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International Field Symposium
2024

Quaternary Sediments, Landscapes, and Early Settlement History in Western Estonia

August 27–30, 2024 | Pärnu, Estonia

Excursion guide

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Cover photo: Kõivasoo Bog (T. Nirgi, 04.05.2018)

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Introduction to the excursion guide

The Peribaltic Working Group conference 2024 will be held in western Estonia. The scientific session on August 26 will be followed by a field trip to the islands of Saaremaa and Hiiumaa **on August 27-30**.

Estonia belongs to the zone of glacial erosion or moderate accumulation, which is why the Quaternary cover is rather thin. Pleistocene cover is mostly formed of glacial and aqueoglacial deposits. The glacial paragenetic deposits can be roughly divided into two groups: glacial drift deposited by glaciers on the ground (subaerial tills) and underneath ice shelves (subaqueous tills). Western Estonia is located along the periphery of the Fennoscandian isostatic land uplift zone, where the Holocene RSL history has been complex, with alternating transgression and regression periods. Transgressive shorelines are marked by ancient coastal landform systems, which often surround former lagoons (present-day wetlands), a preferred landscape for prehistoric settlers. Terrestrial organic sediments, which have been buried under younger coastal sediments, have proven to be valuable archives of sea-level and palaeoenvironmental data, and contain traces of prehistoric settlements.

The field trip will cover various topics through site visits, including:

- Environmental geology (landslides in proglacial clays, wetland restoration, flooding of coastal areas);
- Past and future relative sea-level changes and storminess scenarios;
- Recent discoveries in shallow sea-bed mapping;
- Contemporary coastal processes and the health of beaches in Estonia and elsewhere;
- Geoarchaeology opening the links between landscape and early settlement patterns.

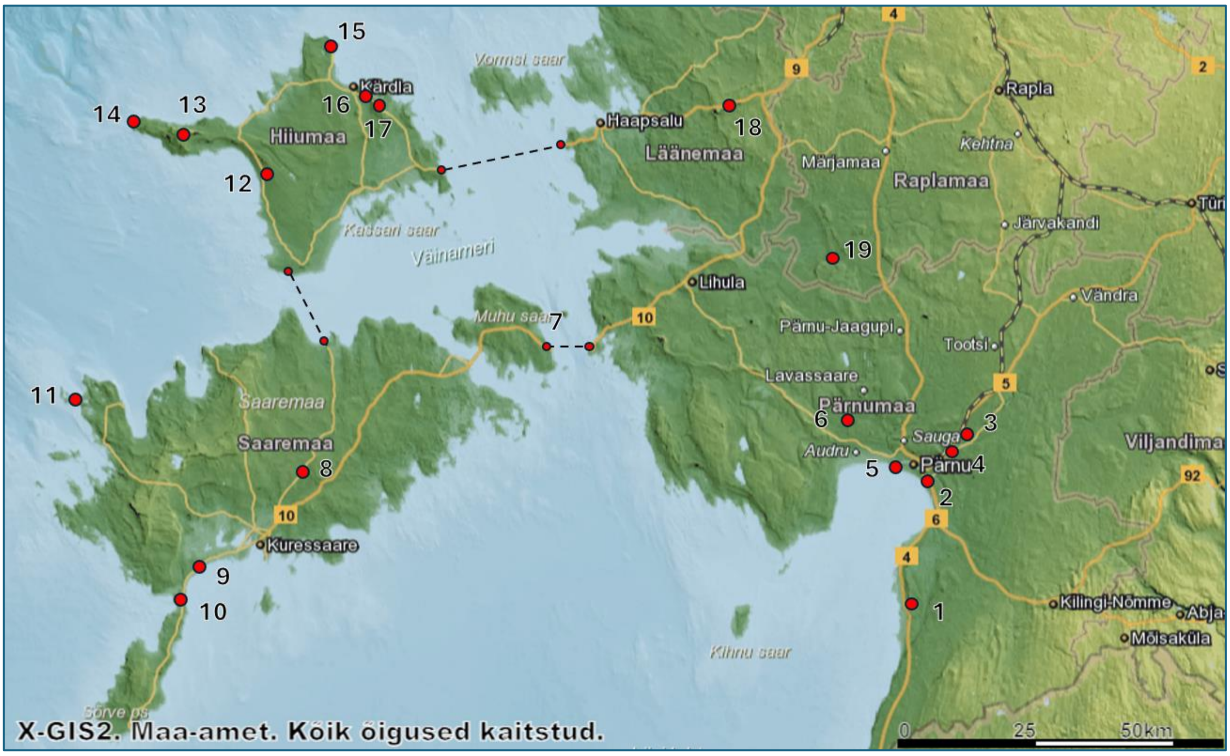

Figure 1. An overview map showing all the places (stops) that will be visited during the excursion.

August 27, Surroundings of Pärnu

Pärnu is a small seaside resort with a sandy beach, shady parks and promenades. It belongs to the climatic zone where winters are mild and summers moderately warm. The prevailing SW winds bring the sun-heated surface water to the shore and the temperature of the water is higher here than in other resorts along the Estonian coast. The Arab geographer Al-Idrisi first mentioned the mouth of the Pärnu River in 1154. The year 1251 is considered the founding year of Pärnu, and the name Perona was first used in 1318. Today, more than 40 000 people live here.

Figure 2. Pärnu town on the ortophoto (Estonian Land Board).

The Pärnu region is situated around the 1 mm a^{-1} isobar of apparent crustal uplift trending SW-NE through the region. The landscape is characterised by a relatively flat terrain with a topography ranging from 0 m a.s.l., along the shoreline, up to ~60 m a.s.l. in the SE. The region can be split into two zones of different bedrock composition, where the NW part is dominated by Silurian dolomitic marl and sandstone, whereas the SE part consists of Devonian sandstone and dolostone. The surface of the bedrock occurs between 0 and -30 m a.s.l. along the eastern area of Pärnu Bay, with some local exceptions.

Deposition of Quaternary sediment has subsequently draped the landscape with deposits consisting of late-Weichselian tills, varved clays, and Holocene sands and silt. The low topography of the area makes it highly sensitive to even minor changes in relative water levels of the Baltic Sea, thus there are several coastal wetlands, which were once lagoons or bays. The inner part of the present-day Pärnu Bay shoreline is characterised by sandy beaches in the N and E part, while more sheltered parts have permitted reed to develop on the SE and W parts.

While the tidal action is considered to be negligible along the Estonian coastline, Pärnu Bay has been subjected to significant water-level changes associated with the slowdown of the crustal uplift, and storm events in the last decades.

Stop 1: Tolkuse palaeolagoon and Rannametsa dunes

We begin our tour in the Tolkuse-Rannametsa area on the eastern coast of the Gulf of Riga, where a former Litorina Sea lagoon is located between the Ancylus Lake and the Litorina Sea coastal ridges (and dunes). Currently, there is a ~5500-ha Tolkuse Bog in the lagoon, with a peat thickness of more than 6 m. Archaeological surveys have revealed several Stone Age settlement sites in the vicinity of the Tolkuse Bog.

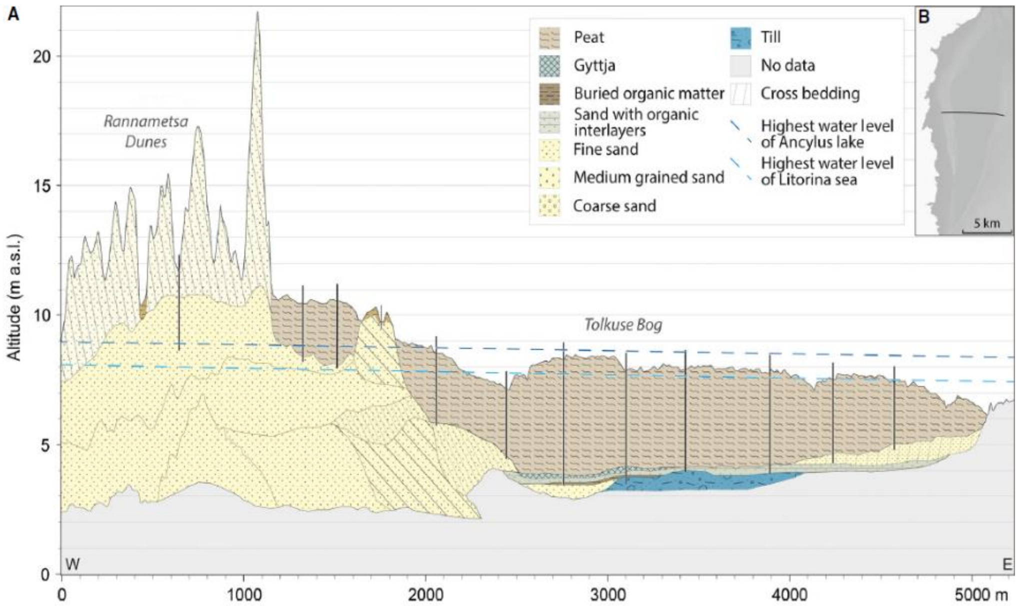

Figure 3. A cross-section of the Tolkuse basin based on coring and GPR data (Habicht et al. 2017).

Parallel spit ridges, associated with the Baltic Ice Lake shoreline, are located in the easternmost part of the area at altitudes around 30–35 m a.s.l. These ridges indicate active longshore transport prior to the Billingen event. The Soometsa dunes located northwest of the Tolkuse bog represent a complex of re-blown dunes which were likely developed slightly above the altitude reached by the culmination of the Ancylus Lake. The western side of the Tolkuse Bog is characterised by irregular dune features. This ~15-km-long Rannametsa dune field which altitudes up to 20 m a.s.l., formed probably during the Litorina Transgression. (Bjursäter 2015)

The palaeogeographical reconstructions show an open coast environment during the Ancylus Lake stage and the formation of a peatland after the lake drainage at about 9000–8600 cal. a BP. The waters of the Litorina Sea flooded the area between 8200 and 7700 cal. a BP, forming a 25-km-long and up to 5.5-m-deep lagoon with two connections to the sea. This brackish water lagoon existed there for about 4000 years and terminated around 3800–3500 cal. a BP as a result of isostatic uplift and growth of the barrier spit (Habicht et al. 2017).

<u>References:</u>

Bjursäter S, Master's thesis (2015) Sup. Risberg J, Preusser F, Rosentau A. Luminescence based chronology of the postglacial coastal development in the Pärnu region, south-western Estonia. University of Tartu, Faculty of Science and Technology, Institute of Ecology and Earth Sciences; Stockholm University, Department of Physical Geography.

Habicht H-L, Rosentau A, Jõeleht A, et al. (2017) GIS-based multiproxy coastline reconstruction of the eastern Gulf of Riga, Baltic Sea, during the Stone Age. Boreas 46(1): 83–99.

Stop 2: Ancient channel of River Pärnu

River Pärnu which drains into the Pärnu Bay, is the longest river in Estonian (144 km). In the Pärnu area, the channel is up to 300 m wide and 10 m deep (3–4 m on average) and is characterised by low gradient in longitudinal profile and low flow energy.

