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THE PROVENANCE OF BEACHES ON THE ESTONIAN ISLANDS OF HIIUMAA AND SAAREMAA

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Abstract. The paper describes the past and present beaches of the islands of Hiiumaa and Saaremaa. The questions where the beach material has come from and whether it is still being delivered are examined.

Key words: Baltic Sea, changes of water level, changes of wave energy, neotectonics, shore lines, beach deposits, coastal formations, transgressions and regressions, dunes.

INTRODUCTION

Around the world's coastline, beach deposits are mainly represented by sand, gravel, and pebbles. Their petrographic and granulometric characteristics are related to the nature of the geological material from which they were derived, and also the environments of transportation to, and deposition on, the beach (Bird, 1988; Кессел & Раукас, 1967; Орвику, 1974; a.o.). Some beach material has been supplied from the erosion of coastal cliffs and bluffs, or foreshore rock outcrops, part of it has been carried to the coast by rivers or washed in from the sea floor by waves and currents.

Some sandy beaches have been fed from dunesands from the land. In recent decades a few beaches have been nourished artificially with sand brought from inland, alongshore or from the sea floor and dumped on the shore (Fig. 1). Many beaches contain sediment supplied from more than one source. Only approximate estimates can be given of the proportion of materials derived from different sources. Some beaches are still receiving sediment and if the gains exceed the losses they are built up seaward, a process termed progradation; others are relict, the sediment sources being no longer available, or the processes of delivery no longer active; and still others are undergoing erosion.

Beaches are dynamic landforms which change in response to sea level movements and weather conditions. In stormy periods, when breaking waves erode beaches, the strong backwash sweeps sediment offshore, whereas in calmer weather the spilling waves restore the beach profile: a sequence known as "cut and fill". Variations in the pattern of coarse and fine sediment, and in micro-topography, including such features as berms, beach cusps, swash marks, and ripples, occur over short periods, and reflect the characteristics of the available beach material.

There are various kinds of nearshore topography accompanying beaches. Some are bordered by rocky or muddy sea floors, which may be partly exposed at low water level; others pass down into smooth, usually concave, nearshore profiles of sand and gravel; others are fronted by one or more sand or gravel bar formations which run parallel to the coastline, or occur in more intricate patterns. These features also show frequent short-term variations, again influenced by the nature of the sediments.

Hiiumaa and Saaremaa, the biggest islands in Estonia, display a large variety of ancient and contemporary shore types, which have been rather well studied lithologically and stratigraphically (Sepp, 1974; Кессел & Раукас, 1967; Орвику, 1974; a.o.). Particularly variable and well developed are ancient coastal formations of transgressive phases (Раукас, 1966). Owing to the moderate crustal uplift (now 2 to 4 mm/year in Hiiumaa and Saaremaa), the coastline was rather stable over long intervals of time during the transgressions and therefore the corresponding beach deposits have a great thickness (6—7 m). In earlier times both Hiiumaa (Fig. 2) and Saaremaa (Fig. 3) were rather small open sea islands washed by strong wave action during heavy storms. The highest areas in Hiiumaa (Kõpu Peninsula) and Saaremaa (West Saaremaa Upland) consist of soft Quaternary deposits, readily eroded and cut into clear series of bluffs at various levels. Kents (1939) mentioned on the Kõpu Peninsula coastal erosional features of the Ancylus Lake and the Litorina Sea at ten levels and beach ridges of the Ancylus Lake at twelve levels.

In general, the epicontinental character of the Baltic Sea is reflected in all processes responsible for the coastal morphology and sedimentation. Tidal changes are minimal. More important are the seasonal variations and short-term changes in the water level induced by strong winds. Because of the rugged shoreline and general shallowness of the coastal waters, longshore drift in the West-Estonian Archipelago has been limited, and material of the local origin prevails. The present paper examines the questions of where the beach material originates from, and whether it is still being delivered with reference to the Estonian islands of Hiiumaa and Saaremaa, which were studied during the joint field trip in September 1991.

