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TECHNICAL COMMUNICATION

Geological Development of the Northern Coast of Lake Peipsi

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INTRODUCTION

The area of Lake Peipsi offers favourable preconditions for further development of recreational and therapeutic facilities and tourism. The lake has a long jagged shore line with a great alternation of shore types and large stores of curative muds and mineral waters. The capacity of its basin is more than 25 cubic kilometres of relatively clean water; this makes the lake a prospective fresh-water reservoir for the towns of North-East Estonia and Tallinn, capital of the republic. The concentration of tourists is especially great on the northern coast of Lake Peipsi where the nice sandy beaches are open to the south (Photo 1). During previous years, strong damage to the beaches has taken place. In this connection, recommendations from geologists and geographers to determine how to protect these wonderful beaches of international interest are urgently needed.

BRIEF PHYSICO-GEOGRAPHICAL AND GEOLOGICAL CHARACTERIZATION OF LAKE PEIPSI

Lake Peipsi on the border of Estonia and Russia (Figure 1) is one of the largest lakes in Europe (3,555 sq km). The average depth is 8 m and the maximum 15.3 m. The lake consists of three main parts: the Peipsi proper, Lake Pihkva with the narrow strait-like Lämmijärv between them.

The formation of the coastal morphology has been controlled by several geological and physico-geographical factors such as winds, waves, nature of sediments, exposure to heavy storms, tectonic movements, *etc.*

Bottom Sediments

Bottom sediments are variegated (Figure 2). In the shallow coastal regions, sediments are relatively coarse-grained (prevailingly sands); whereas in sheltered areas (behind islets a.o.) and in the deep central part of the lake, fine-grained sediments (clayey silts and silty clays) dominate (RAUKAS and RÄHNI, 1981). For the differentiation of mineral particles in the former Soviet Union, the decimal system on the metrescale was used (RAUKAS, 1965). Sand (1.0–0.1 mm) was subdivided into coarse (1.0–0.5), medium (0.5–0.25) and fine (0.25–0.1 mm), silt (0.1–0.01 mm) and clay (pelite) into coarse (0.01–0.005) and fine ($<$0.005 mm), respectively. Coarse fractions were subdivided in ascending size into granules (1–10 mm): pebbles (10–100 mm), cobbles (100–1,000 mm) and boulders ($>$1,000 mm). For mixtures of sand, silt and (clay), the following terms were used: silty sand, (slightly) clayey silt, sandy clay a.o.

Usually, the sedimentary material is carried into the lake by the rivers and as a result of the erosion of the coast and lake bottom; it is then distributed under the influence of waves and streams according to bottom topography. The thickness of deposits is mainly 1–2 m and only exceeds 10 m in the ancient valleys (RÄHNI and TAVAST, 1981). The mineralogical and chemical composition of sand, silt and clay fractions and the content of organic matter (up to 38.98% in L. Peipsi proper, 83.26% in Lämmijärv and 34.52% in the bottom sediments of L. Pihkva, *i.e.*, nitrogen, phosphorus, amorphous silicon, carbonates and microelements) in the bottom sediments is different in various parts of the lake (RAUKAS, 1981). In the northern part of the lake, calcite is the prevailing carbonate mineral in bottom deposits; and in the central part and southern regions, dolomite predominates as a result of the influence of initial rocks. The carbonate content in $CaCO_3$ is the highest (up to 6.92%) in L. Lämmijärv. Amorphous silicon is in correlation with the quantity of diatomaceous algae, and its content is higher in fine-grained silty sediments in the central part of the lake (up to 7.14% in L. Peipsi proper, 6.58% in L. Pihkva and 2.58% in L. Lämmijärv). In sandy fractions, the content of amorphous silicon is less than 1%. The quantity of phosphorus in the water and lake deposits is higher in coastal areas, especially in neighbourhoods, settlements and fields, due to human action (mainly as a result of fertilization).

Agricultural and industrial pollution stimulates exuberant growth of reeds and bulrushes. The long stretches of coastal areas, which some tens of years ago were the favourite tourist

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Photo 1. The picturesque sandy beaches in the northern part of Lake Peipsi opened to the south and offering favourable conditions for holiday makers. Kauksi. (Photo by A. Miidel).

areas are now overgrown and people have to dig the canals to reach the open water.

Tectonic Movements

Tectonic movements have exerted a strong influence on the formation of the shores of the lake. Lake Peipsi has a meridionally elongated configuration, and, therefore, its northern part (closer to Fennoscandia) is neotectonically lifting, the central part is stable and the southern part is sinking (ZHELNIN, 1966; VALLNER *et al.,* 1988; KAKKURI and CHEN, 1992; Figure 3a or 3b). The lake has 30 main inflows (the most important being the rivers Emajõgi, Velikaya and Oudova) and only one outflow (River Narva). The River Narva is situated in the NE, in the lifting area, and needs to be regularly scoured of sandy sediments resulting from longshore drift. The discharge through the River Narva is 5,950 m^3 per year.