A buried river channel with up to 4.2-m-thick organic-rich infill was discovered between the present-day coastline and the southernmost bend of the river River Pärnu. Further studies have shown that the old river valley also continues at the bottom of Pärnu Bay.

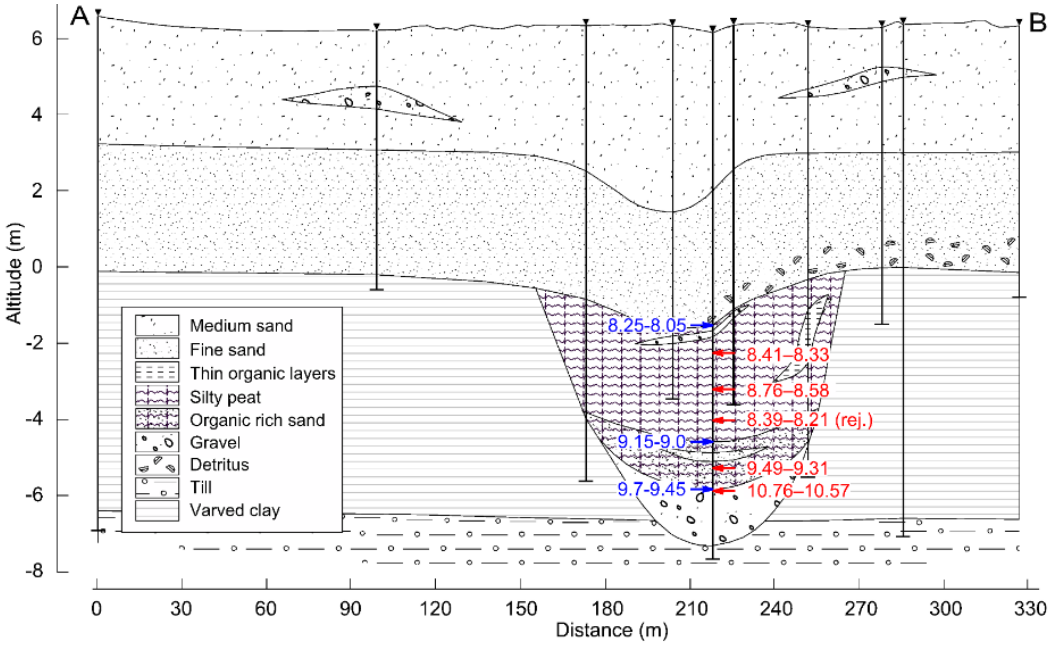

Figure 4. Geological cross-section across the buried channel. The AMS ages (cal. ka BP) are shown in red and modeled ages for the sediment borders are shown in blue colour (based on Nirgi et al. 2020).

On the mainland, the channel cuts through the glaciolacustrine varved clays to the glacial till surface and is covered by up to 7-m-thick Litorina Sea sand deposit. The sediments of the valley infill display three lithological units, which reflect the development of the river from an active period to a stable abandoned channel stage. According to the AMS dates, the channel was there already before Ancylus Lake transgression, but the organic-rich sediment accumulated during the Initial Litorina Sea phase. The seismo-acoustic mapping of the seafloor indicates the continuation of the initial channel of the River Pärnu on seabed more than 5 km offshore.

RSL records show a rise of the Ancylus Lake (10.7–10.2 cal. ka BP) water level of about 18 m at an average rate of 35 mm/yr and a rise of the Litorina Sea (8.5–7.3 cal. ka BP) about 14 m at an average rate of 12 mm/yr. The data suggests that RSL dropped at least down to –5.5 m a.s.l. before the AL transgression and at least to –4 m a.s.l. before the LS transgression.

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Olesk A K, Master's thesis (2024) Sup. Rosentau A. Üleujutatud Holotseeni rannikumaastikud Pärnu lahes. University of Tartu, Faculty of Science and Technology, Institute of Ecology and Earth Sciences.

Nirgi T, Rosentau A, Habicht H-L, et al. (2020) Holocene relative shore-level changes and Stone Age palaeogeography of the Pärnu Bay area, eastern Baltic Sea. The Holocene 30: 37–52.

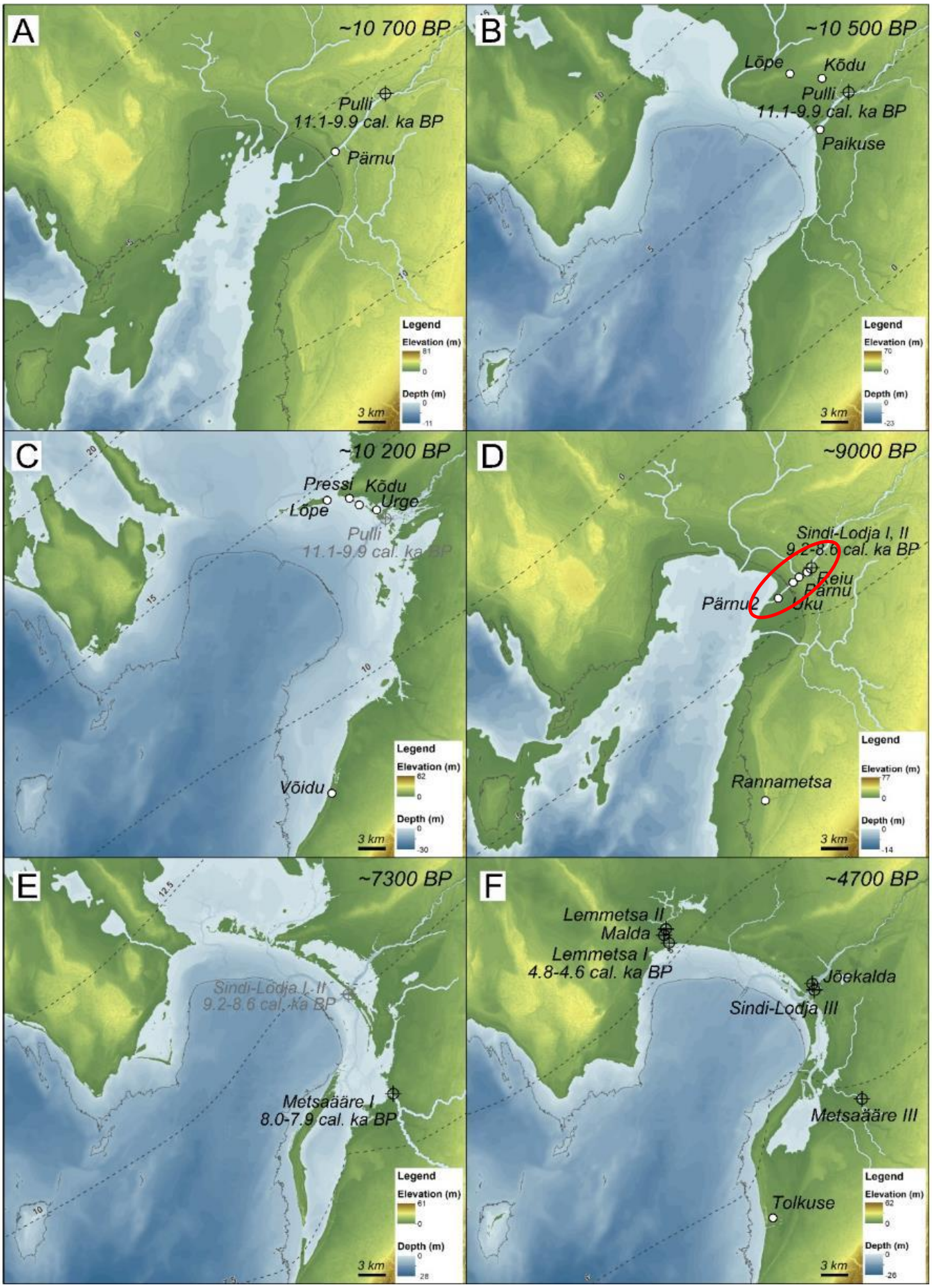


Figure 5. Palaeogeographic reconstructions of the Pärnu Bay area: (a) Ancylus Lake at the beginning of the transgression, (b) Ancylus Lake during transgression, (c) Ancylus Lake during its maximum in the Pärnu area, (d) Initial Litorina Sea lowstand during the coexistence of two channels of the River Pärnu, (e) The Litorina Sea during its maximum and (f) Litorina Sea during regression.

Stop 3: Pulli, earliest archaeological site in Estonia

The earliest known human settlement in Estonia, a seasonal hunting and fishing camp Pulli, is located about 14 km from Pärnu, near the present-day village of Pulli. The settlement was discovered in 1967 from the right bank of the Pärnu River. Subsequently, archaeological excavations were carried out by an archaeologist L. Jaanits and others. More than 1100 items used by Mesolithic people have been found at the Pulli settlement, among them tools made of flint or bone, and accessories made of animal claws (Lõugas 1997). A dog tooth found at the settlement is the oldest evidence of domesticated dogs in Estonia.

Figure 6. Pulli settlement (photo by O. Susi, 2012).

The settlement was probably inhabited during the Ancylus Lake transgression period. According to radiocarbon dating, it was established *ca* 11.1–9.9 cal. ka BP (Lõugas 1997). The habitat location was most probably chosen for its suitability for the pikeperch and pike fishing, and the hunting of water birds, beaver, elk, and other animals (Kriiska & Lõugas 2009). The rising AL flooded the Pulli site within the next few hundred years and covered it with a 2-m-thick coastal sand deposit.

<u>References:</u>

Kriiska A, Lõugas L (2009) Stone Age settlement sites on an environmentally sensitive coastal area along the lower reaches of the River Pärnu (south-western Estonia), as indicators of changing settlement patterns, technologies and economies. In: McCartan, S., Schulting, R., Warren, G. et al. (eds) Mesolithic Horizons. Oxford and Oakville, ON, Canada: Oxbow Books, pp. 167–175.

Lõugas L (1997) Subfossil seal finds from archaeological coastal sites in Estonia, east part of the Baltic Sea. Anthropozoologica 25–26, pp. 699–706.

Stop 4: Sindi-Lodja archaeological site

Subsequent signs of human activity originate from the Initial Litorina Sea lowstand period when the people settled on the banks of the river Pärnu again. This period was characterised by stable climate conditions and relatively low water levels (Nirgi et al. 2020), which was suitable for people, who were now able to remain in one place for a longer period.

Figure 7. The Sindi-Lodja II buried cultural layer, alternating with layers of sand, is located on the steep riverbank, ~6 m below today's ground level (photo by A. Kriiska, 2001).

Mesolithic Sindi-Lodja I and II settlement sites were discovered in 2000: Sindi-Lodja I at the mouth of the River Reiu, on the left bank of the River Pärnu, and Sindi-Lodja II *ca* 400 m upstream from it. According to an AMS date for charcoal from the cultural layer, the settlements were inhabited at about 9.2–8.7 cal. ka BP (Kriiska 2001; Kriiska and Lõugas 2009). Considering the mean age *ca* 9.0 cal. ka BP, the settlements were located *ca* 3 km from the concurrent coastline, on the left bank of the ancient River Pärnu (Nirgi et al. 2020).

