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Reconstruction of Late Holocene development of the submarine terrace in the Eastern Gulf of Finland

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Abstract The coastal slope morphology of the submarine coastal zone of the Eastern Gulf of Finland was identified during a VSEGEI survey involving side–scan sonar profiling, echo sounding, surface sediment sampling. Along the northern coast of the Gulf, the sand terrace sub–surface was mapped at depths of 4-5 m to 8-12 m, top to foot. In order to explain the morphogenesis of the terrace, the development of the coast over the Late Holocene was reconstructed using a mathematical model. Tectonic processes, particularly glacio–isostasy, are suggested to have been the main factors forming the terrace at earlier stages; at later stages sea level changes played the main role. The coastal development during the Late Holocene was subjected to the gradual erosion of the above–water terraces and the formation of underwater terraces. During transgression phases, the rate of coastal recession reached 0.5 m y^{-1}, while at other times it was approximately half that. The submarine terrace, developed 3.2–1.2 kyr ago, broadened as a result of both coastal recession and sediment accumulation on its outer edge. During this time, the coast retreated about 500 m.

Keywords *Submarine terrace, modelling, Late Holocene, Eastern Gulf of Finland, Russia.*

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INTRODUCTION

The investigation of the Holocene shorelines of the Baltic region has a long history. Relative sea level changes in different geological and tectonic settings have been investigated in detail for some Baltic regions (Blazhchishin *et al.* 1982; Uscinowicz 2003; Saarse *et al.* 2009), where Holocene shorelines and coastal landforms have been described. Many researchers have discussed coastal development caused by eustatic sea level change and tectonic movements (Mörner 1980; Eronen 1988; Zhindarev, Kulakov 1996; Harff *et al.* 2001; Eronen *et al.* 2001). Submarine terraces were reported in the western, southern and south–eastern Baltic Sea.

Despite the achievements to date, understanding of the Holocene geological history of the Eastern Gulf of Finland still has some significant knowledge gaps. The adjacent coastal areas (especially the Karelian Isthmus) are well known classic examples of bench lands with Quaternary sequences (Privetninskoye village, Fort Ino, Chernaya River, Luzhki village etc.) (Fig. 1). The earliest studies of the Quaternary deposits were carried out at the end of the 19th century by Kropotkin, De Geer and Berghell (Kropotkin 1876). The terraces related to the Baltic Ice Lake, Ancylus Lake and Litorina Sea shorelines have been described by Yakovlev (1925), Markov (1931) and Hyyppä (1937). The first map of the postglacial basins was published by Yakovlev (1925). In the 1960s and 1970s investigations and dating of on–land postglacial sediments were undertaken by

