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Holocene sea-level changes and glacio-isostasy in the Gulf of Finland, Baltic Sea

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Abstract

Shoreline displacement in the eastern part of the Gulf of Finland during the past 9000 radiocarbon years was reconstructed by studying a total of 10 isolated lake and mire basins located in Virolahti in southeastern Finland and on the Karelian Isthmus, and in Ingermanland in Russia. Study methods were diatom analyses, sediment lithostratigraphical interpretation and radiocarbon dating. In southeastern Finland, the marine (*Litorina*) transgression maximum occurred ca. 6500–6200 ¹⁴C yr BP (7400–7100 cal. yr BP). In areas of the slower land uplift rate on the Karelian Isthmus and in Ingermanland, the transgression maximum occurred ca. 6400–6000 ¹⁴C yr BP (7300–6800 cal. yr BP). The highest *Litorina* shoreline is located at ca. 23 m above present sea-level in southeastern Finland, whereas in the eastern part of the Karelian Isthmus, near St. Petersburg, it is located at ca. 8 m above present sea-level. The amplitude of the *Litorina* transgression in Virolahti area is ca. 4 m, whereas on the Karelian Isthmus and in Ingermanland the amplitude has varied between 5 and 7 m. The regional differences between areas are solely due to different glacio-isostatic land uplift rates. The seven basins studied in this research were connected to the Baltic Sea basin during the *Litorina* Sea stage and their diatom and lithostratigraphical records indicate a single, smooth *Litorina* transgression.

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1. Introduction

Since the opening of the ocean connection via the Danish Straits between 8500 and 8000 radiocarbon years ago, the shore displacement in the Baltic basin has been governed by two factors: the glacio-isostatic land uplift and the eustatic movement of the ocean level.

The *Ancylus* Lake stage which preceded the *Litorina* Sea stage ended in the Baltic Sea ca. 8200–8000 ¹⁴C (9000–8800 cal. BP) years ago, when saline water entered the Baltic Sea basin through the Danish Straits (Björck, 1995). This was caused by a rapid global rise in the ocean level caused by the warming of the climate and deglaciation, especially in Northern America (e.g. Tooley, 1989). In Fennoscandia the rate of land uplift had slowed down after the melting of the continental ice sheet, at which phase the eustatic rise of ocean level in the area of the Danish Straits exceeded the rate of land

uplift (e.g. Eronen et al., 1990; Björck, 1995). The conversion to brackish conditions of the entire Baltic basin took several hundred years, and the change from fresh-water to brackish conditions in the basin was time-transgressive. This weakly saline transition phase from the fresh-water *Ancylus* Lake stage to the brackish *Litorina* Sea stage is known as the *Mastogloia* Sea stage (e.g. Hyvärinen, 1982, 1984). All researchers (e.g. Ignatius et al., 1981; Miettinen, 2002) do not consider the *Mastogloia* Sea stage as an independent phase but rather a part of the *Ancylus* Lake or *Litorina* Sea stage, because it cannot be verified in deep-water sediments, and not always in shallow-water sediments in all parts of the Baltic Sea.

Most of the Baltic Sea was distinctly brackish by ca. 7500 BP (8200 cal. BP), which marks the clear onset of the *Litorina* Sea stage. The beginning of this stage is the clearest observable stratigraphical boundary in the bottom sediment of the Baltic Sea. The grey clay of the *Ancylus* Lake stage is abruptly transformed into finely laminated greenish-grey gyttja clay, usually

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containing some 10–15% organic matter (Ignatius et al., 1981). The effect of saline water gradually increased as the Danish Straits deepened and water could more freely enter the Baltic Sea basin. In 7000–6000 BP (7800–6800 cal. BP) salinity was at its highest during Holocene, exceeding 20‰ near the Danish Straits, ca. 8‰ on the coast of the Gulf of Bothnia, and ca. 5‰ in the eastern part of the Gulf of Finland (Hyvärinen et al., 1988). In areas of moderate to slow isostatic uplift, such as Gulf of Finland, the rate of eustatic rise temporarily exceeded the uplift rate, resulting in trends of transgression in the shore displacement around and after 7000 ¹⁴C yrs BP. The corresponding phase in the Baltic Sea history is known as the Litorina transgression.

In general outline, the relative sea-level trends during the Litorina Sea stage are well established. However, there are essential details which still remain unsettled, the results obtained from different areas being often in apparent disagreement with each other. An important point of controversy is the number of Litorina transgressions (i.e. the existence and significance of short-term fluctuations in the relative sea-level history during the Litorina Sea stage). The data available from areas including Blekinge, Sjælland, Estonia and St. Petersburg have been interpreted in terms of up to six secondary transgressions superimposed on the main curve (Berglund, 1964, 1971; Dolukhanov, 1973; Digerfeldt, 1975; Kessel and Raukas, 1979; Christensen, 1982, 1995). However, the timing and the number of the fluctuations vary in different studies. Some areas on the Finnish side have yielded results pointing to a smooth change, and it has been argued that the Baltic evidence is best interpreted in terms of a single broad Litorina transgression (Eronen, 1974; Hyvärinen, 1980, 1982; Hyvärinen et al., 1992). If the differences between the individual areas and localities are real, they might result from local or regional irregularities in the isostatic uplift. On the other hand, the differences might conceivably be due to a different interpretation or resolution of the data available from each area. If careful studies indicate that the transgressions form a synchronous pattern traceable in separate parts of the Baltic basin, they must then be of eustatic origin (i.e. due to fluctuations in the ocean level).

This paper summarises the main results of the shore displacement study carried out in the eastern part of the Gulf of Finland (Miettinen, 2002). The focus of this study lies on the changes of the relative sea-level of the Baltic Sea in the following three areas of slow land uplift on the eastern coast of the Gulf of Finland: Virolahti in southeastern Finland, the Karelian Isthmus, and Ingermanland in Russia (Fig. 1). The aim of the study was to provide a more comprehensive picture of shore displacement in the Gulf of Finland during the past 9000-radiocarbon (10,000 cal.) years. Interest was focused particularly on the period of 8000–5000 BP

(8800–5700 cal. BP), in other words, the early part of the Litorina Sea stage. The aim was to determine whether there was one broad transgression in the Baltic Sea basin during the Litorina Sea stage or whether there was oscillation of the sea-level. The beginning and end of the Litorina transgression, the transgression amplitude, and the highest Litorina shoreline in the study area were determined. As the glacio-isostatic land uplift is an important factor in shore displacement, the aim was to determine the nature of land uplift in the eastern part of the Gulf of Finland.

2. Glacio-isostatic land uplift in the Fennoscandia area

During the Late Weichselian glacial maximum ca. 18,000 ¹⁴C yr BP (Landvik et al., 1998; Svendsen et al., 1999) Fennoscandia was covered by a continental ice sheet with a maximum thickness of ca. 3 km (Fjeldskaar, 1994; Peltier, 1994) whose weight made the Earth's crust warp downwards by several hundred metres. Land uplift was caused by the Earth's crust aiming to achieve an isostatic balance. The depression created by the Scandinavian Ice Sheet during the Weichselian glaciation is gradually rebounding and part of the mass of the top of the mantle is shifting from outside the area of uplift to its centre. This is why areas covered by ice sheets are now experiencing land uplift and the border areas subsidence.

