

Late Holocene sea-level changes along the southern coast of Finland, Baltic Sea

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Abstract

Lake isolation studies provide a reliable method for reconstructing the sea-level history of areas affected by the glacio-isostatic land uplift. In this study, Late Holocene relative sea-level changes were investigated along the southern coast of Finland, Gulf of Finland in the Baltic Sea, by studying 11 isolation basins in four areas (Kirkkonummi, Orslandet, Tenhola and Prästkulla), which extend across 120 km of Finnish coastline that is characterised by a narrow archipelago. The methods employed were lithostratigraphic interpretation, diatom analyses and radiocarbon dating. Also used in this work are the results from three previously studied isolation basins with four ¹⁴C dates.

The sea-level history varies within the study area. The 3000 yr old Baltic Sea shoreline is located about 11 m above present sea-level (a.s.l.) in Prästkulla, and about 8 m a.s.l. in Kirkkonummi. These differences are due to the differences in isostatic uplift rates, which have been slower in the east. The main trend in relative sea-level along the southern coast of Finland is one characterised by a generally decreasing uplift rate during the Late Holocene. However, we identify the uplift anomalies in two areas where our data show phases of relative sea-level lowering. They are the first verified Late Holocene land uplift anomalies detected in Finnish sea-level data.

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1. Introduction

The aim of the project “Western Uusimaa during the Finnish Late Iron Age and Mediaval Period (c. AD 500 to 1550) — Settlement history from the viewpoint of archaeology, history, biology and geology” was to shed light on a poorly known period in the history of the coast and archipelago of southern Finland. We investigated

sea-level changes, palaeoenvironment, human activities, resource utilization and settlement history of the study area with an emphasis on maritime adaptations and the utilization of the archipelagic resources. Even in periods as recent as the Finnish Late Iron Age and Medieval Period, relative sea-level changes must be taken into account before any topographical analysis or landscape reconstruction can be conducted. This is the motivation for reconstructing more detailed records of sea-level changes in various study areas during the past 3000 yr.

Due to the slow land uplift rate and the presence of numerous isolation basins, the Finnish south coast is one

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of the key areas for investigating the sea-level history of the Baltic Sea. Many sea-level studies have been completed in Finland, but they have mostly been focused on the first half of the Holocene. A small number of sea-level studies of the Late Holocene have been carried out in southern Finland east of Helsinki (e.g. Miettinen et al., 1999; Seppä et al., 2000), but only two studies exist west of Helsinki (Hyvärinen, 1999; Eronen et al., 2001). In this paper we summarise the results of the first sea-level study focused solely on the Late Holocene sea-level changes in the southern coast area. We present the results from an analysis of 11 isolation basins from four areas (Kirkkonummi, Orslandet, Tenhola and Prästkulla). In addition, we use the results from three previously inves-

tigated isolation basins (Hyvärinen, 1999; Eronen et al., 2001). Because of the large amount of new field and laboratory and field data, the results from 13 sites are presented in a summary format. Detailed results are described from one site, Lake Petarträsk (Orslandet), which is a key site for the reconstruction of land uplift anomalies in this area.

2. Geological background

The present Baltic Sea (Fig. 1) is the largest brackish-water basin in the world (surface area 377 400 km², volume 21 200 km³ (Sjöberg, 1992)). The Baltic Sea receives freshwater from over 200 rivers, in total a water



Fig. 1. The present Baltic Sea and the area covered the study areas along the coast of southern Finland.

volume approximately equal to the net outflow from the Baltic Sea (Bergström and Carlsson, 1994). Precipitation and evaporation are more or less in equilibrium, and there is a limited inflow of saltier bottom water from North Sea via Kattegat over shallow (18 m) and narrow thresholds. The water budget maintains a stable salinity gradient: about 15–25‰ in the Kattegat, 8–10‰ in Arkona, 6–8‰ in the central Baltic Sea, and, 1–4‰ in the northern Gulf of Bothnia, Gulf of Finland and Gulf of Riga (Snoeijs, 1999).

During the Late Weichselian glacial maximum, 20–15 ka BP (Svendsen et al., 2004), Fennoscandia was covered by a continental ice sheet with a maximum thickness of about 2.75 km (Siebert et al., 2001) whose weight made the Earth's crust warp downwards by several hundred metres. Most of the areas formerly covered by the ice sheet are now rebounding. The uplift of the crust was rapid immediately following deglaciation and led to movement on major faults along old fracture zones in early post-glacial times in Northern Fennoscandia (Kuivamäki et al., 1998), followed by gradually slower uplift.

Geophysical model predictions indicate that the isostatic recovery will continue for thousands of years with *c.* 90 m of residual land uplift remaining (Ekman and Mäkinen, 1996). Land uplift seems to taking place on a regional scale in a plastic manner, but on local scale as discrete blocks of the bedrock (Kuivamäki et al., 1998). 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) (Ekman and Mäkinen, 1996).