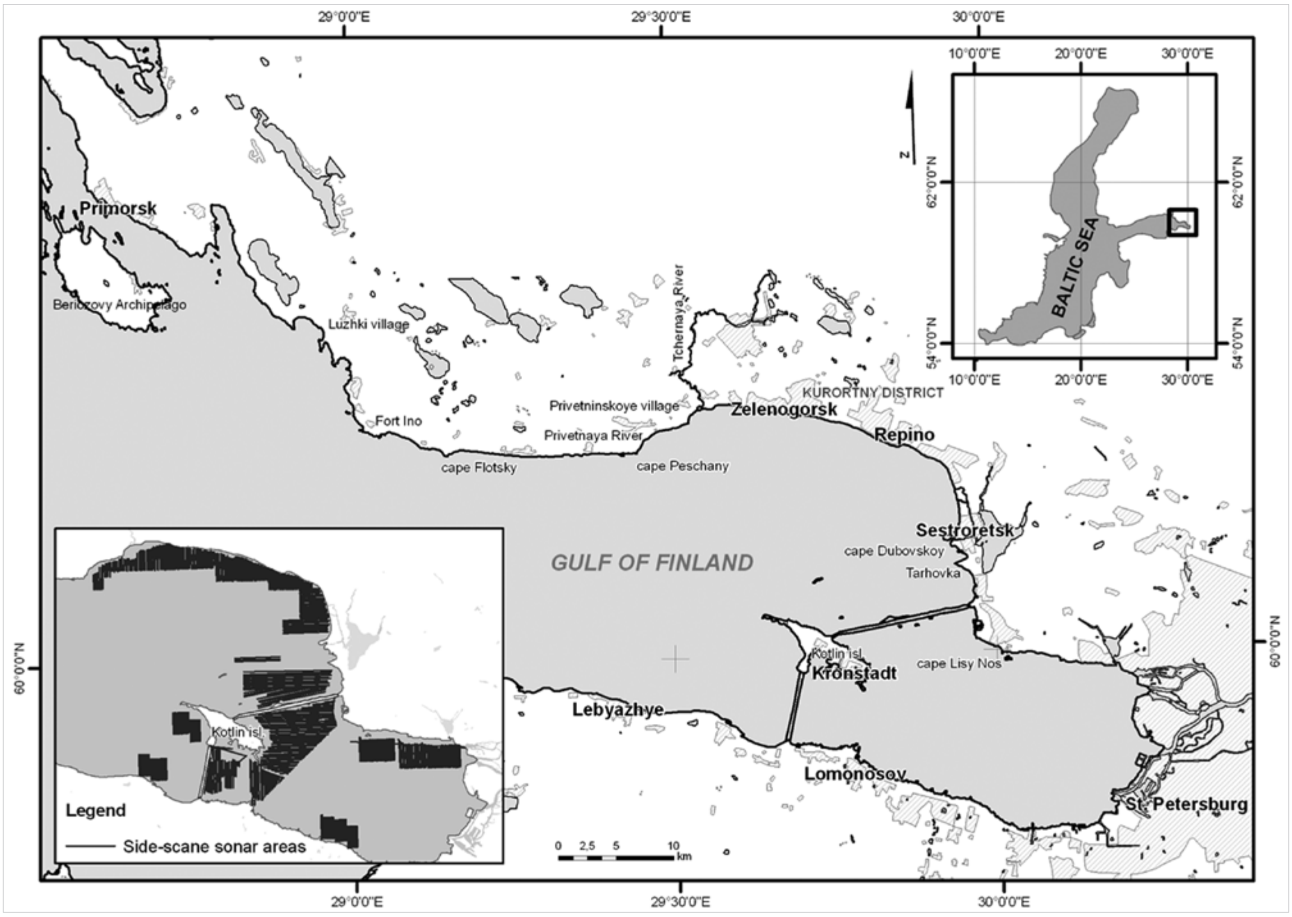

Fig. 1. The study area and scheme of side scan sonar and echo sounding profiling. Compiled by D. Ryabchuk, A. Sergeev, 2010.

Kvasov (1979); Usikova *et al.,* (1967); Znamenskaya, Cheremisinova (1974) and others (Markov 1961; Serebryany, Punning 1969; Malakhovsky 1995). A lot of data were obtained during the geological mapping of Saint Petersburg and surrounding territories (scale 1:50 000) undertaken by the Saint Petersburg Complex Geological Expedition supervised by V.Auslender (unpublished reports). A significant number of ^{14}C dates of the peat samples of Holocene sediments were made in the 1960s and 1970s.

The systematic geological surveys carried out by scientists of the VSEGEI in 1980–2000 have allowed the study of the distribution, composition, structure and thickness of the Quaternary deposits of the Russian part of the Gulf of Finland (Spiridonov *et al.* 2007; Petrov 2010). Some submarine alongshore terraces were found during these studies, but the terraces have never been accurately dated.

In spite of the significant data available, there are a number of questions and unsolved problems about the Postglacial, and especially the Holocene, geological history. Due to some contradictory results of Quaternary sediments ^{14}C dating and the rather complex recent tectonic movements of the different blocks, the sea level changes and shoreline displacements during the Middle and Late Holocene are not yet fully understood. For the Eastern Gulf of Finland there are three published versions of sea–level change curve. The first is compiled by D. Kvasov (1979), but this scheme is too general and it can not explain all data now available. The second curve was presented by P. Dolukhanov (1979). More recently, the palaeoenvironment of the Karelian Isthmus area during the Litorina Sea stage of the Baltic Sea history, between 8800 and 5200 cal. yr BP was reconstructed by studying four sites located on the Karelian Isthmus in Russia (Miettinen *et al.* 2007). They found two transgressions with maximums at 7700 cal. yr BP and 6500 cal. yr BP (Miettinen *et al.* 2007). It should be mentioned that investigation of the Karelian Isthmus lakes did not provide data for last 5000 cal. yr BP, and this curve contradicts D. Kvasov's result. So unlike other parts of the Baltic Sea, there is still no generalized shoreline displacement curve of the Eastern Gulf of Finland.

The objective of this paper is to reconstruct the peculiarities of the morphodynamics of coastal profile development during the Late Holocene using a mathematical modelling approach. A model of coastal development is based on the field geophysical and geological data. The presented model explains the genesis of the submarine terrace located in the northern coastal zone of the Gulf of Finland, between the villages of Repino and Cape Peschany and provides details of coastal development over last four thousand years.

