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The Holocene sedimentation history of Lake Vőrtsjärv, central Estonia

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Lake Vőrtsjärv is one of the biggest lakes in Eastern Europe and possesses a complex geological history. Bottom deposits consist mostly of fine sand and silt, accompanied with sapropel (up to 9 m thick) and lake marl (up to 8 m thick). In places, especially in the northern part where the bottom deposits are absent, varved clay or till are exposed in the lake basin. In the southern part of the lake the deposits are much thicker, indicating a gradual rise of water-level. Like the majority of lakes in the Northern Hemisphere, Lake Vőrtsjärv possesses a more open eastern and a more swampy and overgrown western bank. Shore types and the lithological composition of shore sediments are varied and highly controlled by the bedrock and glacial deposits. Long-shore transport of sediments is limited. The mineral composition of bottom sediments shows great qualitative and quantitative variability which relates to the grain-size and petrography of the parent deposits. Organic-rich sapropel can be used in agriculture and evidently also for medicinal purposes.

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INTRODUCTION

Lakes are an integral part of the Estonian landscape. The total number of lakes in Estonia is over 1500, 42 of which occupy an area of more than 15 km^2. Lake Vőrtsjärv is the second largest lake in Estonia and its area is 270.7 km˛. The maximum length of the lake is 34.8 km and the maximum width is 14.8 km. The shore-line is 96 km long, the maximum depth about 6 m, average depth 2.8 m, the long-term water-level occurs at 33.68 m a.s.l., water volume is 756 million mł, and the drainage basin 3380 km^2 (57°50'–58°30'N and 25°35'–26°40'E). The lake has 18 main tributaries and the outflow is only *via* the Emajőgi River.

Lake Vőrtsjärv is located in central Estonia (Fig. 1) in the shallow Central Estonian Depression of preglacial origin. Through the Emajőgi River, its drainage basin is connected with the drainage basin of Lake Peipsi and the Narva River. The shallow depth and large surface and drainage areas make Lake Võrtsjärv extremely sensitive to climatic fluctuations and other environmental changes occurring in its drainage basin. Therefore, regulation of the water-level towards the long-term annual average is desirable. Human impact has caused high nutrient loading from the catchment area and eutrophication of the lake (Huttula and Nőges, 1998).

This paper summarises results obtained through a study of more than 120 sampling sites (Fig. 2) and long-term (over 20 years) measurements of shore processes.

GEOLOGICAL SETTING

The main aim of the study is to estimate future trends in lake history. Rapid changes in the post natural environment critical to a better understanding of human-induced changes should be recognised and managed.

Coastal erosion and sediments carried by rivers and streams are the principal sources of material for the bottom deposits of Lake Vőrtsjärv. Some of the material is also provided by wind and drifting ice, and redistribution of this by waves is controlled by bottom topography and lake level. Deglaciation processes, tectonic movements and climatic fluctuations controlled erosion and accumulation. Differences in the bedrock and glacial deposits played a leading role in the development of shore types.

In the northernmost part of the depression carbonate rocks of the Middle Devonian Narva Regional Stage mostly crop out. Carbonate rocks of the Lower Silurian Adavere Regional Stage