However, there are contradictory opinions (MIIDEL, 1981, 1992). It seems that the northern part of the lake is lifting at a rate of 0.2–0.4 mm and the southern part is sinking 1.2 mm per year, but in the past these differences were more remarkable. Those processes caused and are still causing the water to flow from north to south; as a result large areas on the western bank lowlands and on Lake Pihkva are severely flooded and/or clogged with muck. The most severe flooding is concentrated at the mouth of the R. Emajõgi, the eastern shore of L. Lämmijärv and the entire low shore of L. Pihkva. In 1956, the flooded area reached 647 km^2 (SOKOLOV, ed., 1983). During the last 1,600 years, the water level rose 0.6–0.8 mm per year in the area of the estuary of Suur-Emajõgi (MIIDEL, 1981). According to R. PIRRUS (PIRRUS and TASSA, 1981), the water-level in Värska Bay has risen 10 m over the last 8,000 years. The area of Piirissaar Island in the southern part of L. Peipsi proper according to A. MIELER (1926) was

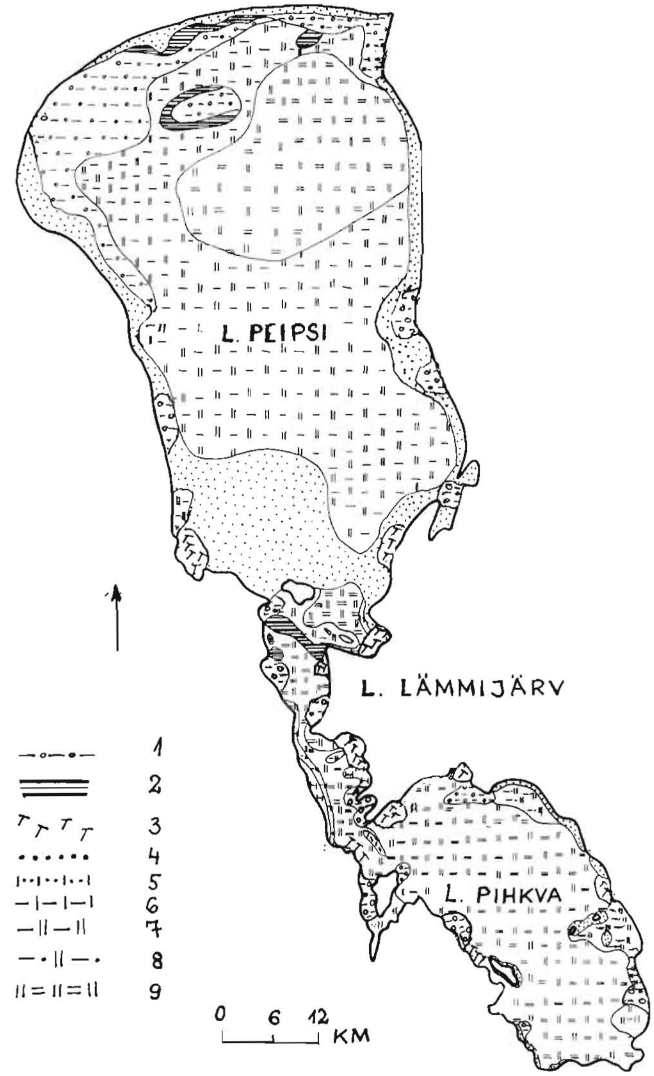

Figure 2. The map of bottom sediments (after RAUKAS and RÄHNI, 1981). (1) till; (2) varved clay; (3) peat; (4) sand; (5) silty sand; (6) sandy silt; (7) slightly clayey silt; (8) sandy clayey silt; (9) clayey silt.

Figure 1. Location of study area.