GEOLOGICAL SETTING

The investigated coastal zone including both the onshore and offshore is totally covered by Quaternary deposits up to 20-40 m. Quaternary deposits thickness reaches maximum values (up to 100-120 m) within palaeo–valleys (Ryabchuk *et al.* 2007). Late Pleistocene glacial till covers large areas in the studied coastal zone. The most widespread type of distal facies of the lacustrine–glacial deposits consists of varved clays (local ice lakes), laminated and homogenous brownish–grey clays. In the investigated area, these sediments do not differ from their analogues on other parts of the gulf bottom. On the contrary Holocene sediments (Ancylus and Yoldia stages, Litorina and Postlitorina seas) are represented mainly by sands of nearshore facies. The investigated part of the northern coastal zone of the Gulf is located in an area of intense differentiated modern tectonic movements.

The on–land bench land, which has been forming since the Middle Holocene, is from 150-200 m to 1-1.5 km wide along the northern coast of the Gulf (with the widest section being 6 km within the ancient bay near Privetnaya River). The maximum level of the Litorina transgression is marked by a distinct scarp at heights from 18 to 35 m (Znamenskaya, Cheremisinova 1974). Between the highest marine terrace and the recent shoreline there are up to four Litorina and Postlitorina terraces (Fig. 2). The shoreline of the Litorina Sea is distinctly marked land around coast of the Eastern Gulf of Finland by erosion scarps and beach ridges. Maximum heights of the marine Litorina terrace surface is located at +3.0 to +3.5 m, while its maximal level is located at + 6 to +7 m (Saint Petersburg); + 8 to +9 m (Gorskaya village) (Krasnov, Zarrina 1982); +10 m (Tarhovka, Sestroretsk); and + 15 to +16 m (Luzhki village) (Znamenskaya, Cheremisinova 1974). The Tchernaya River bank is formed by four Litorina and Postlitorina terraces (with heights 1.5; 4.0; 8.0-9.0 m; and 13.0-14.0 m; the maximal level of the Litorina transgression is at 13 m (Znamenskaya, Romanova 1966).

During VSEGEI investigation performed in 2005–2008 a submarine terrace was recognized along the northern coast of the Gulf (Ryabchuk *et al.* 2007; Ryabchuk *et al*. 2009) (Fig. 3). From the shoreline to a water depth of 2-2.5 m, the submarine coastal slope consists mostly of a boulder–pebble bench, with alongshore sand three–five ridges on the subsurface. At a distance of 400-600 m from shoreline the boulders change to sand sediments. Outward the slope is relatively steep. To the west of Repino village (up to Flotsky Cape) there is a submarine terrace, 18 km long and up to 2 km wide. The terrace is situated at the water depth 4-5 m and covered by sands of different grain size (medium sand dominates). The terrace foot is located at a water depth from 8 m (eastern part) to 12 m (western part).

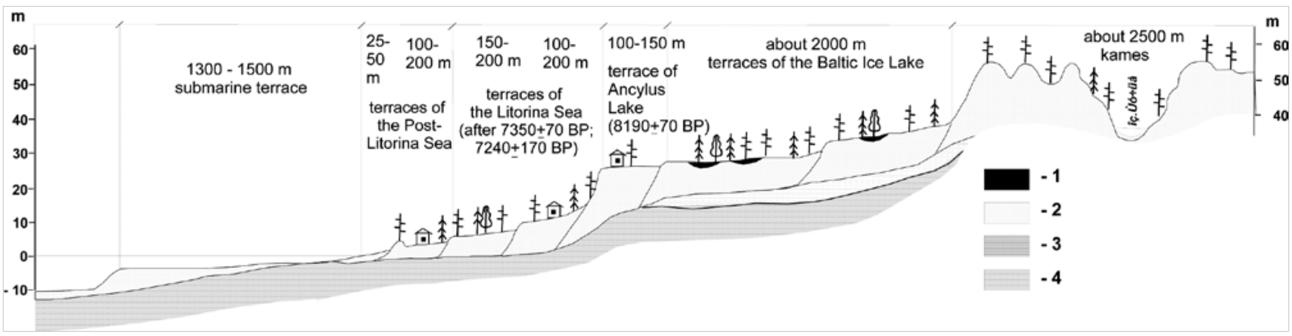

Fig. 2. The study area and a schematic geological–geomorphological coastal profile in the vicinity of Zelenogorsk town. Modified by D. Ryabchuk after V.G. Auslender (1998) and P. Dolukhanov (1979). Explanation: 1 – peat; 2 – sand; 3 – bandy clay; 4 – boulder loam (morain).