Rich archaeological find material from the Sindi-Lodja I and II sites, including animal and fish bones, refer to human habitation at least during the springtime, which was the best time for hunting ringed seals and pikeperch. Compared to Pulli, the ringed seal is more represented in the bone material, indicating the growing importance of seal hunting. The general Mesolithic contexts may justify the assumption of year-round habitation (Kriiska and Lõugas 2009), with temporary fisher camps along the coastline which were most probably located on the shore of this ancient river at the bottom of the present-day Pärnu Bay. The settlement was buried under the transgressive Litorina Sea sediments.

<u>References:</u>

Kriiska A (2001) Archaeological field work on Stone Age settlement site of SW Estonia. In: Tamla Ü (ed) Archaeological field works in Estonia 2000, pp. 19–33. Tallinn, Historic Preservation Department.

Kriiska A, Lõugas L (2009) Stone Age settlement sites on an environmentally sensitive coastal area along the lower reaches of the River Pärnu (south-western Estonia), as indicators of changing settlement patterns, technologies and economies. In: McCartan, S., Schulting, R., Warren, G. et al. (eds) Mesolithic Horizons. Oxford and Oakville, ON, Canada: Oxbow Books, pp. 167–175.

Nirgi T, Rosentau A, Habicht H-L, et al (2020) Holocene relative shore-level changes and Stone Age palaeogeography of the Pärnu Bay area, eastern Baltic Sea. The Holocene 30: 37–52.

Stop 5: Sandy beach in Pärnu

Pärnu Bay is a well-defined marine area (40×25 km^2), and rather shallow (6-8 m on an average). The average annual freshwater inflow from the Pärnu River is about 2 km^3. The Pärnu Bay has a considerable seasonal ice cover, however, as a result of an increase in air temperatures, the average duration of the ice cover has decreased, according to the trendline over the past seventy years, from about 160 days to 90 days at Pärnu and from 150 days to 60 days at Kihnu.

The bottom of the bay is covered with fine marine sand, with an average thickness of 0,5 m but up to 1-2 m in the close nearshore area and in the mouth of the River Pärnu. Glacio-lacustrine varved clays underlie marine deposits and are outcropping in the middle of the bay. Since the bay is opened to S and SW winds and waves, the eroded sandy sediments move mainly along the west and east coast towards the top of the bay. As a result of lasting S winds the water level may rise by more than 2 m above the average and bring over flooding of the low coastal areas.

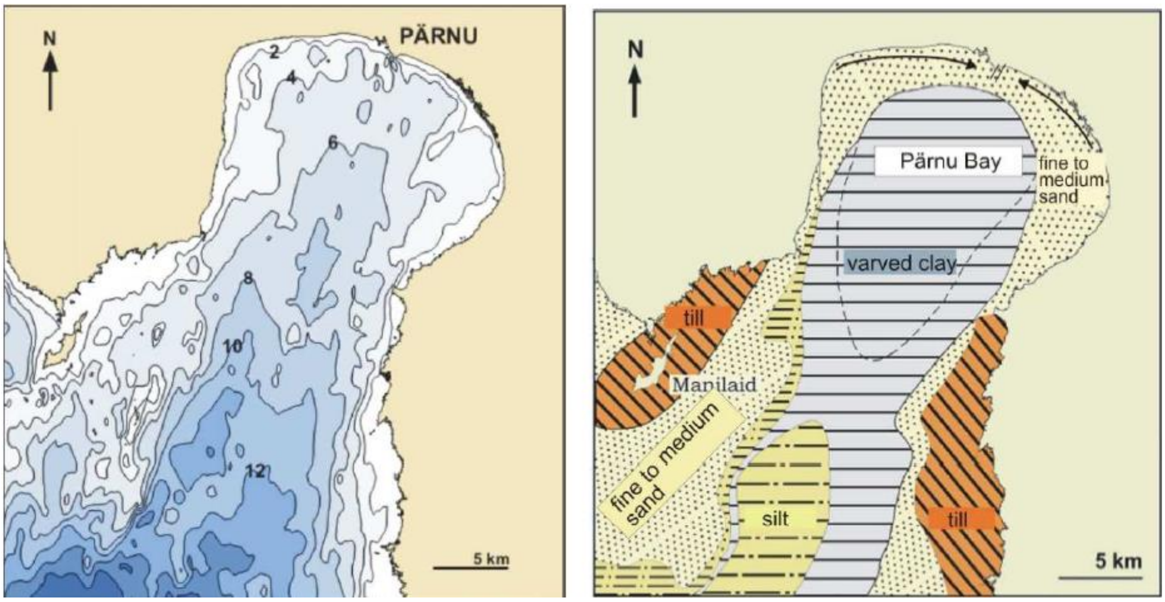


Figure 8. Topography and the distribution of bottom deposits in Parnu Bay (after Lutt and Orviku 2004).

Sea level variations and storm surges

Although the GIA-induced uplift component is around 1.7 mm/year, the RSL is increasing at Pärnu, as a result of global sea level rise and local subsidence of the Pärnu area. Coastal erosion on both sides of the bay and longshore sediment transport towards the Pärnu River mouth is favoured.

The main natural hazards to the Pärnu Bay area are occasional, extreme storm events, which are caused by the North Atlantic cyclones. The town is located on a low-lying coast and due to the SW orientation and specific morphometry of the bay the instrumental era RSL variation range in Pärnu is among the highest in the Baltic Sea. In stormy autumns and winters, there is a chance that the pre-elevated mean Baltic Sea level as a result of preceded storms adds up to the local surge height. During the storm Gudrun on 9 January 2005, the sea level rose 275 cm over the long-term mean and 8 km^2 of the urban area of Pärnu was flooded for about 12 hours. According to the projections for 2100, in case of the coincidence of several unfavourable factors, the water level during an extreme storm may rise to nearly 4 m.

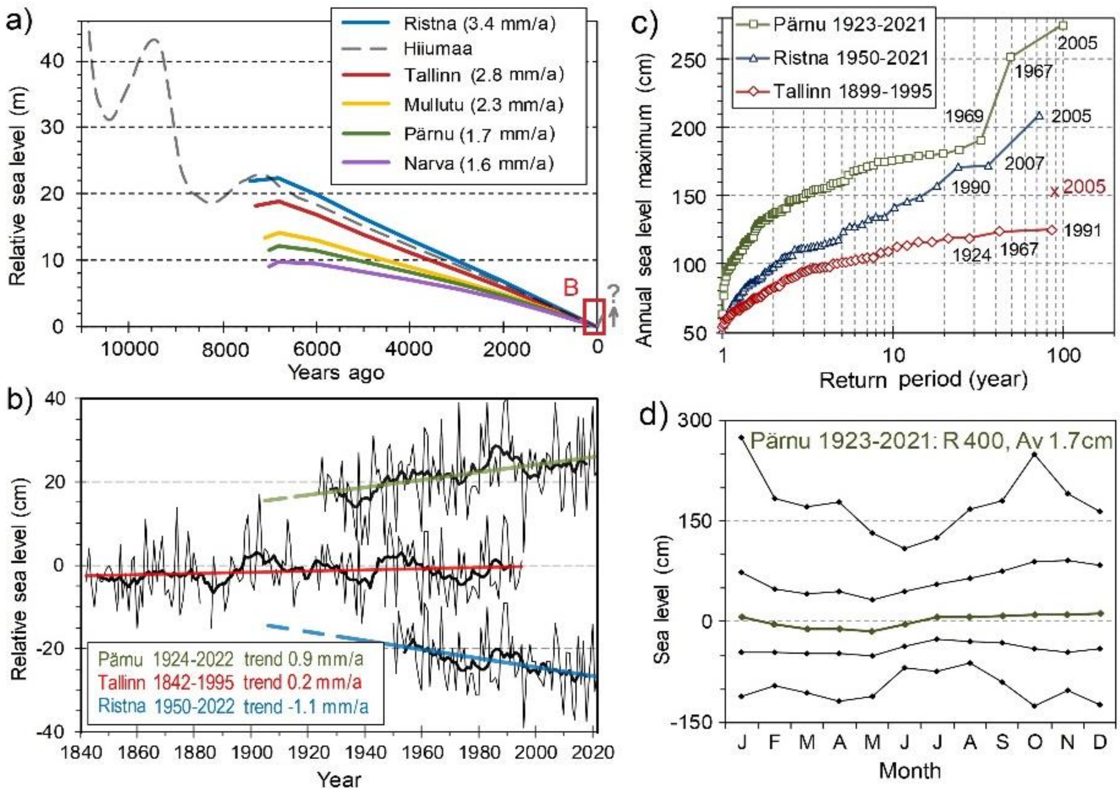


Figure 9. A) RSL variations for the past 7000 yrs. B) Recent data from tide gauges shifted relative to each other by 20 cm. C) Empirical return period graphs for annual maxima. D) Seasonal variations in monthly RSL statistics (absolute max, average max, average, average min, absolute min. (Suursaar et al. 2024)

Coastal protection facilities

In the Middle Ages, the major obstacle to the development of sea trade was the settling of sand at the river mouth. At the request of the merchants in Pärnu, it was ordered by the Russian Empress Catherine II to set up moles to prevent it. In 1769, the first wooden beams were rammed into the river mouth. After their disintegration, the construction of permanent stone moles began. The cornerstone was placed in 1863 by the Governor General of Estonia and Livonia. Work began in winter when Pärnu Bay was covered by thick ice. The dimensions of the moles were marked on the ice, and the mats weaved from the birch beams were carried and spread over the ice over the entire mole area. Then, stones were brought from the surroundings of Pärnu and in spring, the stones sank to the seabed as the ice melted. In the summer, material was also sunk from the ships. Construction work ended in 1869 and the rise of sea trade in Pärnu began.

The base of the 7-m-wide mole is nearly 26 meters wide and its depth is up to 5 m. The lefthand side of the 2.1 km jetty now extends *ca* 1500 m to the sea and landward 600 m is buried under landfill. The righthand side jetty extends *ca* 900 m to the sea and its landward part is extensively merged into port facilities. Since their completion, the jetties have performed as sediment traps favouring the accumulation of sand on both sides of the river outlet.

<u>References:</u>

Suursaar Ü, Torn K, Mäemets H, Rosentau A (2024). Overview and evolutionary path of Estonian coastal lagoons. Estuarine, Coastal and Shelf Science, 303, 108811.

August 28, Pärnu – Saaremaa Island

Saaremaa is one of the biggest islands in the Baltic Sea (2 683 km^2). It has a deeply indented coastline of about 1 300 km with the longest peninsula, Sõrve ps., being *ca* 32 km. The population of Saaremaa is about 31 500, whereas a bit more than 13 100 inhabitants live in the capital of the island, Kuressaare. The formation of Saaremaa started at the end of Late Weichselian (14 000 yr BP) when the ice retreated, but the main part of it emerged during the Holocene.

Figure 10. An overview map of the Saaremaa Island.