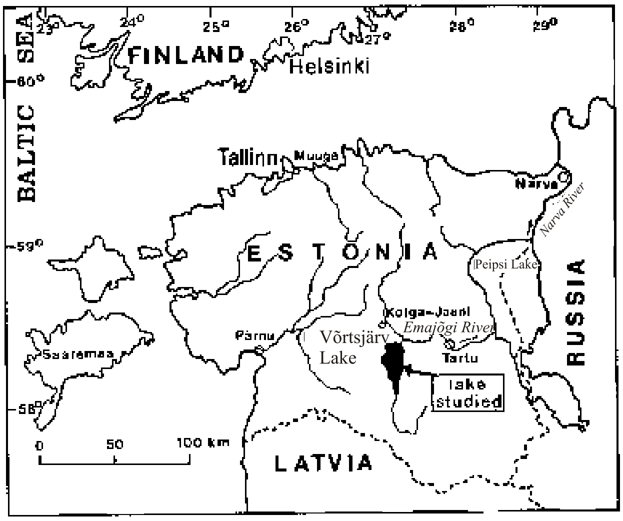

Fig. 1. Location sketch of Lake Võrtsjärv

carbonate clasts (up to 90%) in the gravel fractions. The content of Fennoscandian crystalline rocks in till is about 10%. In the Tamme outcrop on the eastern coast of Lake Võrtsjärv a till overlies reddish sandstone and is strongly influenced by underlying rocks. The upper part of the weakly lithified sandstones has been deformed by the glacier and often incorporated into a till as "injections" and lenses. Locally, a distinct boundary between the diamicton and bedrock is difficult to establish. The till cover in the *ca.* 300-m-long coastal cliff varies in composition. In the matrix of the sandy loam till carbonate clasts of the Silurian bedrock predominate (50–60%), followed by the Fennoscandian rocks (30–40%) and local Devonian sandstones (0–25%). In the boulder fraction the Fennoscandian rocks strongly prevail.

Already at the beginning of the last century the northern part of the lake depression was postulated to have been uplifting faster than the southern part, which strongly affected the evolution of the lake. In the Late Glacial and at the beginning of the Holocene the rate of land uplift was considerably higher than at present (Kessel and Miidel, 1973).

occur as a narrow strip of north-west–south-east trend. The area covered by lake water is mostly underlain by sandstones and siltstones interbedded with clay and dolomitic marl of the Middle Devonian Aruküla Regional Stage, which are exposed on the steep eastern bank of the lake at Tamme, Vehendi and Petseri. Mineralogically, this predominantly comprises quartzose and feldspatic arenite with a high quartz content (up to 90%). The heavy fraction is dominated by ilmenite (30–60%) and transparent allothigenic minerals (15–40%). Among the latter, garnet and zircon are most significant. Tourmaline and rutile are also important (Kleesment and Mark-Kurik, 1997). The bedrock topography at 20–30 m a.s.l. is flat and monotonous (Tavast and Raukas, 1982).

The Quaternary cover is a few metres thick, reaching 5–10 m (Raukas, 1978). Tills in the northern part of the lake depression are grey and carbonaceous, elsewhere they are reddish-brown and enriched in Devonian material. They are covered with glaciofluvial and glaciolacustrine sediments, Late-Glacial sand and silt of Allerød and Younger Dryas age. In drumlins of the Kolga-Jaani drumlin field NW of the lake, the Pleistocene deposits, mainly till, are 20–25 m thick. Late-Glacial and Holocene alluvial deposits occur in river valleys (Väike-Emajõgi, Õhne, Tänassilma, a.o.). Between Sooru and Pikasilla (outside the map area) they are up to 20 m thick (Kajak, 1959).

The Estonian Stratigraphical Chart of Quaternary Deposits (Raukas and Kajak, 1995) shows the composite stratotypes for interglacials and areal stratotypes for glacial units. The Võrtsjärv Subformation, which is the youngest unit of the Upper Pleistocene Järva Formation, was named after Lake Võrtsjärv. In the stratotype area — the Lake Võrtsjärv Basin — depending on the underlying bedrock, contemporaneous grey limy (Valma) and reddish-brown (Tamme) tills are widespread.

The about 1.5 m-high coastal bluff at Valma in the north-western part of the lake basin exposes typical (for the area) grey diamicton with a loamy matrix and a high content of Silurian