From the seismo–acoustic data, the thickness of the sand layer is shown to change from several tens of centimetres (in the zone adjacent to the boulder bench) to 4-5 m (marine edge of the terrace). On the eastern part of the terrace, the surface is disturbed by irregular ridges with runnels between them (relief amplitude 1-2 m), elongated with an angle of about 45^{o} to the terrace edge. Repeated survey has shown that these forms have been stable during five field seasons of observations. These features, and a comparison of our data with old nautical charts, indicate that the terrace is eroded. The most changed part of the terrace is located seaward of Zelenogorsk town (middle part of the terrace). To the west, the terrace surface becomes more planar and the slope more distinct (Fig. 4). For further consideration we generalize the coastal profile with the most important relief features (see Fig. 5a). The average width of the terrace was taken as one km.

From 2004 to 2008 scientists of A.P. Karpinsky Russian Research Geological Institute (VSEGEI) undertook research projects to study the geology and morphology of the submarine coastal zone of the Eastern Gulf of Finland. Within the investigated area, over 900 km of side–scan sonar (CM2, C–MAX Ltd, UK with a working acoustic frequency of 325 kHz) and echo sounding (GARMINI–128) data were collected (including 400 km of repeated survey) (see Fig. 1) enabling the 3D plotting of the bottom surface relief in water depths between 1.5 and 12 m. In 2008

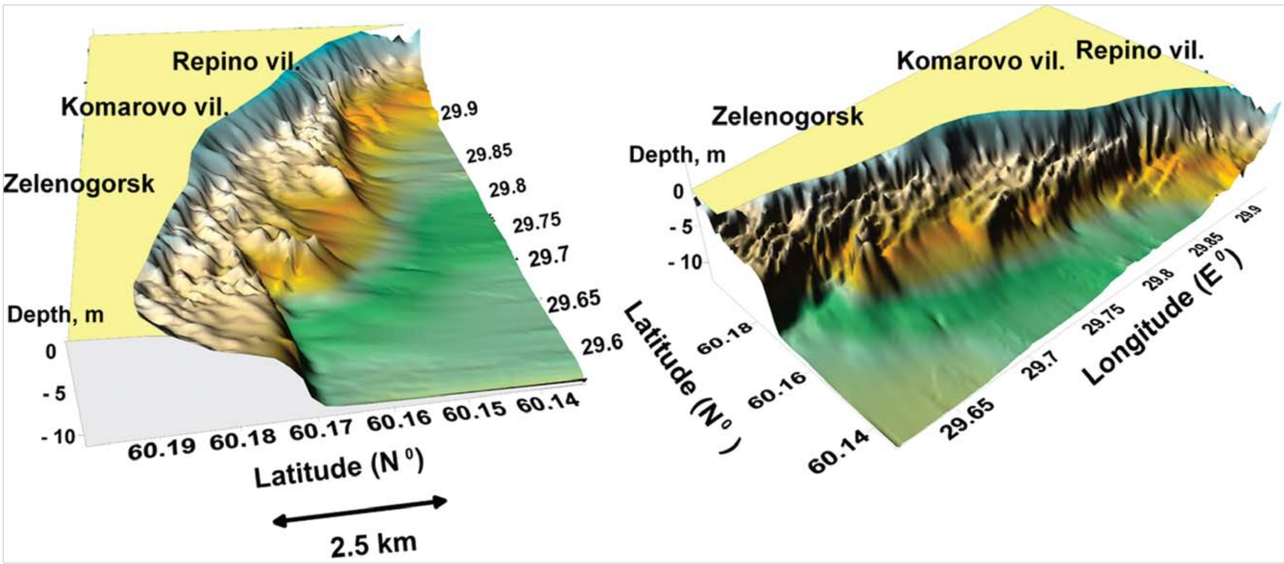

Fig. 3. The morphology of the coastal slope in the Kurortny region of St. Petersburg based on survey data. Compiled by D. Ryabchuk, 2010.

and 2009 52 km of seismo–acoustic profiling has been made. Seismo–acoustic profiling was carried out using digital seismo–acoustic complex GEONT–HRP ("Spectr–Geophysics", Russia), acoustic frequency 30–1500 Hz, 2–7 kHz and 7.5 kHz). All mapping was accompanied by surface sediment sampling

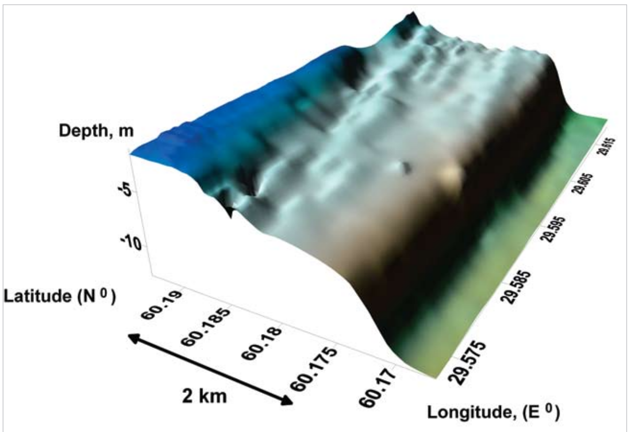

Fig. 4. The morphology of the coastal slope of western part of submarine terrace. Compiled by D. Ryabchuk, 2007.