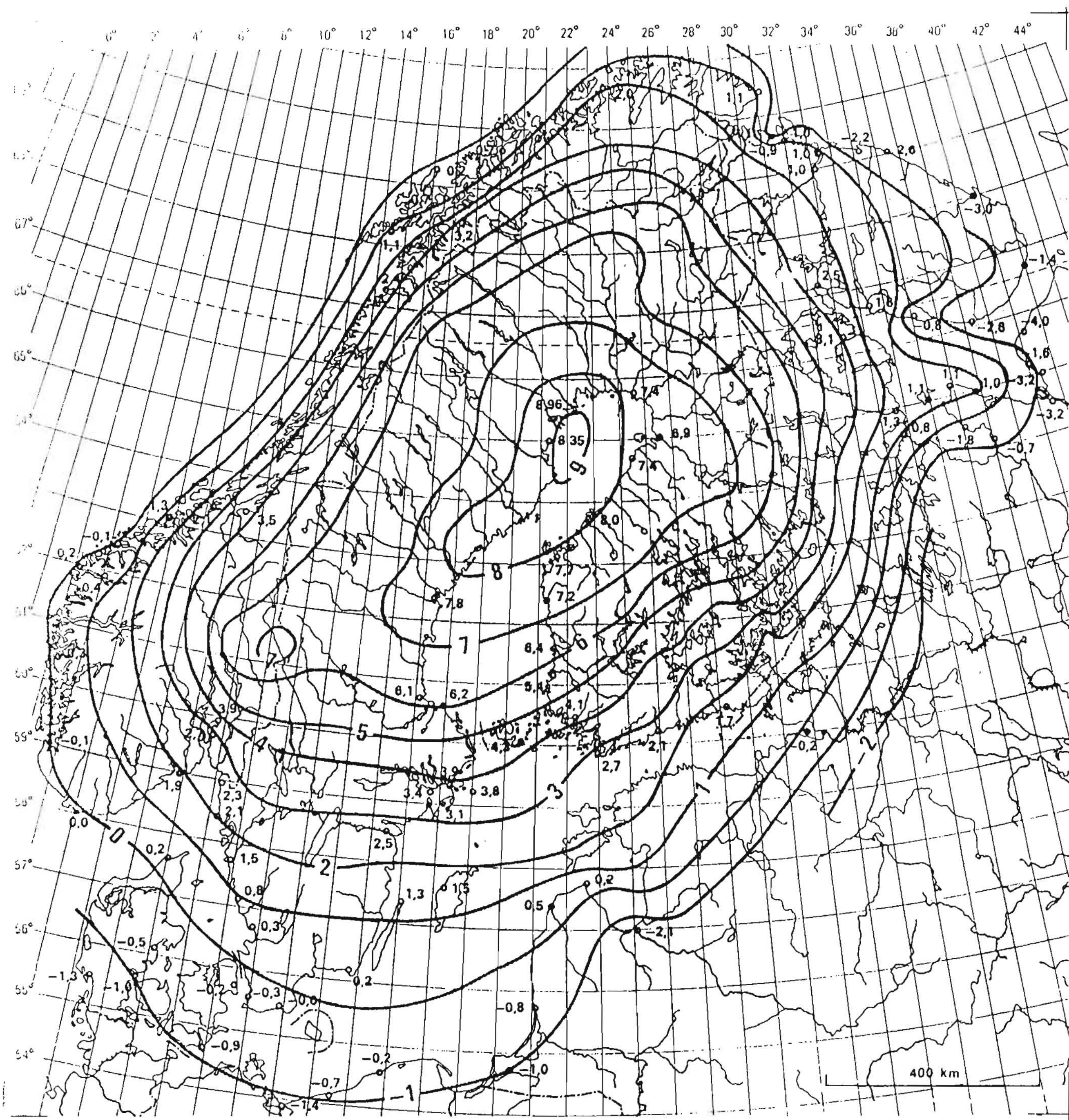

Figure 3a. Contemporary crustal movements of the Fennoscandia area after KAKKURI and CHEN (1992).

in 1796—20.08 km², in 1834—10.64 km²; nowadays its area is only 7.39 km².

HYDROMETEOROLOGY

Water-level fluctuations are considerable (Photo 2). During the last 90 years an amplitude of 3.04 m has been registered. The average water-level of Lake Peipsi is 30.04 m. The lowest water-level of this century was registered on November 7, 1964 (28.72 m a.s.l.) and the highest on May, 12, 1924 (31.76 m a.s.l.). There are also clearly about 11 year periods of high and low water-level (JAANI, 1973). The low water-level at the

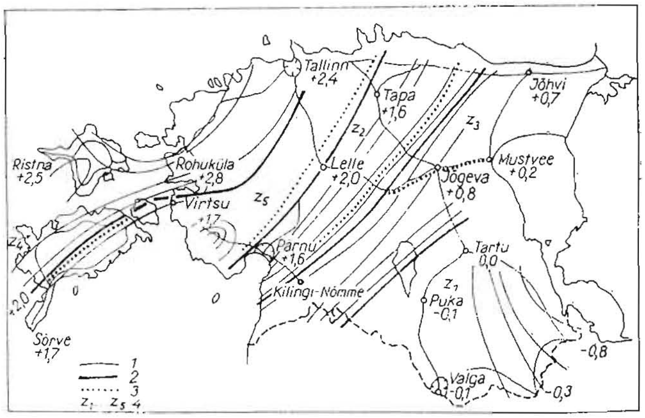

Figure 3b. Scheme of isobases and planes of annual velocities of vertical crustal movements in Estonia after VALLNER *et al.* (1988): (1) leveling network; (2) isobases; (3) bound aries of planes of annual velocities of vertical movements; (4) different lifting and sinking blocks.

Photo 2. The water-level fluctuations in L. Peipsi are considerable. Low water near Kauksi. On the underwater slope till is exposed below sand. (Photo by A. Miidel).

end of the sixties and at the beginning of the seventies has now been substituted by rises in the water-level (Figure 4).

At the end of the 70's and the beginning of the 80's, the water-level was up to 31.02 m (in 1979). Nowadays it is 0.6–0.7 m above its average value.

Winds, Waves and Streams

The south-westerly and southerly (45–50%) winds predominate in the depression of Lake Peipsi causing high rises in the water-level in the northern part of the depression. The width of the beach is only between 5 and 15 metres and the coastal slope is relatively gentle; thus, even a half-metre rise in the water level may cause intensive erosion of the coastal formations. In the western part of the lake, the wind frequently blows from the west and, in the eastern part, from the south, west and north-west. The breezes develop due to the differences in temperature between water and land. The average velocity of the wind is 4–5 m/sec. The maximum speed of the wind measured 20 m/sec and used to be WSW (Tiirikoja) and 24 m/sec WNW (Gdov). The strongest winds blow in October, while June is the calmest month.

Waves are steep and short, and with the wind force 8 m/sec, their height is 60–70 cm (SOKOLOV ed., 1983). Waves with such highs are most common in Lake Peipsi (57%). The highest waves (240 cm) were recorded in 1961 and 1962 with the wind force 20 m/sec.

