Holocene and Recent Shoreline Changes on the Rapidly Uplifting Coast of Western Finland

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ABSTRACT

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The coastal area of western Finland rose from the sea during the Holocene as a result of rapid land uplift that followed deglaciation (9500–9000 BP). Land uplift was extremely powerful immediately after the deglaciation, with relative water level falling approximately 100 m in the northern part of the Gulf of Bothnia in less than 1,000 years. The rates of isostatic decreased markedly between 8500 and 8000 BP. Pronounced shoreline displacement still occurs on this relatively flat coast, at a rate exceeding 8 mm a year. The retreating shoreline has greatly affected the history of settlement on the coast of the Baltic Sea, forcing towns such as Pori and Vaasa to adjust their location as the retreating shoreline has caused their harbours and shipping lanes to become too shallow. Accurate maps compiled at different times are used to compare the manner and rate of shoreline changes during the last few decades. The examples presented here illustrate such changes for various types of coastal environments.

ADDITIONAL INDEX WORDS: *Isostatic rebound, raised shore levels, relative sea-level fall, harbour shifts, coastal emergence.*

INTRODUCTION

"In the summer of 1762, I journeyed to Björkö, 4 miles out to sea from Vasa, for the tax assessment in progress there. All the old men there present affirmed that the water was receding, and that meadows along the shores were thereby expanding, shoals emerging and firmly fixed rocks in the sea becoming exposed", E.O. Runeberg.

This quote from JONES (1977) dates from the 18th century, as recorded by a chartered surveyor commissioned by the Swedish government to carry out a land survey as part of the Great Partition. He noticed a continuing, marked drop in water level of the region known as Ostrobothnia. EPHRAIM RUNEBERG (1765) was the first person to arrive at the conclusion that the land was rising. His assumption was not generally supported by the scholars of that time who believed that sea level was falling, but similar ideas were presented also by the Swedish astronomer BENGT FERNER, who published a paper on this topic in the same year as Runeberg (EKMAN, 1991).

Land uplift, related to deglaciation of Fennoscandia, is still occurring at a maximum rate of over 9 mm a year and continues to be the main factor in the evolution of the Ostrobothnian coast today (KAKKURI, 1985; EKMAN, 1989, 1993). Geological findings indicate that rates of uplift were very much higher during the early Holocene.

POSTGLACIAL UPLIFT AND RAISED SHORELINES

Ostrobothnia refers to the region east of the Gulf of Bothnia, and a large part of it consists of the County of Vaasa, the focus of this paper (Figure 1). This area is located near the centre of the former Weichselian ice sheet, and was, thus, covered by an ice sheet about 3,000 m thick during the glaciation maximum (FJELDSKAAR, 1994a, *cf.* 1994b). Consequently the deglaciation of this region was accompanied and followed by a vigorous glacio-isostatic rebound. Evidence of former high stands of sea levels can be found in numerous raised beaches and marine (and giant lake) sediments (GLÜCKERT *et al.*, 1993).

The supra-aquatic area in the County of Vaasa upon deglaciation (slightly prior to 9000 BP) comprised only a few high regions marking the highest shorelines of the Baltic at 200 m a.s.l. (Figure 1). The land towards the present coast is mainly flat and possesses markedly lower shoreline levels. The 7000 BP shoreline (Figure 1) represents the highest shore of the Litorina Sea, which lies at a current altitude of approximately 90 m a.s.l. in the southern part of the province and a little over 100 m a.s.l. in the north. As the above figures indicate, the rate of uplift has declined since that time; a drop of a hundred metres in the water level took place during the period between 9000–7000 BP. The next 100-metre drop from the beginning of the Litorina Sea stage up to the present day took approximately 7,000 years.

The time 7000 BP does not represent any significant change in the shoreline displacement in the area, even
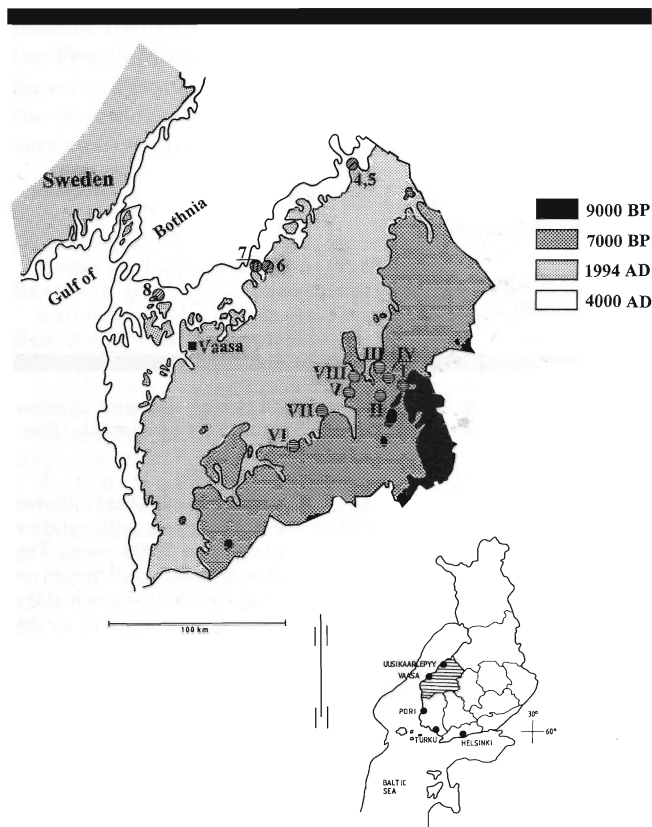
Figure 1. Map showing the County of Vaasa in Finland and sites discussed in the text. The Arabic numerals indicate locations and corresponding figures demonstrating the recent shoreline displacement. The Roman numerals show the sites of stratigraphical studies on the Holocene shore displacement (Figure 2). The different areas marked on the map are defined according to the time of emergence from the sea (*e.g.*, the black colour showing the land emerged by 9000 BP), including also a forecast for the distant future. For further details, see text.

though it marks an otherwise important boundary (*i.e.*, the spread of brackish water and thus the beginning of the Litorina Sea stage in the northernmost parts of the Baltic Sea) (ERONEN, 1974, 1983). When shoreline displacement is considered, the period 8500–8000 BP seems crucial. At that time, the early Holocene extremely rapid rebound of the earth's crust slowed down to a small fraction of the preceding highest values.

