an alternation of drier and wetter conditions (Sillasoo et al., 2009) over an average of 380 years. Still, Väliranta et al. (2007) mentioned that variations in wetness and dryness often were site specific and weakly linked to climate.

The current investigation includes accelerator mass spectrometry (AMS) ^{14}C determinations, LOI and grain-size distribution analyses to explore the link between sedimentary cyclic patterns and climate change with special attention to Lake Veetka (Fig. 1A, B) in the Karula Upland. This had become a subject for concern following the discovery of a cyclic depositional pattern in several small lakes in southern Estonia (Saarse, 2014).

2. Geological setting

The Karula Upland in southern Estonia is bordered by a depression in the east and by lowlands in the west. Its mosaic hilly topography was formed during the retreat of the last Weichselian ice sheet and melting of buried ice blocks. The relief comprises glacial and glaciofluvial sediments and, to a lesser extent, glaciolacustrine deposits, the bedrock consisting of Devonian sandstones. Lake Veetka (hereafter Veetka, on some maps also spelt Viitka; 57°44´ N, 26°28´ E) in the northwestern part of Karula National Park is a small (3.3 ha), shallow (maximum water depth 5.5 m, on average 3.9 m), eutrophic, weakly drained lake at an altitude of 88 m above sea level (a.s.l.; Fig. 1B). Similar to numerous others, Veetka is located in the glaciokarst hollow, surrounded by cupolas and hills, consisting mostly of glaciofluvial silty and sandy deposits. It has a small inlet stream from the east and a small outlet towards the south. The water is alkaline (pH 7.6–7.8) and rich in mineral compounds and organic substances (Mäemets, 1977). Currently, macrophytes *Elodea canadensis*, *Stratiodes aloides*, *Nyphar luteum*, *Carex* and *Phragmites*, cover almost the entire lake bottom. *Betula-Pinus-Picea* groves dominate the east of the lake, with a mire in the south and cultivated land in the western, northern and northeastern part; the lake itself is fringed by a narrow, weedy rim (Fig. 1B).

3. Material and methods

In the early spring of 2013, a 1077-cm-long core was taken from the northern part of lake by a 1-m-long Russian peat corer at a site where water depth was 5 m (Table 1). The topmost 22 cm of loose

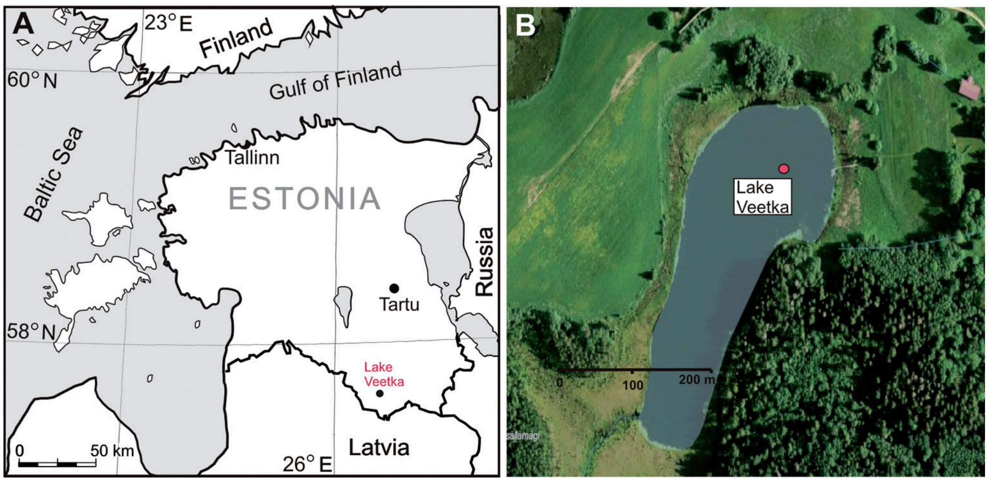

Fig. 1. Location of Lake Veetka (A) and the sampling site, marked by a red dot (B).

Table 1. Lithology of the Lake Veetka sequence.

Depth below water surface [cm]	Age description [cal BP]	
0–500		Water
500–515	1–115	Gyttja, silty, loose, black; mineral matter 60–75%
515–537	115–370	Gyttja, silty, dark grey; mineral matter 80–92%
537–571	370–765	Gyttja, silty, dark brown; mineral matter decreasing downsection from 78 to 42%
571–611	765–1230	Gyttja, dark brown; mineral matter 20–40%
611–779	1230–2500	Gyttja, organic rich, dark brown; mineral matter less than 15%
779–1137	2500–5150	Gyttja, dark brown; mineral matter 20–30%
1137–1179	5150–5600	Gyttja, silty, dark brown; rich in mineral matter, 38–72%
1179–1577	5600–10500	Gyttja, blackish brown, containing vivianite; mineral matter increasing downsection from 30 to 60%; clearly rhythmic sedimentation

Table 2. AMS ^{14}C radiocarbon dates for Lake Veetka.