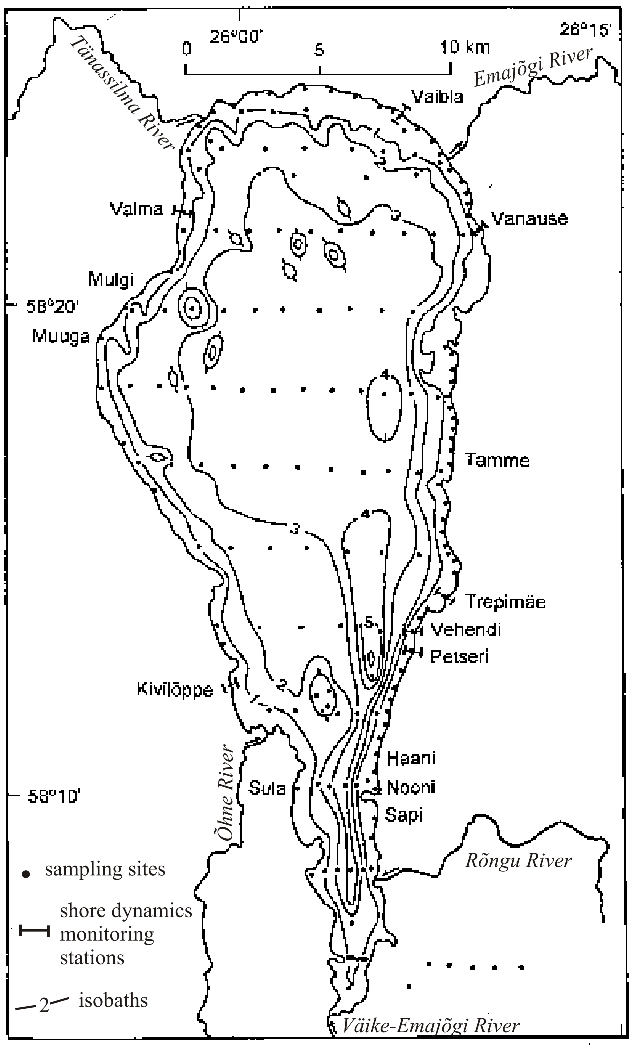

Fig. 2. Sampling sites and bathymetric map of Lake Võrtsjärv

The northern part of the depression is rising at a rate of 0.8 mm/yr, while the southern part is currently sinking (Vallner *et al*., 1988). Over a period of the last 800 years, in the southern part of the lake the average water-level rise was equal to 2.5 mm/yr. Intensive accretion of valley floors and the meandering patterns of the lower reaches of rivers is further evidence for subsidence and continuous lake-level rise (Pirrus *et al*., 1993).

A BRIEF HISTORY OF LAKE VŐRTSJÄRV

The lake has a complicated history. Depending on the precise nature of ice sheet retreat, glacial lakes of different shape and size formed in the Lake Vőrtsjärv Depression. About 12.6 ka BP the southern part of the Vőrtsjärv Depression was occupied by the small Vőrtsjärv Glacial Lake. The outflow from this lake occurred *via* the Väike-Emajőgi Valley to the south. Later, an outflow to the west developed. Due to neotectonic uplift, which was more pronounced in the north-west, the outflow to the west gradually diminished and closed in the Early Holocene. As a result, the Lake Great-Vőrtsjärv (Orviku, 1958) was formed (Fig. 3), contoured on the basis of its bottom deposits. The water-level in the northern part of the basin was at that time 4–5 m higher than at present. At the beginning of the Mid-Holocene, about 7500 yr BP, an outflow to the east developed and gradually the lake acquired its present contours (Orviku, 1973).

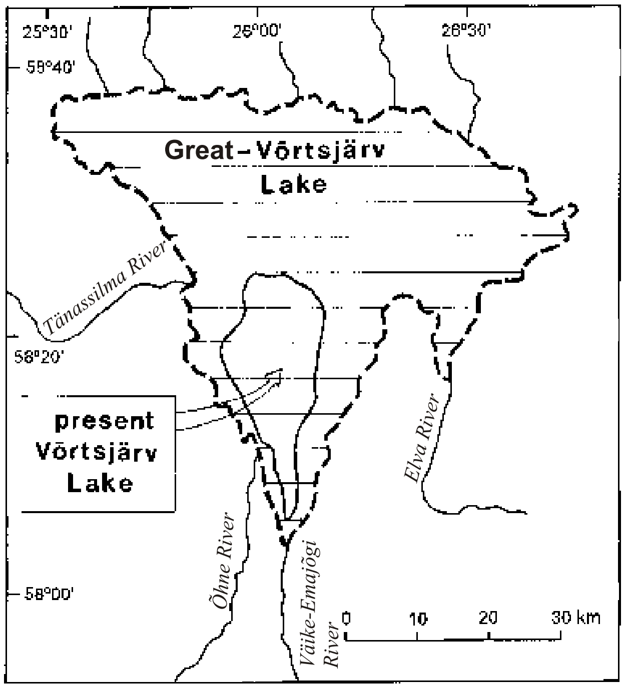

Fig. 3. Lake Great-Vőrtsjärv in the Early Holocene

SHORES

Like the majority of lakes in the Northern Hemisphere (Klinge, 1889), Lake Vőrtsjärv has a more open eastern and a swampy and overgrown western bank. Due to the prevailing south-westerly and westerly winds, active accretionary and erosional shores are widespread in the eastern part of the lake, while swampy coasts overgrown with bushes, bulrush and reeds are characteristic of the western and southern parts. In many places, reed and bulrush form up to 150 m wide belts on the fore-shore. The shallowness of the lake, high water temperatures in summer and increased concentrations of mineral nutrients promote overgrowing of the lake. Due to the encroaching reed, beaches suitable for recreational use keep reducing in extent (Tavast *et al*., 1983).