METHODS USED IN RECONSTRUCTING THE SHORELINE DISPLACEMENT

Three shoreline displacement curves constructed for the Ostrobothnia region are presented in Figure 2. The shape of the oldest curve (SAURAMO, 1940) shows that in those days the early Holocene rapid phase of uplift had not yet been detected. Pollen analysis as the main dating method was not accurate enough to discern the real pattern of development.

The two other curves are based on radiocarbon dates and associated sedimentological and biostratigraphical observations. The curve constructed by SALOMAA (1982) and later completed by SALOMAA and MATISKAINEN (1983, 1985) in-

dicated more linear change at *ca.* 8500–8000 BP than the curve compiled for the present paper according to the data of GLÜCKERT *et al.* (1993).

Similar investigation methods have been used in constructing both of the shoreline displacement curves. The isolation points of the basins were determined by diatom analyses from the sediment cores. Radiocarbon dating together with pollen analyses were used in the age determinations. Both curves were projected to the 7.5 mm per year isobase of uplift (value according to SUUTARINEN, 1983).

The differences between the curves are primarily due to an inadequate amount of data and inaccuracies in dating. SALOMAA and MATISKAINEN (1985) compiled their curve correctly from the data they had, also taking into account the deviations in some radiocarbon dates. There were problems in interpreting the radiocarbon dates in the study by GLÜCKERT *et al.* (1993). It seems to us that three radiocarbon dates for isolation points obtained from the (then existing) Turku radiocarbon laboratory were consistently too young, because they clearly deviated from the majority of other dates (Table 1). Therefore, these dates were omitted from the present paper and only those dates obtained from the radiocarbon laboratory of the Geological Survey of Finland were used in constructing the curve in Figure 2.

The locations of the stratigraphical sites used in compiling the most recent shoreline curve (Figure 2) are shown in Figure 1. Detailed descriptions of the sites as well as the pollen and diatoms diagrams were published by GLÜCKERT *et al.* (1993). This research resulted in only two new usable radiocarbon dates, but it was also possible to draw some conclusions on the course of the relative water-level lowering from the pollen stratigraphy.

The regional pollen assemblage zones (R.P.A.Z) are not well-established in Ostrobothnia. The sediment sequences were strongly affected by uplift and ensuing changes in coastline and deposition environments. Precise ages for the regional pollen assemblage zones cannot be obtained from the small number of radiocarbon dates available from the present study area. Fortunately, there are dates for the crucial zone boundaries in the County of Keski-Suomi (Central Finland), where RISTANIEMI (1987) has dated several isolation points in small-lake sediments. That area is bordering the present study area in the east and therefore the results should be applicable for the present purposes.

The boundary between the *Betula* and *Pinus* R.P.A.Z. (Central Finland) was dated by RISTANIEMI (1987) to *ca.* 9400 BP and the rational limit of *Alnus* to around 8700–8500 BP. These values were used to estimate the ages of the isolation points of the lake basins presented in Figure 2. We admit that these datings are rough, but they are certainly more informative than undated isolations.

The studies by GLÜCKERT *et al.* (1993) show that Lake Basins I and II (Figure 2) became isolated from the Ancylus Lake during the *Pinus* R.P.A.Z. The estimated ages of isolations are 9100 and 8900 BP, respectively. Basin III was isolated at the rational limit of Alnus, age 8700 BP. Basin IV was isolated after the *Alnus* limit; isolation is dated by radiocarbon to 8390 ± 160 BP. Basins V–VII were all isolated
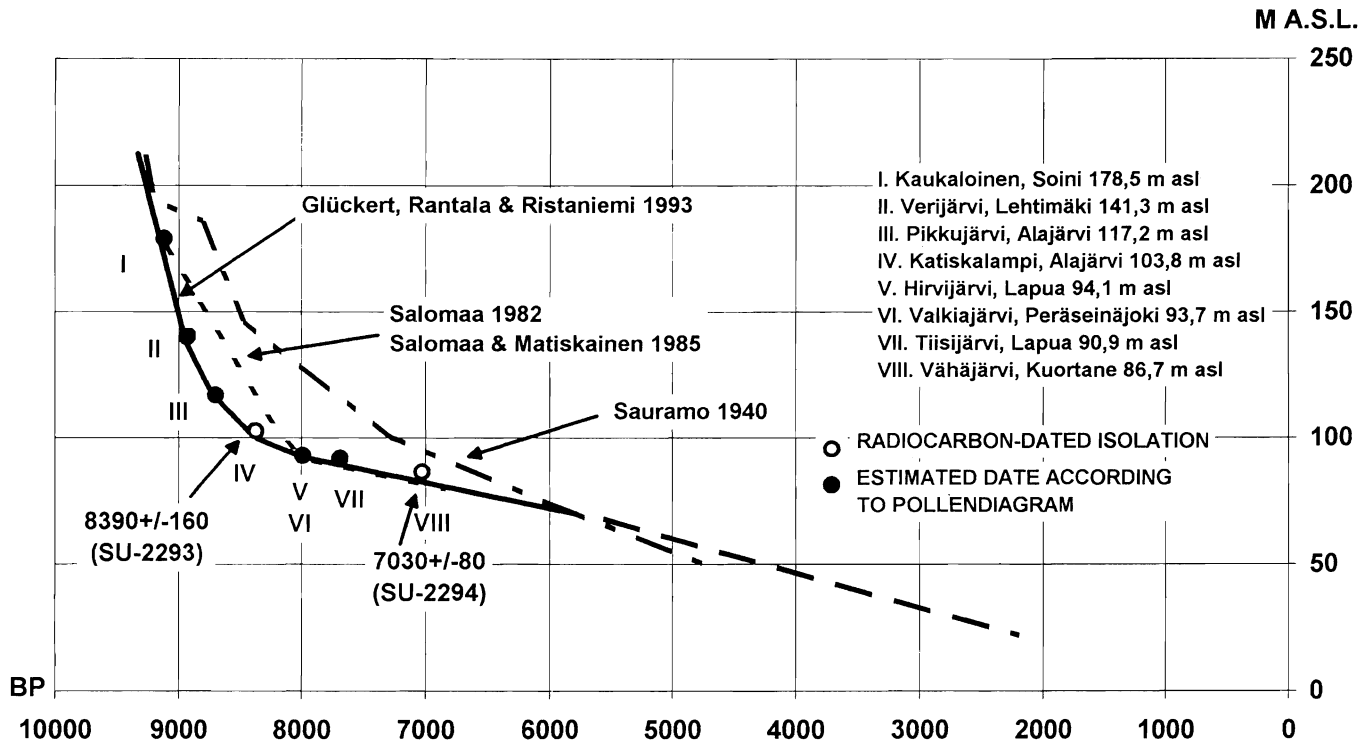
Figure 2. The early to mid-Holocene shoreline displacement in southern Ostrobothnia according to three different curves.