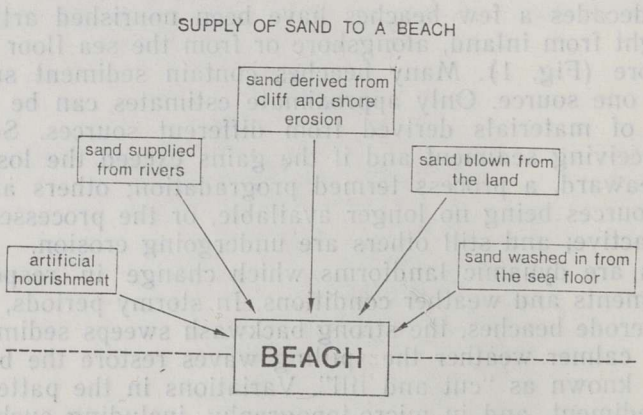

Fig. 1. Supply of sand to a beach. Gravel is supplied from four of these sources, but only sand is blown to the beach from the land.

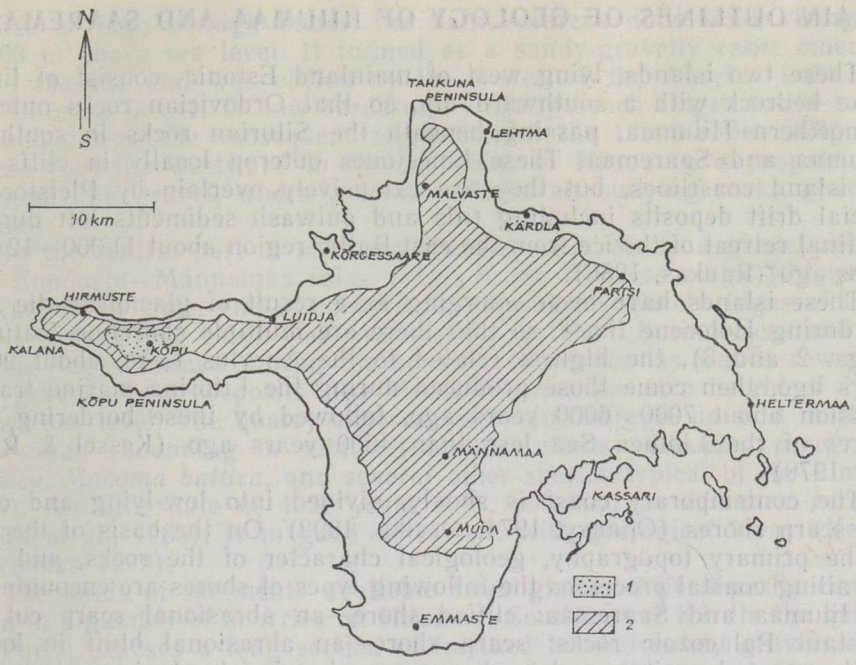

Fig. 2. Evolution of Hiiumaa Island in postglacial time after Kessel and Raukas (Кессел & Раукас, 1967) with complements.
1 small island (about 1 sq. km) at the time of the Ancylus transgression about 9000 years ago; *2* Hiiumaa at the end of the Litorina Sea about 4500 years ago.