Depth [cm]	14C date	Calibrated age, BP	Laboratory number	Deposit
550	425±30	480–520 (500±20)	Poz-61320	gyttja
620	1425±30	1300–1340 (1320±20)	Poz-55553	gyttja
851	3300±50	3460–3580 (3520±60)	Poz-61321	gyttja
980	4015±35	4440–4520 (4480±40)	Poz-61322	gyttja
1153	4475±35	5040–5280 (5160±120)	Poz-55554	wood
1217	5570±40	6310–6400 (6360±45)	Poz-61323	gyttja
1365	6940±40	7710–7820 (7770±55)	Poz-61324	gyttja
1470	8580±50	9500–9580 (9540±40)	Poz-61325	gyttja
1552	9110±50	10210-10370 (10290±80)	Poz-55556	gyttja

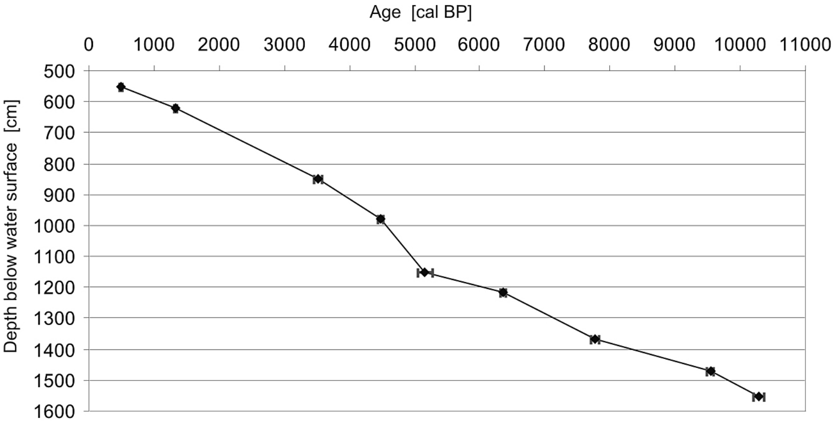

Fig. 2. An age-depth model for the Lake Veetka core.

sediment was obtained by a Willner-type sampler. Cores were described in the field, photographed, wrapped in plastic half-tubes and transported to the laboratory for future analysis and documentation.

The AMS dates from eight bulk gyttja and one woody piece were determined in the Poznań Radiocarbon Laboratory (Table 2; Fig. 2). The chronology of the core studied is based on the calibration of radiocarbon dates using the IntCal13 program (Reimer et al., 2013). In the present study, calibrated ages (cal BP relative to AD 1950) at one sigma are employed (Fig. 2; Table 2).

To quantify the organic, carbonate and mineral matter content, LOI analysis at 525 °C and 900 °C was performed continuously for 2-cm-thick samples (Fig. 3). The amount of residue containing clastic material and biogenic silica was described as mineral matter and counted up against the sum of organic and carbonate compounds. An LOI diagram was plotted with the TILIA and TILIA.Graph programs (Grimm, 2011). Grain size distribution was studied in seven intervals of the core with the help of the *Partica* laser analyser LA-950V2. The laser analyser used measured grain size in the range of 0.011–3000 μm and distinguished 93 magnitudes. Organic matter (OM) was removed by wet oxidation with 30% hydrogen peroxide and carbonates by 10% HCl (Vaasma, 2008). Grain size classification follows the Udden-Wentworth scale with the limit between clay and silt fraction at 1.95 μm, between sand and silt fraction at 62.5 μm, between sand and pebble (gravel) at 2 mm (Last, 2001).

4. Results

The core collected from the northern part of Veetka extends back in time to 10,500 cal BP, and sediments accumulated steadily because radiocarbon dates showed a good stratigraphic order (Fig. 2). The sedimentation rate was, on average, 1.01 mm yr^{-1}, surpassing twofold the rate of gyttja (0.5 mm yr^{-1}) for Estonian lakes (Saarse, 1994), and the average (0.65 mm yr^{-1}) in temperate lakes in the USA (Webb &Webb III, 1988).

The alternation of gyttja and silty gyttja allowed five lithostratigraphical units to be distinguished, two of which (Ve-2 and Ve-5) were highly minerogenic (Fig. 3). The basal unit, Ve-1 (1577–1181 cm; 10,500–5,680 cal BP) is composed of gyttja in which mineral matter decreased upsection from 60% to 20% and OM increased from 35% to 75%. The carbonate content was less than 8%. Regularly changeable OM and mineral matter formed a cy-