during the *Betula-Pinus-Alnus* R.P.A.Z., (*i.e.,* well before the arrival of *Picea*).

The isolation of basin VIII (Vähäjärvi) is dated by radiocarbon to 7030 ± 80 BP. Brackish water diatoms were found in the sediment below the isolation point, which indicates that the basin rose above the waters of the Baltic only after the spread of saline water into the Gulf of Bothnia (*i.e.,* after the beginning of the Litorina Sea stage). It is interesting to note that ERONEN (1974) has earlier dated the isolation of a nearby lake, Porraslampi, to 7750 ± 260 BP (Hel-450). That lake is about four metres further above sea level (90.5 m) than Lake Vähäjärvi (VIII), and no distinct rise in salinity was found in the pre-isolation sediment. Thus, these two lakes bracket the Litorina limit in that region between *ca.* 86.5 and 90.5 m a.s.l. and its age between ca. 7700 and 7000 BP. The dating is in accordance with the previous results (ERONEN, 1974, 1983; ERONEN *et al.,* in press).

Table 1. *Radiocarbon dates of the isolations of lakes (GUCKERT et al., 1993).*

Site	Height m a.s.l.	^{14}C Age BP	Lab. No.
IV Lake Harjulammi	133.4	7,430 ± 90	TKU-56*
VI Lake Katiskalampi	103.8	8,390 ± 160	Su-2293
XII Lake Vähäjärvi	86.7	7,030 ± 80	Su-2294
XIII Lake Vähäjärvi	84.4	6,090 ± 90	TKU-55*
XIV Lake Kalliojärvi	36.2	3,370 ± 90	TKU-57*

*Dates obviously too young. Omitted from Figure 2

THE SHAPE OF THE SHORELINE DISPLACEMENT CURVE

The inflection point in the present shoreline displacement curve around 8500 BP probably represents a sharp decrease in the rates of isostatic rebound. A clear slowing down in relative lowering in sea level roughly in the same period of time has been found also along the coasts of western Norway (PIRAZZOLI, 1991, and references therein). In the Baltic area, there is also an additional factor which contributed to the relative sea-level change 8500–8000 BP. Before that period the level of the Ancylus Lake had been falling since ca. 9200 BP, but the eustatic rise of the ocean level raised waters over the thresholds of the Danish Straits in the southwest; this caused the Baltic to come to the same level as the ocean before 8200 BP, as the first signs of an influx of saline water from that time show (BJÖRCK, in press). The giant Ancylus Lake began to change gradually to a brackish water inland sea. The ocean level was still rapidly rising due to the melting ice sheets and that rise retarded the relative lowering in sea level on the coast of the Gulf of Bothnia.