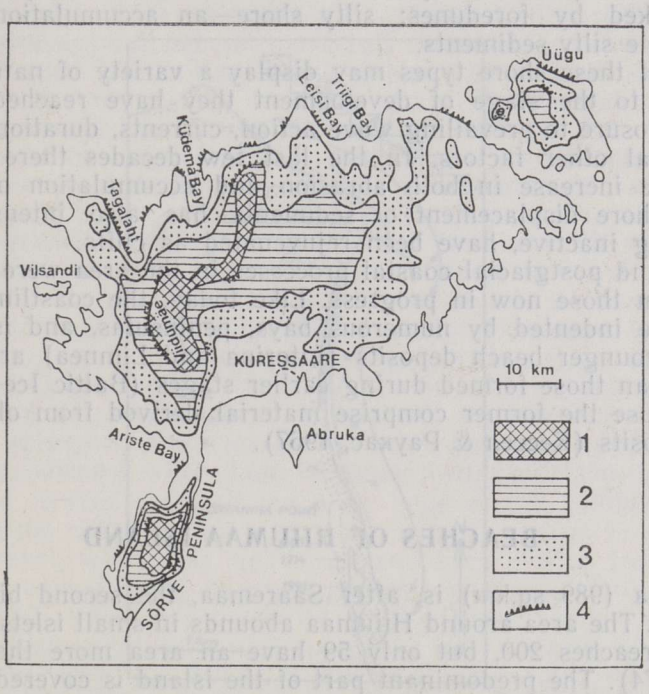

Fig. 3. Evolution of Saaremaa Island in postglacial time after Kessel and Raukas (Кессел & Раукас, 1967) with complements.
1 area above the Ancylus transgression; *2* area above the Litorina transgression; *3* area above sea level at the beginning of the Limnea Sea (about 4000 years ago); *4* cliffs and scarps.

MAIN OUTLINES OF GEOLOGY OF HIIUMAA AND SAAREMAA

These two islands, lying west of mainland Estonia, consist of limestone bedrock with a southward dip, so that Ordovician rocks outcrop in northern Hiiumaa, passing beneath the Silurian rocks in southern Hiiumaa and Saaremaa. These limestones outcrop locally in cliffs on the island coastlines, but they are extensively overlain by Pleistocene glacial drift deposits including tills and outwash sediments left during the final retreat of the ice from the east Baltic region about 11 000—12 000 years ago (Raukas, 1986).

These islands have been emerging as a result of glacioisostatic uplift during Holocene times, so that there are multiple shoreline features (Figs. 2 and 3), the highest related to the Ancylus Lake, about 9000 years ago, then come those produced during the Litorina marine transgression about 7000—6000 years ago, followed by those bordering the shores of the Limnea Sea less than 4000 years ago (Kessel & Raukas, 1979).

The contemporary coast is shoaly, divided into low-lying and cliff and scarp shores (Орвику, 1974; Orviku, 1992). On the basis of the tilt of the primary topography, geological character of the rocks, and the prevailing coastal processes the following types of shores are encountered in Hiiumaa and Saaremaa: cliffed shore—an abrasional scarp cut in resistant Palaeozoic rocks; scarp shore—an abrasional bluff in loose Quaternary deposits; rocky shore—an abrasional sloping shore in resistant limestone bedrock; till shore—an abrasional sloping shore with a protective cover of pebbles and boulders; gravel shore—an accumulation shore with stony beach ridges of material derived from longshore drift or from local deposits; sandy shore—an accumulation sandy shore (beach) often backed by foredunes; silty shore—an accumulation shore with considerable silty sediments.

Each of these shore types may display a variety of natural patterns according to the stage of development they have reached, depending on the exposure to prevailing wave action, currents, duration of exposure and several other factors. In the last few decades there has been a remarkable increase in both abrasion and accumulation on the coast. The longshore displacement of sediments has also intensified. Some bluffs, long inactive, have been rejuvenated as cliffs.

Late- and postglacial coastal processes in the area were slightly different from those now in progress. Like today, the coastlines of earlier times were indented by numerous bays, peninsulas, and islands. As a rule, the younger beach deposits (Litorina and Limnea) are more fine-grained than those formed during earlier stages (Baltic Ice Lake, Ancylus), because the former comprise material derived from older shallow-water deposits (Кессел & Раукас, 1967).

BEACHES OF HIIUMAA ISLAND

Hiiumaa (989 sq.km) is, after Saaremaa, the second biggest island in Estonia. The area around Hiiumaa abounds in small islets, the number of which reaches 200, but only 59 have an area more than 0.5 sq.km (Sepp, 1974). The predominant part of the island is covered with plains (*c.* 85% of the island's territory). These are mainly marine sand plains, left behind by the Litorina and Limnea Sea regressions (Fig. 2). The Kõpu Peninsula, the westernmost part of Hiiumaa, which is up to 67 m above present sea level, was the first portion to rise above sea level at the end of the Baltic Ice Lake regression about 10 500—10 200 yr B.P.