Owing to the glacio-isostatic uplift and consequent tilting of the land, several water connections between the Baltic Sea and the North Sea existed, which were closed at various points in times during the Late Weichselian and the early Holocene (Björck, 1995). Concurrently with land uplift, relative sea-level changes in the Baltic basin were strongly affected by the global “eustatic” rise in sea-level. The post-glacial evolution of the coastlines in the northern part of the Baltic basin has been dominated by the emergence of new land areas.

The precise information on local and regional relative sea-level change is obtained from small uplifted lake

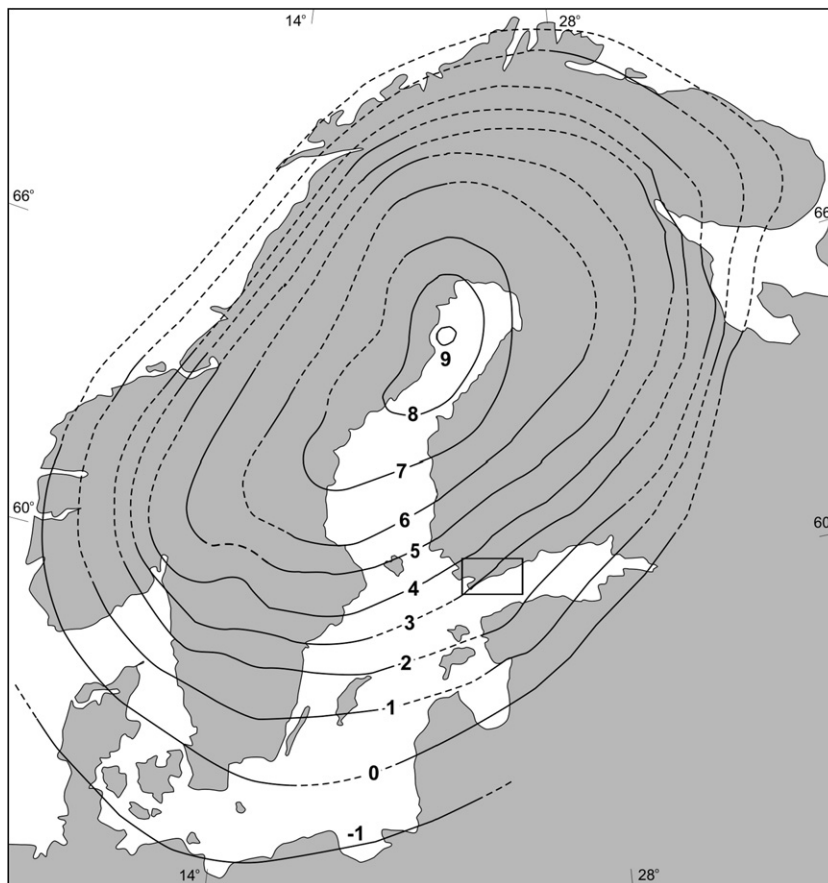


Fig. 2. Present apparent glacio-isostatic land uplift (mm/yr) in Fennoscandia (modified from Ekman and Mäkinen, 1996).

basins where the isolation of the basin from the sea can be detected in the changes of sediment and diatom composition. These radiocarbon dated isolation contacts can be used as sea-level index-points.

The four study areas are located along the southern coast of Finland (Fig. 3). The area is characterized by narrow topographical zones stretching in an east–west direction. In the middle archipelago zone there are several east–west geological valley formations that even today form good fairways, whilst deep, fjord-like bays cut the mainland in the north–south direction. Many fracture zones exist in the bedrock of the study area (Vuorela, 1982). The bedrock consists mainly of early Proterozoic metamorphic and igneous rocks (age >1.8 Ga) (Korsman et al., 1997). The present apparent land uplift rate varies from 3.1 to 2.5 mm/yr from west to east in this area (Fig. 2). The area is suitable for sea-level studies due to abundance of small lakes situated at various elevations above present sea-level (a.s.l.).

3. Methods

3.1. Sampling

The cores were taken from 11 isolated lake basins located between 0.8 and 13.0 m above present sea-level. The thresholds of the basins consist of till, and the threshold elevations were determined from topographic maps. In the Orslandet area, these elevations were also

levelled. The investigated lake basins were relatively small and shallow; their size varies between 0.1 and 0.5 km² (mostly between 0.1 and 0.2 km²), and the depth between 1.0 and 5.5 m (mostly between 2 and 3 m). Where possible, the cores were taken from the deepest part of the basins. The samples were taken through the ice in the wintertime using a Russian peat sampler (Ø 8 cm, length 1 m). Because one purpose of this study was to define the isolation contacts of the basins, we collected cores that extended across the isolation contacts for detailed laboratory analyses. These isolation contacts were preliminary identified during coring by the visual observations of sediment composition.