Thus, the sudden decrease in the rate of relative lake/sea-level fall was not only caused by a decrease in isostatic rebound, but was also influenced by a change from a falling lake level to the effect of the eustatic rise. On the southwestern and western coast of Finland, and in areas further south, the glacio-eustatic rise resulted in the Litorina transgression (GLÜCKERT, 1991, 1994; ERONEN and RISTANIEMI, 1992; ERONEN *et al.,* in press; ERONEN, in press).
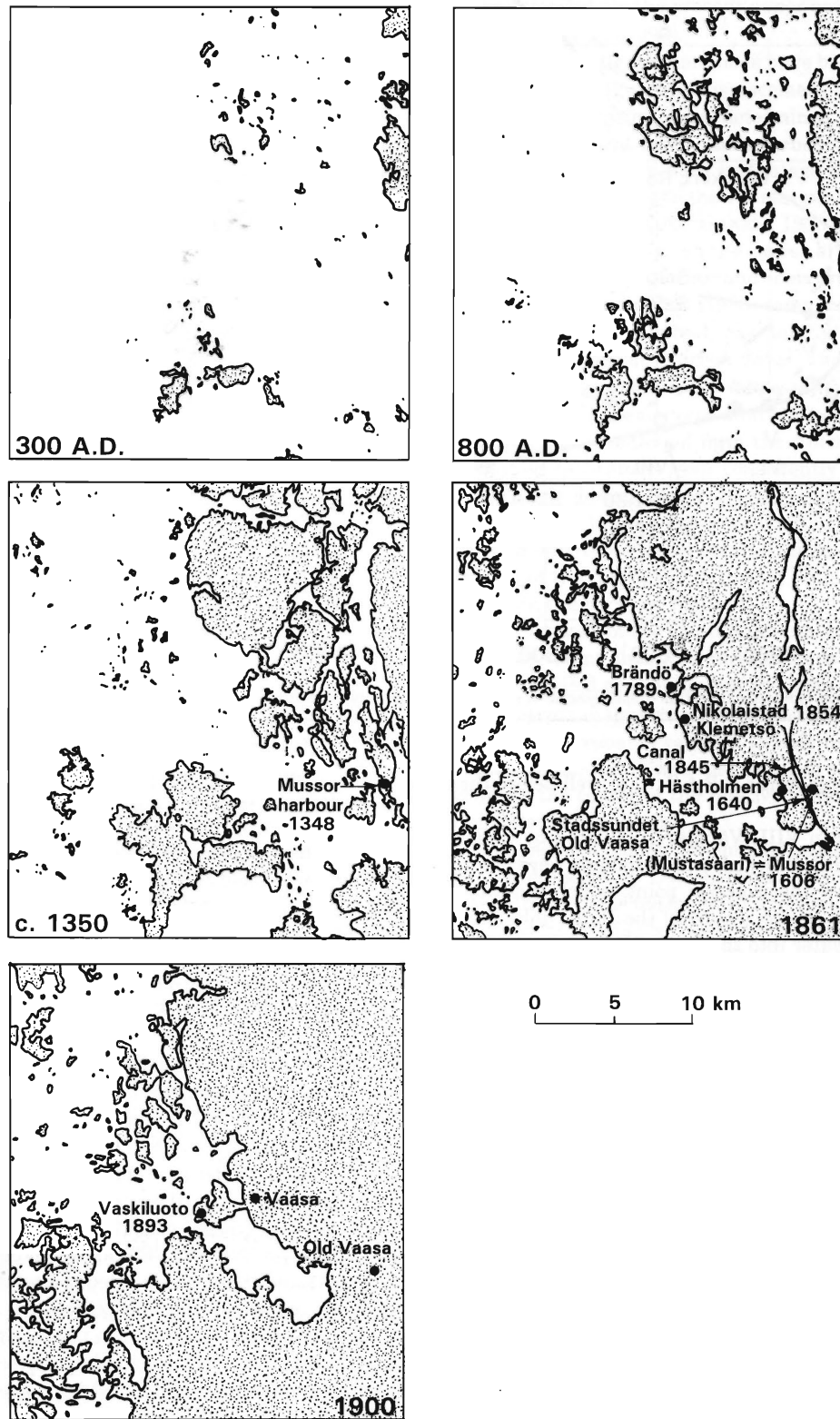
Figure 3.   Changes caused by land uplift off Vaasa since approximately 300 AD. Redrawn from JONES (1977) and PALOMÄKI (1987b). Place names and years indicate times at which the town and its harbours have changed locations. For further details, see text.
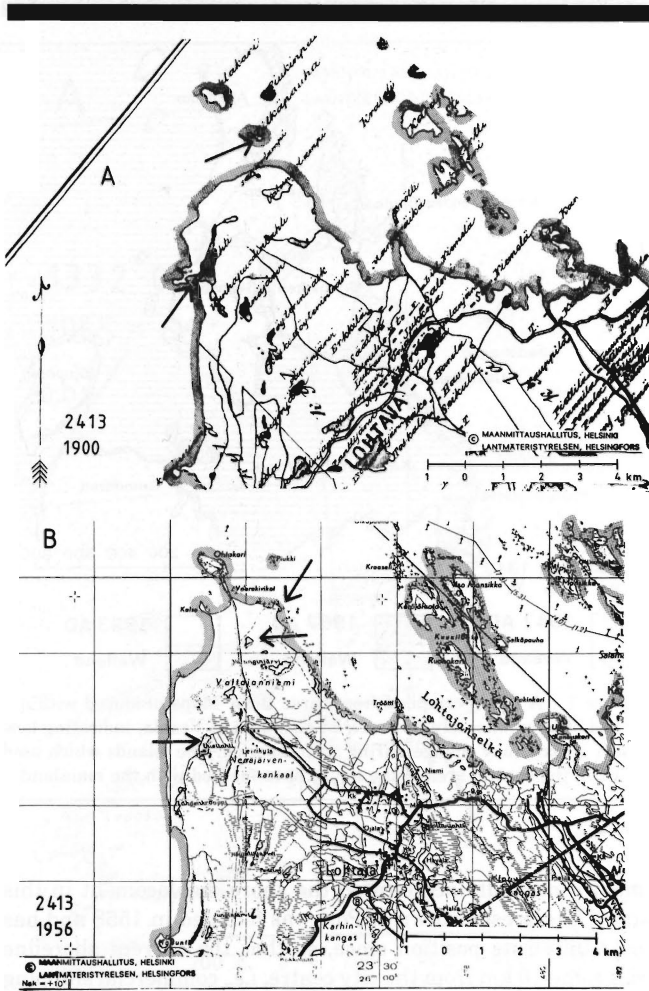
Figure 4. A provincial map (A) and topographical map (B) of Lohtaja (scale 1:100,000) indicate the changes which have taken place in the shoreline of the sandy spit of Vattajanniemi during a period of over 50 years. The left-hand arrow points to Uusilahti (New bay), which used to be a bay in 1900, but had formed a small separate lake by 1956. The upper arrow points to a small island which changed into a spit on the lower map. The middle arrow on map B points to a pond, also shown in Figure 4A, at a site covered by the sea in 1900, as indicated by the slightly inaccurate provincial map.
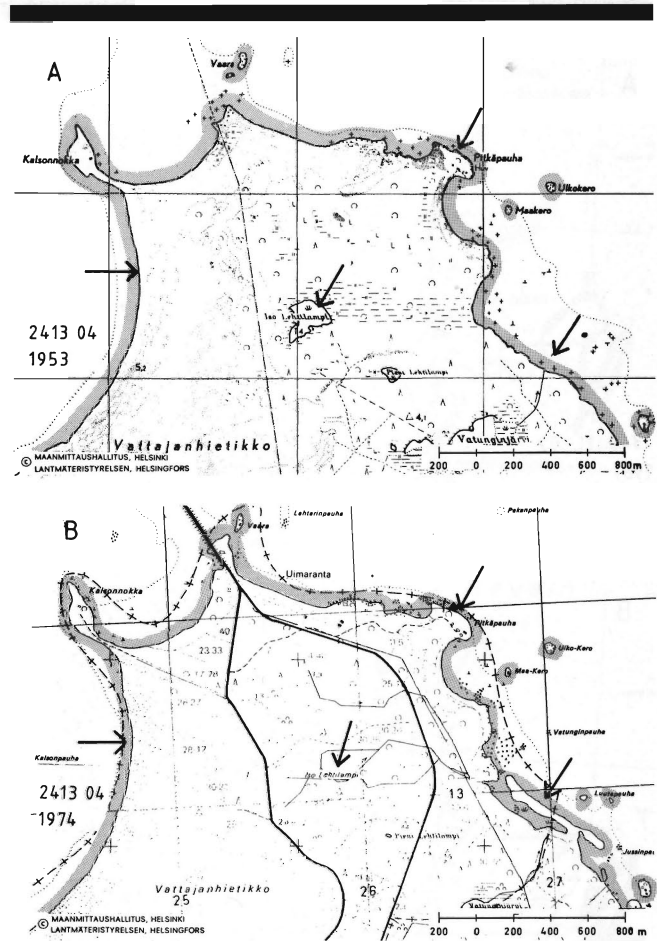