Wind-drift, wind-gradient (compensation), flow, seiche and internal pressure streams (KALLEJÄRV, 1973) exist in Lake Peipsi. Each part of the lake (Peipsi proper, Lämmijärv and Pihkva) has a different system of streams. The surface water moves in the direction of the wind in the northern part of Lake Peipsi proper, and anticyclonic and cyclonic circulation is characteristic of the southern part of the lake. Near the bottom of the northern part of the Lake Peipsi proper, the compensation streams form; in the shallow southern part, the surface currents reach the bottom. Lake Pihkva is shallow and the streams follow the direction of the wind. In Lake

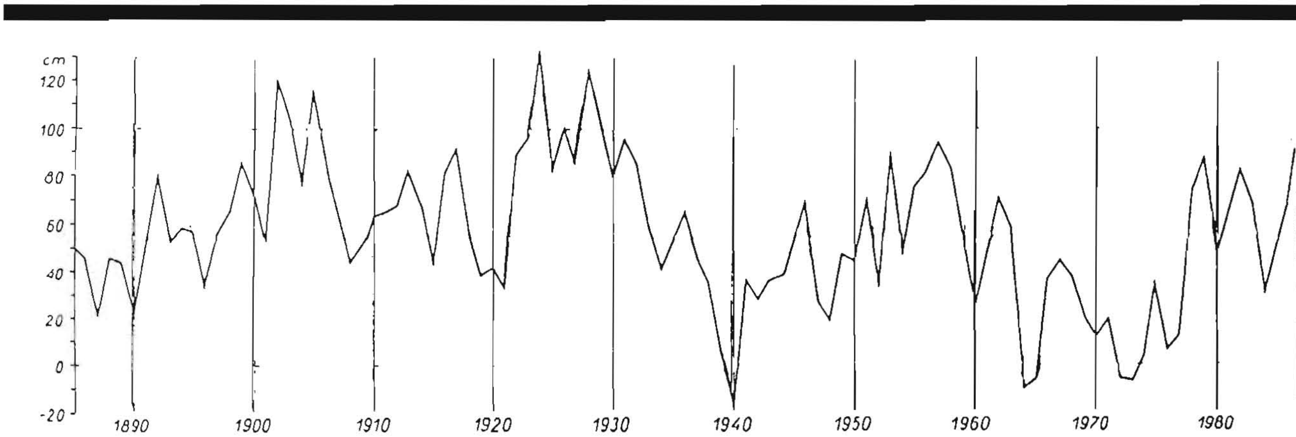

Figure 4. Long period (1885–1987) medium annual water levels (after KULLUS, 1990).

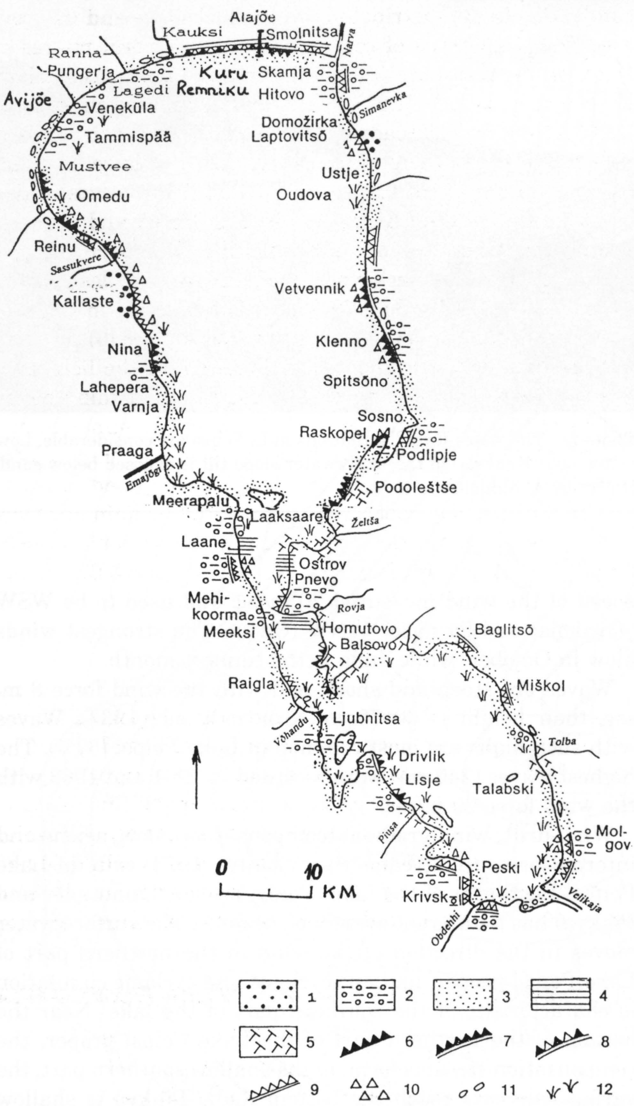

Figure 5. Shore types (after E. TAVAST, 1984a) of the Lake Peipsi. (1) Devonian sandstone; (2) till; (3) sand; (4) clay; (5) peat; (6) cliff; (7–9) bluffs in Quaternary loose sediments; (7) active; (8) passive vegetated; (9) dead; (10) erratic boulders; (11) beach ridge; (12) bulrush and reed zone.

Lämmijärv, the water moves from south to north in the lower layers and from north to south in the upper layers.

The ice cover lasts 114 days. It usually forms in December and melts in April; its average thickness is 50–60 cm in March. During mild winters, the ice cover forms only near the coast within the 1–2.5-km-wide area. Autumn–winter ice drift and abundant formations of frazil ice are usual phenomena on the River Narva, but an extraordinary ice jam was formed at the outflow of the river near the village of Vasknarva in November, 1971. This ice dam blocked the water flow from the lake and the difference between the water-level in the river and the lake was 64 cm (usually 8–12 cm; EIPRE, 1973). This unusual phenomenon was preceded by an abrupt fall in temperature and strong westerly winds.