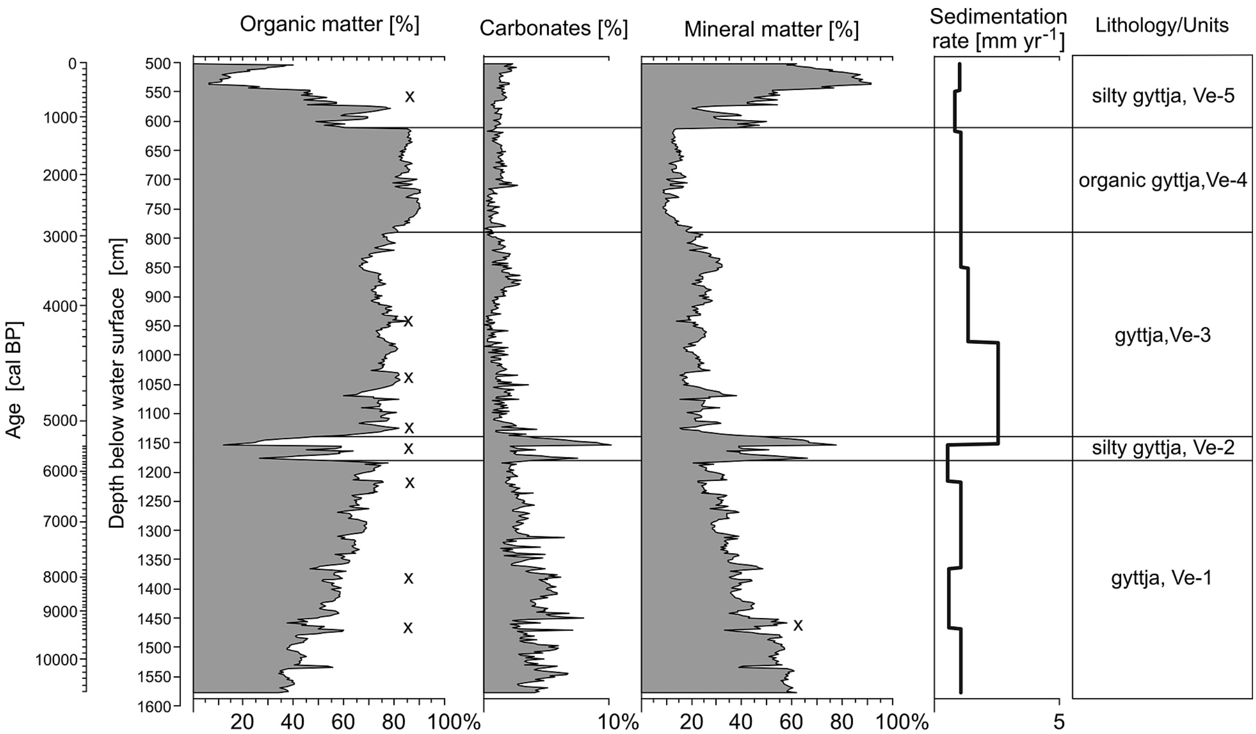

Fig. 3. Lithology, loss-on-ignition and sedimentation rate results for the Veetka sequence; the position of cycles for which grain size analyses have been carried out is marked by X.

clic pattern averaging 200–400 years. For this unit, sediment grain-size was studied in three different cycles: two OM-rich cycles and one rich in mineral matter (Fig. 3, marked by x). In the mineral-rich cycle between 1467 and 1449 cm (9,490–9,180 cal BP) mineral matter attained 59% at 1461 cm (9,390 cal BP) that surpassed OM at 22% (Fig. 4A). Medium and coarse silt prevailed; the sand content was less than 6%, but increased towards the upper limit of the cycle and its distribution mostly resembled that of carbonates. Grain size is clayey in nature in the median part of the cycle (Fig. 4A). This cycle lasted 310 years, the sedimentation rate having been 0.58 mm yr^{-1}.

OM showed a clear cycle at 1387–1365 cm (8,140–7,760 cal BP), which was the most sandy (reaching 60%) among the cycles studied (Fig. 4B). At the start of the cycle, the OM content was rather low (46%), but this increased rapidly to 60%. In view of the fact the carbonate content was stable and low (less than 7%), the mineral matter curve mirrored that for OM and was very close to the silt fraction curve (Fig. 4B). The clay fraction was missing altogether. Due to the prevalence of the sand fraction the mean grain size was considerably coarser than that of the first cycle. In spite of the coarse grain size in comparison with the first cycle, mineral matter even decreased (Fig. 4A, B). This cycle lasted 380 years, with an average sedimentation rate equal to the first cycle studied (0.58 mm yr^{-1}).

The grain size composition of the third cycle, between 1241 and 1213 cm (6,580–6,280 cal BP) was fairly comparable with that for the first cycle (Fig. 4A), with a prevalence of medium and coarse silt, but differed by a low clay fraction content (Fig. 4C). At the onset and the end of the cycle, the OM was 64% and, accordingly, the mineral matter 34%. In this cycle both mineral matter and sand fraction have diminished in comparison with the previous cycle (Fig. 4D, E). The third cycle lasted 300 years, approximately matching the first cycle, but the sedimentation rate had almost doubled, at 0.93 mm yr^{-1}.