Figure 5. The end of the peninsula in Figure 4 as shown on more recent maps to a scale of 1:20,000 (the number of map sheet is given above the year of publication). The left-hand arrows indicate a beach on which sand has begun to accumulate, and the middle arrows point to a pond which has disappeared between the times of publication of the maps. The upper right-hand arrows indicate an island which had merged with the mainland (cf. Figure 4A), while the lower ones point to a new sandbar which developed on the eastern shore of the peninsula.

COASTAL CHANGES AFFECTING HUMAN ACTIVITIES IN SOUTHERN AND WESTERN FINLAND DURING HISTORICAL TIMES

The effect of land uplift is well marked in the location of prehistoric settlements. Signs of Stone Age settlements once inhabited by fishermen and seal hunters are found at progressively lower ancient shoreline levels from the oldest to the younger ones (SALOMAA and MATISKAINEN, 1985). In the historical period (since AD 1150), all the old coastal towns in Finland had to adjust to shoaling harbors caused by land uplift. It has always been important for coastal towns to have sheltered, sufficiently deep harbours and development is markedly hampered when the harbours and the channels

leading into them become too shallow as a result of land uplift.

Turku, the oldest city in Finland, with an apparent uplift of approximately 4.2 mm/yr has retained its original medieval position near the castle and around the cathedral, but it has been necessary to move the harbour downstream along the River Aurajoki, which flows through the city. The harbour currently lies opposite the castle, which was erected in the 13th century in front of the river mouth on a small island. It was then separated from the mainland by a strait approximately 500 m wide. This island merged with the mainland during the 16th century as a result of land uplift (GLÜCKERT and PAATONEN, 1994).

The city of Helsinki, the current capital of Finland (with an apparent uplift slightly below 3 mm/yr), had to be moved in 1640, 90 years after its foundation, because its original location at the mouth of the River Vantaanjoki had become
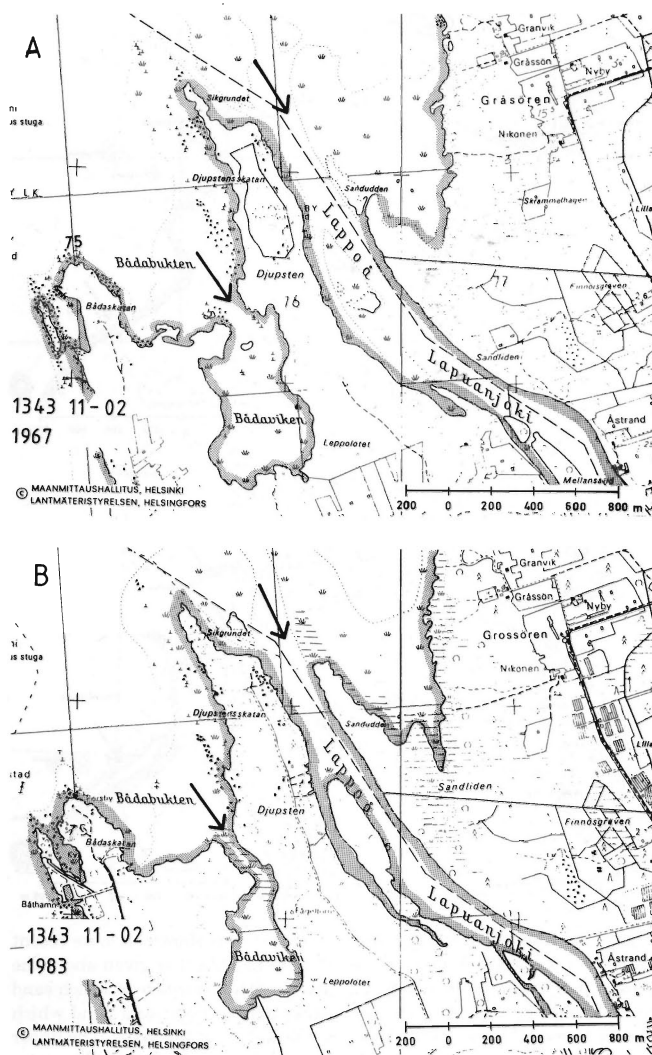
Figure 6.   Changes occurring at the mouth of the small River Lapuanjoki during a period of approximately 16 years. The accumulation of sediments as a result of land uplift has caused the mouth of the river to move out towards the sea. The bay to the southwest of the river mouth is beginning to become isolated from the sea and to fill in with vegetation.
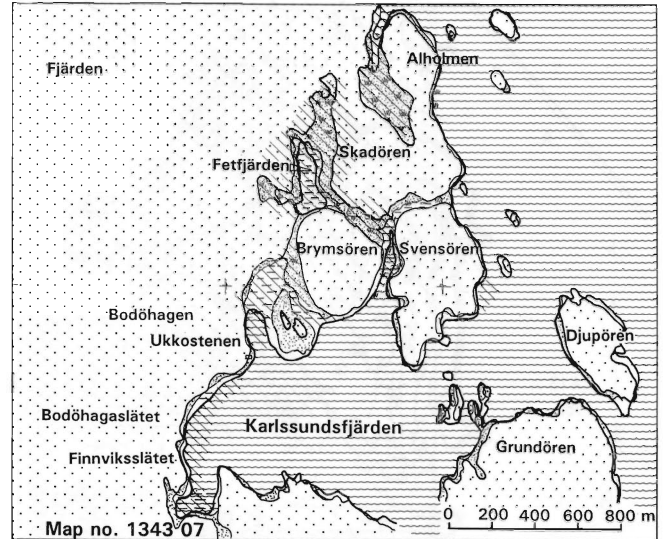