3.2. Loss-on-ignition

The amount of organic matter was determined by loss-on-ignition (LOI). To measure LOI, samples (10–12 g) were dried overnight at a temperature of 105 °C, after which their dry weight was measured. The samples were then ignited in an oven at a temperature of 550 °C for 2.5 h. Sediment types were confirmed through LOI and visual observation. LOI percentage values of 2%, 6% and 20% were used as limit values to determine sediment type boundaries of clay/gyttja clay, gyttja clay/clay gyttja, and clay gyttja/gyttja, respectively. Usually, when a basin becomes isolated from the Baltic Sea, the accumulating sediment shows a distinct change. The Baltic Sea sediments consist of clay or clay gyttja, but as

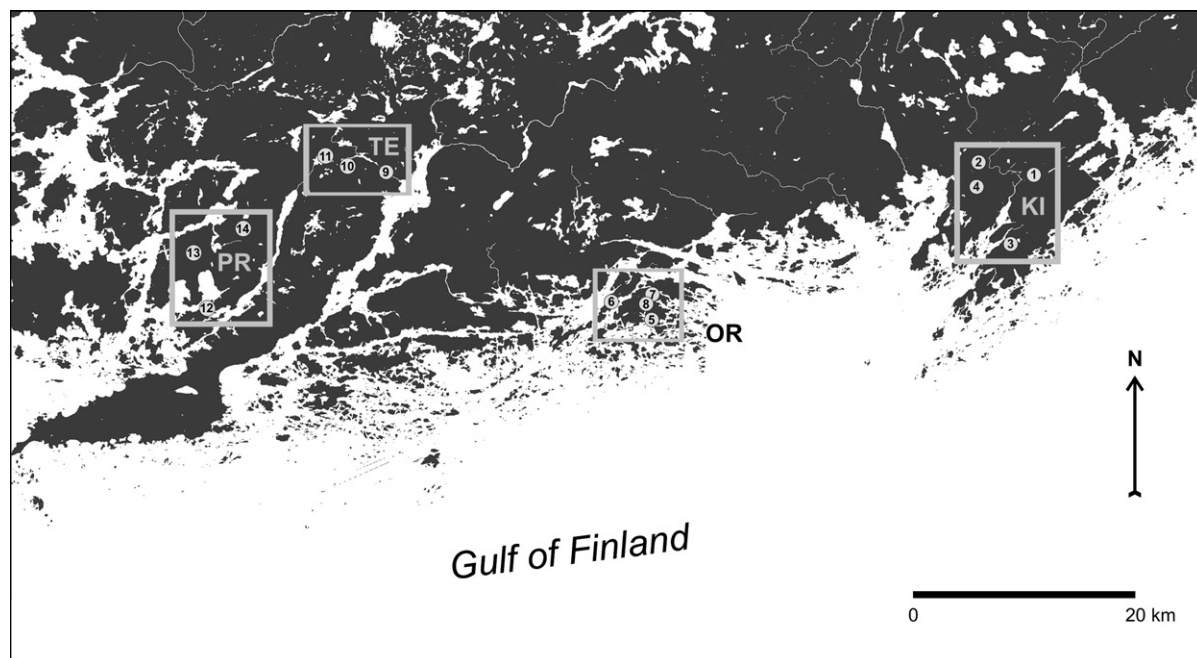


Fig. 3. Four study areas along the southern coast of Finland. KI=Kirkkonummi; OR=Orslandet; PR=Prästkulla; TE=Tenhola. Sites numbering at Table 1.

lake basins became isolated, organic gyttja accumulates in the basins.

3.3. Diatom analyses

Diatom analyses were made to assist in the identification of the isolation contacts. At first, the presumed isolation contact was defined from sediment by LOI and lithostratigraphic interpretation, and then, the depths for diatom analyses were chosen from both sides of the supposed isolation contact. The diatom samples were prepared according to standard methods (Battarbee, 1986). Where possible, approximately 200 valves were counted in each sample. The taxonomy and grouping of diatoms according to their biotype and salinity preferences is based on the following sources: 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). The main diatom groups are defined according to biotype into planktonic and littoral forms, with the latter group divided further into benthic and epiphytic forms. The diatoms are also grouped according to salinity using the halobian scheme and the following main groups: polyhalobous (marine; salinity >30‰), mesohalobous (brackish-water; 5–20‰), oligohalobous halophiles (<5‰) and indifferents (0–2‰), and halophobous (freshwater; 0‰).

3.4. ^{14}C analyses

Fourteen ^{14}C AMS analyses were carried out from the 11 basins in the Dating Laboratory of Poznan, Poland (Table 1). In addition, four conventional ^{14}C analyses were used from three isolation basins previously investigated by Hyvärinen (1999): Lake Molnträsk and Vintervästräsket, Kirkkonummi, and from Eronen et al. (2001): Lake Rombyträsket, Prästkulla. These are the only previous ^{14}C results from isolation basins in southern Finland (west of Helsinki) from the Late Holocene. The radiocarbon ages were calibrated to calendar years with OxCal v3.10 program (Bronk Ramsay, 1995, 2001, 2005).