CONCEPTUAL MODEL OF HOLOCENE DEVELOPMENT

Many authors report eustatic sea level rise about 8000–8500 BP in the global sea level records started at depths about minus 20-25 (Badukova, Zhindarev 2007). In the south–eastern Baltic Sea, shorelines of this time are recognized at –29–25 m (Gelumbauskaitė 2009; Blazhchishin *et al.* 1982). Due to glacio–isostasy and diachronous time boundaries, the ancient shorelines displacement moves northwards and eastwards (Eronen 1988; Kessel, Raukas 1979; Kleimenova *et al.* 1988; Harff *et al.* 2001). Within study area, which is easternmost part of the Baltic, pre–Litorina shoreline located at +4-+5 m. In the Tchernaya River sequence the minimal level of the pre–Litorina regression (Mastogloia phase) is at +5 m, dated at 8500 cal. yrs BP. In Privetninskoye mire, which was separated from the open sea during the pre–Litorina regression, and become a lagoon during Litorina stage, regression dated by peat layer 8350–8170 cal. yrs BP (Miettinen *et al.* 2007). In the Lahta mire a peat layer at +4 m, formed during pre–Litorina regression, is dated as 8203–8265 cal. yrs BP (Krasnov, Zarrina 1982).

As a result of saltwater intrusion from the North Sea caused by eustatic ocean level rising, the Litorina Sea began to form about 8500–8300 cal. yrs BP (Berglund 1964; Uścinowicz 2003; Bitinas, Damušytė 2004; Berglund *et al.* 2005). The Litorina Sea existed during the Atlantic and Subboreal. Different authors divided from two to six Litorina transgressions in different parts of the Baltic Sea.

The Post-Litorina stage embraces the second part of the Subboreal and Subatlantic time. The boundary between the Litorina and Postlitorina phases (4300–4800 cal. yrs BP) is uncertain because of insignificant environmental change in the Baltic Sea. There are some ^{14}C dates of peat and gyttja on different parts of the Karelian Isthmus between 5213–5474 cal. yrs BP and 3613–3728 cal. yrs BP (Kleimenova *et al.* 1988). In some sequences up to two transgression phases were found. Unfortunately there are only very poor data about sea level change during the late Holocene.

The rates of glacio–isostatic rebound have decreased during the Holocene. In environs of the Tchernaya River, the rate of uplift was about 9 mm/year 9500 cal. yrs BP and just about 2 mm/year 5000 cal. yrs BP (Krasnov, Zarrina 1982).

So for modelling study it is believed that eight thousand years ago the sea level was several meters lower than present. The tectonic block which includes the investigated area, was hypsometrically lower than it is now, but it has been rapidly tectonically uplifting as a result of glacio–isostasy. The glacio–isostatic rise was one of the main influences on the coastal zone with the process complicated by sea level fluctuations (the Litorina transgression). As a result, after the maximum of the Litorina transgression in the Middle Holocene, the coast evolved under a stepped sea level regression, with the successive formation of terraces, that can still be observed on land (see Fig. 2) (Auslender 1998). By 5.0 kyrs BP, the glacio–isostatic uplift had slowed (Krasnov, Zarrina 1982). Since that time the coast has been developing under the influence of sea–level rise, which included three transgressions (about 3.0–4.0, Gelumbauskaitė 2009; 2.0–2.5, and 1.0 kyrs BP, Badukova *et al.* 2007).

To reconstruct the process of coastal profile development, we need to take into account that due to only moderate storm activity in the eastern Gulf of Finland, the zone where the waves cause the significant movement of the bottom material ("active part of the profile") is limited to the water depth h_* of about 3 m (Leont'yev 2008). It is this feature that determines the water depths of the modern marine terrace, which was formed on the nearshore part of coastal profile (Fig. 5a). By taking into account h_*, we can conclude that the terrace-like section of the profile at a water depth of 8 m could have been formed with a sea level of –5 m, while the terrace located at depth of 5 m formed with the water level at –2 m. Linking these values with the probable time of the transgressions (about 3–4, 2–2.5 and 1 thousand years ago), we can assume the sea level change scenario as shown in Fig. 5b.