Grewingk (1869) was the first to study the shores of Lake Vőrtsjärv. He described a flat, sandy beach with a convex shore-line in the northern part of the lake, and many elongated cobble and pebble hillocks on the lake bottom, now interpreted as submerged drumlins. Zur Mühlen (1918) differentiated the scarp shore eroded in the Devonian sandstone and till, and flat shores developed in sand and till. He mentioned that aggrading shores were formed partly under the influence of hummocky lake ice.

Lake Võrtsjärv has a variety of shores (Fig. 4). Cliffed shores, up to 8.5 m high, occur mainly in zones of bedrock hillocks with a till cover. Scarp coasts in the unconsolidated Quaternary deposits are more widespread. Bluffs may be eroded in till and sandy-gravel deposits, seldom in peat. Scarp till shores, formed mainly in drumlins, occur on the eastern and northwestern coast of the lake. The scarps are usually 1.5–2 m high, and from some hundred metres up to several kilometres long. Abundant boulders and cobbles on the subaqueous slope and at the foot of the scarp form a stony floor with a thin layer of sand and pebbles. The till escarpments, the so-called dead bluffs, usually lie at a distance of 10 to 100 m from the shore-line and are covered with bushes.

Sandy beaches with adjacent scarps occur in the northern (Vaibla) and western (Kivilőppe) part of the lake. An ancient bluff is situated at a distance of about 50 m from the present shore-line. The beach is covered with bushes and dense brush; reed grows on the subwater coastal slope.

Flat coast may be developed in till, sand, silt or peat. Coasts of this type are covered with bushes and brush, and reed grows on the subaqueous slope. Flat sandy shores occur sporadically in some parts of the lake. The whole southern tract of the lake is bordered by flat peaty shore.

SHORE-LINE CHANGES AND BEACH EROSION

To differentiate the mineral particles, a decimal metric system was used (Raukas, 1965). Beside seasonal fluctuations, the annual mean water-level can vary by more than 1.5 m in successive years. In 1996, the lowest daily water-level occurred at 32.14 m a.s.l.; while in 1928 it was about 3 m higher (35.28 m a.s.l.). Measurements recorded during 126 years indicate lake level fluctuations lasting 4–6 and 20–30 years, respectively (Järvet and Nőges, 1998). During the low-level periods no erosion was noted and a broad fore-shore plain up to a kilometre wide emerged (Fig. 5). But when the water-level rose, the lake shores were subjected to heavy erosion and serious damage was caused to constructions (Fig. 6).