4. Results

Data on lithostratigraphy and LOI with radiocarbon dated isolation contacts of 11 lakes investigated are presented in Fig. 4, as are the results from three isolation basins previously investigated by Hyvärinen (1999) and Eronen et al. (2001). In most cases, the isolation process has been rapid and a single date has been adequate. However, in Tronsbölträsket and Rombyträsket (sites 12 and 14), the isolation process was gradual, and two dates were needed. In seven basins, the clay-rich Baltic Sea sediment changes to organic gyttja before the final isolation. This indicates that during the final phase of the isolation process, the connection between the sea and

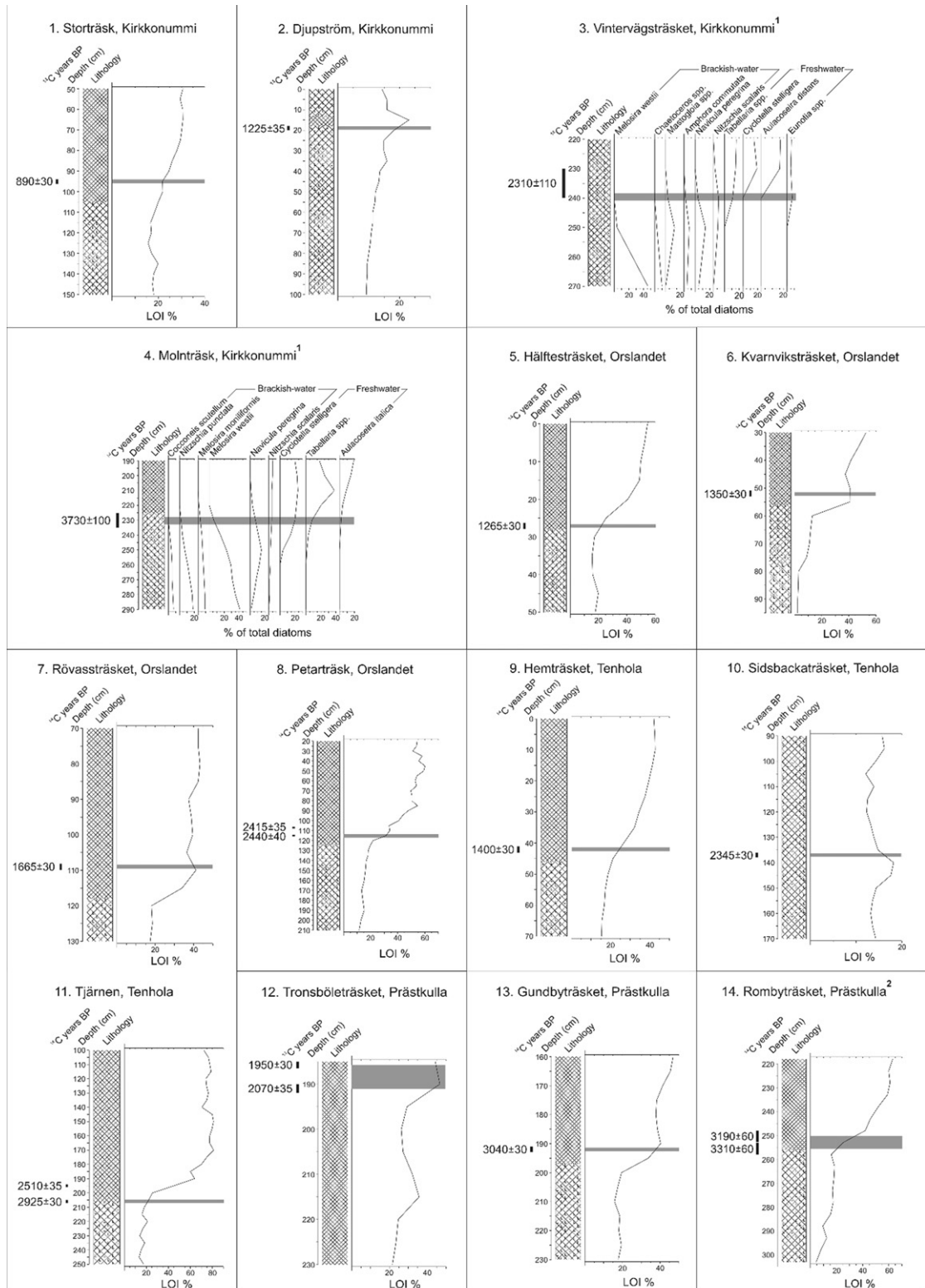
Table 1
Radiocarbon analyses carried out in 14 sites in southern Finland