The second unit Ve-2 (1181–1139 cm; 5,680–5,100 cal BP) differed by an alternation of gyttja with two mineral-rich, slightly carbonaceous layers (Fig. 3); the uppermost layer contained woody pieces dated at 5,160 cal BP (Table 2). In a mineral-rich layer between 1155 and 1139 cm (5,190–5,100 cal BP; Fig. 4D), the OM content constantly and rapidly decreased from 43 to 12% and grain size became more silty with small addition of clay. In the organic layer, comprising 17 cm between 1172–1155 cm and representing the time from 5,510 to 5,190 cal BP, OM reached 60%, but grain size was very variable (Fig. 4D). In the lowermost mineral-rich layer (1181–1172 cm), the mineral matter shows a clear peak which roughly coincides with the silt peak

(Fig. 4D). Altogether, this unit lasted 580 years, during which beds rich in mineral matter (i.e., the first and third) accumulated over 90 and 170 years, respectively, and the organic-rich bed between them accumulated over 320 years. The sedimentation rate was 1.78, 0.53 and 0.53 mm yr^{-1}, respectively.

The third unit, Ve-3 (1139–790 cm), comprised gyttja (OM 60–82%), which was deposited between 5,100 and 2,950 cal BP. The sedimentation rate decreased upwards from 2.5 to 1.03 mm yr^{-1}. Eight cycles could be distinguished, with total range of 270 years, being irregular and short (on average 120 yr) between 5,120 and 4,750 cal BP. In one such short cycle (1091 and 1069 cm; 4,910–4,830 cal BP), covering only 80 years, grain size was studied (Fig. 4E). The silt fraction predominates, sand and clay fractions being rare (Fig. 4E). Both the LOI and grain size records were fairly regular. Grain size of the longer cycle between 959 and 931 (4,320–4,110 cal BP) differed from that of the short cycle in containing more sand and lasting 210 years (Fig. 4F), but comprising *c.* 5% less mineral matter.

Unit Ve-4 covered the core depth 790–610 cm and time slices of 2,950–1,200 cal BP (Fig. 3). It showed the highest OM content and lowest percentage of mineral matter, but a clear rhythmic signal is absent (Fig. 3). The sedimentation rate was rather rapid: 1.03 mm yr^{-1}.

The topmost unit, Ve-5 (610–500 cm; from 1,200 cal BP to the present), is similar to unit Ve-2 in revealing variable LOI, and especially high, albeit unstable, mineral matter with two well-developed peaks. The carbonate content was equal and did not correlate with the mineral matter peaks as in unit Ve-2 (Fig. 3). The lowermost peak of mineral matter was centred at 601 cm (approximately 1,100 cal BP); the highest mineral matter peak was at 535 cm (340 cal BP). This was separated from the lowest by an OM peak at 579 cm (830 cal BP). The OM content varied drastically throughout this unit, from 6 to 77%. As the carbonate content was low, the mineral matter and OM graphs showed opposite trends (Fig. 3). The grain size distribution record covered the entire unit and was dominated by silt; the sand fraction fluctuated between 4 and 31%, and the clay fraction between 0.6 and 14% (Fig. 4G). The average sedimentation rate remained below 1 mm yr^{-1} (0.92 mm yr^{-1}). In this unit, five cycles with an average range of 240 years were identified (Fig. 4G). In the topmost cycle, 521–500 cm to 210 cal BP, the sedimentation rate was 1.0 mm yr^{-1}. The OM regularly decreased and the mineral matter increased by 30%, but grain-size composition remained fairly stable. In the next cycle (547–521 cm, 460–210 cal BP, sedimentation rate 1.04 mm yr^{-1}), the OM declined to 539 cm and then abruptly increased to 46% (Fig. 4G). In grain-size distribution, the sand fraction shows a peak at 30% (Fig. 4G). This is the sole cycle studied in which the high mineral matter content coincides with an elevated sand fraction; yet, their peaks do not overlap. From 571 to 547 cm (740–460 cal BP, sedimentation rate 0.86 mm yr^{-1}) the OM increased in a stepwise manner, but grain-size distribution remained fairly identical. On this accumulation period followed an interval (1,200–740 cal BP) during which both the LOI and grain size changed remarkably. During this time window, two cycles have been distinguished with the boundary between them at 591 cm (980 cal BP) and sedimentation rate accordingly 0.83 and 0.86 mm yr^{-1}.

5. Discussion

Sedimentation in Lake Veetka is of special interest on account of cyclic OM and mineral matter deposition. This pattern is best seen between 1470–1180 cm (9,200–5,600 cal BP), where nine cycles with an average duration of *c.* 400 years were identified (Fig. 3). This portion of sediment was deposited mostly during the Holocene Thermal Maximum (HTM).