It has a ridge of high dunes, the Saint-Andreas dune field, rising up to 63 m above sea level. It formed as a sandy-gravelly esker emerged from the sea and was cliffed by the waves of the Ancylus Lake and the Litorina Sea. It is now bordered by sandy beach ridges to the north formed during the subsequent regression of the Limnea Sea (Fig. 4). These continue westward to the far point at Hirmuste, a cuspate spit of sand and gravel, where a tombolo links an outlying rocky gravelly island.

In the central part of southern Hiiumaa near Muda a gravel spit in the Emmaste—Männamaa esker ridge of the Palivere stage (Раукас & Ряхни, 1966) ends, and is bordered by descending beach ridges of limestone gravel. The esker was over-washed by the Litorina Sea, and the beach ridges formed during the ensuing regression as waves reworked the gravelly esker deposits. The Muda location lies at a height of 10 m above sea level. The quarry exposes sands and shingle up to 4 m thick, the sands abounding in subfossil mollusc shells (*Limnaea peregra* f. *baltica*, *Macoma baltica*, and several other species typical of the Limnea Sea). An ESR date of 4950 years B.P., obtained on *Limnaea peregra* (Hütt et al., 1985), is in good agreement with geological ideas (Kessel & Raukas, 1979).

The kinds of sediments available from glacial drift deposits can be seen in a number of quarries on Hiiumaa. Southeast of Kärdla the quarry at Partsi exposes a long section of inclined bedded sandy gravels, well rounded but poorly sorted, containing marine molluscs and formed as a spit in the lee of a bedrock island by the waves of the Litorina Sea.

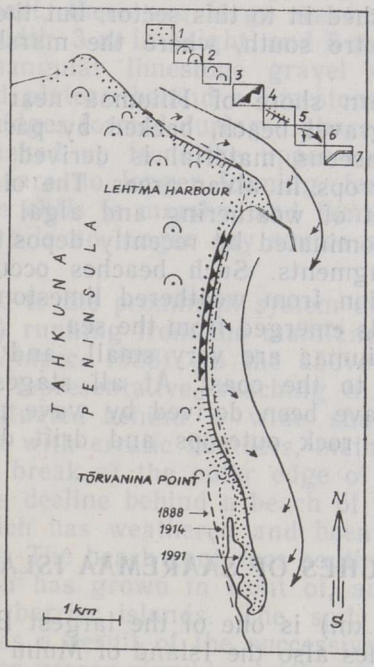

Fig. 4. Sandy beaches on the Tahkuna Peninsula, Hiiumaa Island.
1 sand (and gravel); *2* coastal dunes; *3* foredunes; *4* bluffs; *5* erosion of accumulative shores; *6* direction of sand movement; *7* breakwater of the Lehtma harbour. Compiled by K. Orviku.

Beaches of the Tahkuna Peninsula in the northernmost part of the island consist of sand and gravel washed out from a large glaciofluvial delta (Fig. 4). On the northeast coast of the peninsula, the harbour of Lehtma was formed by building a breakwater on a sandy shore in 1916. Longshore drifting of sand derived from glaciofluvial deposits had supplied sand to the beaches (Орвику, 1974). It has recently accumulated to form a prograded foreland, with low dunes, on the western side of the breakwater, where about 10 000 cu. m of sand has been trapped, while comparison of 1916 and 1975 charts shows that an offshore shoal of about 80 000 cu. m of sand has formed. Longshore drifting has thus been about 1500—2000 cu. m per year. The harbour entrance has to be dredged annually, and the sand deposited at sea. To the east the sandy shore is backed by parallel beach ridges formed during earlier progradation, but the coast is now eroding because the longshore sand supply has been cut off by the Lehtma breakwater. The sandy shore is scarped, and there are undercut and fallen big trees; beach erosion was severe during the February 1990 storm surge, which formed sandy washovers into the backing beach ridges. Farther east, the eroded sector gives place to a prograded area, where longshore sand drifting has built a complex recurved longshore spit. Accretion here has also been some 1000—1500 cu. m per year.