Study area	Lake basin	Site no.	Altitude (m a.s.l.)	Lab. no.	Depth (cm)	Dated sediment	Age BP	Cal. age BP (1sigma)	Dated event
Kirkkonummi	Storträsk	1	0.8 (1.8)	Poz-8268	95	Gyttja	890±30	730–800	Isolation contact
	Djupström	2	2.5	Poz-8275	19	Gyttja	1225±35	1060–1180	Isolation contact
	Vintervästräsket ^a	3	5.6	Hel-2006	230–240	Clay gyttja	2310±110	2150–2490	Isolation contact
	Molnträsk ^a	4	12.5	Hel-2000	225–235	Gyttja	3730±100	3960–4240	Isolation contact
Orslandet	Hälftesträsket	5	2.5	Poz-3546	27	Gyttja	1265±30	1170–1260	Isolation contact
	Kvarviksträsket	6	3.0	Poz-12510	52	Gyttja	1350±30	1270–1305	Isolation contact
	Rövassträsket	7	3.4	Poz-3551	109	Gyttja	1665±30	1525–1570	Isolation contact
	Petarträsk	8	9.5	Poz-3550	115	Gyttja	2440±40	2350–2500	Isolation contact
Tenhola				Poz-14723	107	Gyttja	2415±35	2350–2490	Lake sediment
	Hemträsket	9	2.5	Poz-14722	42	Gyttja	1400±30	1290–1330	Isolation contact
	Sidsbackträsket	10	4.6	Poz-14676	137	Clay gyttja	2345±30	2330–2365	Isolation contact
	Tjärnen	11	13.0	Poz-12513	206	Gyttja	2925±30	3070–3210	Isolation contact
Prästkulla				Poz-17113	195	Gyttja	2510±35	2500–2600	Lake sediment
	Tronsbölträsket	12	6.2	Poz-8279	191	Gyttja	2070±35	1990–2070	Isolation begins
				Poz-12511	186	Gyttja	1950±30	1865–1935	Isolation ends
	Gundbyträsket	13	12.6	Poz-12512	192	Gyttja	3040±30	3210–3270	Isolation contact
	Rombyträsket ^b	14	14.5	GrN-19650	253–258	Clay gyttja	3310±60	3460–3620	Isolation begins
				GrN-19649	248–253	Gyttja	3190±60	3350–3470	Isolation ends

The original threshold altitude of Lake Storträsket (site 1) is 1.8 m a.s.l. Depth (cm) refers to depths below sediment surface.

^a Hyvärinen (1999).

^b Eronen et al. (2001).

¹ Hyvärinen (1999)² Eronen et al. (2001)

isolating basin was limited, and organic gyttja accumulated in the basin.

4.1. Results from Lake Petarträsk

Detailed results are presented from Lake Petarträsk as an example of the diatom method used in this study. Lake Petarträsk (59°57'N, 23°52'E) is a small lake basin located 9.5 m above present sea-level on the island of Orslandet (Table 1 and Fig. 3). The samples were taken from the middle part of the lake, where the water depth was 4.7 m.

4.1.1. Lithostratigraphy

The sediment sequence of Lake Petarträsk is 190 cm thick and can be divided into four lithological units. Unit 1 (210–123 cm below the sediment surface) comprises a greenish grey, laminated clay gyttja. A major lithological change occurs at 123 cm, where the sediment changes to organic, greyish brown, slightly laminated gyttja (Unit 2, 123–117 cm). Unit 3 (117–105 cm) consists of greyish brown gyttja, whilst Unit 4 (105–20 cm) is a dark brown gyttja with fine plant detritus.

4.1.2. Diatoms

The sequence between 80 and 130 cm is subdivided into two diatom assemblage zones (d.a.z.), named PDZ 1–PDZ 2 from the base upwards (Fig. 5).

4.1.2.1. PDZ 1, (130–118 cm). The basal part of the zone is strongly dominated by the mesohalobous planktonic species *Melosira westii* fo. *parva* and *Melosira moniliformis*. In the uppermost part of the zone mesohalobous littoral species *Navicula peregrina*, *Amphora commutata* and *Nitzschia scalaris* dominate. Other common species are oligohalobous *Epithemia* spp, mesohalobous *Navicula rhynchocephala* and *Campylodiscus clypeus*.

4.1.2.2. PDZ 2, (118–80 cm). In the beginning of the zone the mesohalobous diatoms are replaced by oligohalobous and halofobous species, e.g. *Fragilaria* spp and *Fragilaria construens* var. *venter*. After this short *Fragilaria* maximum, *Epithemia* spp, *Cymbella* spp, *Pinnularia* spp, *Tabellaria flocculosa*, *T. fenestrata*, *Cyclotella stelligera* and *C. pseudostelligera* become dominant. Towards the top of the zone, the planktonic *Aulacoseira* species appear.

4.1.3. Palaeoenvironment

The diatom stratigraphy indicates a shift from pelagic and brackish-water environment to a shallower and less saline coastal environment. The isolation of the basin can be seen as a clear change in the diatom stratigraphy with the up-core replacement of brackish-water taxa by freshwater taxa.

The lithostratigraphic changes from clay gyttja to gyttja are approximately synchronous with the isolation contact detected by diatoms. The remarkable feature in the diatom stratigraphy is the dominance of *Fragilaria* species during the isolation event.

Two ^{14}C analyses were carried out on the sediment sequence (Table 1). The first date 2440 ± 40 (2350–2500 cal. BP) was carried out at the depth of 115 cm on the isolation contact and the second date 2415 ± 35 (2350–2490 cal. BP) at 107 cm. The dates are compatible with each other and indicate that the isolation took place c. 2400 cal. BP.

4.2. Relative sea-level changes along the southern coast of Finland

The sea-level index-points are now used to reconstruct sea-level curves for southern Finland area (Fig. 6). The highest shoreline of the Late Holocene was located about 11 m a.s.l. in Prästkulla, and about 8 m a.s.l. in Kirkkonummi c. 3000 cal. yr BP. The generalized map of this shoreline is illustrated in Fig. 7, in which the shoreline has been placed on the 10 m contour. The rate of emergence of the shoreline has been 3.7 mm/yr at Prästkulla and 2.7 mm/yr at Kirkkonummi during the past 3000 yr. The shoreline was located 6.5 m a.s.l. in Prästkulla, and about 5 m a.s.l. in Kirkkonummi 2000 cal. yr BP. At 1000 cal. yr BP, the difference between these areas is small, only c. 0.5 m (Fig. 6). The data are not precise enough to distinguish any differences between the various study areas during the past 500 yr.