The Lower- and Middle-Silurian carbonate bedrock has a smooth surface at an altitude from –30 to 25m. On the N and W coasts of the island, the cliffs up to 20 m in height are a part of Silurian Clint which continues westwards under the Baltic Sea. The Silurian bedrock is overlain by thin Quaternary cover usually less than 1 m, reaching to some meters within glacial accumulative forms of relief. The most outstanding relief form, a plateau-like West Saaremaa upland (54 m a.s.l.) is composed of till and glaciofluvial deposits. The main landforms are limestone plains (alvars), abraded till plains at higher altitudes, and coastal plains at lower areas. The western slope of the West Saaremaa upland and the eastern part of the Sõrve peninsula are in places abraded to scarps. Peat bogs at different altitudes mark the overgrown coastal lakes from different stages of the Baltic Sea.

The coastal development has been considerably affected by the uplift of the Earth's crust, which at present is about 2 mm/yr. Thus, the ancient coastal formations of different Baltic Sea stages are located at different altitudes. Due to differences in hydrodynamics, morphology, geological settings and evolution, different shore types occur in the coastal zone of the Saaremaa Island.

Stop 6: Landslide in 2022 on the right bank of the Audru River

Before going on the ferry, there is still one more place to visit in mainland Estonia.

Low altitude (<20 m a.s.l.) areas at the eastern coasts of the Baltic Sea are smoothed to even topography by deposits of proglacial lakes and by bottom deposits of the Holocene marine and lacustrine stages of the Baltic Sea. In such conditions, landslide hazards are usually considered to be rare. However, in recent decades, the frequency of landslides in Pärnu area has grown.

Figure 11. Mass movements of the Sauga landslide due to river undercutting (photo: T. Hang)

All landslides occurred at the riverbanks in the conditions of increasing inhabitation. The valleys are typically 10–15 m deep, with the steepest slopes (25–30^{o}) at the outer bend of the meanders. Late-Weichselian loamy till on the bedrock is overlain by 5–10 m (max 30 m) glaciolacustrine varved clay, which is in turn, covered by 2–3 m of the Holocene marine sand. The weakest soil type in the area is the glaciolacustrine clay, which has been deposited in a single vast proglacial sedimentary basin. Geotechnical parameters of the clays change vertically while conversion is even and without rapid changes.

Three different groups of landslides were distinguished based on the soil/sediment type involved, the position of the rupture surface, the failure mechanism, and the size of the slides.

A - The largest slides are retrogressive slide complexes developed in the glaciolacustrine clay with their rapture surface penetrating the whole clay sequence and the slumped material always reached the river channel.

B - The second group includes slides in marine sand and silt in the upper section of the slopes with the sliding material not reaching the river channel; slides are triggered by extra shear stress generated by groundwater flow in the slope.

C - The third (sub)group consists of small landslides at the riverbank with the rapture surface 2-3 m deep, that are actually the first stage in developing retrogressive landslide complexes.

The critical slope angle is ≥10° in the glaciolacustrine clay and >20° in fine-grained marine sand. Fluvial erosion is the main process in decreasing the stability of slopes in the varved clay. In the case of sand slopes the additional shear stress, generated by water seepage also destabilizes the upper portions of slopes. Comparison of the collected geological data and the existing slope angles with the critical values derived from the geotechnical modelling allows to locate stable and potentially unstable sections and slopes in the valleys. According to hazard zonation, the slopes in marine sand are seldom hazardous; but most of the river valley slopes in the glaciolacustrine varved clay are potentially unstable, particularly if human activities are involved.

References:

Kohv M, Talviste P, Hang T, et al. (2009) Slope stability and landslides in proglacial varved clays of western Estonia. Geomorphology, 106, 315−323.

Kohv M, Talviste P, Hang T, Kalm V (2010) Retrogressive slope failure in glaciolacustrine clay: Sauga landslide, western Estonia. Geomorphology, 124, 229−237.

Kohv M, Hang T, Talviste P, Kalm V (2010) Analysis of a retrogressive landslide in glaciolacustrine varved clay. Engineering Geology, 116, 109−116.

Stop 7: Mapping of the shallow sea floor and geology of the Suur Strait and the inner part of the Väinameri in the West Estonian Archipelago

A group of four larger islands (Saaremaa, Hiiumaa, Muhu, Vormsi) and numerous smaller islets around them form the **West Estonian Archipelago**.

The islet-rich water expanse that separates the Estonian mainland from Saaremaa and Hiiumaa and opens through narrow passages into the Baltic Sea and the Gulf of Riga, is called **Väinameri** (*Sea of Straits*).

Dissecting the Estonian mainland from Muhu Island, **the Suur Strait** (*Big Strait*) forms the SE branch of the Väinameri.

Figure 12. Väinameri in the West Estonian Archipelago (Tuuling et al. 2022).

The Estonian Transport Administration regularly conducts hydrographic surveys in our territorial waters. Since 2012, the research vessel Jakob Prei has surveyed more than 10,000 km^2 of seafloor, mostly on the Western Estonian Shelf. More than 30,000 km of seismo-acoustic profiles have been recorded alongside the multibeam bathymetric data, allowing detailed mapping of seafloor sediments and geomorphological features. Estonian Geological Survey has compiled nautical charts containing information about the geological structure of the Estonian sea area and mineral resources. For the mapping of shallow waters, the Survey has a research vessel that is equipped with various devices (seismoacoustic profilers, sonar systems, sediment samplers etc.).

Geology of the Suur Strait

The Suur Strait was chosen as a pilot mapping area due to the idea of a bridge/tunnel construction across this water divide. The main feature in bedrock topography is a N-S trending deep depression/channel reaching the depth of 45 m which assumably represents a preglacial river valley. Depression is likely a tributary of a W-E trending depression in southern Väinameri where the bedrock surface drops to 60 m b.s.l. In the south, the main depression is bordered by a plateau-like watershed between the Gulf of Riga and the strait.

The thickness of the Quaternary sequence follows the underlying bedrock relief, reaching *ca* 50 m in the depression. Widely spread Late-Weichselian till and occasionally emerging glaciofluvial sediments and eskers cover the bedrock. The varved clays of the Baltic Ice Lake and the vaguely laminated massive clays of the Yoldia Sea/Ancylus Lake stages are levelling the unevenness of the underlying bedrock relief. The occurrence of the sandy/silty sediments of the Litorina Sea, resting on a striking unconformity surface of unknown origin, is limited to a deeper bedrock area. Where till is outcropping, the topography is drumlinised.

Characteristic features are eskers and esker fields. A buried esker that arises in a seismic line between Kesselaid and Muhu Island continues southwards in four successive profiles (estimated length, width and height are >5 km, *ca* 200 m, and >20 m, respectively). Numerous eskers, mostly forming esker fields, emerge in the NE corner of the Gulf of Riga. As most of them crop out on the seafloor, their emergence in a detailed sea bottom multibeam map is striking. The length of these eskers remains within the limits of 1 km, as their height rarely exceeds 10 m.

Main geological settings of the Väinameri

The distribution and thicknesses of the Quaternary cover in Väinameri are highly dependent on the general depth of the bedrock and the location of its low-laying topographic forms.

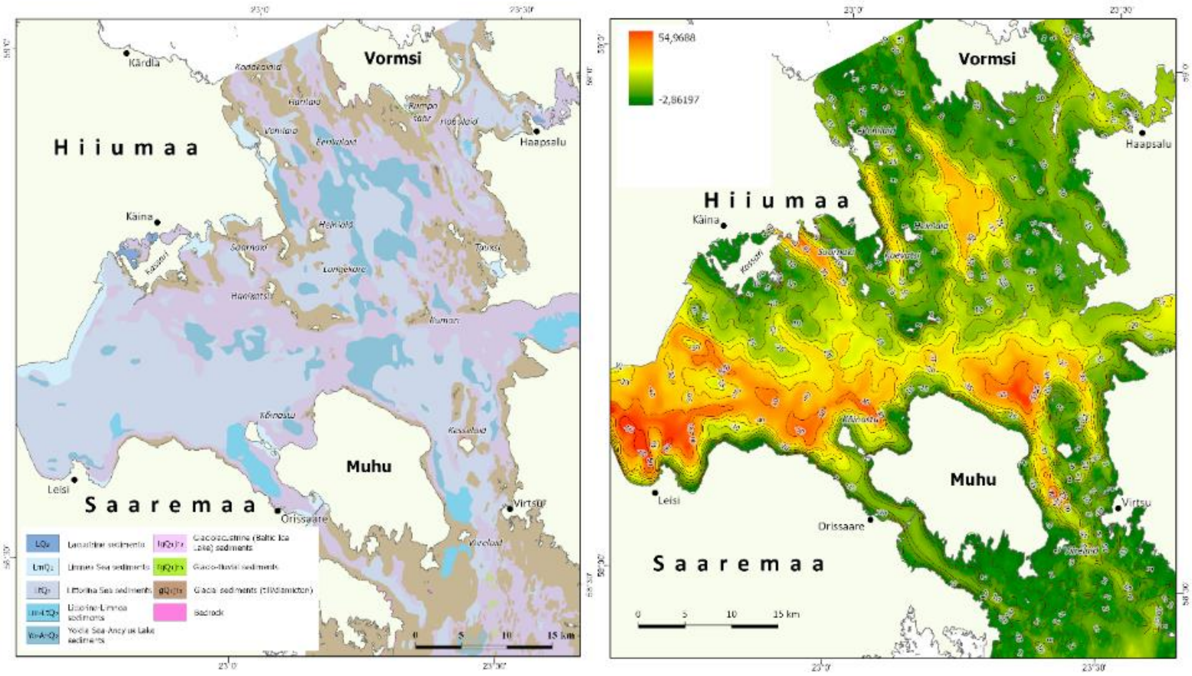


Figure 13. Map of Quaternary sediments (left) and the thickness of Quaternary cover of Väinameri.

The thickest (occasionally >50 m) and stratigraphically more complete Quaternary cover occurs in the central Väinameri, where two most prominent and 60 m b.s.l. falling bedrock forms – the Muhu depression and the Soela Strait channel – emerge.

The glacial till and the Baltic Ice Lake varved clays that are cropping out in the nearshore areas spread almost all over the Väinameri, as the younger units occur and are exposed further away from the mainland in and around the channels passing the central parts of the different branches of the Väinameri. Most of the bedrock depression below the Väinameri is filled with the Baltic Ice Lake clayey sediments that can surpass 25 m in thickness. The Yoldia Sea–Ancylus Lake and the Litorina Sea units can reach up to 15 m and 10 m in thickness.

The general trends of the bedrock relief in the different branches of the Väinameri suggest that the waters along these branches were spilling towards the Muhu depression in the centre of the Väinameri. Thus, in the pre-glacial time, there was probably a river stretching from the Estonian mainland towards the Soela Strait, which formed a cuesta-type bedrock relief between Hiiumaa and Saaremaa. This cuesta relief continues westwards across the central Baltic Sea up to the Swedish island of Gotland, where the large River Eridanos once flowed towards northern Europe.

Murtoos – first offshore observation

Another striking geomorphological feature in the glacial topography of the Suur Strait is the occurrence of sc **murtoos.** Murtoos are triangle, chevron, or lobate shape subglacial landforms consisting of heterogeneous diamictic and sand-dominated sediments which are thought to be formed by repeated flooding and sediment reorganisation along subglacial non-channelised meltwater corridors, followed by subsequent subglacial deposition and deformation related to warm-based glaciers.