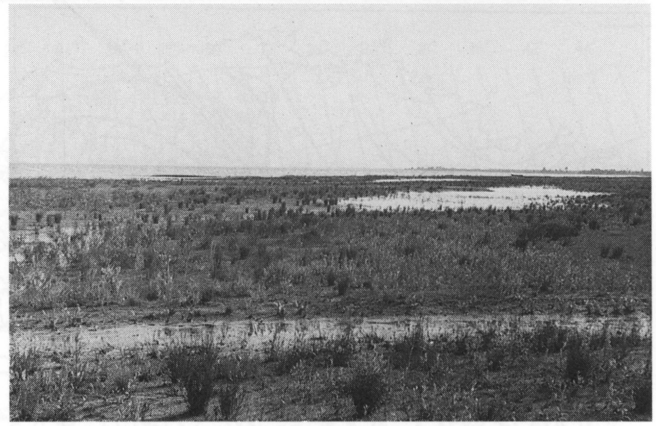

Photo 3. The shores in the western part of the lake are often swampy and overgrown with bushes, bulrush and reeds. Lohusuu. (Photo by A. Miidel).

SHORE TYPES

The first data concerning the coasts of Lake Peipsi were presented by G. HELMERSEN (1864). He differentiated the "cliffed" coast (in Devonian sandstone, till, sand and peat), dune coast and peaty coast.

A. RAUKAS and E. TAVAST (1989) differentiated in Lake Peipsi the following shore types (Figure 5): cliffed (in Devonian sandstones), scarped (in till, sand or peat), flat (in till, sand, peat, silt). The scarped shores can be active or swampy and overgrown with bushes. The flat shores are usually swampy and often with a wide reed and bulrush zone (Photo 3). In the northern part of the lake, sandy beaches are prevailing offering good recreational facilities (Figure 4, Photos 4 and 5).

Like the majority of lakes in the northern hemisphere (KLINGE, 1889), Peipsi has a more open eastern and a more swampy and overgrown western bank. Due to the prevailing south-westerly southerly and westerly winds, the active ero-

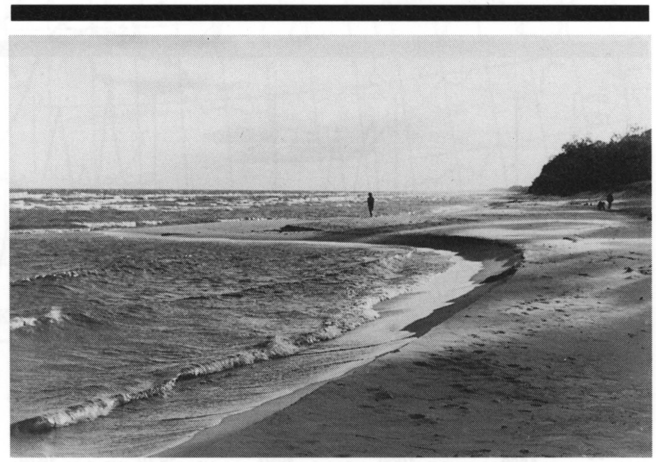

Photo 4. During southerly winds the water-level in the northern part of Lake Peipsi rises rapidly. (Photo by A. Miidel).

Photo 5. After the storm a new equilibrium will be formed. (Photo by A. Miidel).

sion-accumulative or erosional shores are spread in the eastern and northern parts of the lake; while the swampy coasts overgrown with bushes, bulrush and reeds are characteristic of the western and southern parts (Photo 3).

GEOLOGY AND EVOLUTION OF THE NORTHERN COAST

The northern coast of L. Peipsi proper, about 40 km in length, can be divided according to the geological structure into 4 regions: (1) Mustvee-Avijõe, (2) Avijõe-Brook Kauksi, (3) Kauksi-River Narva, and (4) River Narva-Brook Simanevka.

The *sediments* in the coastal zone of the northern part of the lake are mostly represented by till (in the NW part) and sands. Sands are distributed on the backshore and till, covered with some tens of centimetres up to several metres of sand, on the foreshore (Photo 2). Well-sorted (the coefficient of sorting is usually [1.2–1.3] fine and medium-grained sand [Md 0.15–0.47]) is spread on the stretch of the beach between Avijõe and the outflow of the Narva River (Figure 6). Fine, well sorted sand (Md 0.15–0.20; So 1.26–1.14) occurs in the coastal zone between Avijõe and Kauksi Brook and between Jaama and the outflow of the Narva River. Due to river input and erosion of the backshore, medium-grained, less sorted sand (Md 0.38–0.44; So 1.29–1.7) is encountered in an area between Kauksi Brook and Jaama (Tavast, 1984b).

The mineralogical composition (Figure 7) of the light subfraction (density lower than 2.89 Mg/m^3) is dominated by quartz (84–94%) and feldspars (7–16%). Other minerals are represented in amounts less than 1%. Heavy minerals form 0.16–3% (max 75%) in some layers. Magnetite and ilmenite (up to 49.2%) and garnet (up to 36.4%) are the main minerals in the heavy subfraction. The quantity of valuable components, mainly zircone, is comparatively low (1.2–5.6%) in the heavy subfraction.