Figure 7.   A figure compiled from three Basic Maps produced within a period of approximately 36 years for this area of Vexala, indicating how much a coast may change during such a period. The islands which used to lie in the central area of the figure have merged with the mainland.

highly unfavourable due to the shallowness of the water. This resulted from both land uplift and silting up of the estuary of the river. The retreat of the shoreline was particularly rapid at the mouths of rivers which were apt to deposit silt (JONES, 1977).

The city of Pori (apparent uplift approximately 6.5 mm/yr) at the mouth of the River Kokemäenjoki in southwestern Finland continues to pursue its ancient role as a trading centre for the region. A small harbour and town had developed at the mouth of the river by around 1000 AD, but today this town, Teljä, lies approximately 40 km inland. The harbour has in fact been moved 6–7 times and the town was re-established near the harbour at intervals of approximately 200 years until the 16th century. The rapid silting of the river

mouth markedly accelerated the shore displacement in this area. The present town of Pori was founded in 1558 and has not shifted its position since, so that the current shoreline lies some 10 km from the city centre, *i.e.,* commercial shipping is handled at the outer harbours (JONES, 1977; PALOMÄKI, 1987a).

Numerous variations on the above pattern are found in the history of towns located on the rapidly uplifting coast of the Gulf of Bothnia (JONES, 1977; PALOMÄKI, 1987a,b). This is exemplified by the stages in the development of the city of Vaasa, which provide indisputable evidence of the effect of land uplift in the area. The gradual rise of the Vaasa area from the sea during the last 1,700 years is illustrated in Figure 3. The first signs of land in this area were small skerries which became more and more exposed over the centuries, some of them merging with one another and some with the mainland. A harbour and trading post developed at Mussor as early as the 14th century and the city of Vaasa was founded close to it on the island of Mustasaari in 1606. At this time, the harbour had already become so shallow, however, that a new one had to be constructed at Hästholmen. This in turn also became too shallow, and a deeper site was eventually found approximately 10 km away on Brändö (Palosaari), where a harbour was constructed in 1789. Since the road leading from the harbour to the town was in poor condition, hampering the transportation of goods, a decision was made to construct a channel leading from the old harbour to the town centre and a shipping lane, Stadssundet, passing through it. This channel which was completed in 1845 could
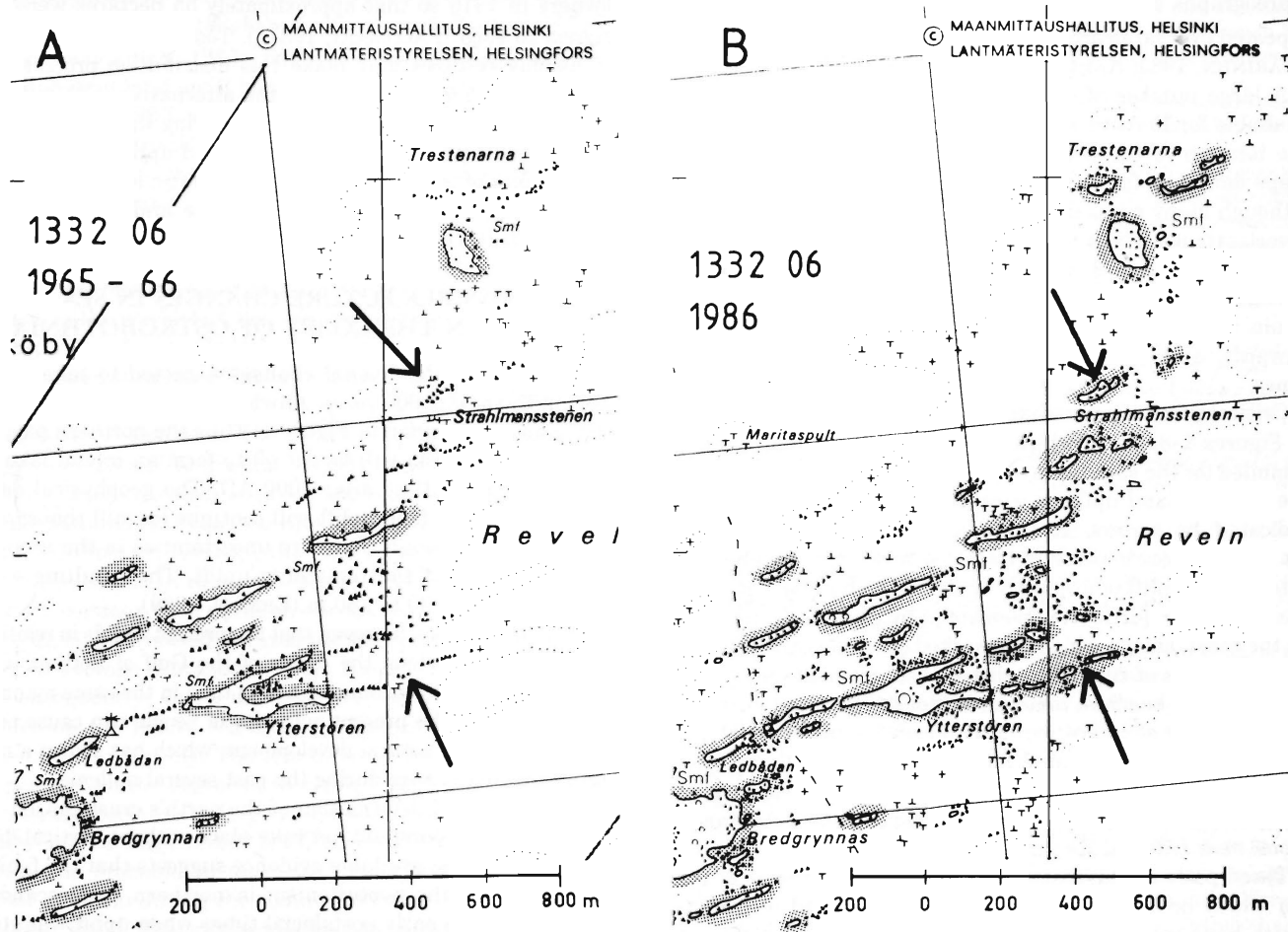
Figure 8. As indicated by the two maps, new islands are emerging from water, becoming visible first of all in the form of rocks protruding slightly above the water level, which then gradually join together to form small islands during the following few decades. The longish islands on the map are end moraines (De Geer moraines) which have gradually risen from the sea. An extensive cluster of such moraines exists in the archipelago off Vaasa (ZILLIACUS, 1987).

only be used by small vessels, however. The entire town was then destroyed by fire in 1852.