It is assumed, that four thousand years ago, the relative sea level was –5 m. The spread of data does not exclude such a possibility (Badukova *et al.* 2007; Bitinas, Damušytė 2004). During the first transgression between three-four thousand years ago the sea level rapidly rose up to –2 m, and up to two thousand years ago it slowly advanced to –1.5 m. Other sea level fluctuations (such as a transgressive–regressive event about 2–2.5 thousand years ago) did not leave visible traces in the relief.

Therefore the first transgression displaced the wave base to the new hypsometric level. The result should have been reflected in the relief as an emergence of a relatively steep section of coastal profile, above which a new terrace began to form. The sediment dynamics facilitated coastal erosion and shoreline retreat. Eroded material was carried away from the active part of the profile and accumulated behind the edge of the steep section. As a result a terrace berm was formed and the terrace grew seaward (this behaviour is supported by the significant thickness of the sand layer observed along the marine side of the terrace). Thus the terrace widened both landward and seaward.

During the transgression which took place about one thousand years ago, the sea level rose one meter. The process repeated at a smaller scale and a relatively steep section of profile was formed and a new terrace began to form. In contrast to the previous stage, however, the new terrace did not spread seaward as accretion along its outer edge is not observed. A possible reason for this behaviour is a sediment deficit, as the sand sources accumulated during previous development could have been depleted. As a result the substrate composed of glacial till with a small amount of sand (about 15%) was exposed to waves. Fine clay particles of the moraines eroded easily and were carried away from coastal zone. The terrace stopped growing seaward, and as demonstrated by repeated echo sounding profiling data, its marine edge is eroded and is retreating (Ryabchuk *et al*. 2007). The lower part of Fig. 5c shows the sea level change rate $w = d\zeta / dt$ (ζ– sea level; t – time). During the transgressions w could reach 5-6 mm year $^{-1}$.

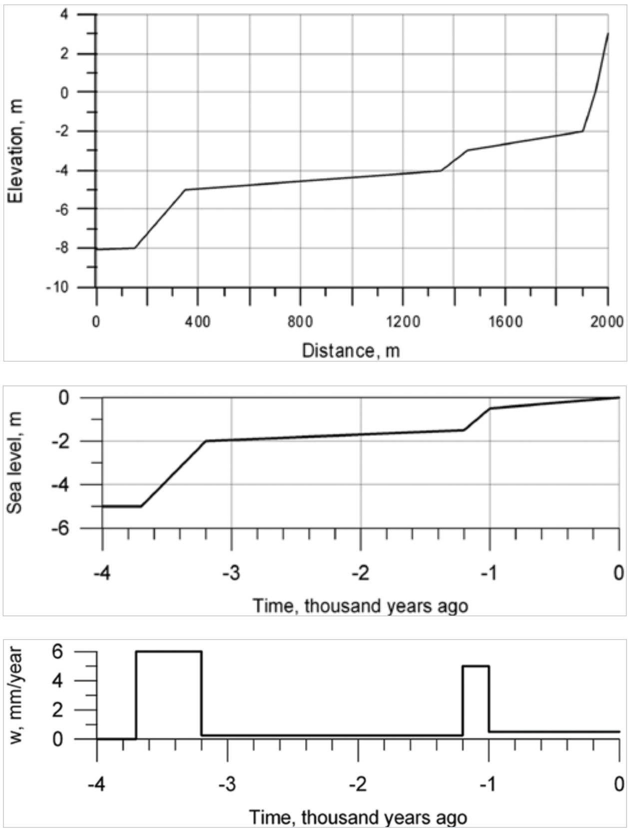

Fig. 5. The generalized coastal profile taken as a prototype for the modelling study (a), and the scenario of sea level change (b, c). Compiled by I. Leont'yev, 2010.

RESULTS OF MATHEMATICAL MODELING

The scenario described above was reproduced using the Leont'yev model (2008), based on a sediment balance equation in a morphodynamic system,

$$\partial\chi / \partial t = \left(h_* + z_{cl}\right)^{-1}\left(wl_X - B\right),$$
$$B = q_* - q_{Aeol} - \partial Q / \partial y + \Omega . \qquad (1)$$

This equation links the rate of displacement of the shoreline (and the active part of coastal $\partial\chi / \partial t$ profile) with the sea level change and the sediment budget B. Here h_* is the closure depth, limiting the active part of profile, z_{cl} is the elevation of the upper profile boundary, l_X is the distance between h_* and z_{cl}. The sediment budget includes the cross–shore sediment fluxes through the lower and upper boundaries of the coastal zone (q_{Aeol} and q_*), the alongshore sediment flux gradient ($\partial Q / \partial y$) and any additional sediment source or sink (Ω). The value B is measured in cubic meters per meter of shoreline per year ($m^3m^{-1}year^{-1}$). $\partial Q / \partial y$ and Ω are assumed to be negligible in the following analysis.