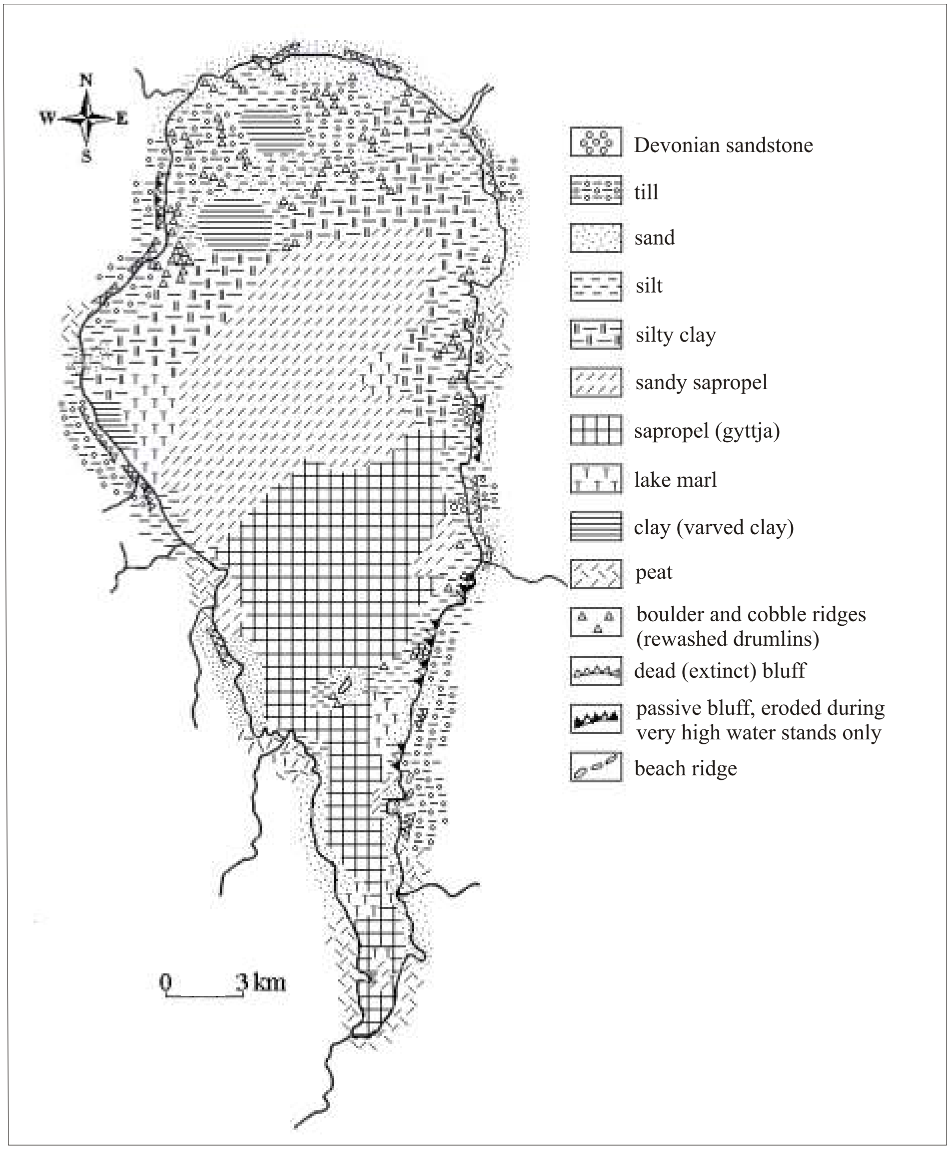

Fig. 4. Geology and morphology of shores (modified after Tavast *et al*., 1983) and lithology of bottom sediments of Lake Võrtsjärv after R. Pirrus, A. Raukas and E. Tavast (modified after Raukas and Tavast, 1990)

On the morainic coast at Vehendi several changes have occurred during the last 20 years (Fig. 7). Extensive changes on the coast are also due to ice-push action. Ridges up to 8 m high, of hummocky lake ice, generated by persistent winds and pushed forward against the shore with enormous force, play a significant role in shaping the shore and transporting erratic boulders. Occasionally, stone walls reaching tens of metres in length occur in front of till scarps that they protect from further erosion.

MINERALOGY OF BEACH SEDIMENTS

The petrographic composition of cobble and pebble fractions is identical to that of parent deposits nearby, mainly on till outcrops. The mineral composition of the recent near-shore sediments is more varied, being partly related to grain-size variation. Among more than 50 different minerals and mineral groups identified in the sand and silt fraction, quartz, feldspars, carbonates, micas, amphiboles-pyroxenes, ore minerals (mainly ilmenite) and garnets prevailed, making up about 99% of all the minerals recognised.

The content of quartz in beach sands is over 75%, the content of carbonates (up to 14.1%) is highest near the outcrops of till, particularly in the northwestern part of the lake.

The proportion of the heavy fraction (density over 2.89 Mg/m^3) is usually small (0.32–0.45%). The beach sediments characteristically bear a direct relationship to the parent rocks and deposits. The content of garnets is the highest (mainly 25–35%) on the Devonian outcrops (up to 58% in Trepimäe) in the eastern part of the lake (Fig. 8). The contribution of amphiboles and pyroxenes (up to 56% near Mulgi farm) is the highest near the outcrops of till (Tavast, 1990).

Fig. 5. Low water-level at Trepimäe on September 19, 1997

Fig. 6. Damage of the coast at Tamme on June 25, 1998

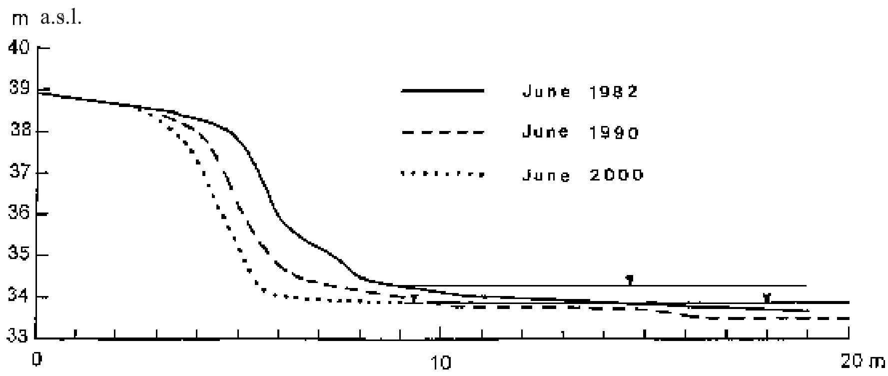

Fig. 7. Beach profiles at Vehendi on June 25, 1982, June 27, 1990 and June 16, 2000; triangles indicate water-level