Glacio-isostatic land uplift was extremely rapid at the end of, and immediately after deglaciation. Major late- or postglacial faults in northern Fennoscandia date back to this time (Kujansuu, 1964; Lundqvist and Lagerbäck, 1976; Lagerbäck, 1990; Kuivamäki and Vuorela, 1994). The rate of land uplift decreased significantly ca. 8500–8000 BP (9500–8800 cal. BP) (Eronen et al., 1995; Ristaniemi et al., 1997). Judging from data collected in different parts of Fennoscandia, it seems that land uplift has taken place under the last 10,000 yrs dominantly and without major irregularities. Regionally observed, land uplift seems to take place plastically, but locally the uplift is realised as movements of blocks of the bedrock (Kuivamäki and Vuorela, 1994).

In determining the rate of recent Scandinavian uplift—based on geodetic observations—the uplift of the crust relative to mean sea-level is called the apparent land uplift, which in the northern part of the Gulf of Bothnia, in the centre of the area of uplift is about 9 mm/yr (Fig. 2) (Kääriäinen, 1966; Kakkuri, 1987; Ekman, 1987, 1989; Ekman and Mäkinen, 1996). The uplift has been determined by using a network of 54 mareographs that record the fluctuations of water level on the coast of the Baltic Sea and the North Atlantic, and by repeated precise levelling in the inland areas (e.g. Kakkuri, 1985).



Fig. 1. The Baltic region and location of the study area in the eastern part of the Gulf of Finland.

3. Study area

The study area covers the coast of the eastern part of the Gulf of Finland: the Virolahti area in southeastern Finland, the Karelian Isthmus, and Ingermanland in Russia (Fig. 3). Altogether 10 basins were cored for this study (Table 1). In southeastern Finland in Virolahti, samples were taken from five lake basins (Vähäjärvi, Virojärvi, Saarasjärvi, Mustalampi and Valkjärvi) and one mire basin (Ruokolamminsuo) located at different altitudes between 7.5 and 26.6 m above present sea-level (a.s.l.). The basins are located relatively close to one another at almost same land uplift isobases. In the Virolahti area the present rate of apparent land uplift is ca. 2 mm per year, which is the lowest uplift rate in Finland (e.g. Kääriäinen, 1966; Ekman and Mäkinen,

1996). On the Karelian Isthmus samples were taken from two lake basins (Vysokinskoye and Glukhoye) and one mire basin (Privetninskoye) located at altitudes between 6 and 12 m a.s.l. (Fig. 3). In Ingermanland samples were taken from one lake basin, Babinskoye (6 m a.s.l.). In the centre of the Karelian Isthmus the present uplift rate is ca. 1 mm per year and the St. Petersburg area is located close to the zero uplift isobase.

4. Methods

In this study, research methods were lithostratigraphic interpretation, diatom analysis, and radiocarbon dating. When a basin becomes an independent lake

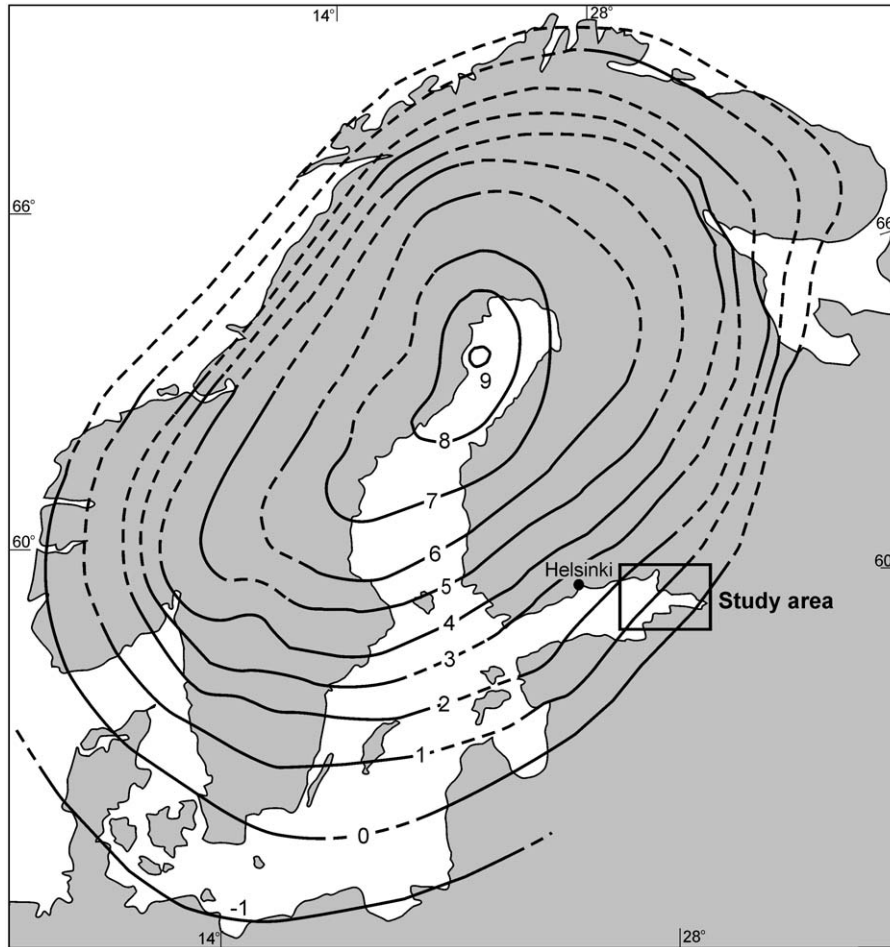


Fig. 2. Apparent land uplift (mm/yr) in Fennoscandia (modified from Ekman and Mäkinen, 1996).

isolated from the sea because of land uplift, or when a basin is again connected to sea because of a transgression, the accumulating sediment shows a distinct change. Especially in the early phases of the Holocene, clay was deposited in coastal waters, but as lake basins became isolated, gyttja was deposited in the basins. This lithostratigraphical change is clear in most basins. Diatoms can be used to show how large-lake (i.e. Ancylus Lake) or brackish-water forms were replaced by small-lake forms in connection with the isolation of the basin.

4.1. Sampling

The studied cores were taken from eight lake basins and two mires in 1995–1998. When possible, the cores were taken from the deepest part of the basins. From the lake basins samples were taken through the ice in the wintertime using a Russian peat sampler (\varnothing 5 cm, length 1 m) and a Livingstone corer (acrylic tubes with a diameter of 5 cm, and length 2 m). From

the mires, samples were taken using a Russian peat sampler.

4.2. Loss-on-ignition

The amount of organic matter was determined as loss-on-ignition. To measure loss-on-ignition, samples weighing 10–12 g were dried overnight at a temperature of 105°C, after which their dry weight was measured. Then the samples were ignited in an oven at a temperature of 550°C for 2.5 h. Sediment was confirmed through loss-on-ignition and visual observation. LOI% 2, 6 and 20 were used as limit values to determine sediment type boundaries clay/gyttja clay, gyttja clay/clay gyttja, and clay gyttja/gyttja, respectively.