The main driving factor of the cyclic sedimentation during the early and mid-Holocene (boundary at 8,200; Walker et al., 2012) in Lake Veetka is not clear. It could be that cyclic sedimentation is associated with an alternation of wet and dry climate conditions that determined the hydrological variations in the lake and had an impact on primary production. In order to test this hypothesis, sediment LOI and grain size results were compared with different proxies from Estonia and neighbouring areas.

The globally distributed palaeoclimatic record reveals six periods during which climate changed rapidly: 9,000–8,000; 6,000–5,000; 4,200–3,800; 3,500–2,500; 1,200–1,000 and 600–150 cal BP (Mayewski et al., 2004), underpinned by multiple driving factors. LOI results from the Veetka core show a high mineral matter between 10,500 and 9,200 cal BP, which might be indicative of a cooler climate, as deduced from oxygen isotope data of Lake Äntu Sinijärv (59°03´N, 26°14´E, northern Estonia; Laumets et al., 2014) and Lake Igelsjön (58°28´N, 13°44´E, southern Sweden; Hammarlund et al., 2003). A clear peak in mineral matter between 9,400 and 9,200 cal BP (Fig. 3) coincides with a temperature drop in the northern Baltic region, as inferred from pollen data (Heikkilä & Seppä, 2010; Veski et al., 2014). At the same time, a distinct lowering of water levels was recorded for several lakes in southern Sweden (Digerfeldt, 1988)