BOTTOM SEDIMENTS

The bottom sediments of Lake Võrtsjärv consist mostly of fine sand and silt, sapropel (up to 9 m) and lake marl (up to 8 m thick). In the northern part of the lake, sapropel and lake marl either form a thin layer or are entirely absent. About two thirds of the topmost part of the sediments consist of sapropel (gyttja) and sandy sapropel (Fig. 4). Silty clay, lake marl and other sediments are less abundant. In places, especially in the northern part where the bottom sediments are absent, the lake depression exposes varved clay or till. In the southern part of the lake the sediments are much thicker than in the northern part indicating a gradual rise of water-level due to local subsidence in the southern portion of the basin (Pirrus and Raukas, 1984).

Sediment resuspension prevails in the lake during ice-free periods. It determines the temporal and spatial pattern of the sedimentation rate, which is higher in the shallow northern part of the lake (Nõges *et al*., 1998). The distribution of bottom sediments shows a typical pattern where the lighter and small-grained fractions such as sapropel and sapropelic silty clay are eroded from the shallow northern areas of the lake and transported to deeper and sheltered places in the central and southern part of the lake. The content of free carbonates varies in the contemporary surficial sediments of Lake Võrtsjärv, e.g. in places the content of $CaCO_3$ exceeds 20% (Fig. 9). The carbonate content is higher in fine-grained sediments and in the southern part of the lake due to water discharge from the Väike-Emajõgi River, which has a high content of calcium bicarbonate.

The mineral composition of fine sand (0.1–0.25 mm) and coarse silt (0.05–0.1 mm) demonstrates a large qualitative and quantitative variation caused by variability in the granulometric composition and parent deposits (Fig. 10). Differences caused by hydrodynamic variations are unclear. The content of carbonaceous minerals, feldspars, micas and accessories (zircon, fluorite, rutile, sphene, brookite, anatase) in the silty fraction increases and the content of quartz, haematite, pyroxenes, amphiboles, epidote, staurolite and disthene decreases. The latter minerals form larger crystals in the parent rocks.

We have focussed on the mineral composition of sandy-silty sediments in the northern part of the lake, because it was difficult to extract mineral particles from the sapropel and practically impossible from the lake marl, covering the central and southern parts of the lake bottom (Fig. 4). There, we could study the mineral composition only of near-shore sediments.

In the light fraction of fine sand (less than 2.89 Mg/m^3) quartz formed 80–90% (occasionally up to 95%, in some places 70–75%), feldspars — 10–15% (occasionally up to 20%, in some places 5%), and carbonates — 0–7% (occasionally up to 15%).

In the heavy fraction the most common concentrations (in %) were the following: haematite and limonite — 1.0–2.5

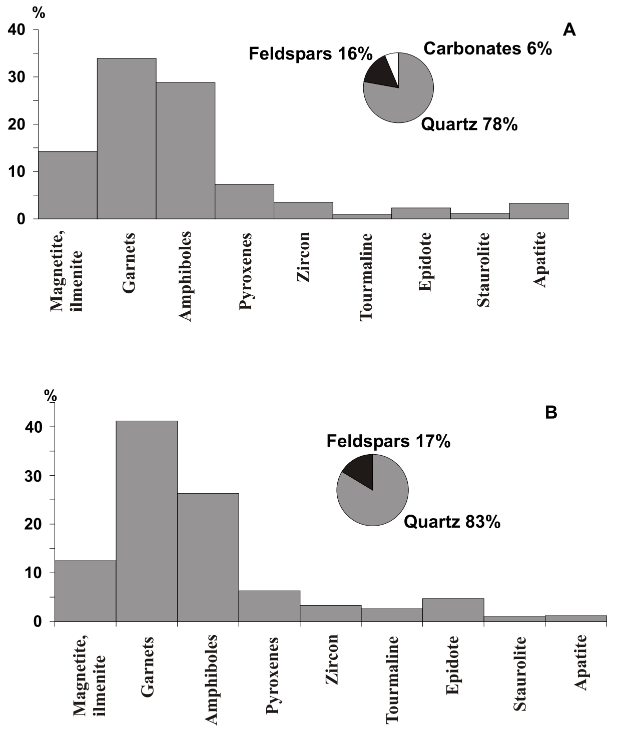

Fig. 8. Mineral composition of fine sand fraction (0.1–0.25 mm) of beach deposits close to: A — carbonaceous till at Muuga, and B — Devonian sandstones near Tamme