4.3. Diatom analysis

The diatom samples were prepared according to standard methods (Battarbee, 1986). Where possible, approximately 300 valves were counted in each sample.

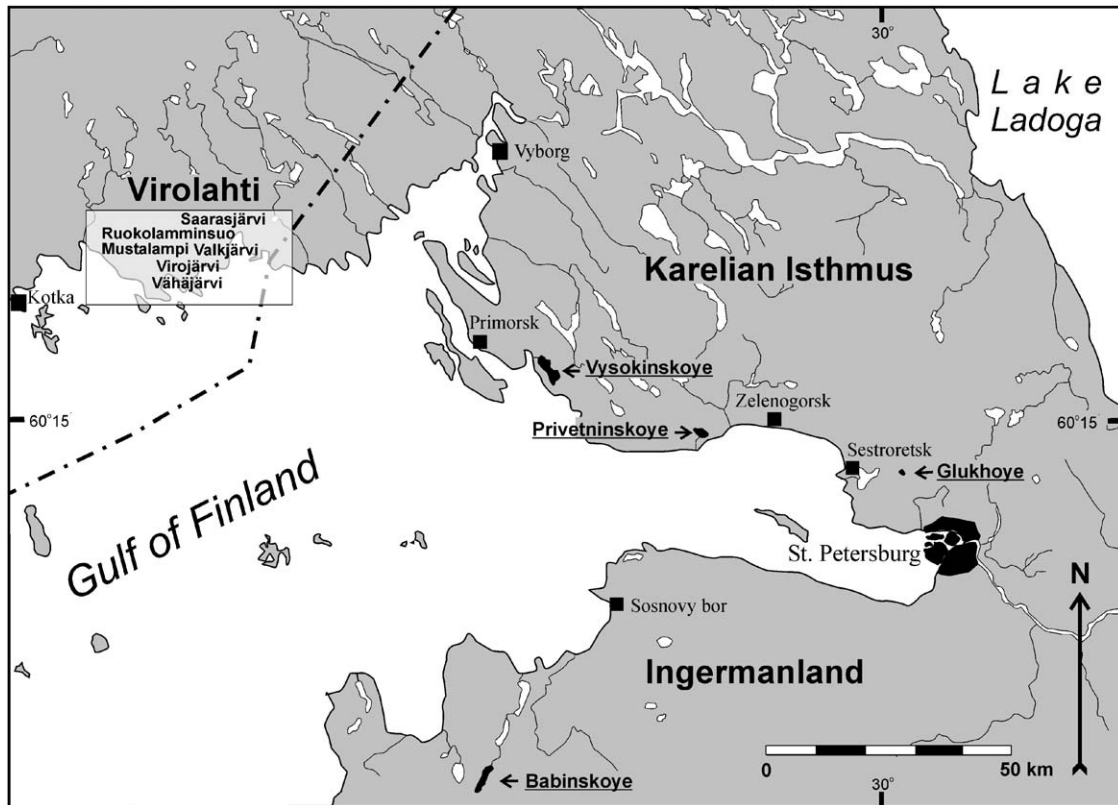


Fig. 3. Map of the study area in the eastern part of the Gulf of Finland.

Table 1
Studied sites in Virolahti, southeastern Finland, on the Karelian Isthmus and in Ingermanland, Russia

Basin	Geographical location	Coordinates	Altitude (m a.s.l.)	Present uplift rate (mm/yr)
Lake Vähäjärvi	Southeastern Finland	60°30'N, 27°34'E	7.5	2.0
Lake Virojärvi	Southeastern Finland	60°32'N, 27°35'E	18.7	2.0
Lake Saarasjärvi	Southeastern Finland	60°36'N, 27°37'E	19.5	2.0
Ruokolamminsuo mire	Southeastern Finland	60°34'N, 27°26'E	21.0	2.0
Lake Mustalampi	Southeastern Finland	60°33'N, 27°31'E	23.0	2.0
Lake Valkjärvi	Southeastern Finland	60°33'N, 27°31'E	26.6	2.0
Lake Vysokinskoye	Karelian Isthmus	60°17'N, 28°52'E	12.0	0.8
Privetninskoye mire	Karelian Isthmus	60°10'N, 29°25'E	6.0	0.5
Lake Glukhoye	Karelian Isthmus	60°05'N, 30°04'E	9.0	0.0
Lake Babinskoye	Ingermanland	59°36'N, 28°36'E	6.0	0.5

The taxonomy and grouping of diatoms according to their biotype and salinity preferences is based on the following sources: Miller (1964), Mölder and Tynni (1967–1973), Tynni (1975–1980), Krammer and Lange-Bertalot (1986–1991), Snoeijs (1993), Snoeijs and Vilbaste (1994), Snoeijs and Potapova (1995), Snoeijs and Kasperovičienė (1996), and Snoeijs and Balashova (1998). Main groups according to biotype are planktonic and littoral forms. The latter group is divided further into benthic and epiphytic forms. According to salinity diatoms are classified into the following main groups: euhalobous polyhalobous (salinity > 30‰) and

mesohalobous (5–20‰), oligohalobous halophiles (< 5‰) and indifferent (0–2‰), and halofobous (0‰).

4.4. ^{14}C analyses

A total of 38 ^{14}C analyses were carried out from the 10 basins included in this study, 30 of which conventional dating and eight AMS carried out in the Dating Laboratories of the University of Helsinki (Hel/Hela), University of Lund (LuA) and Geographic Institute of the University of St. Petersburg (LU) (Table 2). Dating results are given as years starting from the year 1950 AD

Table 2
Radiocarbon analyses carried out in 10 basins in Virolahti, on the Karelian Isthmus and in Ingermanland, Russia