A decision was made after the fire to re-establish the town on the island of Klemetsö. Following its erection, the town bore the name Nikolaistad for a short period after which it regained its previous name of Vaasa. A new harbour had to be constructed at Vaskiluoto in 1893, and the harbour and the town have managed successfully in the same positions since. Today the city of Vaasa is a lively commercial and administrative centre with 54,000 inhabitants, and it was undoubtedly the re-establishment of the city at its new site that ensured this dynamic economic development.

The town of Uusikaarlepyy (NYKARLEBY, Figure 1) was a lively trading centre in the 17th and 18th centuries, even though it had problems with its shallow harbour similar to those of Vaasa. The town was also destroyed by fire in 1858 after which a new site was considered, but the idea was rejected and the town was erected on its former site. As the old

harbour had already become too shallow for large vessels, the town's economic development came to a halt and Uusikaarlepyy remained a little provincial town (JONES, 1977).

The old, shallow harbours of many towns on the coast of the Gulf of Bothnia have more recently been converted into marinas for the mooring of small boats; while a new, deep outer harbour, often located some way off, is used by commercial shipping. The operating life of harbours can be increased by dredging, a method not available in previous centuries (cf. JONES, 1977; PALOMÄKI, 1987a).

RECENT SHORELINE CHANGES

The sea bottom continues to become shallower on the coast of the Gulf of Bothnia as a result of land uplift, a process which reduces the depth of shipping and boating channels. To ensure the continuity of shipping, these changes must be monitored continuously. The rate of land uplift has been mea-

sured in Finland from the 19th century onwards by means of mareographs and precision levelling, the latter having been repeated over large areas three times (KÄÄRIÄINEN, 1966; SU-UTARINEN, 1983; KAKKURI, 1985).

A large number of maps dating from different times are available for Finland which show the effect of land uplift on the location of the shoreline. Some use has been made of maps dating as far back as the 18th century (JONES, 1977), although many maps from that time are too inexact for such investigations. The Provincial Maps (scale 1:100,000) published at the turn of the century are quite good, although changes on the coast can best be monitored using Basic Maps (scale 1:20,000). These have been published from the 1940's onwards, and some have been updated as many as three times.

Critical parts of pairs of maps of differing age are presented in Figures 4–8, one of which contains changes in three maps compiled for the same area at different times. Points at which the effect of land uplift is exceptionally well illustrated are indicated by arrows. It takes less than two decades for marked changes to occur in this area which has an apparent rate of land uplift of around 8 mm/yr. The changes caused by land uplift are further supplemented by geological processes on the coast, among which the marked effect of sedimentation at the mouths of rivers has already been pointed out. In the case of sandy beaches, material is moved effectively by wave action. Sandy soils are found at places on the coast of the Gulf of Bothnia where an esker created by glaciofluvial processes occurs at the present shoreline. An example of such an esker being continuously shaped by wave action is Vattajan-niemi near Lohtaja, shown in Figures 4 and 5.