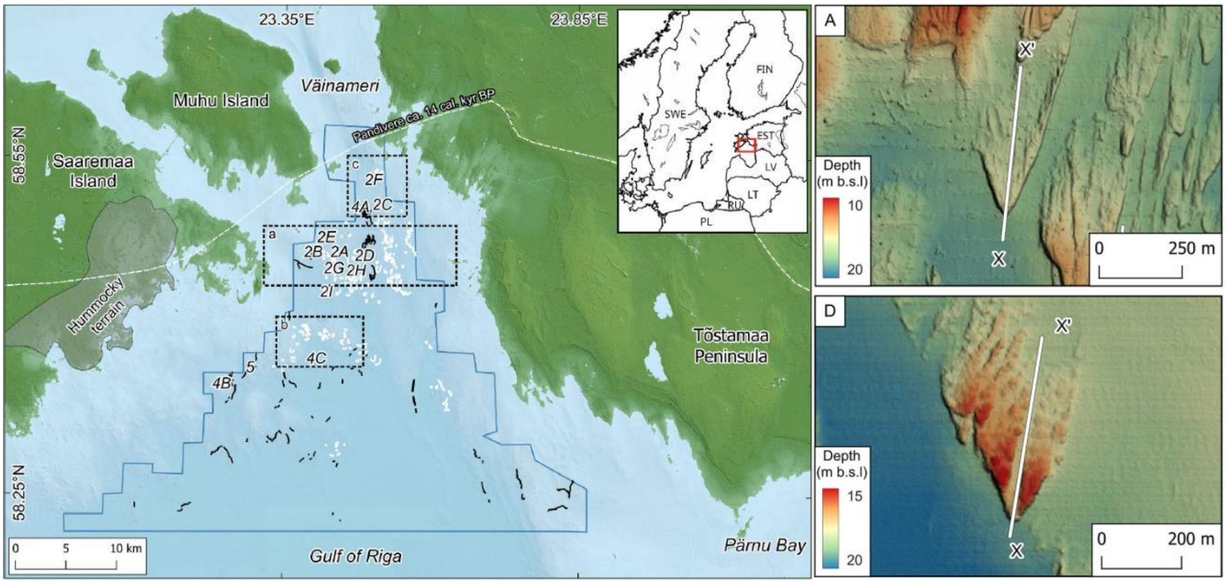


Figure 14. Distribution of mapped murtoos (white) in the bottom of Suur Strait, and some close-up images of murtoos and murtoo-like geomorphological features, and their topographic profiles. Ice flow direction aligns with the direction of topographic profiles (modified from Karpin et al. 2023).

Murtoos are typically 30–200 m in length and 30–200 m in width with a relief of commonly <5 m. Murtoos have straight and steep edges, a triangular tip oriented parallel to the ice-flow direction, and an asymmetric longitudinal profile with a shorter, but steeper down-ice slope. Different types of murtoos and murtoo-related landforms are spatially and geomorphologically related, as they typically appear in the same murtoo fields. They share a similar composition and architecture of sediments, which indicates the similarity of their formative processes and environment. Murtoos occur commonly in central parts of Scandinavian Ice Sheet, specially up-ice from Younger Dryas endmoraine zone, their spatial distribution and geomorphic relation to other landforms indicate subglacial formation during times of climate warming and rapid retreat of the Scandinavian Ice Sheet when large amount of meltwater was released (Ojala et al. 2019).

Thus, the documentation of murtoos at the bottom of Suur Strait was the first discovery of those landforms outside of Scandinavia and in offshore conditions. Altogether, 287 individual murtoos and murtoo-like bedforms were identified. Murtoos occur in distinct fields at water depths between 8 and 22 m (mean 15.8 m), over an area of *ca* 300 km^2. The offshore murtoos appear to be longer (43–748 m), narrower (12–394 m), and lower (0.5–7.8 m) on average, compared to those previously reported from land.

References:

Karpin V, Heinsalu A, Ojala A, Virtasalo J (2023) Offshore murtoos indicate warm-based Fennoscandian ice-sheet conditions during the Bølling warming in the northern Gulf of Riga, Baltic Sea. Geomorphology, 430

Ojala A E K, Mäkinen J, Ahokangas E, et al. (2021) Diversity of murtoos and murtoo-related subglacial landforms in the finnish area of the Fennoscandian Ice Sheet. Boreas 50, 1095–1115.

Tuuling I, Suuroja S, Ausmeel M (2022) The outlines of the bedrock relief and the Quaternary cover between the Estonian mainland and the islands of Muhu and Saaremaa in the West Estonian Archipelago. Estonian Journal of Earth Sciences, 71, 2, 111–126

Stop 8: Kaali impact crater(s) and the timing of the event

During the last 10 ka Estonia has been the target of 4 crater forming impacts and 5 registered meteorite falls. The Kaali impact crater field in Saaremaa is well known due to its easy access, proven meteoritic origin, well-preserved morphology, and evergreen discussions about the direction of the fall, measures of the meteoroid, and, of course, the timing of the event.

Kaali impact site with eight smaller craters formed by the impact of the fragmented *ca* 1000 t IAB iron meteoroid. It fell at 35^o angle and released the energy of *ca* 20 kt of TNT. In total *ca* 2.5 kg of meteorite iron with the largest piece of *ca* 300 g has been collected so far. The craters were described already by von Luce in 1827 but were confirmed as meteorite craters in 1938 (Reinwald, 1938) when a ~100 g piece of meteoritic iron was found in crater 2 which also has a nice print of an impact cone in the bottom. Until then various hypotheses were advanced, for example, volcanic origin, formation due to the eruption of gas and steam, or due to tectonic faults and karst. Also, an idea of anthropogenic origin has been discussed and an ancient stronghold at Kaali, where a natural karst lake surrounded by a man-made wall served as a well, was proposed (Eichwald, 1854).

Figure 15. The main crater (photo: https://www.nordicexperience.com/?attachment_id=11485&lang=et)

Kaali meteorite craters were formed in Silurian dolomite covered by clayey till. The dolomites, uplifted and destroyed during the impact, could be followed in the wall of the main crater. This largest crater has a diameter of 110 m and a depth from the rim to the bottom of 22 m, the rim being raised 6-7 m above the surroundings. There is a 1-6-m-deep Lake Kaali at the bottom of the main crater. The others, locally known as dry craters, are 1-4 m deep hollows with a diameter of 12-40 m.

The age of the Kaali impact structure is still a matter of debate, and the estimates provided by different authors vary as much as ~6000 yr, ranging from ~7600 to ~2500 yr BP. The ages were obtained using a wide range of methods. Some of the youngest and the oldest ages were derived by ^{14}C dating of marker peat horizons in nearby Piila bog, characterised either by a slightly elevated iridium content yielding a calibrated age of ~2500 yr BP or occurrences of glassy siliceous material (particles supposedly formed by melting and vaporization of the impactor and target material during the impact) giving an age estimate of ~7500 yr BP. ^{14}C dating of bottom sediments of the Kaali lake yielded ages between ~3700 to 3300 BP. These dates could underestimate the age of impact as organic sediments within the crater started to form at an unknown period after the impact and the sediments could be corrupted by a reservoir effect. The latest age estimate, 3237 ^{14}C BP, is based on the ^{14}C dating of charred plant material (spruce) within the proximal ejecta blanket, which makes it directly related to the impact structure.

References:

Losiak A, Wild EM, Geppert WD, et al. (2016) Dating a small impact crater: An age of Kaali crater (Estonia) based on charcoal emplaced within proximal ejecta. Meteoritics & Planetary Science 51 (4), 681–695.

Stop 9: Järve beach

Several sandy beaches high in recreation value have strongly suffered from strong storms over the last half-century. Järve beach on the southern coast of Saaremaa is one example. There, more than 6,500 m^3 of sand has been eroded from the 4km-long scarp. This coastal destruction resulted from the cumulative effect of strong storms with high sea levels and the absence of ice cover.

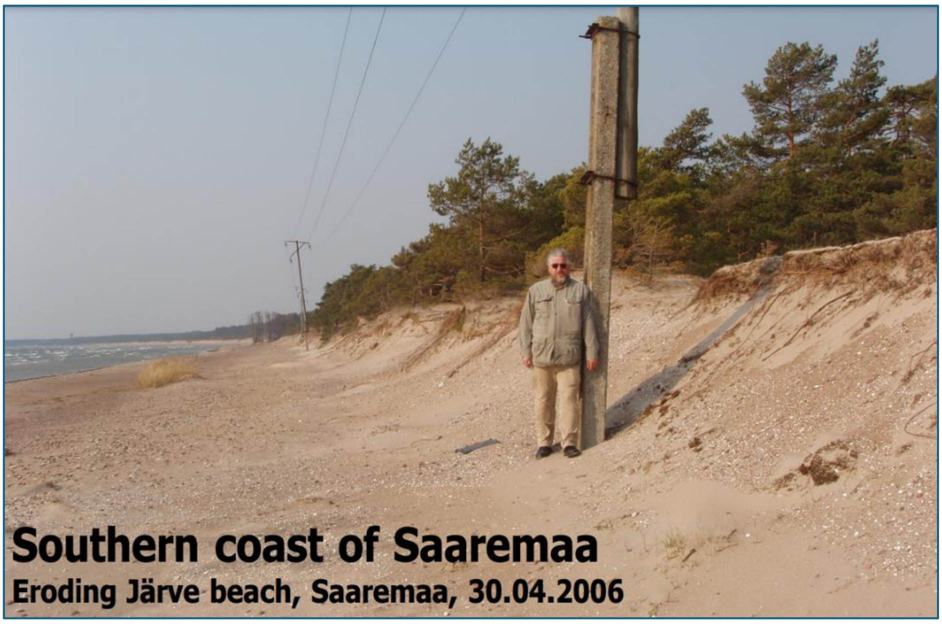


Figure 16. Järve beach (T. Soomere).

Stop 10: Salme Viking Age boat burials

Two Pre-Viking Age ship burials were found from Salme village in 2008, containing the remains of seven men in the smaller and 34 men in the larger ship. The burials form a unique archaeological find complex, which has provided substantial data about the Scandinavian Vikings and their expeditions (Konsa et al. 2009; Price et al. 2020). There are very few known burials of Viking war bands. Salme is the oldest one of them, and the only one where fallen warriors have been placed together in their ships.

Figure 17. Fallen warriors in one of the ships (photo by R. Allmäe, 2012).

Presumably, the Salme ships belonged to a Viking crew from the Stockholm-Mälaren region. The ships were buried around 700–750 AD into the sandy-gravelly coastal deposits which accumulated in the open coastal zone about 710–450 years earlier, around 60–320 AD. Reconstructions show that the burials were located about 2–2.5 m above the coeval sea level and at 130–170 m from the coastline. Thus, it is likely that both ships were moved from the shore to the higher ground for burial.