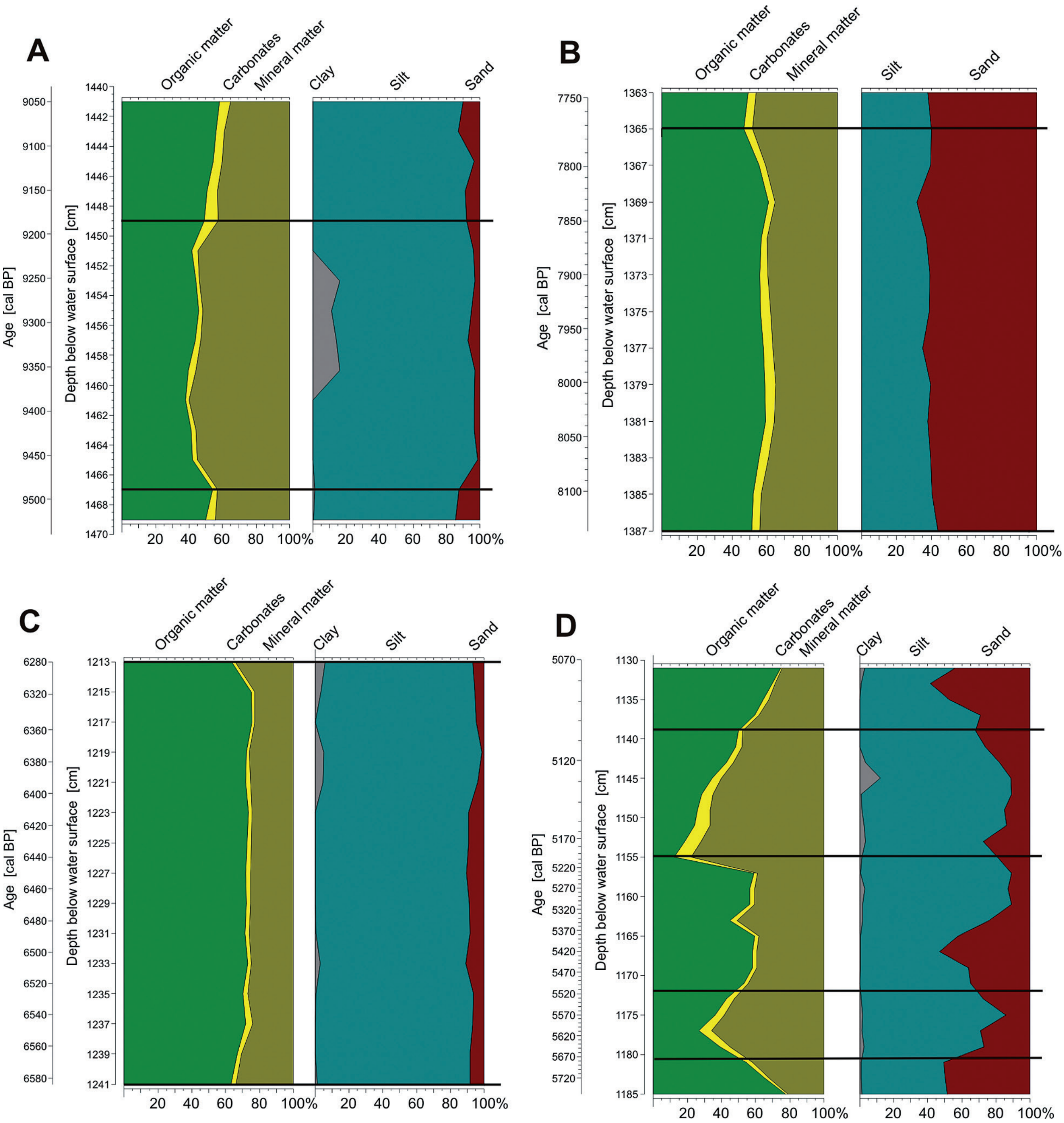

Fig. 4. Grain size distribution and comparison with LOI results at core depths of 1469–1441 cm (A); 1387–1363 cm (B); 1241–1213 cm (C); 1185–1131 cm (D); 1093–1069 cm (E); 969–931 cm (F); 611–501 cm (G). Limits of cycles are marked by horizontal lines.

and Estonia (Saarse et al., 1995), indicating a drier climate.

Pollen records and climate reconstructions from southern Estonia and Latvia confirm that a prominent warming phase started approximately at 9,000 cal BP (Niinemets & Saarse, 2006; Heikkilä & Seppä, 2010), which matches a progressive decline in mineral matter and an increase of OM in the Veetka core (Fig. 3). A temperature drop at 8,200, triggered by an outburst from Lake Agassiz that led to a globally recognised cooling (Alley et al., 1997), is not clearly reflected in the Veetka LOI graph (Fig. 3), although this cooling was registered in two pollen records from southern Estonia, but not in the LOI data (Veski et al., 2004; Niinemets & Saarse, 2007b).

Between 9,200 and 5,600 cal BP, the OM and mineral matter content changed rhythmically, albeit not regularly at the same magnitude (Fig. 3). The oxygen isotope curve from Lake Äntu Sinijärv also changed steadily, documenting nine cycles be-