The sea-level curves of Kirkkonummi and Prästkulla demonstrate a regular land uplift with a gradually decreasing trend during the Late Holocene. There is no evidence for any distinct sea-level transgressions in this time period. The results are in agreement with the previous sea-level data east of present study area, where the land uplift rate is slower (Hyvärinen, 1999; Miettinen et al., 1999; Seppä et al., 2000; Miettinen, 2002, 2004).

Fig. 4. Lithostratigraphy, loss-on-ignition curves and ^{14}C dated isolation contacts from 14 basins. Grey lines indicate the isolation contacts defined by diatoms. Lithostratigraphy, diatoms and ^{14}C dates from Vintervägräsket and Molnträsket are redrawn from Hyvärinen (1999), lithostratigraphy, LOI and ^{14}C dates from Rombyträsket from Eronen et al. (2001).

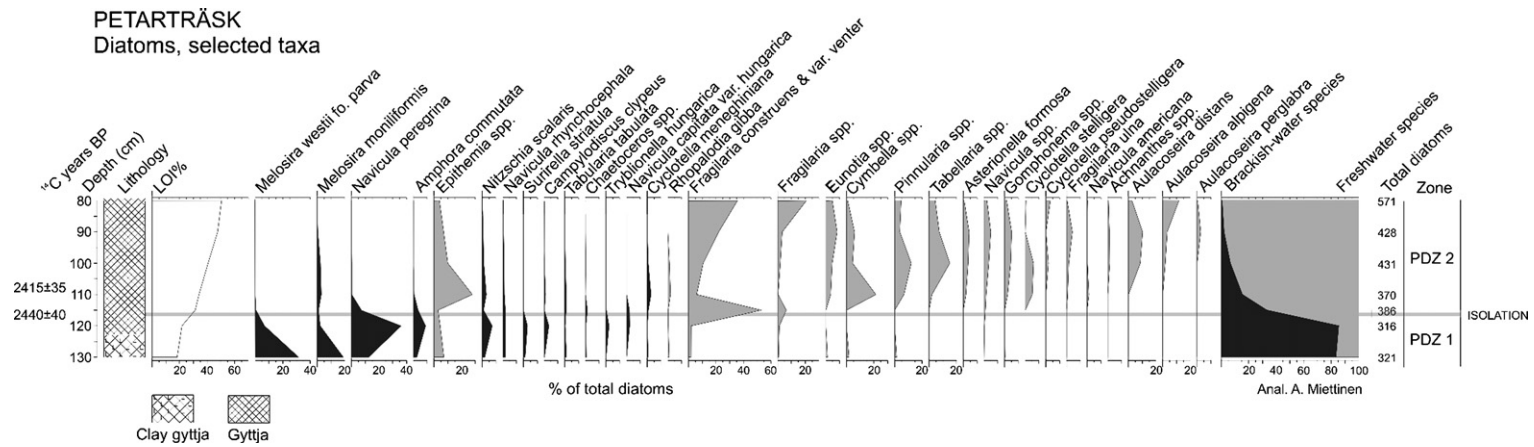


Fig. 5. The diatom diagram of Petarträsk, Oslandet. Black curves represent brackish-water, and grey curves freshwater diatoms.