Palaeogeographic reconstructions display up to 2.8-m-deep semi-enclosed strait at 750 AD with 80–100 m wide eastern part. About 170 years after the burial of the Salme ships the strait began to fill with laminated silty gyttja. Sedimentological evidence and diatom data refer to the following closing of Salme palaeostrait between 1270–1300 AD. The Late-Holocene RSL curve for the last *ca* 3000 shows an almost linear RSL fall from the 5.5 m a.s.l. to the present-day level with an average rate of 2 mm/yr and a slight slowdown in regression after 1300 AD.

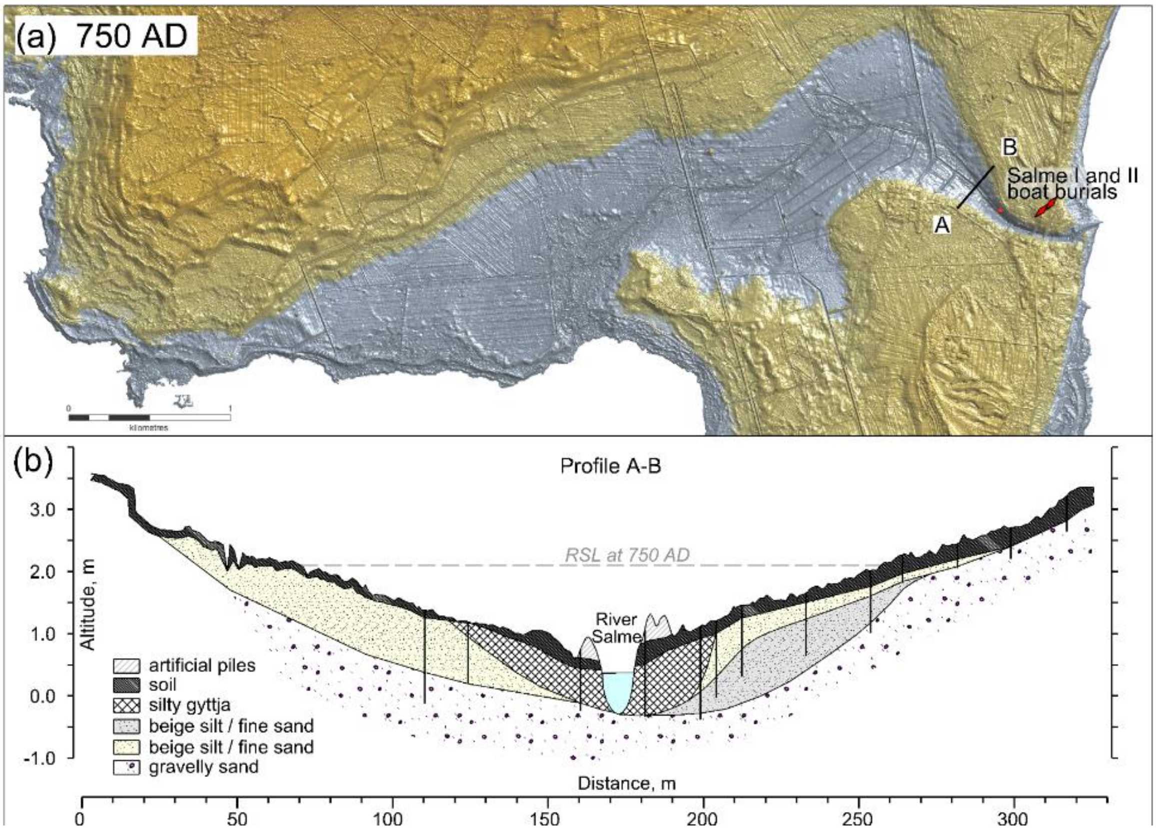


Figure 18. a) A palaeogeographic reconstruction of Salme strait at the Vendel Period at 750 AD, when the ships were buried; b) A geological profile across the Salme palaeostrait (based on Nirgi et al. 2022).

<u>References:</u>

Konsa M, Allmäe R, Maldre L et al. (2009) Rescue excavations of a Vendel Era boat-grave in Salme, Saaremaa. Archaelogical Fieldwork in Estonia 2008: 213–222.

Nirgi T, Grudzinska I, Kalińska E et al. (2022) Late Holocene relative shore-level changes and palaeoenvironment of the Pre-Viking Age ship burials in Salme, Saaremaa Island, eastern Baltic Sea. The Holocene, 32(4), 237-253.

Price TD, Peets J, Allmäe R et al. (2020) Human remains, context, and place of origin for the Salme, Estonia, boat burials. Journal of Anthropological Archaeology 58: 1–13.

Stop 11: Harilaid Peninsula

Kelba spit

The sediment barrier formation as a process of secondary importance mostly functions on the coasts exposed towards the Baltic Proper, where wave action is stronger and sea level variations are more substantial. Although it occurs on the background of land uplift, too, such lagoons separate from the open sea much quicker (within 20–100 yrs) than the apparent uplift alone would have allowed. One such fast-evolving example of alongshore sediment transport and barrier forming onshore accumulation is the Kelba spit on the Harilaid Peninsula. It has elongated annually by *ca* 20−80 m, mostly after winter storms. Incremental sediment fluxes have created a series of rhythmic beach ridges and spits, and small lagoons at different phases can be seen. The largest (0.34 km^2) and the most recent lagoon was formed after a storm in spring 2022 when the 2 km long Kelba spit (composed of shingle and boulders) eventually rejoined the mainland. The spit is nearly 1 m high at its lowest part. Assuming typical sea level variations in the area, it is probably inundated a couple of times per year. The up to 1.5−2 m high barrier that separates a lagoon (the Laialepa Bay) on the same peninsula, has been occasionally breached during extreme storms like in 2005 and 2007. (Tonisson et al. 2008)

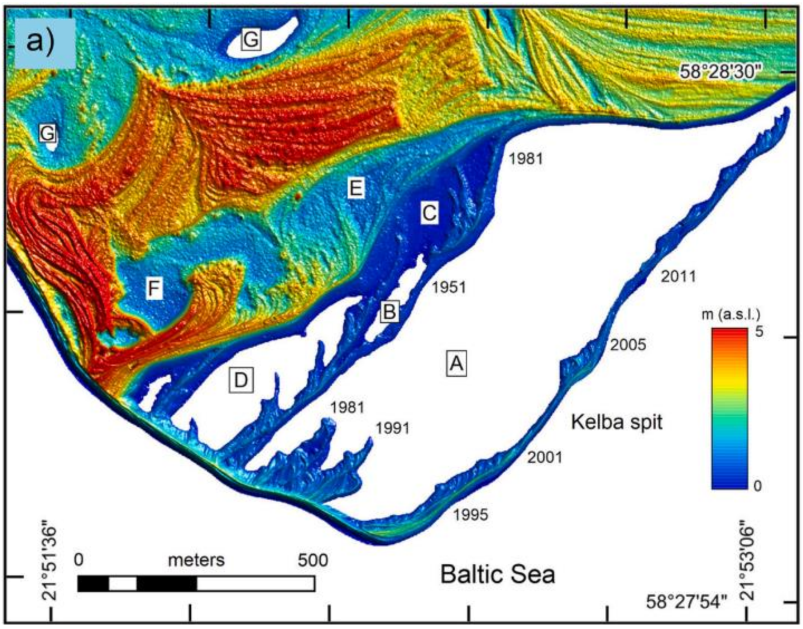


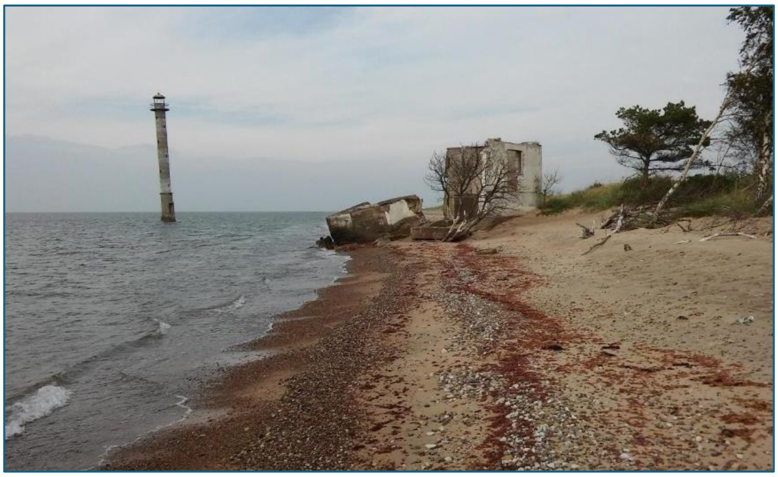
Figure 19. Relief-shaded DTM of the Kelba spit. It has gradually elongated (years indicated) and closed the lagoon A in 2022. The lagoons B and C closed between 1951 and 1980, D closed in the 1920s, the forest covered E−F isolated 300−500 years and G ca 500 years ago. (Suursaar et al. 2024)

Cape Kiipsaare

Another example describing the intensity of coastal processes can be found on the NW coast of Harilaid Pensinsula – Cape Kiipsaare. On the N and NE coasts of the cape, a 4-5 km wide and up to 15 km long submarine glacial ridge is stretching to the NW forming a near-shore shoal. Due to refraction, the wave's front changes its direction here, and the waves attack the beach under an acute angle, bringing about strong erosion of shore sediments in high sea-level conditions.

Since the beginning of the 1990s, one of the most favourite sights for visitors of Saaremaa has been the local „Pisa Tower" – the **Kiipsaare lighthouse**, which stands in the sea and is tilting 7 to 9^{o} off vertical.

The 25 m-high ferro-concrete lighthouse was built in 1933 in the middle of Cape Kiipsaare. Due to an increase in storminess over the last couple of decades, the cape has been changing rapidly. The aerial photographs from 1955 showed more than 100 m of distance between the lighthouse and the shorelines. During the next 50 years, the mean annual velocity of shoreline retreat was about 2 m/yr, which was followed by even more rapid shoreline retreat, 3 m/yr, between 1981 and 1990. As a result of ongoing erosion the lighthouse got onto the active beach, then on the shoreline, and finally, into the sea. By 1995, the lighthouse was in the middle of an active sandy beach and was tilting 7^{o} towards the sea.



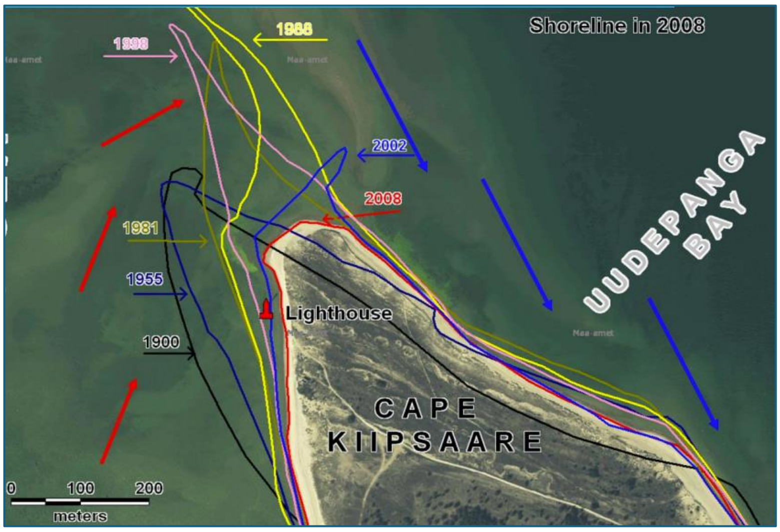


Figure 20. Kiipsaare beach and lighthouse in 2015 (photo: M.Muru)
Figure 21. Shoreline and scarp changes (after Tõnisson et al. 2008).