The north coast of Hiiumaa, east and west of Kõrgessaare, is an indented coast of Ordovician limestone, overlain by the sandy deposits of a large glaciofluvial delta. The sandy beach at Luidja, to the west, has broad emergent bars in front of a grassy backshore sand terrace, and sandy beach ridges covered by alder woodland. Sand is still being delivered to this shore, washed in from sandy glaciofluvial delta deposits on the adjacent sea floor. Near Malvaste, a fine sandy beach is backed by beach ridges under forest, but fronted by scattered boulders. Sand is no longer being washed in to this sector, but the beach deposits have drifted about a kilometre south, where the marshy morainic coast of Kõrgessaare begins.

On the south-eastern shore of Hiiumaa near Heltermaa (Fig. 2) there is a limestone gravel beach, backed by parallel beach ridges of this material. Carbonaceous material is derived from weathered and eroding limestone outcrops in alvar areas. The older gravels are dark in colour as the result of weathering and algal colonisation, whereas the present beach is dominated by recently deposited pale creamy non-rounded limestone fragments. Such beaches occur at various levels, reworked by wave action from weathered limestones on the shore and nearshore as the islands emerged from the sea.

The streams on Hiiumaa are very small, and carry only a little fine-grained sediment to the coast. At all stages the beach deposits (sand and gravels) have been derived by wave processes working on coastal and nearshore rock outcrops and drift deposits, and are not of fluvial origin.

BEACHES OF SAAREMAA ISLAND

Saaremaa (2668 sq.km) is one of the largest Baltic Sea islands. In a wider sense it includes also the Island of Muhu (201 sq.km) and 500 smaller islands and islets. Saaremaa has a strongly indented coastline, the longest peninsula being Sõrve (32 km). The Silurian bedrock is overlain by uneven Quaternary cover, generally only some metres thick. In the West-Saaremaa and Sõrve uplands, composed of till and glaciofluvial sediments, the thickness of deposits amounts to several

dozens of metres. Those uplands have been truncated by wave action when sea level was higher, producing beaches and dunes, now stranded some way inland. On the southwestern slope of the West-Saaremaa Upland near Viidumäe the traces of the sea are observable up to the height of 53.0 m. The first spots of the land emerged from the waters of the Baltic Ice Lake about 10 500 B.P. During the Ancylus transgression about 9000 B.P. an island, 3.5 km in width and 40 km in length (Кессел & Раукас, 1967), was subject to wave action here (Fig. 3). Coastal bluffs (up to 23 m high) were formed on the slopes of the West-Saaremaa and Sõrve uplands at absolute heights of 30—35 m and 20—25 m, respectively. In several places, e.g. at Viieristi on the Sõrve Peninsula, large quarries show inclined layers of poorly sorted well rounded sand and gravel. Here glaciofluvial deposits were reworked by the waves of the Ancylus Lake and contain numerous fresh-water molluscs in the upper part of the section. The northern part of the Viieristi quarry is sandy, cut into dunes that formed on the shore of the Ancylus Lake. To the east of the quarry there is a steep bluff, cliffed by the Litorina Sea, which deposited a series of descending beach ridges on the coastal plain during the ensuing emergence. As this emergence proceeded, sand derived from the Sõrve Upland was withdrawn to lower levels to form the Limnea marine deposits at Järve (Fig. 5). Sandy beaches derived from these reworked glaciofluvial deposits are on the east coast rather than the west coast of the peninsula, and it is possible that westerly winds helped to distribute the sand to the lee shore.

The highest Litorina Sea coastline ranges from 20 m near Küdema and Viidumägi to 15 m at Mõntu on the Sõrve Peninsula. In the Late Holocene about 4000 and 2800 B.P. the level of the Limnea Sea stabilized at heights of 11—9 m and 7—5 m, respectively.

At the 10—12 m high and 300 m long Üügu Cliff on Muhu Island, off the northeast coast, there are large wave-cut notches and caves reaching 3—7 m in width, 3 m in height, and 5 m in depth, and uplifted beach ridges of subangular limestone gravel with an amplitude of 1.5 m on an emerged plateau behind a limestone cliff 3 to 4 m above sea level. The beach ridges formed during a phase of gradual emergence, when gravel was washed up from the upper weathered layers of the Silurian strata. They are no longer forming, for the present shore in front of the limestone cliffs is marshy, and there are varved clays out on the fea floor. There is no longer any source of supply of gravel for beach building.