Shore Description

Shore types are determined by the bottom topography, tectonic movements, lithology of the initial rocks and the exposure of the shore to winds. The swampy overgrown sandy shore spreads from Mustvee to the mouth of the River Avijõgi (Photo 3). The foreshore is bordered by a low beach barrier (0.5–1.5), the upper part of which has been blown into dunes. This low swampy sandy shore, overgrown with bushes, also stretches from Avijõe to the Kauksi Brook. Bushes cover the

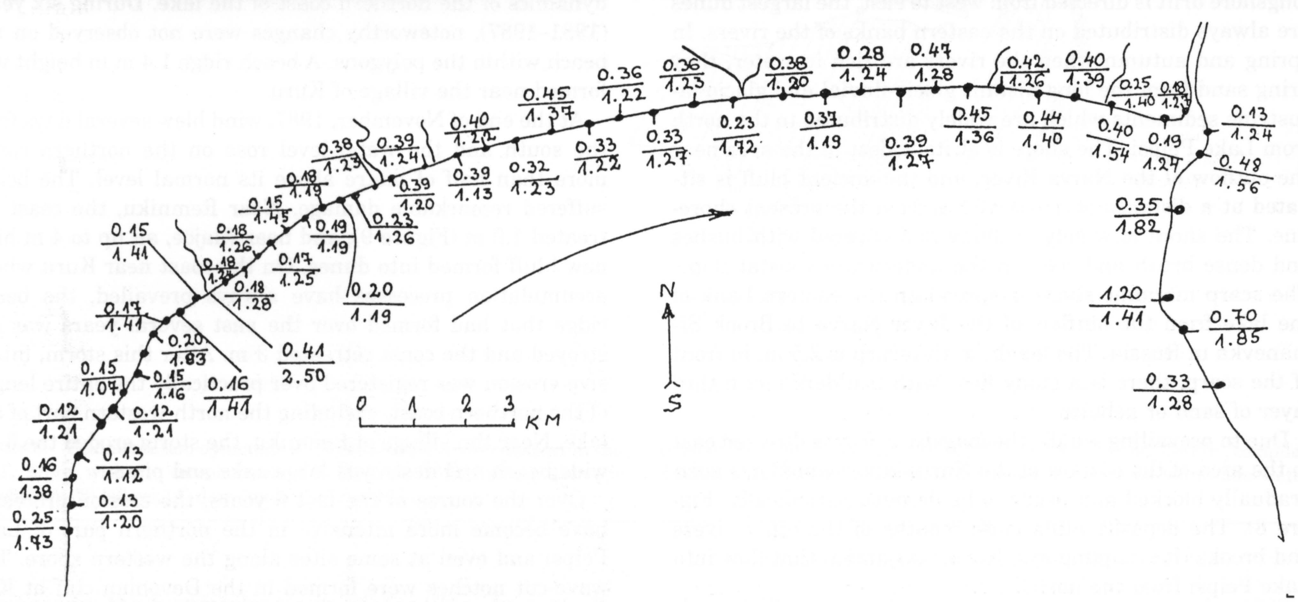

Figure 6. The grain size coefficients of the beach deposits in the northern part of the Lake Peipsi (after Tavast, 1984b; with complements): denominator—the coefficient of sorting, numerator—the median. Arrow shows direction of the drift of the sediments.

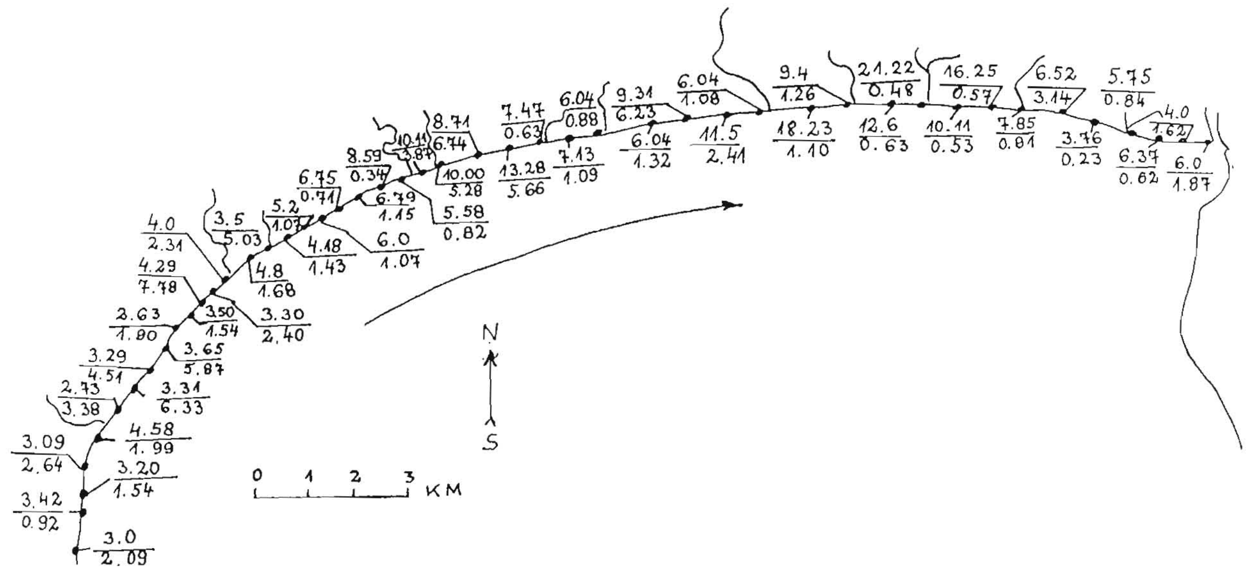

Figure 7. Mineralogical composition of beach sediments. Denominator—the ratio of quartz to feldspars, numerator—the ratio of amphiboles and pyroxenes to garnet. Arrow shows direction of the drift.