Basin	Lab.no.	Depth (cm)	Dated sediment	Age BP	Cal. age
Lake Vähäjärvi	Hel-4185	38–48	Gyttja	2400 ± 90	2360
Lake Virojärvi	Hel-4191	200–210	Gyttja	5250 ± 110	5960
	Hel-4190	255–265	Gyttja	6300 ± 100	7210
	Hel-4189	322–332	Gyttja	7420 ± 110	8160
Lake Saarasjärvi	Hel-3906	240–250	Gyttja	5940 ± 100	6760
	Hela-58	341	Wood	6225 ± 110	7110
	Hela-59	360	Wood	6890 ± 390	7660
	Hel-3907	430–440	Gyttja	7630 ± 110	8390
	Hela-60	572	Wood	8015 ± 135	8780
Ruokolaminsuo mire	Hela-62	157	Wood	4425 ± 100	5020
	Hel-3719	167–174	Gyttja	5700 ± 110	6480
	Hel-3720	192–198	Gyttja	7520 ± 110	8320
Lake Mustalampi	Hel-4186	200–207	Gyttja	6980 ± 100	7760
	Hel-4151	236–243	Gyttja	7930 ± 110	8690
	Hel-4152	255–262	Gyttja	8560 ± 100	9490
	Hel-4153	268–275	Gyttja	8660 ± 110	9540
Lake Valkjärvi	Hel-3932	80–85	Gyttja	5960 ± 100	6840
	Hel-3931	100–105	Gyttja	7890 ± 110	8590
Lake Vysokinskoye	LU-3863	70–90	Gyttja	3430 ± 140	3660
	LU-3886	110–130	Gyttja	4950 ± 170	5660
	LU-3887	150–170	Clay gyttja	5820 ± 190	6660
	LU-3866	180–190	Gyttja	7160 ± 110	7930
	LU-3885	190–210	Gyttja	8120 ± 130	8990
	LU-3860	280–300	Clay gyttja	8370 ± 150	9420
Privetninskoye mire	LU-3845	100–110	Clay gyttja	4920 ± 120	5650
	LU-3846	140–150	Clay gyttja	5350 ± 100	6130
	LU-3847	180–190	Clay gyttja	6110 ± 120	6970
	LU-3852	280–290	Peat	7440 ± 80	8170
	LU-3849	320–330	Gyttja	8060 ± 290	8980
Lake Glukhoye	LU-3897	135–145	Gyttja	4560 ± 120	5290
	LU-3898	155–165	Gyttja	4480 ± 90	5190
	LU-3899	175–185	Gyttja	6400 ± 170	7270
	LU-3900	195–205	Gyttja	8380 ± 100	9410
	LU-3896	225–235	Gyttja	9140 ± 180	10040
Lake Babinskoye	LuA-4883	317.5–327.5	Gyttja	940 ± 115	840
	LuA-4882	942.5–947.5	Clay gyttja	5375 ± 95	6180
	LuA-4881	1052.5–1057.5	Gyttja	7135 ± 95	7920
	LuA-4880	1137.5–1142.5	Clay gyttja	9565 ± 110	10750

and they are based on the half-life of the ^{14}C (5568 y). The radiocarbon ages were calibrated to calendar years with a program developed by [Stuiver and Reimer \(1993\)](#). There were inaccuracies in some radiocarbon ages (e.g. the large margin of error (± 190) in the isolation age of the Vysokinskoye basin) and a statistical linear model was used in order to examine the relationship between age and depth. This model plots a polynomial graph of estimated age ([Maddy and Brew, 1995](#)).

5. Results

5.1. Shoreline displacement in Virolahti, Southeastern Finland

Data on shoreline displacement in Virolahti were used to reconstruct a shoreline displacement curve ([Fig. 4](#)). All the studied basins are located in close proximity to one another at almost the same land uplift isobase, so land uplift has not caused any significant changes in the

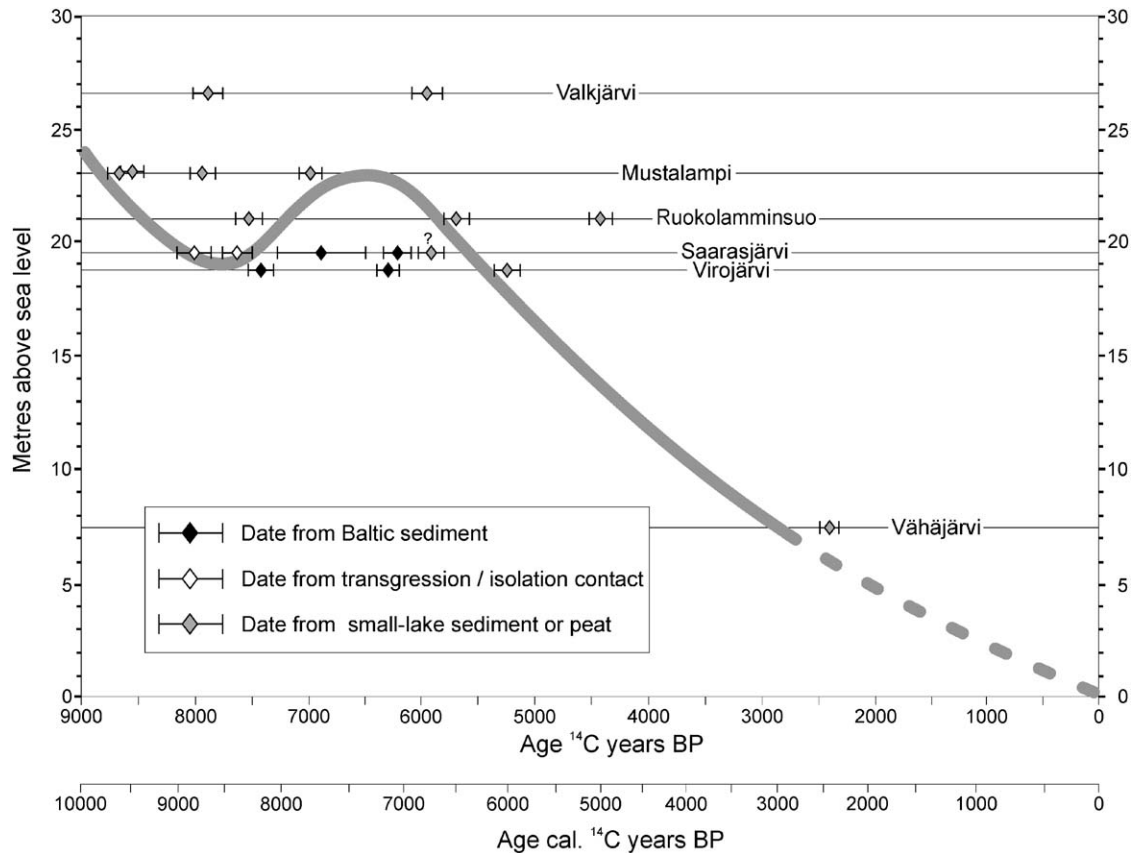


Fig. 4. Shore displacement curve for Virolahti area and southeastern Finland. Datings details are presented in Table 2.

relative altitudes of the basins. Thus, it is possible to place the present threshold altitudes directly in the diagram.

Before the beginning of the Litorina Sea stage, sea-level in Virolahti was at its lowest during the Ancyclus regression, which occurred towards the end of the Ancyclus Lake stage. Of the basins studied in this research, Valkjärvi and Mustalampi became isolated as independent basins in an earlier phase of the Ancyclus regression than Ruokolamminsuo and Saarasjärvi, which are located at somewhat lower altitudes; Saarasjärvi became isolated during the final phases of the regression ca. 8000 BP (8800 cal. BP). The first small-lake phase of Saarasjärvi and Ruokolamminsuo represents a low-water phase in the Baltic Sea basin, that is, a transition phase from the Ancyclus Lake stage to the Litorina Sea stage. Judging by radiocarbon ages from the Ruokolamminsuo core and particularly from the Saarasjärvi core, this transition phase took place ca. 8000–7600 BP (8800–8400 cal. BP).