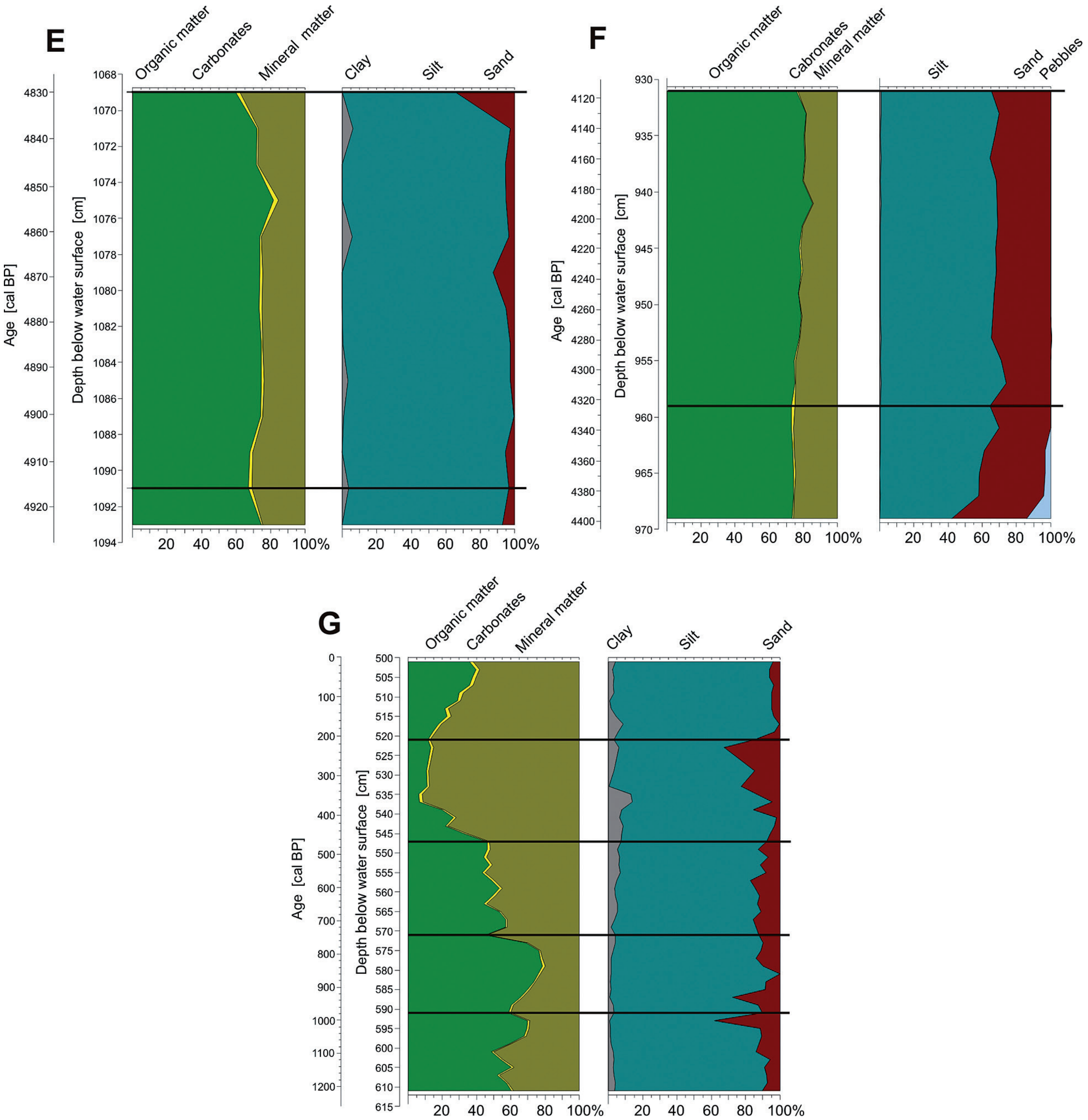

Fig. 4. continued.

tween 9,000 and 5,800 cal BP (Laumets et al., 2014). This period (roughly HTM) is characterised by a warm and rather dry climate (Seppä et al., 2009; Luoto et al., 2012). Glaciers retreated in the Alps, which was explained by solar activity and high summer insolation (Simonneau et al., 2014). Lake level reconstruction showed a rise between 9,000 and 7,500 cal BP (Digerfeldt, 1988). The predominance of the sand fraction in the studied portion of the sediment between 8,100–7,760 cal BP could have been driven by increased runoff into the lake and transportation of coarser-grained material (Fig. 4B). Due to increased dryness (Seppä et al., 2009) lake level started to drop at 7,500 cal BP (Digerfeldt, 1988; Sohar & Kalm, 2008). The rhythmic deposition of OM and mineral matter in Veetka and other lakes in southern Estonia was probably caused by changes in lake productivity, driven by thermal variability and changes in precipitation as the main controlling factors.

Between 5,700 and 5,100 cal BP mineral matter and carbonate percentages sharply increased (Fig. 3) and the sediment became more sandy in comparison with the time interval between 6,600 and 6,300 cal BP (Figs 4C, D). Lake level lowering and catchment erosion caused a rise of washed-in carbonates, consistent with a cooling between 5,800 and 5,100 cal BP, as recorded from different parts of Europe and linked to the changing circulation pattern (Seppä et al., 2009). Glacier advance in Scandinavia and the Alps (Magny & Haas, 2004; Nesje, 2009), culminating approximately at 5,300 cal BP (Denton & Karlén, 1973), also provides evidence of climate deterioration. However, climate alone can barely explain such a drastic change in LOI and grain size data as recorded in Veetka (Fig. 4D). The sand fraction and mineral matter show a changing, but not uniform trend, obviously as a result of fluctuating lake level and catchment erosion (Digerfeldt, 1988; Sohar & Kalm, 2008). As for pollen profiles, a sharp decline in *Tilia* and an increase in *Picea* pollen at 5,300 cal BP also support climate cooling (Niinemets & Saarse, 2006). Therefore, the LOI signal in Veetka was probably controlled by the hydrological balance in the lake, by catchment erosion and by bioproduction driven by climatic variability.

The termination of the HTM is dated roughly at 5,200 cal BP; however, this was not a synchronous event across Europe (e.g., Hammarlund et al., 2003; Seppä & Poska, 2004; Galka & Apolinarska, 2014). In northeast Europe it was detected up to 4,000 cal BP (Heikkilä & Seppä, 2010), and up to 4,500 cal BP in Estonia (Seppä & Poska, 2004). Subsequent climate deterioration was terminated by brief warming events and alternating wetter and drier climate conditions (Sillasoo et al., 2007, 2009; Väliranta et al., 2007).

Between 5,100 and 3,500 cal BP, a cyclic sedimentation pattern occurred, but its pacing and character differed from the cyclic patterns between 9,200 and 5,600 cal BP (Fig. 3). Nevertheless, eight cycles could be distinguished with an average duration of 200 years and an accumulation rate of 1.81 mm yr^{-1}. This interval coincides with an annual temperature decrease in the Baltic region (Heikkilä & Seppä, 2003, 2010; Seppä & Poska, 2004), fluctuating lake levels (Digerfeldt, 1988; Saarse et al., 1995) and the replacement of warm-tolerant tree taxa by cold-tolerant species (Niinemets & Saarse, 2006, 2008; Reitalu et al., 2013). Increased wetness, in response to a lower summer temperature, in southern Sweden started approximately at 4,000 cal BP (this date was proposed for the middle-upper Holocene boundary; Walker et al., 2012) and was explained by shifts in the atmospheric circulation pattern (Jessen et al., 2005). A decrease in OM and slight increase in mineral compounds in Veetka also started approximately at 4,000 cal BP and terminated at *c.* 3,500 cal BP (Fig. 3), suggesting a rise in humidity.