shore sporadically. The foreshore is generally flat, and the bed of bulrush or reed is 40–50 m wide. One or two low beach barriers border the foreshore. The active sandy beach begins from Kauksi Brook (Photo 1) and runs as far as the Narva River. One or several bluffs have developed on the ancient dune sands. Shrubs seldom grow in front of the bluff; there is neither reed nor bulrush on the foreshore. The dunes are usually 5–6 m high. At the river mouths, the dunes are higher and in some places they form several parallel ridges. The highest dunes are situated near Alajõe and Smolnitsa. As the longshore drift is directed from west to east, the largest dunes are always distributed on the eastern banks of the rivers. In spring and autumn when the rivers are rich in water, they bring sand from the long distant glacio-fluvial and glacio-lacustrine sediments which are widely distributed to the north from Lake Peipsi. The shore is at its widest in the area near the outflow of the Narva River, and the ancient bluff is situated at a distance of about 100 m from the present shoreline. The shore is widely swampy and covered with bushes and dense brush and reed on the underwater coastal slope. The scarp morainic shore is spread on the eastern bank of the lake from the outflow of the River Narva to Brook Simanevka in Russia. The height of the scarp is 2.5 m; in front of the scarp, there is a stony floor with boulders and a thin layer of sand or pebbles.

Due to prevailing winds, the *longshore drift* is directed east to the area of the outflow of the Narva River which has been gradually blocked and needs to be dredged periodically (Figure 8). The deposits often close mouths of the other rivers and brooks (Rannapungerja, Kuru, Karjamaa) that flow into Lake Peipsi from the north.

Damages have always been great on the eastern and northern coasts of Lake Peipsi which are more open to the wind. During the high water-level, the effect of the deep and short waves on the coast and buildings is considerable. The profile of equilibrium is formed at the coast by winds with a normal velocity of 4–5 m/sec. When the speed of the wind is more than 6–7 m/sec, the bluffs (50–60 cm high) feston and small ridges are formed on the beach. Considerable changes will take place when the speed of wind is more than 15 m/sec.

To assess the intensity of the erosion processes, we set up three polygons on the northern coast of Lake Peipsi in 1981 (Tavast and Raukas, 1991). In 1981–1993, we investigated at least twice a year (in early spring and late autumn) the dynamics of the northern coast of the lake. During six years (1981–1987), noteworthy changes were not observed on the beach within the polygons. A beach ridge 1.4 m in height was formed near the village of Kuru.

At the end of November, 1987, wind blew several days from the south and the water-level rose on the northern coast; more than half of metre above its normal level. The beach suffered remarkable damage. Near Remniku, the coast retreated 1.9 m (Figure 9); and near Alajõe, an up to 4 m high new bluff formed into dunes. On the coast near Kuru where accumulation processes have always prevailed, the beach ridge that had formed over the past several years was destroyed and the coast retreated 3 m. After this storm, intensive erosion was registered over practically the entire length of the northern coast, excluding the north-western part of the lake. Near the village of Remniku, the storm eroded the 5-m-wide beach and destroyed large oaks and pines.

Over the course of the last 6 years, the erosion processes have become more intensive in the northern part of Lake Peipsi and even at some sites along the western shore. The wave-cut notches were formed in the Devonian cliff at Kallaste (Photo 6).

In some places, for example at Rannapungerja in the north-west part of Lake Peipsi, the zone of bulrush and bushes was