After the Ancyclus regression sea-level began to rise when the thresholds in the Danish Straits were flooded by the rising ocean level. Saarasjärvi was invaded by the waters of the Litorina transgression ca. 7500 BP

(8200 cal. BP) and the Ruokolamminsuo basin, located at a somewhat higher altitude, ca. 7400 BP (8100 cal. BP). Located at a lower altitude (18.7 m a.s.l.) than the other basins, Virojärvi did not become isolated during the Ancyclus regression; instead, diatom stratigraphy indicates that the Ancyclus Lake stage was followed directly by the Litorina Sea stage. Thus in Virolahti sea-level before the Litorina transgression was at its lowest ca. 19 m a.s.l..

During the Litorina transgression, sea-level in Virolahti reached ca. 23 m above sea-level at its highest. This can be concluded from the fact that Mustajärvi, which is located at this altitude, remained as a small lake throughout the Litorina transgression. A few individual brackish-water species in the diatom flora indicate that the sea-level rose very close to but not clearly above the basin threshold altitude. Radiocarbon analyses carried out on the Saarasjärvi and Virojärvi cores indicate that sea-level was at its highest ca. 6500–6200 BP (7400–7100 cal. BP). A relatively reliable estimate of the amplitude of the Litorina transgression in Virolahti can be concluded from the analyses carried out on the cores. Before the Litorina transgression, sea-level in the Baltic Sea basin was ca. 19 m and during the

transgression maximum ca. 23 m above present sea-level. Thus the amplitude of the Litorina transgression can be estimated at ca. 4 m.

Four of the studied basins (Mustalampi, Virojärvi, Ruokolamminsuu and Saarasjärvi) are located relatively close to the highest Litorina shoreline, and during the transgression the sea-level rose at most a couple of metres above the threshold altitude of three of these basins (Ruokolamminsuu, Virojärvi and Saarasjärvi). Thus, these presently shallow basins were shallow sea bays during the Litorina Sea stage. This is also indicated by the brackish-water diatom flora, which includes almost solely littoral forms. Located closest to the highest Litorina shoreline and having been invaded by the transgression, the Ruokolamminsuu basin has been particularly shallow, since its diatom flora does not contain any pelagic planktonic species. In Saarasjärvi and Virojärvi, a few pelagic planktonic species occur towards middle section of the core. At this phase water depth in the basins was at its greatest and the connection to the Baltic Sea at its broadest. Only shallow-water littoral forms occur on both sides of this planktonic flora peak in the middle section of the core. If sea-level had fluctuated during the transgression phase, the fluctuations should be clearly identifiable in these shallow basins as peaks in the occurrence of planktonic diatom taxa. Since only one such occurrence is found in the studied basins among littoral taxa, it is reasonable to conclude a single-phase transgression.

The threshold altitude of the Vähäjärvi basin is 7.5 m a.s.l.. Because of the low basin threshold altitude, the basin was an open sea bay during the Litorina transgression when the sea level rose 15–16 m above the threshold altitude. This is marked in the diatom flora by the relatively abundant occurrence of the planktonic flora favouring a higher degree of salinity (including *Thalassiosira baltica*, *T. eccentrica*, *Coscinodiscus asteromphalus* and *Actinocyclus octonarius* var. *tenellus*). The proportion of planktonic flora remains high until the basin gets shallower and shallow-water littoral flora becomes dominant. If a significant rise in the sea-level had occurred, it should be visible as an increase in planktonic flora in relation to littoral flora; a fall of the sea-level would show an opposite shift in the diatoms. Lithostratigraphical evidence of such an occurrence would also be expected, but is not evident in the region studied.

Once the rate of eustatic rise of the sea-level began to slow, relative sea-level fell because of land uplift, and basins located close to the highest Litorina shoreline became isolated to form independent lake basins. The shoreline displacement curve shows a discrepancy in the relative isolation ages of the Ruokolamminsuu, Saarasjärvi and Virojärvi basins, as according to the ages Ruokolamminsuu would have become isolated as an independent lake ca. 5900–5800 BP (6700–6600 cal. BP),

Saarasjärvi, which is located at a lower altitude, somewhat over 6000 BP (6800 cal. BP) and the lowest basin, Virojärvi, ca. 5500 BP (6300 cal. BP). In view of the overall evidence, it seems likely that the Saarasjärvi age of 5940 ± 100 BP is erroneous. The discrepancy may be due to a dating error or to local conditions which affected the isolation development of the basins. In reality the correct isolation date of Saarasjärvi is probably ca. 5700–5600 BP (6500–6400 cal. BP).

The research material obtained in Virolahti contains evidence of only one Litorina transgression which began ca. 7600 BP (8400 cal. BP) and ended ca. 5700–5500 BP (6500–6300 cal. BP), thus lasting ca. 2000 yr. In this context, the “duration of the transgression” means the time interval from the beginning of the transgression to the point when the sea-level reverts back to the level preceding the transgression. Lithostratigraphical and diatom analyses did not yield evidence of sea-level fluctuations.

The studied material does not show any signs of irregularities in land uplift. The shore displacement development in the region corresponds to other shoreline displacement studies carried out in southern Finland (e.g. Eronen, 1974; Hyvärinen, 1984). Datings and the transgression peaks differ from the results obtained in more western areas, but this is only to be expected in view of the slower rate of land uplift in southeastern Finland.

5.2. Shoreline displacement on the Karelian Isthmus and in Ingermanland, Russia

It was not possible to reconstruct shoreline displacement on the Karelian Isthmus and in Ingermanland as accurately as in Virolahti. The problem concerns the relatively long distances between the basins located at different land uplift isobases. For the purposes of this study the basins were placed on the same shoreline displacement curve by calculating a rough threshold altitude for the basins on the basis of present absolute values of land uplift (Fig. 5).

As a result of the Ancyclus regression, sea-level in the Baltic Sea basin fell. Located in the eastern part of the study area near St. Petersburg, the Glukhoye basin became isolated from the Ancyclus Lake somewhat over 9000 BP (10,000 cal. BP). Located at a higher altitude (12 m a.s.l.) but in an area where land uplift is more rapid, the Vysokinskoye basin became isolated from the Ancyclus Lake ca. 8500 BP (9500 cal. BP). With a land uplift intensity between that of the Glukhoye and Vysokinskoye basins and located at the lowest altitude (6 m a.s.l.), the Privetninskoye and Babinskoye basins became isolated from the Ancyclus Lake 8100–7800 BP (9000–8500 cal. BP). Judging by radiocarbon analyses made from the above mentioned basins, sea-level in the Karelian Isthmus and Ingermanland was at its lowest