These pairs of maps also contain examples of bays of the sea which have been isolated to form lakes and of islands which have merged either together or with the continent. A summer cottage located by the sea in this area may prove an investment which rapidly loses its value as the shoreline retreats and the open water turns into a muddy wetland.

EMERGING LAND AS PROPERTY

The inhabitants of the coast of Northern Ostrobothnia have had to adjust their social activities to the changes caused by land uplift. One of the main problems has been the ownership of the new land which emerged from the sea. A surprisingly simple solution was found at an early stage in Swedish legislation, according to which such land belongs to the owner of the water area concerned. As Finnish legislation is essentially based on that of Sweden, due to the two countries' common history, it is in line with the latter in this respect, too. Thus, since the water areas were traditionally owned jointly by all the inhabitants of the village concerned, the people who own strips of shore also shared the new land which emerges. This land is held in joint ownership at first and then divided officially among the various owners at given intervals in accordance with specific regulations. The proportion received by each person is dependent on the value of the land already owned and attention is paid to both the extent and value of the new land when dividing it up. Eight hundred and thirty two hectares of land which emerged on the island of Raip-

paluoto off the town of Vaasa was distributed between 15 owners in 1910 so that approximately 55 hectares were assigned to each (PALOMÄKI, 1987a). Today the many owners of holiday cottages may make this distribution process impossibly complicated, and thus the alternative is to sell the new land to those interested in purchasing it; even this may be a difficult process. Nevertheless, land uplift provides the inhabitants of the coast with extra property, even though the environmental changes on the shoreline and in the coastal waters also give rise to numerous problems.

POSSIBLE FUTURE CHANGES IN SEA LEVEL ON THE COAST OF OSTROBOTHNIA

A forecast of the coastal changes expected to take place during the next 2,000 years, provided that the current trend continues, is included in Figure 1. Thus the northern part of the Gulf of Bothnia will be cut off to form an inland lake of its own at some time after 4000 AD. The geophysical data indicate that the land uplift will continue for still thousands of years, even though there are uncertainties in the numerical calculation of the remaining uplift. The resulting estimates vary from 30 to 150 m (EKMAN, 1989).

There are threats, however, that the present trends in relative sea-level change along the coasts of the Gulf of Bothnia and elsewhere will not continue for a long time in the same manner as in the past. The present activities of people can cause perturbations in the natural development, which has shown a relatively regular change during the past several millenia.

The postglacial deformation of the earth's crust caused by the isostatic rebound did not take place without vertical dislocations, but the available evidence suggests that the faults resulting from the neotectonism in northern Fennoscandia date back to the early postglacial times when uplift was still very rapid (LAGERBÄCK, 1990; WAHLSTRÖM, 1993). No evidence for vertical displacement between bedrock blocks has been found in the Finnish shoreline displacement data, and it is concluded that the large scale uplift has generally taken place in a uniform manner. It is not excluded, however, that minor local disturbances of uplift can still be found in the shoreline data produced in Finland (ERONEN, 1994; ERONEN *et al.,* in press). The historical documents on coastal changes discussed above are similarly indicative of a lowering in sea level at a steady rate.

There are several relatively long tide-gauge records from the uplifting coast of the Baltic. The longest one of these, the Stockholm record, provides data on sea-level lowering since 1774. According to the analysis by EKMAN (1988a,b), the data indicate a change in the apparent land uplift in the late 19th century. The annual value of sea-level lowering in 1774–1884 was about 4.9 mm but in 1885–1984 it was 3.9 mm on average. The climatic warming after the Little Ice Age and ensuing increased eustatic rise is suggested as the reason for that change. The above data does not indicate any increase in world-wide sea-level rise in the 20th century. Similarly the Finnish tide-gauge data do not show any appreciable change in the land uplift or sea-level rise in this century (KÄÄRIÄINEN, 1975); except for, perhaps, in the last two decades.

The longest tide gauge series in Finland is measured in the

southernmost tip of the country, in Hanko, where the observations started in 1887. Since that year the mareograph has shown a steady rate (slightly over 3 mm/yr) of sea-level lowering (KÄÄRIÄINEN, 1975), but that trend changed in 1975. The apparent land uplift has slowed down to some degree and there is now a 90% probability that the change is not caused by random fluctuations (KAHMA, 1992). Something has probably happened to the rate of sea-level change over the Baltic Sea region, because, according to the analysis by BINDERUP and FRICH (1993), the Danish Baltic tide gauge records indicate an intense rise in sea level after 1974. These observations are not necessarily an indication of a trend in the oceans of the world; but they are connected to meteorological conditions and water balance in the Baltic Sea area.

The general assumption is that the ocean level is slowly rising, but there is a relatively large uncertainty about the magnitude of that rise. The recent estimates of yearly rise vary from 0.5 mm to 2.4 mm (GRÖGER and PLAG, 1993; PIRAZZOLI, 1993). According to PIRAZZOLI, the European tide-gauge data indicate that the rate of eustatic rise must be less than 1.26 mm/yr. Anyway, the land movements often determine the trends in relative sea levels, and since subsidence is more common than uplift on coastal regions, the tide gauge records may be biased towards the higher values of sea-level rise on average (PIRAZZOLI, 1993; BAKER, 1993).

Consequently, there are also very widely differing estimates on the future sea-level rise caused by the predicted greenhouse warming. The rise in ocean level will be largely dependent on the degree of warming and the response of the glaciers, especially the large ice sheets. According to the "best guess" of the most recent IPCC scenario (HOUGHTON et al., 1992) the probable eustatic rise in sea level will be to the order of 50 cm during the coming 100 years (cf. WIGLEY and RAPER, 1992). That rise would lead to catastrophes in many coastal areas, but on the coast of the Gulf of Bothnia, it would only substantially reduce the apparent land uplift.

ACKNOWLEDGEMENTS

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