Since 3,500 cal BP, OM considerably increased, reaching a maximum between 2,500 and 2,100 cal BP, and mineral matter dropped to a minimum (Fig. 3). Between 3,500 and 1,200 cal BP, several alternating wet and dry periods can be differentiated on the basis of plant macrofossils and testate amoebae records from Estonia and Finland (Sillasoo et al., 2009; Väliranda et al., 2012), thus reflecting climate variability. A clear cyclic pattern in the Veetka sediment core is absent, probably obscured by the very high OM content and/or human impact. A cooling event detected in several parts of Europe (e.g., Matrin-Puertas et al., 2012), consistent with an increase in ice rafted debris in the North Atlantic approximately at 2,800 cal BP (Bond et al., 2001), cannot be traced in the Veetka (Fig. 3) and other LOI graphs from southern Estonia (Niinemets & Saarse, 2006, 2007a, b). It seems that changes in LOI results were rather site specific and influenced by the hydrological regime of the lake and by bioproduction.

Changes in sediment composition between 1200 and the present were mostly induced by human activities and climate, such as the Medieval Warm Period around AD 950–1350 and climate deterioration during the Little Ice Age (LIA) between AD 1350 and 1850 (Wanner et al., 2008). LIA was not an isolated event, but widespread climatic deterioration and the coldest phase in the millennium-scale cycle most clearly expressed in the North Atlantic region (Denton & Karlén, 1973).

The sharp decline of OM in the Veetka core at 1,200 cal BP and elevated mineral matter (Fig. 3) resulted from the expansion of land cultivation and disafforestation as crop farming became the predominant means of subsistence (Väli et al., 2014). This promoted soil erosion in a highly mosaic landscape and an influx of mineral matter into the lake. Yet carbonate content remained almost stable, obviously as a result of the humid climate, which caused leaching of carbonates from the upper part of soil profiles and their acidification.

Based on drastic changes in LOI results, five sedimentological cycles have been distinguished (Fig. 4G). The lowermost cycle covers the interval 1,200–980 cal BP (611–591 cm) is characterised by changeable OM and mineral matter percentages, resulting primarily from the nature of agricultural practice and climatic conditions. As fire cultivation was the principal land-use practice, soils rapidly became depleted in nutrients and fields were abundant and left to be overgrown by bushes (Jääts et al., 2010). Climatic warming and increased nutrient supply into the lake that led to increased bioproduction during the Middle Ages probably were the main reasons why OM accumulation in the lake increased during the cycle between 980 and 740 cal BP (591–571 cm; Fig. 4G). The next sharp change in sediment composition, between 740 and 460 cal BP (571–547 cm) coincides with the German crusade invasion into Estonia, which introduced serfage and a lifestyle change among local people. A rise in population and export of agricultural products resulted in the need for new arable land, leading to large-scale woodland clearing and an increased influx of mineral matter into the lake (Fig. 4G). High percentages of mineral matter between 460 and 210 cal BP (547–521 cm) are coincident with the coldest period of the LIA (e.g., Tarand & Nordli, 2001; Tarand et al., 2013; Luoto et al., 2008) and with a high influx of cereal pollen, indicating increased agricultural activities (Niinemets & Saarse, 2007a, b). Utilisation of new agricultural techniques and the expansion of stock farming as the main source of fertiliser mitigated the need for new land and reduced soil erosion since 210 cal BP (521 cm; Fig. 4G). Previous (Saarse & Niinemets, 2007) and current results indicate that climatic deterioration during the LIA favoured a mineral matter flux into the sediment basin, whereas the Medieval Warm Period promoted bioproduction and organic deposition, and human impact was unable to obscure this trend, at least in southern Estonia. However, a clear correlation between grain size and mineral matter is not seen.

6. Conclusions

Cyclic sedimentation of organic and mineral matter is a characteristic pattern in Lake Veetka and several other lakes in southern Estonia. Cyclicity is observed better in the lowermost portion of sediment, where human impact was absent or extremely low. The best cyclicity was recorded between 9,200 and 5,600 and roughly coincides with the HTM, which is characterised by a stable or slightly changing climate. Nevertheless, the cyclicity was not strictly periodic, but changed between 200 and 400 years, probably indicating a climate in which brief warming was punctuated by colder phases. The most drastic change in the LOI data coincides with regionally altered climate systems, at approximately 9,000–9,300; 5,600–5,200 and during the last 1,200 years (Heikkilä & Seppä, 2010; Seppä et al., 2009; Veski et al., 2014). However, several local driving forces, such as lake level fluctuation, soil erosion, bioproduction and human impact, also have an impact on the sediment composition and cyclic pattern.

Acknowledgements

I wish to thank Atko Heinsalu and Siim Veski, for assistance in the field. Anonymous referees are acknowledged for critical remarks and suggestions. I also appreciate Elsevier language editing team for correcting English. This study was supported by institutional research funding IUT 1-8 and ESF Grant 9031.

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Manuscript submitted 3 October 2014
Revision accepted 19 January 2015