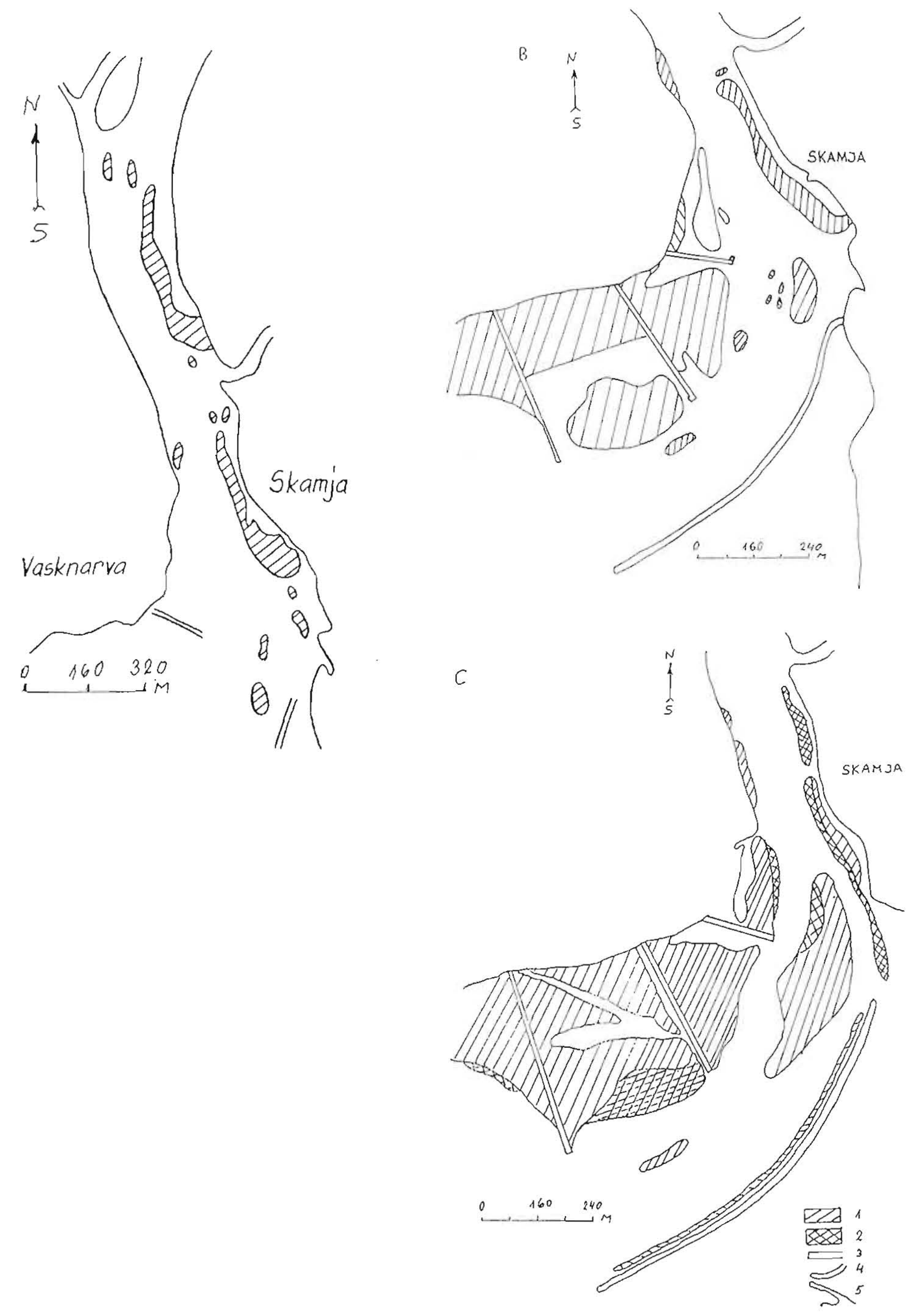

Figure 8. Sedimentation dynamics of longshore and river transport in the jettys near the River Narva outflow in 1937 (a), 1947 (b) and 1981 (c), compiled by T. Eipre, with the complements of E. Tavast. (1) the accumulative area, fixed with vegetation; (2) extending accumulative area with underwater vegetation; (3) jelleys; (4) dam (mole); (5) channels.

damaged by the hummocky ice in winter time. As a result the damage of the coast during its ice free time has increased.

Recommendations for protection. The mass of sand, eroded during the storms from dunes, is mainly carried by the longshore drift to the outflow of the River Narva. In the 1980's, it caused a rise in the water-level. Dredging of the outflow of the river lowers the water-level and reduces somewhat erosion of the shores. Some engineers have proposed to build

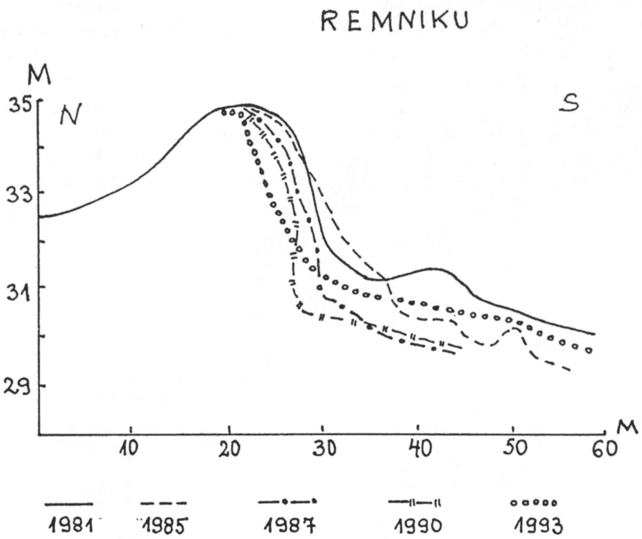

Figure 9. Beach erosion at Remniku. For the location of the profile see Figure 5.

defending walls and buuns in the lake to defend the coast. This action is probably not necessary and from an ecological and aesthetic point of view is not acceptable. Another period of relatively low water-level is expected in the near future (KULLUS, 1990). In the more distant future, erosion will stop here completely due to neotectonic movements of the earth's crust. In view of this, it may be concluded that, here on the shore, we have no need of protective structures, because the situation will soon be normalized. At the same time, the low water-level will be an unsuitable environ for fishing and fisheries. Lake Peipsi ranks among all the lakes in Europe as one of the best fishing grounds. The average catch is 25–34, occasionally 40–42, kg of fish per hectare; in 1915–1917, two hundred thousand centners of smelt were caught per year.

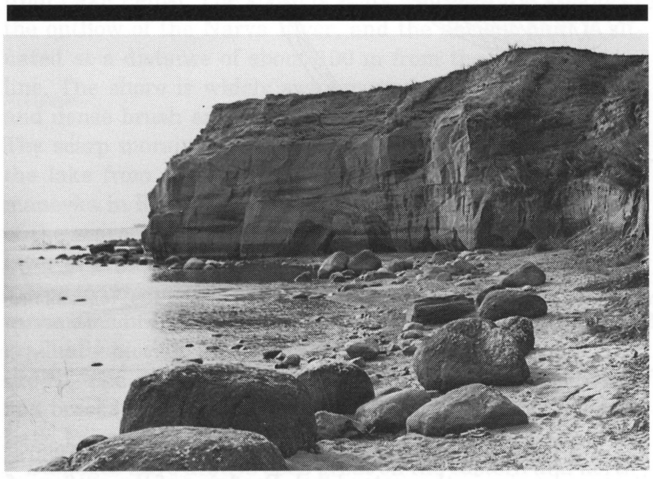

Photo 6. The small wave-cut notches in the Devonian cliff at Kallaste. (Photo by B. Murd).

Lake Peipsi produces about 95% of the total catch of fish from Estonian inland waters, and its water-level must be regulated. The task of geologists and geographers is to determine what will happen on the beaches of the lake if the water-level remains at the same level throughout the year, close to the long time average.

It is necessary to regulate the tourist industry in overcrowded areas, measures should be taken to popularize the regions now being only moderately used.

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