More severe storm damages occurred in the winter of 2002/2003 and in January 2005 when the shoreline receded by 30 m during these winters. After the January storm of 2005, the angle of the lighthouse had increased up to 9^{o} off vertical, but it wasn't enough to make it fall down. On the contrary, in February 2008 it got vertical again because the strong water turbulence around the beacon started to erode a funnel on the landward side of the lighthouse base. Today, the lighthouse is tilted again. The latest inspection, in August 2017, revealed that the seaward side of the concrete base is significantly damaged and metal rebars are exposed.

<u>References:</u>

Orviku K, Tonisson H, Kont A, et al. (2013) Retreat rate of cliffs and scarps with different geological properties in various locations along the Estonian coast. Journal of Coastal Research, 552–557.

Suursaar Ü, Torn K, Mäemets H, Rosentau A (2024) Overview and evolutionary path of Estonian coastal lagoons. Estuarine, Coastal and Shelf Science 303, 108811.

Tonisson H, Orviku K, Jaagus J, et al. (2008) Coastal damages on Saaremaa island, Estonia, caused by the extreme storm and flooding on January 9, 2005. J. Coast Res. 24 (3), 602–614.

Tonisson H, Suursaar U, Rivis R, et al (2013) Observation and analysis of coastal changes in the West Estonian Archipelago caused by storm Ulli (Emil) in January 2012. Journal of Coastal Research, SI 65 (1), 832–837.

August 29, Saaremaa Island – Hiiumaa Island

The Hiiumaa Island is situated in the eastern part of the Baltic Sea. It is separated from the mainland by the 22 km-wide Väinameri and from the Saaremaa Island by the 6 km-wide Soela strait. The area of Hiiumaa is about 1000 km^2. There are *ca* 9300 inhabitants, of whom about 3000 live in the capital of the island, Kärdla.

Figure 22. An overview map of the Hiiumaa Island.

Only a few coves and islets joint the 325 km long coastline of the island. The coastal sea is shallow and full of reefs. The best known of them is Hiiumadal in the north-west, where hundreds of ships have wracked. The relief of the island is generally rather flat, but there are some steep hills too. The highest point of Hiiumaa (68 m a.s.l.) at Kõpu is also the highest spot in western Estonia. The island is situated in an area of intensive glacioisostatic uplift, about 2-3 mm/yr.

The geological setting of Hiiumaa differs from that of Saaremaa mostly because of a thicker Quaternary cover which is usually 10-20 m and reaches up to 80 m at Kopu. Glacial deposits are prevailing, including three types of till: grey stony till on the bedrock; yellowish-grey or beige stony till in the neighborhood of bedrock heights and in end-moraines; and brownish clay till in the western part of the island which often contains erratics of varved clays.

Glaciofluvial deposits are represented by cover sands and eskers, and glaciolacustrine sediments by fine sand and varved clays. Usually, varved clays are covered with up to 3 m thick marine sands. Holocene sediments are mainly represented by marine sediments. Characteristics of the island are wide areas with low (up to 2 m) coastal bars separated by swampy depressions.

Quite a remarkable area of the island is covered by mires. *Ca* 50% of those are fens and *ca* 30% are raised bogs. The peat lies often on gyttja which indicates the lacustrine or lagoonal origin of the mires.

Stop 12: 6.5 ka palaeostorminess record from Tihu coastal spit system

Tihu strandplain is a fan-shaped ridge-swale system, consisting of ~100 sandy ridges at an altitude between 4–20 m. Between the relatively low (0.2-1 m) ridges with a spacing of 20-40 m, are groups of higher (0.5-2.5 m) ridges with a spacing of 300–800 m. Repetitive patterns of the larger ridge sets and a decrease in relative height of individual ridges within these groups toward the contemporary coastline reflect the gradual progradation of the spit system due to GIA-dominated uplift, occurrence of high storminess periods during the spit formation, and a decrease in exposure of the area through the time.

Considering that aeolian contribution to the ridge growth was relatively small and uniform, it was possible to utilize an age estimation method based on terrain elevation and pre-determined RSL curves. The tested relative sea level curves converged around a linear trend during the past 7 ka, the rate of which (3.1–3.2 mm/a) is well correlated with the relative-to-geoid uplift model.

The Tihu system started to emerge from the sea ~5.4 ka ago. In its older part, it includes a complex of elevated barrier spits where both the isostatic uplift and gradual sediment aggradation due to longshore transport contributed to its nucleation and initial progradation. In its lower (younger) section, a forced progradation "staircase" of palaeocoastlines was formed in a regime of sediment deficit and low-energy hydrodynamic conditions. Analysis of near-cyclic occurrences of beach/foredune ridges and larger ridge sets revealed time intervals of enhanced storminess during 5.4–4.9, 4.8–4.5, 4.6–4.3, 4.1–3.8, 3.7–3.4, 3.2–2.9, 2.7–2.4, and 2.2–1.9 ka BP. These match with some previous European Atlantic storminess reconstructions for Mid- to- Late Holocene.

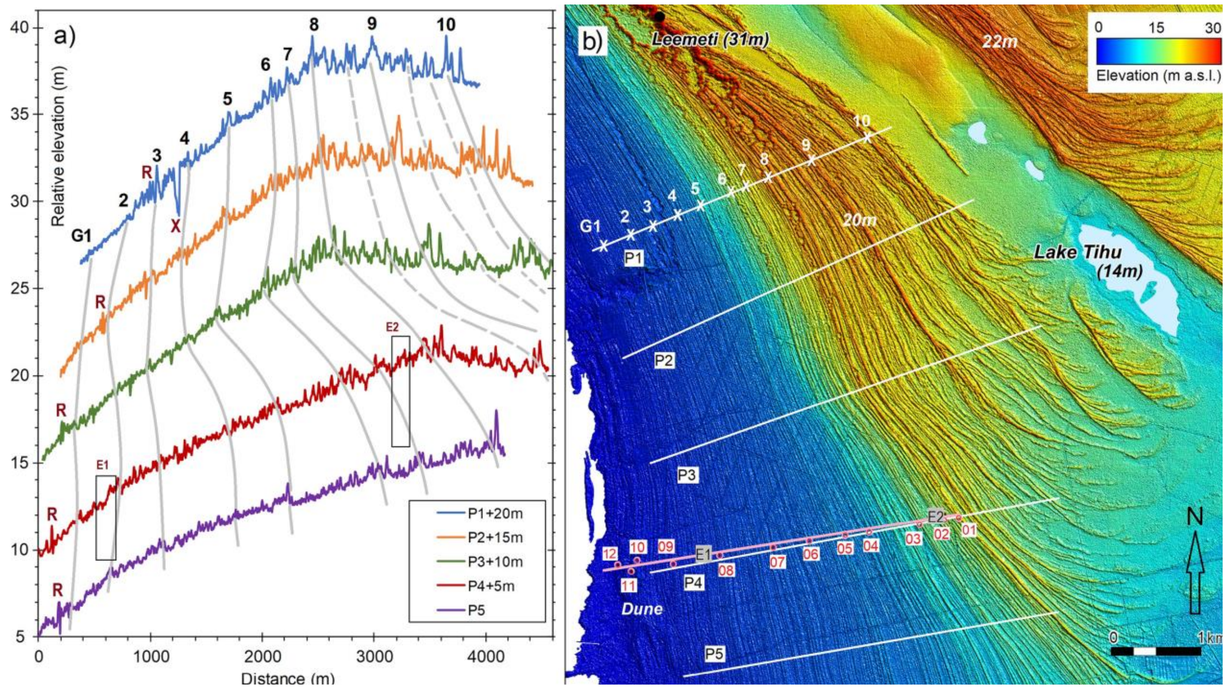


Figure 23. a) Elevation profiles, offset by 5 m for better visualization. Grey lines indicate the high ridge sets; b) Profiles P1–P5 on the DTM, the GPR profile (near P4) and luminescence samples (Suursaar et al. 2022).

References:

Suursaar Ü, Rosentau A, Hang et al. (2022). Climatically induced cyclicity recorded in the morphology of uplifting Tihu coastal ridgeplain, Hiiumaa Island, eastern Baltic Sea. Geomorphology, 404

Stop 13: The Kõpu peninsula and the oldest lighthouse in Estonia

The highest part of Hiiumaa, the Kõpu peninsula, was the first piece of land emerging from the sea. During its earliest occupation in the Stone Age, less than 1% of its terrain was above the sea level forming a Kõpu islet. Today Kõpu is representing *ca* 20 km long peninsula in the western part of the island. Steep-sloped Mägipea height forms a central part of it with a 10 m high Tornimägi hill (68 m a.s.l.) in its western part and high dunes in its eastern part. The oldest mire sediments on the island are known from the Kõivasoo Bog on the southern slope of the Kõpu height, which started to develop as a coastal lake at the end of Ancylus Lake stage.

Kõpu coastal formations, which are surrounding the Kõivasoo Bog, can be divided into two sets. The first developed during the Ancylus Lake regression period *ca* 10.0–9.9 ka and the second set during the Litorina Sea regression at *ca* 6.4–3.9 ka. These two sets are separated by an unconformity related to the Litorina Sea transgression. During the Ancylus Lake regression, a freshwater mesotrophic Kõivasoo palaeolagoon formed between the coastal formations. Due to the uplift of the basin above the threshold elevation, the lagoon was isolated from the BSB and turned into a lake around 8.8 cal. ka BP. The infill on the Kõivasoo basin, from the bottom to the top, consists of calcareous silt, calcareous gyttja, gyttja and peat.