Üügu Cliff belongs to the prominent system of Silurian cliffs (West-Estonian Escarpment) running from the mainland through the northern coast of Saaremaa (Мярсс, 1988). In the above-mentioned system the Panga Cliff is most representative, reaching in places over 20 m in height. The cliff is situated behind a wide shallow platform cut in limestone, and strewn with erratic boulders, mainly of crystalline rocks from Finland. Waves break at the outer edge of this platform. On the western side the cliffs decline behind a beach of angular to subangular limestone gravel, which has weathered and been eroded from the cliff and platform outcrops. The beach continues southwards until it becomes a recurved spit, which has grown in front of, and partly overrunning, earlier lunate gravel barrier islands. The spit, called Küdema, has lengthened 3—4 km as a result of the successive storm surges, and is now growing back over grassy marshland (Орвику, 1974). The measurements of the position of coastal bars at the tip of the spit show that during the course of the last 10—15 years (1975—1990) the rate of the growth of the spit's length has been some ten times as much as during the preceding (1960—1975) years (Orviku, 1992).

On the west coast of the Sõrve Peninsula there are low cliffed headlands in bedded limestone, separated by bays and occasional cuspate promontories (such as Loode Ness). There are beaches and beach ridges of locally-derived limestone gravel. At Ohesaare the 4 m cliffs of fossiliferous Silurian limestone are fronted by a shallow sea with large ice-rafted erratic boulders of pink granite, and capped by festoons of beach ridges of limestone gravel, derived from the upper frost-shattered horizons of the limestones.

Beaches of sand, gravel, or both occur on several sectors of the island. They are interspersed with indented marshy and bouldery morainic coasts and stretches of cliff and rocky shore. In some places the beach forms a narrow fringe to the coast, but several sectors show beaches backed by beach ridges which have formed as a result of intermittent progradation, or by dunes of sand blown from the shore. As on Hiiumaa, the rivers on Saaremaa, such as the Leisi Stream, are

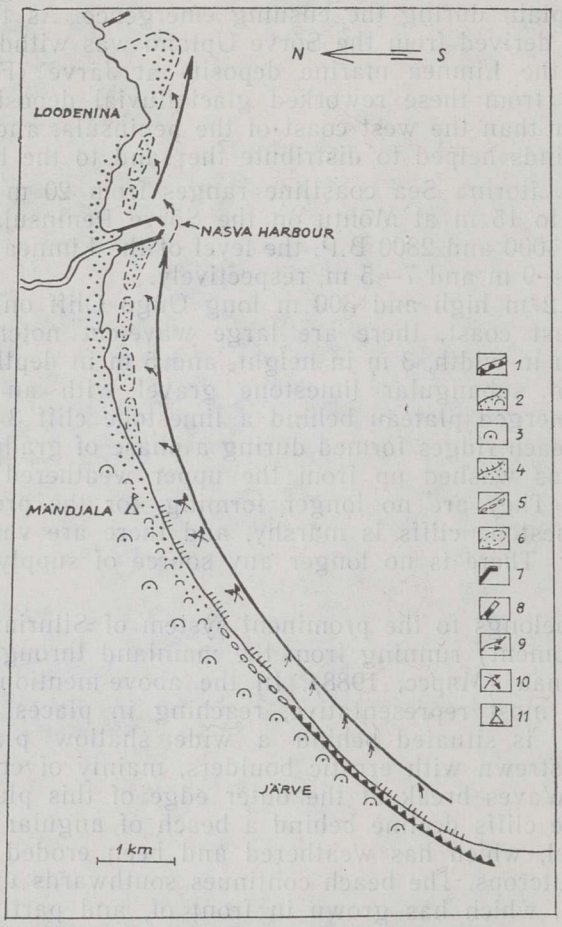

Fig. 5. Coastal features between Järve and Nasva, Saaremaa Island.
1 bluffs; *2* sandy beach and foredunes; *3* coastal dunes; *4* erosion of accumulative shores; *5* gravel shore; *6* underwater bar; *7* jetty; *8* destroyed jetty; *9* direction of sand movement; *10* inversion of sand movement; *11* Mändjala camping ground. Compiled by K. Orviku.