(occasionally up to 5.6), magnetite and ilmenite — 12–20 (28.2), leucoxene — 0.5–2 (3.0), garnet — 25–40 (47.0), amphiboles — 18–35 (38.0), pyroxenes — 3–6 (8.0), biotite — 0.2–0.1 (3.0), zircon — 1–7 (11.0), tourmaline — 1–2 (4.0), epidote — 3–5 (6.0), staurolite — 0.5–1 (2.0), sillimanite — 0–0.2 (0.4), apatite — 0.5–3 (4.0) and dolomite — 0.2–5 (8.0). Quite often, collophane (broken mollusc shells) is present in both the light and heavy fractions.

^{14}C dates and palynological studies suggest (Pirrus and Raukas, 1984) that a layer of limy clayey silt with a terrigenous component of up to 79% accumulated in the southern part of the lake at the beginning of the Holocene during the first half of the Pre-Boreal chronozone. In the second half of the Pre-Boreal and Boreal, about 1 m-thick layer of marl with a high content (*ca.* 70%) of $CaCO_3$ and a low content of organic matter (3–18%) was deposited. Accumulation of lake marl was enhanced (5.5 m) in the Atlantic Period. At the beginning of this chronozone it contained more $CaCO_3$ (60–65%) than at the end of it (about 48%). The content of organic matter increased from 10–15 to 20–30% and of terrigenous component from several percent to 32%. In the Sub-Boreal the content of terrigenous and organic matter (up to 37%) increased, being highest in the Sub-Atlantic sediments, where the $CaCO_3$ content is only 1–2%. Similar changes in the chemical composition have been established in the southernmost part of the lake (Pirrus *et al.*, 1993), where the $CaCO_3$ content regularly decreases and the organic matter content in the second half of the Sub-Atlantic is over 40%. At the beginning of the Holocene (PB, BO), the water-level was about 8 m lower here than at present (*ca.* 26 m a.s.l.) and at the end of the Mid-Holocene it was 3–4 m lower still (*ca.* 30 m a.s.l.) than today (Pirrus *et al.*, 1993).

The Lake Võrtsjärv holds about 200 million m^3 of sapropel (gyttja). The total reserves of sapropel and lake marl are estimated at about 360 million m^3 (Veber, 1973), and these have not been exploited up to the present. The sapropel in Lake Võrtsjärv varies from light beige to black (mostly greenish-grey) in colour; and from jelly-like to plastic in consistency. The average water content is 90%, though after drying the colour changes. The chemical composition of sapropel varies, depending on grain-size composition and contents of carbonates, sand, silt and clay. Most of our analyses indicated that sapropel is rich in organic matter (30–40%) and contains 0.6–1.2% of potassium (K_2O), 1.1–2.53% of nitrogen, and microelements. The organic part contains humic substances, β-carotine, cellulose and hemicellulose, carbohydrates and bitumens. Most probably, this type of biogenic sapropel can be used not only as