In the described case of coastal retreat ($\partial \chi / \partial t > 0$), we are dealing with a negative sediment budget ($B<0$), meaning that the material is carried out of the active profile zone. Sediments can be transported both seaward (flux q_*) and landward (aeolian flux q_{Aeol}). A fraction of the material, moving seawar d, αB, accumulates behind the terrace edge, so the rate of the seaward advance of the terrace, $\partial x_T / \partial t$, can be estimated as

$$\partial x_T / \partial t = \alpha B / Z_T, \qquad 0 \le \alpha \le 1, \quad (2),$$

where Z_T is the height of the terrace escarpment. The total rate of terrace widening is determined by quantity – $\partial \chi / \partial t - \partial x_T / \partial t$.

The main goal of the modelling study was to reproduce the coastal profile development and coastal retreat under the scenario of sea level change described above. The rates of coastal recession were calibrated by variation and selection of the sediment budget value B. The parameters of the active profile were assumed to be constant: h_*=2.9 m, z_{cl}=3 m, l_X=300 m, the width of dry beach section l_b=50 m.

The result of the modelling is presented in Fig. 6. The graph fixes the location of the active profile at different time moments over the last four thousand years and marks the trajectory of movement of its seaward edge. This trajectory, per se, reflects the bottom profile formed after the landward shore recession. Calculations were performed for three different cases: 1) α = 0 – no sediment material is accumulated along marine boundary of the terrace which is widening to landward; 2) α = 0.5 – a half of the sediment flux is accumulated along the marine terrace edge causing the terrace to widen seaward; 3) α = 1 – all outgoing sediment is accumulated near marine terrace boundary. Fig. 6 demonstrates that in the first case the shore recession is quite rapid (Fig. 6a), in the second case the contributions of both shore recession and sediment accumulation to the widening of terrace are approximately the same (Fig. 6b) and in the third case the main reason for the terrace widening is sediment accumulation (Fig. 6c). The similarity of the final profiles with the prototype (see Fig. 5a) is obvious.

Table 1 shows the modelled estimates of the sediment budget B, and also the rates of coastal recession $\partial \chi / \partial t$ and the terrace edge displacement $\partial x_T / \partial t$ during different time periods t for the three scenarios of coastal development. It remains uncertain as to which scenario best represents reality. It should be noted however that the sediment budget is a generally conservative parameter, and from this viewpoint Scenario 2 (α = 0.5) appears to be more probable. According to this scenario, during transgressions, the rate of coastal recession reaches its maximum (0.5 m $year^{-1}$), while during periods of relative sea–level stability this rate is two times less. The terrace widened both seaward and landward at a similar rate.