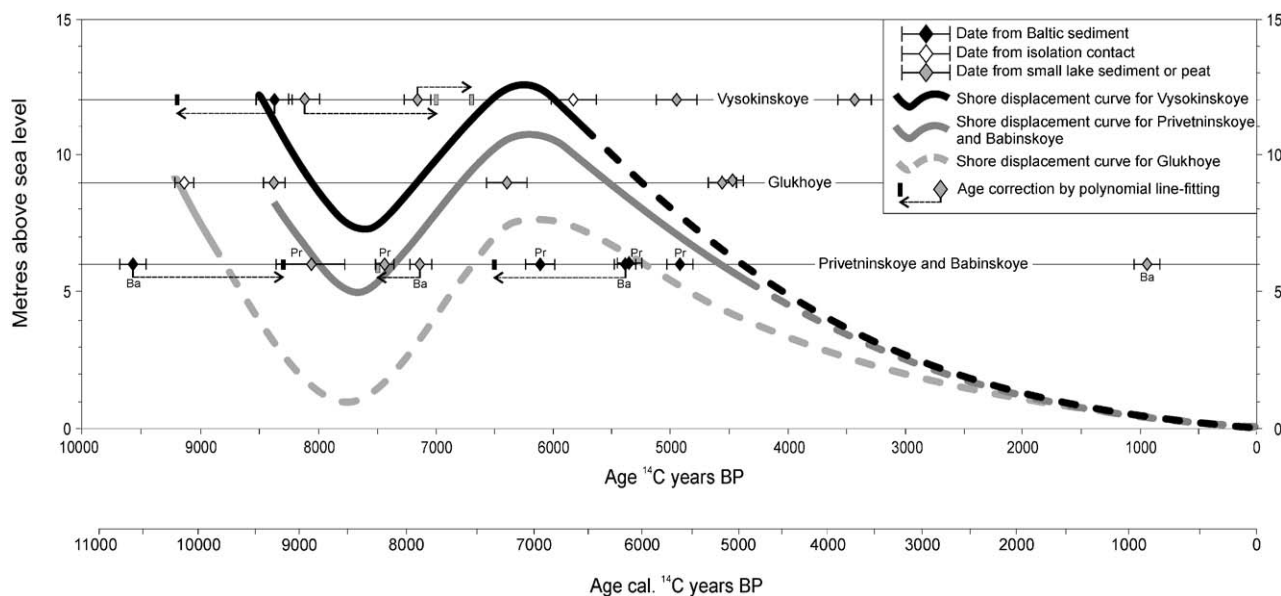


Fig. 5. Shore displacement curves for the various sites on the Karelian Isthmus and in Ingermanland.

towards the end of the Ancylus regression ca. 8000–7500 ^{14}C years ago (8800–8200 cal. BP).

It is not possible to pinpoint the exact position of the sea-level during the low-water phase between the Ancylus Lake and Litorina Sea stages. Estimates of this low-water phase are based on observations from the Privetninskoye and Babinskoye basins, located relatively at lowest altitudes. They indicate that the basins remained independent lake basins for a period of 300–700 radiocarbon years, a relatively short time. Thus, sea-level during the lowest phase of the Ancylus regression must have been quite close to the threshold altitude of the basins, possible ca. 1 m below the threshold (ca. 5 m above present sea-level).

After the Ancylus regression sea-level began to rise again in the Karelian Isthmus and Ingermanland around 7700–7600 BP (8400 cal. BP) as a result of the Litorina transgression. Located at lower altitudes than the other basins, Privetninskoye and Babinskoye were invaded by the Litorina transgression ca. 7400 BP (8100 cal. BP). Located at a higher altitude and in an area of more rapid land uplift, the Vysokinskoye basin was not invaded by the Litorina transgression until ca. 6500 BP (7400 cal. BP).

When determining the maximum of the Litorina transgression, the focus lies on the Glukhoye and Vysokinskoye basins, which are located close to the highest Litorina shoreline. Lithostratigraphical and diatom evidence indicates that the Litorina transgression reached the Vysokinskoye basin but not the Glukhoye basin, which was at a relatively higher altitude at this time. In the eastern part of the study area in the Glukhoye region the highest Litorina

shoreline is thus at less than 9 m above present sea-level, probably at 8–9 m a.s.l.. Judging by radiocarbon analyses undertaken from above and below the transgressive horizon of the Vysokinskoye core, the Litorina Sea transgression extended to the basin between about 6500 and 6100 BP (7400 and 6900 cal. BP). The dating for the beginning of the transgression is less well-defined, so it is possible that the transgression began somewhat earlier (7000–6500 BP) (7800–7400 cal. BP). During the transgression the sea-level has just barely reached the threshold altitude of the Vysokinskoye basin, since both radiocarbon ages and diatom and lithostratigraphical evidence indicate a short brackish-water phase whose diatom flora consists of littoral forms and shows that the basin remained a shallow lagoon throughout the phase. It may be estimated that the sea-level exceeded the basin threshold by ca. 1 m. As the threshold altitude in the Litorina Sea stage was ca. 12 m a.s.l., the highest Litorina shoreline in this area is ca. 13 m a.s.l.. The occurrence of the transgression maximum ca. 6300–6200 BP (7200–7100 cal. BP), as estimated on the basis of the diatom stratigraphy of the Privetninskoye basin, corresponds to the Vysokinskoye transgression maximum. Towards the middle of the Karelian Isthmus and in Ingermanland in the Babinskoye region the transgression maximum occurred ca. 6400–6200 BP (7300–7100 cal. BP). There are no new radiocarbon ages available from the eastern part of the Karelian Isthmus, in the St. Petersburg area, but on the basis of the previous dating, the age of transgression maximum in this region can be estimated at ca. 6200–6000 BP (7100–6800 cal. BP).

When determining the amplitude of the Litorina transgression, the focus lies on the Privetninskoye and Babinskoye basins, located close to the lowest level of the Ancylus regression, and the Vysokinskoye basin located close to the Litorina maximum. The amplitude of the Litorina transgression at Vysokinskoye in the middle of the Karelian Isthmus is 5–6 m and somewhat farther to the east, in the Privetninskoye region, ca. 6 m. At Glukhoye the amplitude is estimated at ca. 7 m.

The Vysokinskoye basin became isolated from the Litorina Sea ca. 6000 BP (6800 cal. BP). Lithostratigraphical and diatom evidence indicates a short transgression phase with duration of ca. 400 radiocarbon years. There are no signs of fluctuations during this period. The Privetninskoye and Babinskoye basins became isolated from the Litorina Sea ca. 4600 BP (5300 cal. BP). The Litorina transgression thus lasted ca. 2800 radiocarbon years in this land uplift isobase. In the Privetninskoye basin, the maximum occurrence of the planktonic diatom flora towards the middle of the transgressive layer and the minimum organic content correspond well with one another and indicate a transgressive maximum. Before and after the transgressive maximum the diatom flora is dominated by shallow-water littoral forms. The development of the Babinskoye basin follows a similar pattern, although its lithostratigraphy and diatom stratigraphy are more varied.

In the Karelian Isthmus and Ingermanland the Litorina transgression began ca. 7700–7600 BP (8400 cal. BP) and ended mainly ca. 4500 BP (5100 cal. BP), culminating 6400–6000 BP (7300–6800 cal. BP). The transgression amplitude (=the rise of relative sea-level from a low-water phase preceding transgression until transgression maximum) totalled 5–7 m, depending on the region and the rate of land uplift. Research carried out on basins situated on the Karelian Isthmus and in Ingermanland indicates one clear Litorina transgression. However, the present results do not exclude the possibility of fluctuations of sea level during the past 4500 ¹⁴C years, if the amplitudes of the fluctuations were small and remained below the present threshold altitude of 6 m of the Privetninskoye and Babinskoye basins, which are located at lower altitudes than the other studied basins.