clear-flowing runoff from an emerging land, and they have delivered very little sand or gravel to the coast. The beach sediments on Saaremaa have also been derived either from erosion of cliffed and rocky shores, or by inwashing from the sea floor. They have been distributed along the coast by longshore drifting mainly due to the action of waves approaching the shore obliquely and associated current action.

At Järve (Fig. 5) the sandy beach is being fed by material eroded from a bluff cut into bedded Limnea sand, shells, and gravel, which here stand up to 3 m above sea level. Sandy material has drifted northwards from here to form a beach extending past Mändjala, where it is backed by beach ridges indicating progradation. Beyond Mändjala the shore becomes reedy, perhaps because the low sandy beach has been invaded by reed vegetation (Bird et al., 1990). However, sand is drifting on along nearshore bars which have built up alongside the Nasva harbour jetties, completed in 1965. This accumulation of nearshore sand has required dredging to maintain navigability into the harbour, and the dredged sand is pumped over to the lee side.

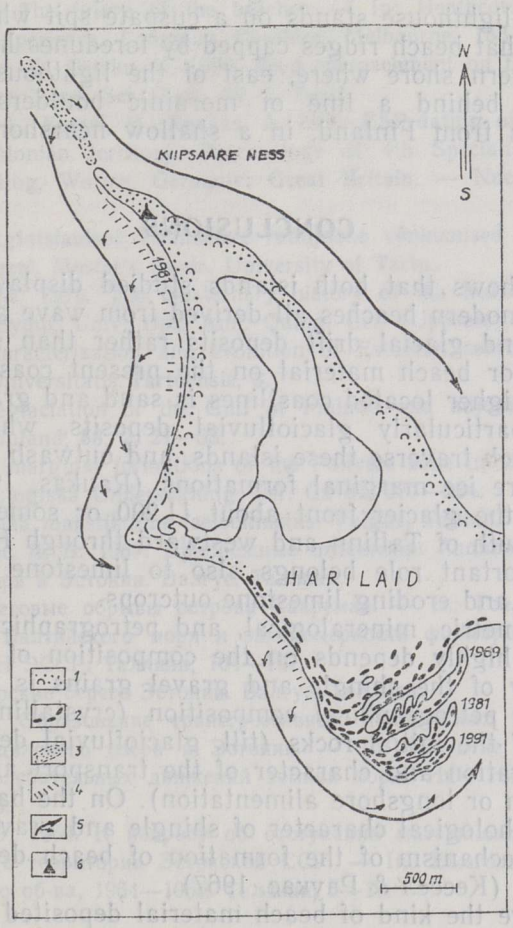

Fig. 6. Erosion of the sandy shore at Kiipsaare Ness.
1 sandy beach and foredunes; *2* beach ridges; *3* underwater sand deposits; *4* erosion of accumulative shores; *5* direction of sand movement; *6* lighthouse. Compiled by K. Orviku.

The bays of Leisi and Triigi at the north coast of Saaremaa have reedy and morainic shores with scattered boulders, emplaced by winter ice. West to Küdema Bay an irregular beach of sand and gravel is fronted by a shallow sea with scattered boulders, emplaced by winter ice. From time to time, part of this foreshore is exposed, and it is clear that little sand is now coming in from the sea floor. This seems to be an example of a beach system that was nourished by shoreward drifting of material derived from submerged glaciofluvial deposits on the sea floor, but land uplift has cut off this supply and the existing beach is a relict landform. Farther west, at the top of Tagalaht Bay, there is a sandy beach backed by hummocky dunes under forest. The sandy shore has prograded, with development of several beach ridges capped by dunes. The beach sand could not have come from the boulder clay, which must previously have been capped by sandy deposits. Land emergence has raised this beach and the derived dunes above the level at which shoreward sand drifting occurred. On the western tip of Saaremaa at Kiipsaare Ness (Fig. 6) glacial drift deposits and sand and gravel have been reworked by wave action and built into a complex foreland, with extensive beach ridges, whose pattern shows stages in its evolution. A lighthouse stands on a cuspate spit which has migrated northwards, so that beach ridges capped by foredunes have been truncated on the southern shore where, east of the lighthouse, a lobate foreland curves out behind a line of morainic boulders, mainly erratic crystalline rocks from Finland, in a shallow nearshore sea.