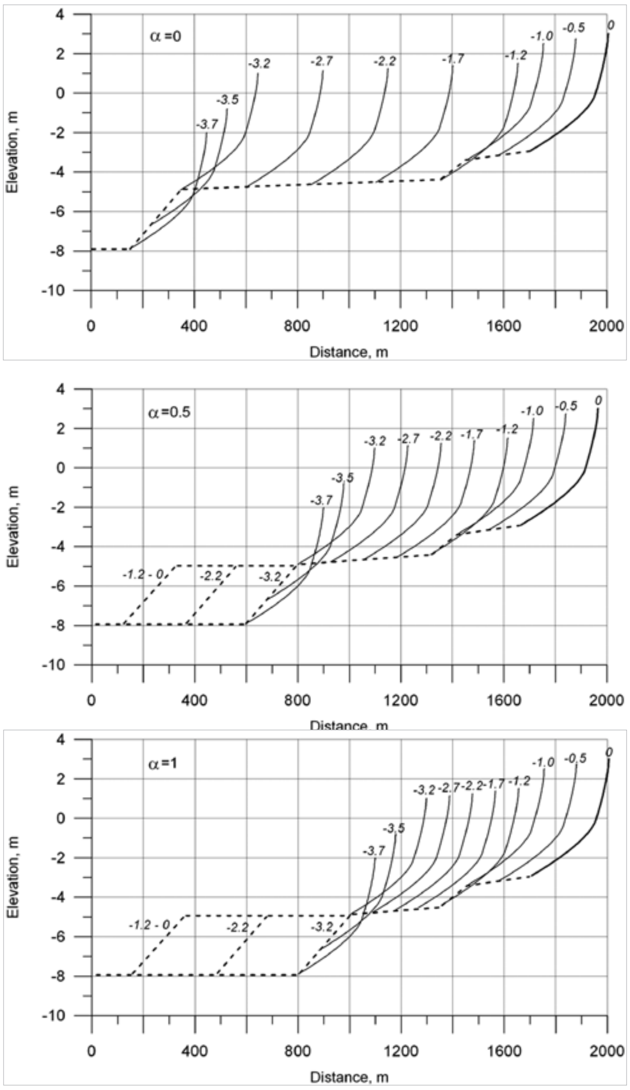

Fig.6. Modeling of three possible cases of coastal evolution during the late Holocene: (a) α = 0 – no sediment material is accumulated along seaward boundary of the terrace which is widening only in a landward direction; (b) α = 0.5 – half of the sediment flux is accumulated along the seaward terrace edge causing the terrace to widen seaward; (c) α = 1 – all outgoing sediment is accumulated near the seaward terrace boundary. Successive locations of the active profile are shown at different moments of time (thousands years ago). Dashed lines trace the trajectory of the moving outer edge of the active zone that reflects the bottom profile formed after landward coastal recession. For cases α = 0.5 and α = 1 the stages of seaward widening of terrace are also marked (by the dashed line). Compiled by I. Leont'yev, 2010.

Table 1. Sediment budget, rates of coast recession and rates of displacement of the terrace edge during different time periods.

t, thous. years ago	w, mm y^{-1}	α = 0		α = 0.5			α = 1		
		B, m^{2}y^{-1}	$\partial\chi/\partial t$, m y^{-1}	B, m^{2}y^{-1}	$\partial\chi/\partial t$, m y^{-1}	$\partial x_T/\partial t$, m y^{-1}	B, m^{2}y^{-1}	$\partial\chi/\partial t$, m y^{-1}	$\partial x_T/\partial t$, m y^{-1}
-3.7-3.2	6.00	-0.55	0.50	-0.55	0.50		-0.55	0.50	
-3.2-1.2	0.25	-2.90	0.50	-1.45	0.26	-0.24	-0.98	0.18	-0.32
-1.2-1.0	5.00	-1.45	0.50	-1.45	0.50		-1.45	0.50	
-1.0-0.0	0.50	-1.32	0.25	-1.32	0.25		-1.32	0.25	

It should be mentioned that the results relate to generalized coastal profile with a uniform height of the submarine terrace. In reality, the terrace becomes wider in a western direction, where its base is located at greater depth. It is obvious that at that location, the rate of the terrace widening was higher due to more intense sediment flux (the absolute value of B was higher).

The results received by mathematical modelling do not contradict with the major part of published data about sea level change (Eronen 1988; Kessel, Raukas 1979; Harff *et al.* 2001; Badukova, Zhindarev 2007; Gelumbauskaitė 2009). The result does not pretend to be complete, as mathematical modelling should be supported or corrected by geological data. Future field investigation should provide more information for model verification.

CONCLUSIONS

During VSEGEI survey (side–scan sonar profiling, echo sounding, surface sediment sampling) along the northern coast of the Gulf of Finland, subsurface of the sand terrace was mapped at the depths from 4-5 m (top) to 8-12 m (foot). In order to explain these submarine relief features an attempt was made to reconstruct the coastal profile development over last four thousand years using a mathematical model.

It does not take into account many hydrodynamic factors influencing the bottom relief. The key assumption of our model is that at an earlier stage tectonic processes were most significant, while at a later stage sea level changes were of greatest importance. The tectonic block comprising the investigated area of the Gulf of Finland at first rapidly uplifted, but it then stopped and began to flood due to sea level rise. This development has resulted in the formation of a series of terraces. The earliest terraces are now on dry land, while the later terraces are on the submarine slope. The coastal evolution during the Late Holocene is therefore the result of the gradual erosion of the on–land terraces and the formation of terraces underwater.

The mathematical modelling results show that during the sea transgressions (three–four and one thousand years ago) the rate of coastal recession was at a maximum (0.5 m year^{-1}), and during period of relative sea level stability this rate was two times less. The submarine terrace, formed over the period from 3.2–1.2 thousand years ago, was widening at a similar rate both landward (as a result of shore recession) and seaward (as a result of sediment accumulation along the terrace edge). The shoreline during that period was displaced landward by 500 m and the mean rate of sediment accumulation at outer edge of terrace was about 0.7 m^{3}m^{-1}year^{-1}.

Finally, it should be once again mentioned that the terrace is not of uniform width. The sand ridges and runnels, elongated at an angle to the shoreline and observed on the terrace surface at its eastern part could act as water outflow channels caused by storm surge and floods. Sediments which were moved to the terrace edge did not accumulate at this location, so the terrace did not widen seaward. The height of the storm surge gets higher in an eastern direction. Possibly, this factor can be one of the reasons for the difference in the western and eastern coastal profile morphologies.

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