6. Discussion

Shoreline displacement in the eastern part of the Gulf of Finland was reconstructed by studying a total of 10 lake and mire basins located in Virolahti in southeastern Finland and on the Karelian Isthmus and in Ingermanland in Russia. Due to the slow rate of land uplift in these areas, even minor movements of the sea-level are

relatively easy to reconstruct and they are visible in the lithostratigraphy and diatom stratigraphy of the basins.

In the eastern part of the Gulf of Finland, the manifestation of the Litorina transgression is not chronologically synchronous because of variations in the regional land uplift intensity. In southeastern Finland, the Litorina transgression began ca. 7600 BP (8400 cal. BP), the transgression maximum occurred ca. 6500–6200 BP (7400–7100 cal. BP) and the transgression ended ca. 5700–5500 BP (6500–6300 cal. BP) (Fig. 6). In areas of slower land uplift rate on the Karelian Isthmus and in Ingermanland the transgression began earlier, ca. 7700–7600 BP (8400 cal. BP), the transgression maximum occurred somewhat later ca. 6400–6000 BP (7300–6800 cal. BP), and the transgression also ended later, ca. 4500 BP (5100 cal. BP). The duration of the Litorina transgression was in southeastern Finland ca. 2000 yr and in Russia somewhat over 3000 yr. Such a large difference between the areas is solely due to the different land uplift rate.

For the same reason, that is, as the land uplift rate continues to slow down when we move eastwards from Virolahti across the Karelian Isthmus towards St. Petersburg, the altitude of the highest Litorina shoreline above present sea-level decreases (Fig. 7). Three of the studied basins are located above the highest Litorina shoreline. At 26.6 m a.s.l., Valkjärvi in Virolahti lies clearly above the highest Litorina shoreline, while Mustalampi, situated at 23 m a.s.l., is located immediately at the level of the highest Litorina shoreline or just above it. In the eastern part of the Karelian Isthmus at 9 m a.s.l., Glukhoye is located somewhat above the highest Litorina shoreline. Thus in Virolahti in southeastern Finland the highest Litorina shoreline is situated at ca. 23 m above present sea-level, whereas in the eastern part of the Karelian Isthmus it is located at ca. 8 m above present sea-level. The gradient of the highest Litorina shoreline is ca. 10 cm/km in the area between Virolahti and Glukhoye in the eastern part of the Gulf of Finland.

Land uplift also explains regional differences in the amplitude of the Litorina transgression. In Virolahti, the amplitude maximum is ca. 4 m. On the Karelian Isthmus and in Ingermanland the amplitude varies between 5 and 7 m, reaching up to ca. 7 m near St. Petersburg and ca. 5 m farther west on the Isthmus.

Altogether seven basins studied in this research were connected to the Baltic Sea basin during the Litorina Sea stage and their diatom and lithostratigraphical evidence indicates a single, smooth Litorina transgression. The relative sea-level has first risen to its culmination point as a result of the eustatic rise of the sea-level, beginning to fall after the eustatic rise slowed down. The development is particularly clear in the two basins (Saarasjärvi and Privetninskoye), located at relatively low altitudes, that had become isolated as

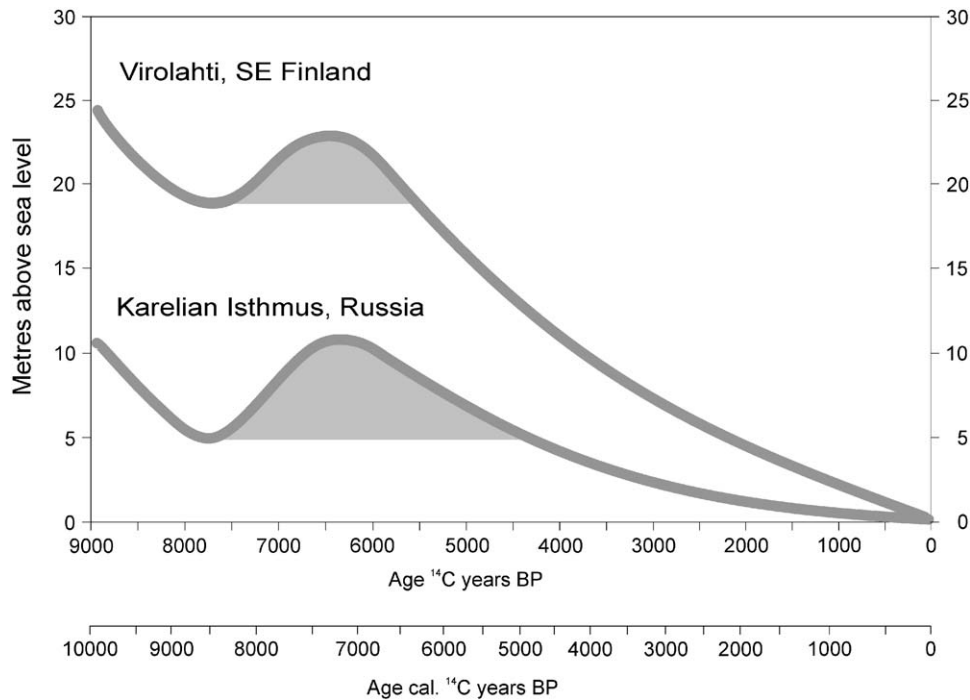


Fig. 6. Shore displacement curves for southeastern Finland (Virolahti) and the central part of the Karelian Isthmus and Ingermanland (Privetninskoye–Babinskoye). The shaded area represents the duration of the Litorina transgression.

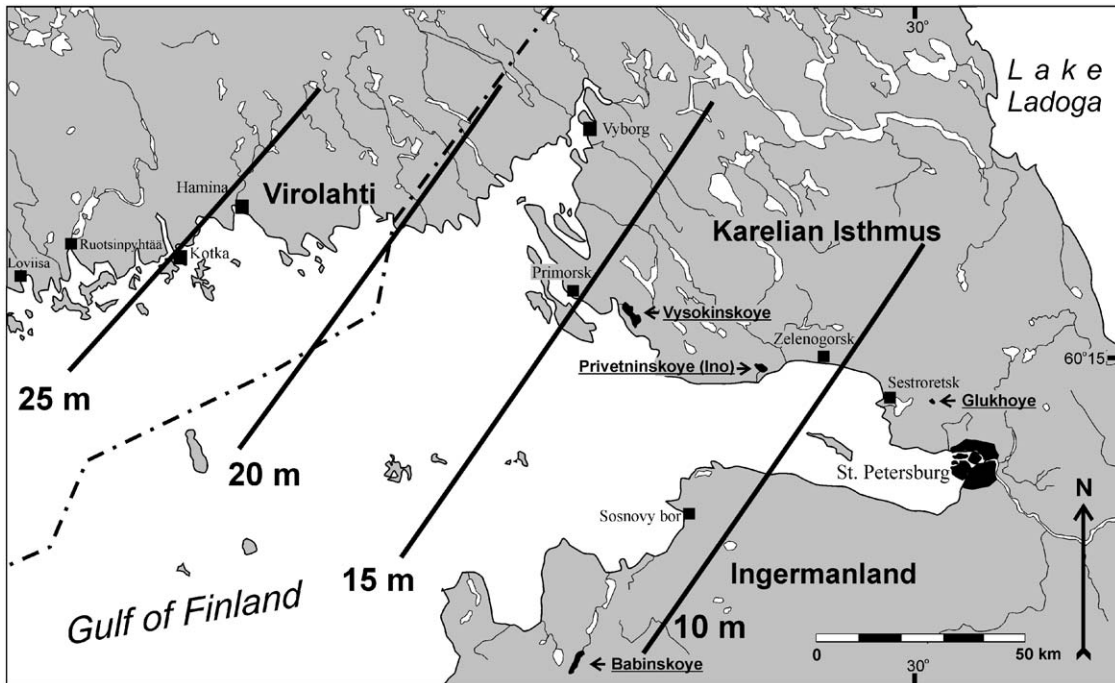


Fig. 7. The highest Litorina shoreline isobases in the eastern part of the Gulf of Finland.