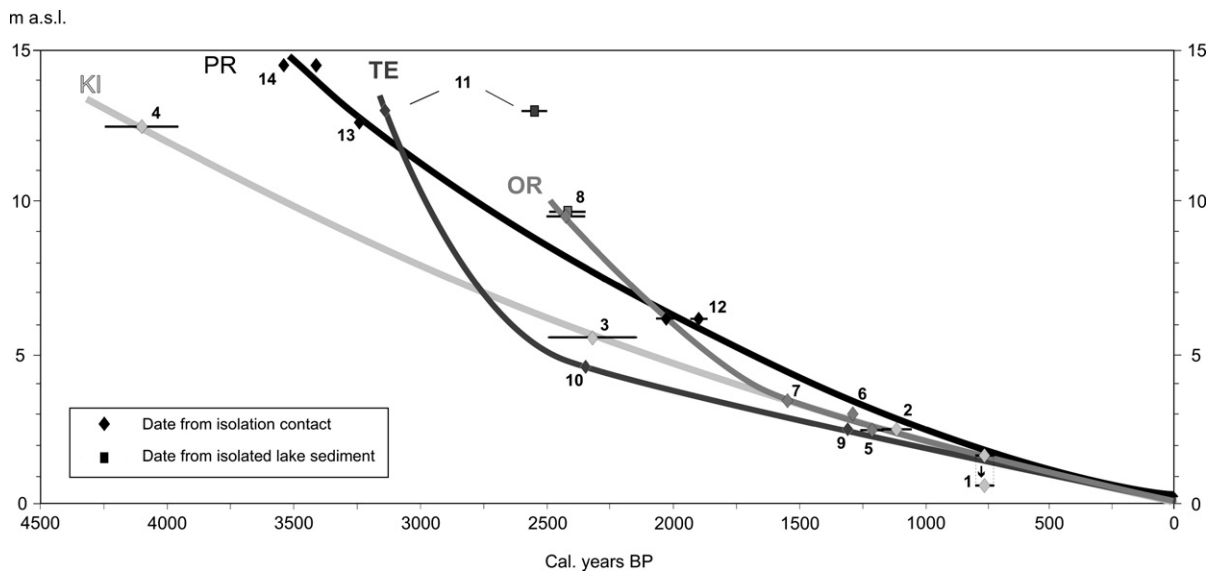


Fig. 6. Sea-level curves for southern coast of Finland. KI=Kirkkonummi; OR=Orslandet; PR=Prästkulla; TE=Tenhola. Sites are numbered at Table 1.

The results from Orslandet and Tenhola differ markedly from those of Kirkkonummi and Prästkulla (Fig. 6). The sea-level curve for Tenhola shows a rapid sea-level lowering (11.2 mm/yr) between 3100 and 2350 cal. yr BP, and after that, between 2350 and 1300 cal. yr BP, the land uplift rate is very slow compared to the other areas. The situation is somewhat similar in Orslandet, where the sea-level curve shows a rapid fall

(7.2 mm/yr) between 2400 and 1550 cal. yr BP. However, after that it follows the uplift trends observed in the Kirkkonummi and Prästkulla areas.

It is important to note that the different results from Tenhola and Orslandet are caused by the isolation data from only three basins (Lake Hemträsket and Sidsbackaträsket, Tenhola, and Lake Petarträsk, Orslandet) so further data are required to test this pattern in more detail.

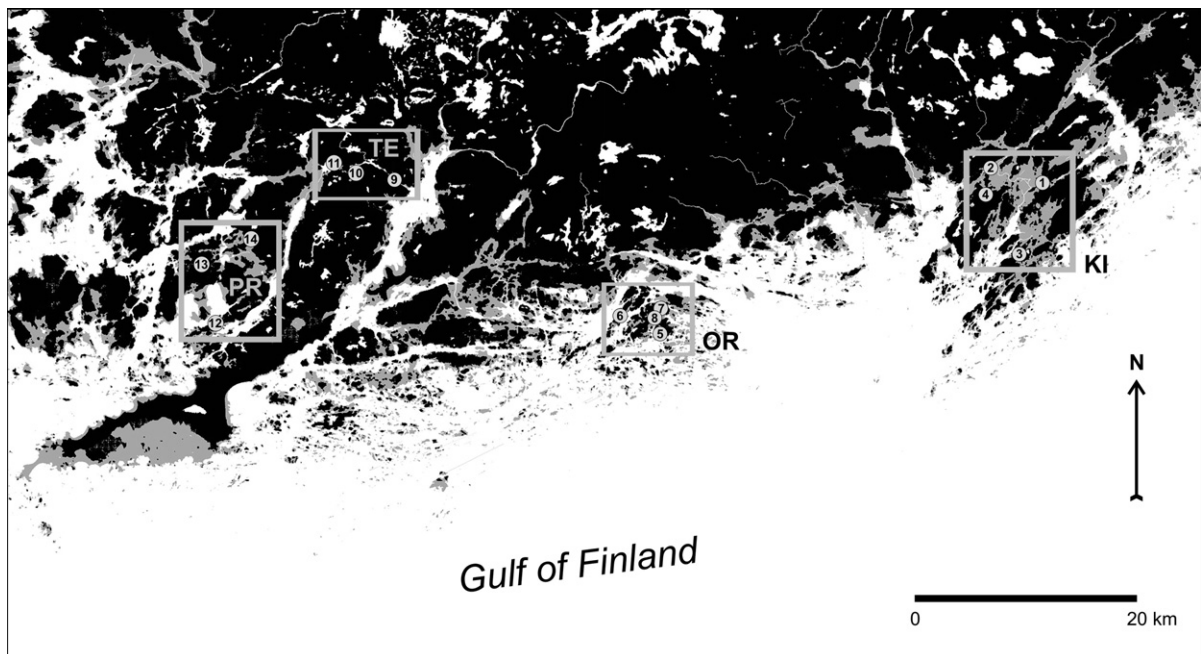


Fig. 7. Southern coast of Finland 3000 yr ago (dark colour) and the present shoreline.

The Finnish lake sediments seem to be well suited for radiocarbon dating, because there are no large age differences between the uppermost brackish-water Baltic Sea sediment and the freshwater sediment of isolated basin. This indicates that there is probably no marked reservoir age effect in the coastal sediments of the northeastern Baltic Sea (cf. Hyvärinen, 1999; Eronen et al., 2001; Miettinen, 2002). The salinity in this part of the Baltic Sea is low (c. 6‰) and, thus, the marine reservoir effect is probably very small. Furthermore, Precambrian crystalline rocks dominate and no limestones occur in the southern Finland (Korsman et al., 1997).