CONCLUSIONS

The above shows that both islands studied display a great variety of ancient and modern beaches all derived from wave action working on rock outcrops and glacial drift deposits rather than supplied by river action. The major beach material on the present coastlines as well as on earlier and higher located coastlines is sand and gravel derived from glacial drift, particularly glaciofluvial deposits, which form eskers, segments of which traverse these islands, and outwash plains, associated with the Palivere ice marginal formations (Raukas, 1992), which were deposited from the glacier front about 11 200 or somewhat more years ago, and run south of Tallinn and westward through Hiiumaa and Saaremaa. An important role belongs also to limestone gravel, produced from weathered and eroding limestone outcrops.

The granulometric, mineralogical, and petrographical composition of beach material highly depends on the composition of the initial rocks. The morphology of the shingle and gravel grains is controlled by the lithological and petrographical composition (crystalline or calcareous), the character of the initial rocks (till, glaciofluvial deposits, calcareous rocks, etc.), duration and character of the transport and genesis of the deposits (bottom or longshore alimentation). On the basis of the composition and morphological character of shingle and gravel grains one can elucidate the mechanism of the formation of beach deposits and define the initial rocks (Кессел & Раукас, 1967).

At each stage the kind of beach material deposited has depended on available sources of sand and gravel from rocky outcrops and drift deposits along the contemporary coastline and nearshore areas, and on the emplacement of marine material by wave action onshore or alongshore. There are several sections where the modern shore deposits are different from those at higher levels because the sediment now available is coarser or finer than that washed and deposited at earlier stages,

before the land was further uplifted. Contrasts in sediment calibre may also be correlated with contrasts in wave energy due to past and present nearshore gradients: larger waves broke on the coast where the nearshore water was deep, but an emerging gentle gradient has diminished wave energy so that only finer sediment is moved and deposited on the beach. Thus the explanation of past and present beach features and sediment types depends partly on the available materials and partly on the incoming wave energy at each stage of uplift.

The coasts of Hiiumaa and Saaremaa provide a scientific heritage for studying the postglacial geological history of the Baltic Sea. They also serve as an excellent laboratory, where geomorphological and environmental processes and the effects of the changes going on in land and sea levels can be studied.

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EESTI SAARTE HIIUMAA JA SAAREMAA RANDADE KUJUNEMINE

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Hiiumaa ja Saaremaa on mõlemad möödanikus olnud väiksemad nüüdisaegsest. Nad on olnud aastatuhandete vältel avatud tuultele ja tugevatele tormidele ning seetõttu on erinevad rannavormid siin paremini esindatud kui mandrialal. Töös on antud ülevaade mõlema saare rannavormide kujunemisest. Detailsemalt on kirjeldatud üksikute võtmealade arengut.

ФОРМИРОВАНИЕ БЕРЕГОВ ОСТРОВОВ ХИЙУМАА И СААРЕМАА, ЭСТОНИЯ

Анто РАУКАС, Эрик БИРД, Каарел ОРВИКУ

В геологическом прошлом площадь крупнейших островов Западно-Эстонского архипелага — Хийумаа и Сааремаа — была значительно меньше нынешней. В течение многих тысячелетий эти острова были открыты воздействиям сильных ветров и штормовых волнений, в результате чего сложившиеся здесь береговые формы более крупные и разнообразные, нежели на материке. В статье рассматриваются история побережья островов Хийумаа и Сааремаа за послеледниковое время, особенности формирования современных берегов, в ключевых районах детальнее, и источники питания древнебереговых форм и современной береговой зоны.