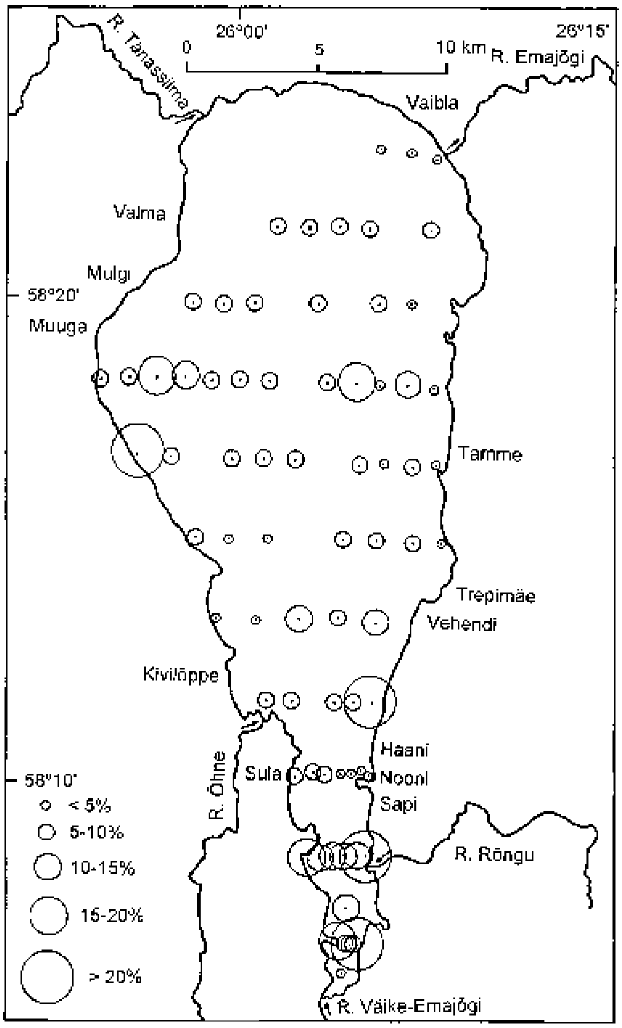

Fig. 9. Content of free carbonates calculated to $CaCO_3$ in the bottom sediments of Lake Võrtsjärv

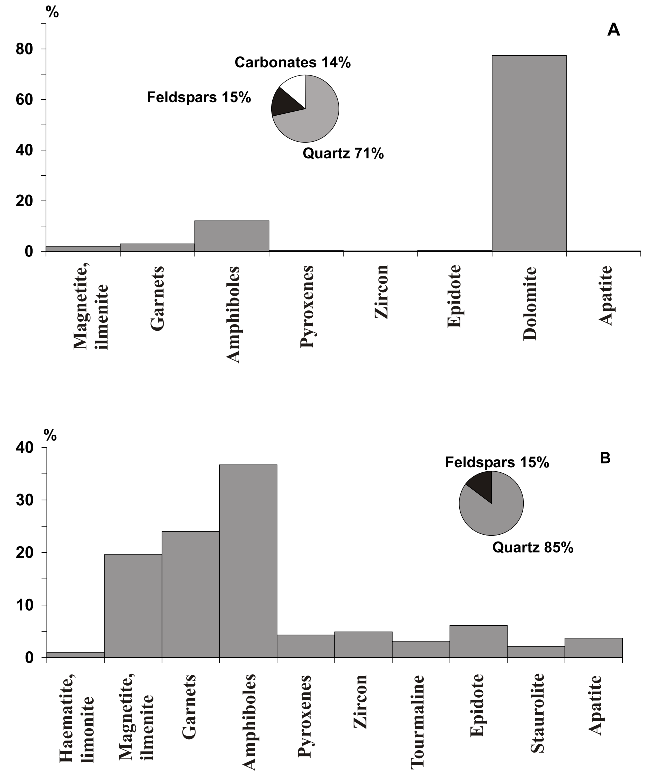

Fig. 10. Mineral composition of fine sand fraction (0.1–0.25 mm) of: A — wave-reworked till near Valma, and B — near-shore silty sand at Vaibla

a fertilizer in agriculture but also for medicinal purposes and for production of medicine (humisol).

CONCLUSIONS

Lithology, thickness and facies distribution, but also the geomorphology of shores and of adjacent valleys show that the southern part of the Lake Vőrtsjärv is undergoing a slow but continuous subsidence. At the beginning of the Holocene the water-level in the southernmost part of the lake was about 8 m lower than at present and at the end of the Holocene it was still 3–4 m lower than today. Nowadays, the water-level in the lake varies greatly. In 1922 the maximum annual amplitude was equal to 2.2 m, the long-term amplitude in the last century was over 3 m and the rise during the spring flood was up to 174 cm. Wide fluctuations of lake level have given rise to some significant geomorphological features, causing damage on the beach during the high-water level and hampering the development of recreational facilities during the low-water period. Low-water poses a significant threat to fisheries. Therefore, the regulation of the lake to the long-term annual average is of urgent necessity. However, this should be economically grounded, because with higher water-level the erosion on beaches increases. The close relationship of mineral composition of the beach deposits to the parent deposits and rocks demonstrates that long-shore drift is weak or absent and the sediment redistribution is mainly by waves, and influenced by bottom topography.

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