5. Discussion

In most basins in this study, the isolation contact is very clear, and it is seen both in lithostratigraphy and diatom stratigraphy. In some basins the isolation process was more gradual, as reflected by the lithostratigraphy. In these cases gyttja was deposited in the basins even before the final isolation of the basin from the sea. However, diatom analysis has proven a very practical method in determining the isolation contact. As a rule, diatoms show a clear succession from a deep and brackish pelagic environment to a shallower and less saline coastal environment, with finally the brackish-water diatom taxa replaced by freshwater taxa during the isolation itself.

The interesting feature in most of the diatom stratigraphies in the sites studied is the dominance of *Fragilaria* species during the isolation event. This is a very common feature in numerous other isolation basins (e.g. Eronen, 1974; Shennan et al., 1993; Seppä et al., 2000; Miettinen, 2002). This feature is often related to the isolation of the lake, but may also occur before, during or after the isolation of the lake (e.g. Stabell, 1985). In the isolation basins of the Finnish coast, the main peak of *Fragilaria* species seems to occur directly after the disappearance of the brackish-water taxa and the rise of the organic content of sediment, and thus, after the isolation (e.g. Seppä et al., 2000; Miettinen, 2002). According to Stabell (1985), the *Fragilaria* peak is probably not solely caused by salinity changes but is due more to the rapid changes in water chemistry during the isolation.

The observed rapid sea-level lowering in the Tenhola area between 3100 and 2350 cal. yr BP, indicates a very rapid uplift rate compared to the present maximum rate of 8–9 mm/yr in Ostrobothnia area. Moreover the results from the Orslandet area indicate a more rapid uplift rate compared to the present situation between 2400 and

1550 cal. yr BP. In the Tenhola area, the uplift trend is reversed between 2350 and 1300 cal. yr BP, when the uplift rate here is very slow compared to the other areas. This is interesting, because the present uplift rate is most rapid in the Tenhola area of the areas studied. Because the relative sea-level lowering is slow and steady in the other areas (Kirkkonummi and Prästkulla), and is also very similar to present uplift trends, the reason for these anomalies in the sea-level data cannot be related to “eustatic” sea-level changes, but to anomalies in the regional land uplift pattern.

The key question is whether the observed anomalies are real, caused by the irregularities in land uplift, or an artefact arising from erroneous radiocarbon dates or incorrect interpretation of the isolation data. The anomalous sea-level index-point from Lake Petarträsk, Orslandet appears to be reliable (see above, Fig. 5), whilst the isolation processes from the basins located in the Tenhola area are clear. Unfortunately, there are two radiocarbon dates only for the uppermost site, Lake Tjärnen (Table 1 and Fig. 4), whilst at the other two sites, Hemträsket and Sidsbackträsket, each have only a single date and may therefore be in error (Table 1 and Fig. 4).

It is important that these potential uplift anomalies are studied in further detail. However, there are no other isolation basins in Orslandet suitable for sampling, so it is not possible to confirm the observed anomaly on this relatively small island. There are, though, possibilities to find isolation basin between 2 and 13 m a.s.l. from Tenhola. Further ^{14}C dates are also needed for the two basins located in the Tenhola area.

The presumed land uplift anomalies occurred in Tenhola and Orslandet at different times, which indicate that they are independent features. We hypothesise that the anomalies may record movements of blocks along old fracture zones which exist around the study areas. The size of bedrock blocks varies from some square kilometres to hundreds of kilometres. Present geophysical levelling profiles certify that local changes in the present land uplift rate exist between bedrock blocks. For example, of the 53 levelling profiles carried out in Finland in 1974–1992, 27 had undergone significant local changes in elevation, with the highest measurement of 33.4 mm/yr (Veriö et al., 1992; Kuivamäki et al., 1998). So, it is possible, that many small blocks exist, each with their own particular vertical motions in Fennoscandia, but so far they have not been discovered in Finnish sea-level data.

One main conclusion that can be drawn from the available data is that the Late Holocene uplift in southern Finland may not have proceeded as regularly as previously believed. The published Finnish shoreline

data provide no evidence for remarkable vertical displacement between bedrock blocks. However, the possibility of local disturbances of uplift caused by vertical faulting in the course of glacio-isostatic rebound has been discussed also for southern Finland (e.g. Kakkuri, 1985; Donner, 1995; Lehmuskoski, 1996; Kuivamäki et al., 1998; Eronen et al., 2001).

6. Conclusions

- The Late Holocene (3000 yr old) highest shoreline is located about 11 m a.s.l. in Prästkulla, and about 8 m a.s.l. in Kirkkonummi, southern coast of Finland. These differences are solely due to the different land uplift rates, which decrease eastwards along the coastal area.
- No clear sea-level transgressions can be detected in the sea-level data.
- Two land uplift anomalies were detected in the Tenhola and Orslandet. They possibly represent local events. To verify these anomalies more investigations are needed.
- The accuracy of the isolation method is not precise enough for distinguishing any differences between the various study areas during the past centuries. However, the sea-level reconstructions of this study are potentially very useful for archaeological landscape reconstructions.

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