independent basins towards the end of the Ancylus Lake stage, but were reconnected to the Baltic Sea already in the early phases of the Litorina transgression. The sedimentary sequences of these basins representing the

Litorina Sea stage are relatively long, and their diatom stratigraphy shows a clear succession from shallow-water littoral flora to planktonic flora indicating deeper water. During regression the succession is reversed until

the isolation of the basin. Located at relatively higher altitudes, the Ruokolamminsuo and Vysokinskoye basins were invaded by the transgression for a shorter period of time and their diatom flora represents only shallow-water littoral flora. The absence of a deep-water phase that is part of the development of basins at lower altitudes indicates that these two basins were located close to the highest Litorina shoreline. The development observed in the diatom flora of the basins located at lower altitudes in particular indicates one distinct transgression during the Litorina Sea stage in the eastern part of the Gulf of Finland.

The diatom taxa found in this study include a relatively small number of polyhalobous forms indicating a high salinity. During the Litorina Sea stage the salinity of the sea-water in the eastern part of the Gulf of Finland was higher than present (cf. Myrberg, 1998), but has probably remained below 5‰ (cf. Hyvärinen et al., 1988). The studied basins have been relatively shallow sea bays also during the Litorina transgression maximum and in deeps the salinity has naturally been higher.

The development of the Litorina Sea stage in the eastern part of the Gulf of Finland has been the subject of several studies, most of them following along the same lines concerning issues such as the duration and amplitude of the Litorina transgression. Discussion has focused mostly on the nature of the Litorina transgression, as various studies have provided contradictory results. The results of this study, indicating one smooth transgression is in agreement with the results of Markov (1931, 1934), Virkkala (1953), Eronen (1974, 1983), Hyvärinen (1980, 1999), Matiskainen (1989) and Seppä et al. (2000). Evidence of a multi-stage Litorina transgression by some researchers (Hyypä, 1937; Sauramo, 1940, 1958; Salmi, 1961; Valovirta, 1965; Tynni, 1966; Dolukhanov, 1979; Znamenskaya et al., 1980) was not found.

Due to the small number of suitable study sites close to the present sea-level, shoreline displacement in southern and southeastern Finland in the late Holocene during the past 6000 ¹⁴C years has not been studied as extensively. This is why the possibility of fluctuations of the sea-level in this period cannot be excluded. The problem also applies to the Karelian Isthmus. Although the basins now studied are located at 6–12 m above the present sea-level and thus at considerably lower altitudes than in southern and southeastern Finland, because of slower land uplift they became isolated from the Baltic Sea already at an early phase.

The Litorina transgression resulted from the global rise in sea-level, which affected the shoreline levels along all coastal areas in the eastern part of the Gulf of Finland, where the sea-level rise clearly exceeded the rate of uplift in period 7500–6000 BP (8200–6800 cal. BP). The new results from Virolahti in the eastern part

of the Gulf of Finland gives a distinct picture of a smooth development of the Litorina transgression in the period 7500–5500 BP (8200–6300 cal. BP); a corresponding smooth transgressive development in the period 7600–4500 BP (8400–5100 cal. BP) is indicated by data obtained from the Karelian Isthmus and Ingermanland. Thus, our understanding of the Litorina Sea stage development in the eastern part of the Gulf of Finland in this period lies on a sounder foundation than before, but shoreline displacement in the late Holocene or during the past 4500 radiocarbon (5100 cal.) years remains uncertain. Nevertheless, stratigraphical data from the Vähäjärvi basin (7.5 m a.s.l.), strongly suggests a smooth regression of the sea-level until the isolation of the basin ca. 2500 BP (2600 cal. BP). Thus, it is likely that there were no any significant fluctuations of the sea-level in the period 4500–2500 BP (5100–2600 cal. BP). It seems, that the sea-level has lowered at a rather steady rate due to the isostatic land uplift during the past 6000 ¹⁴C (6800 cal.) years, although the occurrence of minor fluctuations in this period or during the past 2500 radiocarbon years cannot be excluded. The results of this study cannot be considered final; full certainty of shoreline displacement in even this relatively small area would require more extensive research.

7. Conclusions

1. The global rise in sea-level clearly exceeded the rate of glacio-isostatic land uplift in the eastern part of the Gulf of Finland in period 7700–6000 BP (8400–6800 cal. BP), which phase in the Baltic Sea history is known as the Litorina transgression.
2. The Litorina transgression is not chronologically synchronous because of variations in the regional land uplift intensity. In southeastern Finland the Litorina transgression began ca. 7600 BP (8400 cal. BP) and ended ca. 5700–5500 BP (6500–6300 cal. BP), culminating ca. 6500–6200 BP (7400–7100 cal. BP). In the Karelian Isthmus and Ingermanland the Litorina transgression began ca. 7700–7600 BP (8400 cal. BP) and ended mainly ca. 4500 BP (5100 cal. BP), culminating 6400–6000 BP (7300–6800 cal. BP).
3. Because the rate of land uplift continues to slow down when moving eastwards in the Gulf of Finland, the altitude of the highest Litorina shoreline above present sea-level decreases. In southeastern Finland the shoreline is located at ca. 23 m a.s.l., whereas in the eastern part of the Karelian Isthmus it is located at ca. 8 m a.s.l.. The gradient of the highest Litorina shoreline is ca. 10 cm/km in the area between southeastern Finland and the eastern part of the Gulf of Finland.

4. Glacio-isostatic land uplift explains regional differences in the amplitude of the Litorina transgression. In southeastern Finland, the amplitude maximum is ca. 4 m. On the Karelian Isthmus and in Ingermanland the amplitude varies between 5 and 7 m, reaching up to ca. 7 m near St. Petersburg and ca. 5 m farther west on the Isthmus.
5. Results indicate a single, smooth Litorina transgression. The relative sea-level has first risen to its culmination point as a result of the eustatic rise of the sea-level, and due to the land uplift, beginning to fall after the eustatic rise slowed down. Results did not yield evidence of sea-level fluctuations, although the occurrence of minor fluctuations during the past 2500 radiocarbon years cannot be excluded.

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