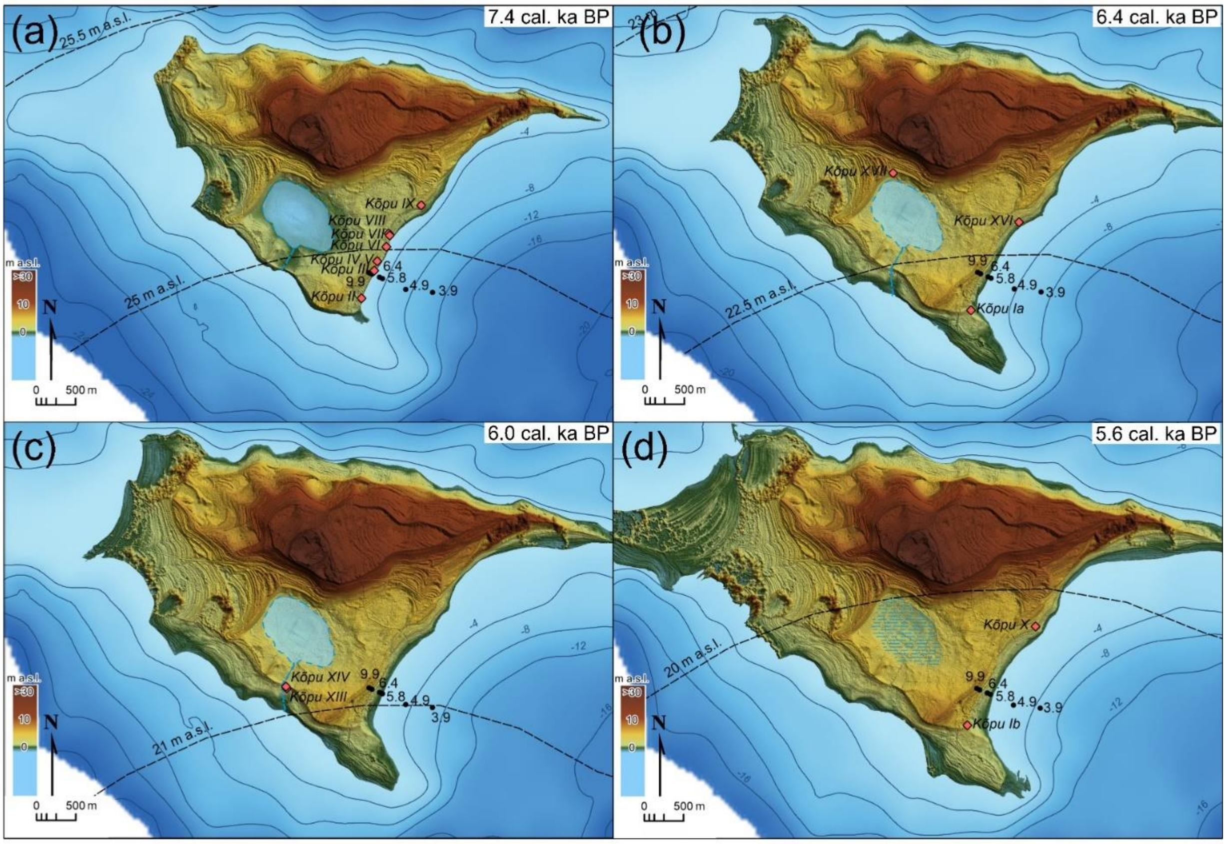


Figure 24. Palaeogeographical reconstructions of the Kõpu palaeoisland RSL isobases and concurrent archaeological sites (red diamonds): a) LS maximum, during the earliest Narva culture settlement sites; b) at 6.4 cal. ka BP; c) before the overgrowing of the Kõivasoo lake, and d) during the onset of peat formation in Kõivasoo. Black dots mark the mean IRSL ages (ka) from the studied coastal section and white areas at the bottom corners mark the present-day Baltic Sea (Rosentau et al. 2020).

The reconstructed RSL curve reveals a 20 m drainage of Ancylus Lake followed by a land-uplift-driven 3-m regression during the Initial Litorina Sea period. The Litorina Sea transgression was less than 4 m in this area. During the 7.4–6.0 cal. ka BP, RSL fall was about 4.3 mm/yr and about 1 mm/yr less during the last 6000 years suggesting deceleration in the isostatic rebound.

Hiiumaa was first inhabited *ca* 7.6–7.5 cal. ka BP, probably by hunter-gatherers from the Saaremaa Island. The earliest campsites were established at shores of the Kõpu palaeobay successively at lower elevations following the shoreline retreat of the Litorina Sea, but Corded Ware and younger sites were not shore-connected. Archaeological surveys and excavations have revealed 17 Stone Age settlement sites.

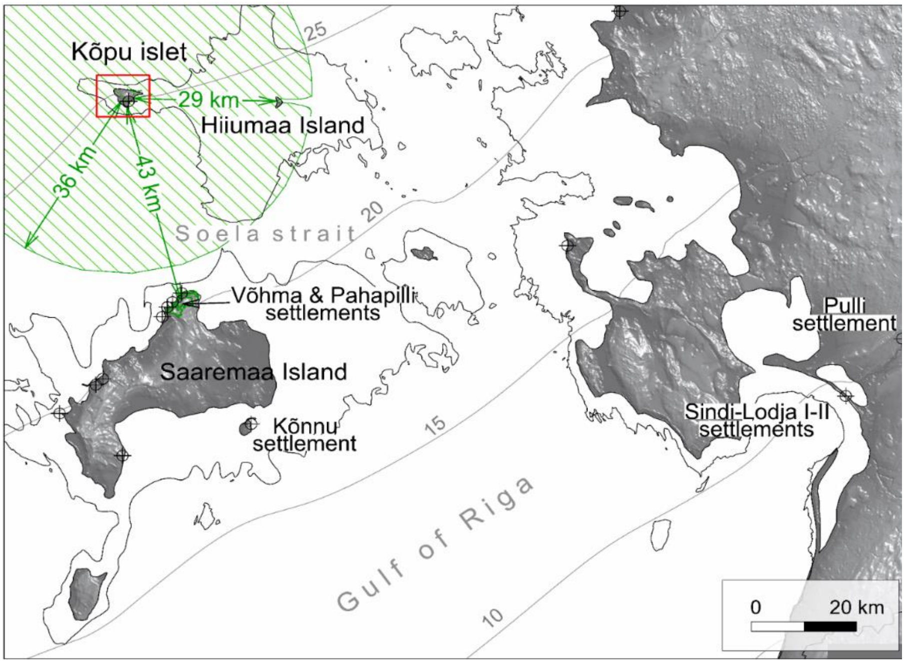


Figure 25. Western Estonia with Mesolithic settlements and a viewshed from the highest point of the Kõpu palaeoislet (green areas) during LS highstand at about 7.4 cal. ka BP. The present coastline is shown by black contours. (Rosentau et al. 2020)

Kõpu lighthouse

One of the oldest lighthouses in the world is located in the middle of the Kõpu peninsula. The Hanseatic merchants wanted to mark this peninsula with an outstanding landmark already before the year 1490, because of an important east–west shipping lane passing the area. On April 20, 1500, Bishop Johannes III Orgas gave the permission to build a massive stone pillar without any openings. Thus, originally, the tower was a solid stone without any rooms, and when it was equipped with light, the top of the lighthouse was reached by external stairs. During the reconstruction in the 1800s, a stairway and two rooms were cut into the tower.

The Kõpu lighthouse, which is built of local limestone and glacial erratic stones, has a unique shape of a square prism with massive buttresses in the four cardinal directions. The height of the building is 37.7 m, and the light reaches *ca* 103 m a.s.l, making it the highest coastal light on the Baltic Sea. The lighthouse has been in continuous use since its completion in 1531 and has gone through the stages from a medieval landmark up to a modern electrified lighthouse. Today it is in use as an aid to navigation and it is managed by Estonian Maritime Administration.

Figure 26. Kõpu lighthouse in 13.08.2012 (photo: https://en.wikipedia.org/wiki/Kõpu_Lighthouse#/media/File:Kõpu_tuletorn_Hiiumaal.jpg)

References:

Rosentau A, Nirgi T, Muru M, et al. (2020) Holocene relative shore level changes and Stone Age hunter-gatherers in Hiiumaa Island, eastern Baltic Sea. Boreas 49, 783–798.

Tiik L (1976) The Lighthouse of Kõpu (Formerly Dagerot). Transactions of the Tartu State University, 159-165.

Stop 14: Ristna spit and mapping of the offshore glacial landforms

Ristna spit is located at the tip of Kõpu peninsula and it is the westernmost place of Hiiumaa. Footprints of the Baltic Ice Stream in the shallow sea bottom but not only in the surroundings of Hiiumaa but wider – BaltStream tells us the story.

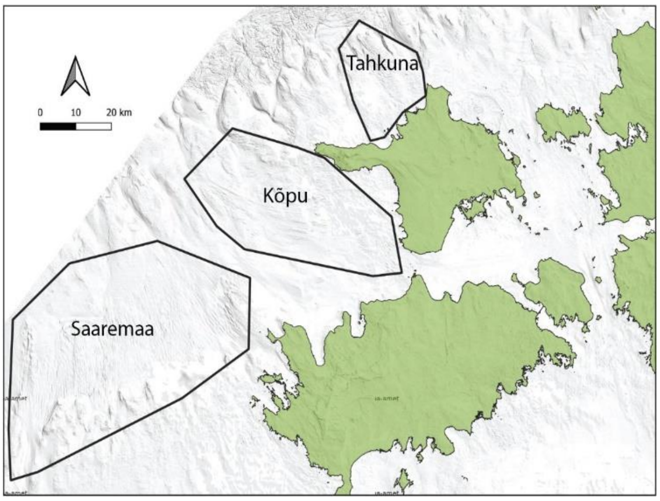


Figure 27. Location of three Offshore areas with radial glacial bedforms. Kõpu set of offshore bedforms is located S-SW from Kõpu Peninsula covering an area of ca 1 429 km²; comprising 311 mapped landforms with dominating orientation N-S.

Stop 15: Lehtma harbour

Lehtma harbour, the second largest harbour in Hiiumaa, is located in the NE corner of the Tahkuna Peninsula, northern Hiiumaa Island. Glaciofluvial gravelly deposit forms the dome of the peninsula. Some researchers interpret it as a glaciofluvial delta formed in front of the latest standstill of the retreating ice sheet. Owing to the emergence of the area due to GIA, many coastal formations, dominantly coastal spits, have formed and are well visible as ridge-swale systems. Characteristic feature along the W and N coastline is up to 5 m high dune ridge dated to LIA period. Openness to storm waves and availability of fine-grained sandy sediments have caused intensive longshore transport of sediments from the northern tip of the peninsula towards the south, resulting in the development of sandy spit.

In 1916 first jetty was built to protect the small harbour in the NE tip of the peninsula. It was oriented perpendicular to the coastline, and it cut the longshore sediment transport. Soon the northern side of the jetty was loaded with sediments which started to move around obstructing the fairway. Therefore, this jetty was reconstructed several times, reaching the water depth of 5 m after the last reconstruction (1985). Today there is a wide artificial sandy beach with few-meter-high dunes and even a parking lot, and sand still happily moving around the end of the jetty.

Figure 28. A view of the jetty of the Lehtma harbour with a sandy beach at the northern side (photo: A. Nurs)

Then, coastal erosion started at the distal side of the jetty. Thus, military buildings once built on the mainland are now in the water, and only a narrow sandy stripe has remained of one of the longest sandy beaches on the island, Tõrvanina. As the Lehtma harbour is economically important for the island and must be in working order, the harbour fairway has been dredged from time to time. However, the dredging volumes have been larger (3000-2500m^3) than the calculated long-term annual sand movement volume (1400-1600m^3). Thus, in the south of the jetty, there is a deficit of sediments protecting the beaches. What makes it worse is that the dredged material is dumped into the deeper part of the bay, where it is no longer subject to wave transport.

According to the studies on the wave climate, water, and sediment movement, the dumping area should be shifted towards the SW of the jetty to a water depth of 3-4 m, where the most intensive westerly (shoreward) movement of sediments has been measured. The waves could then carry the dumped sediments to the beach, which would be a good measure for coastal nourishment.

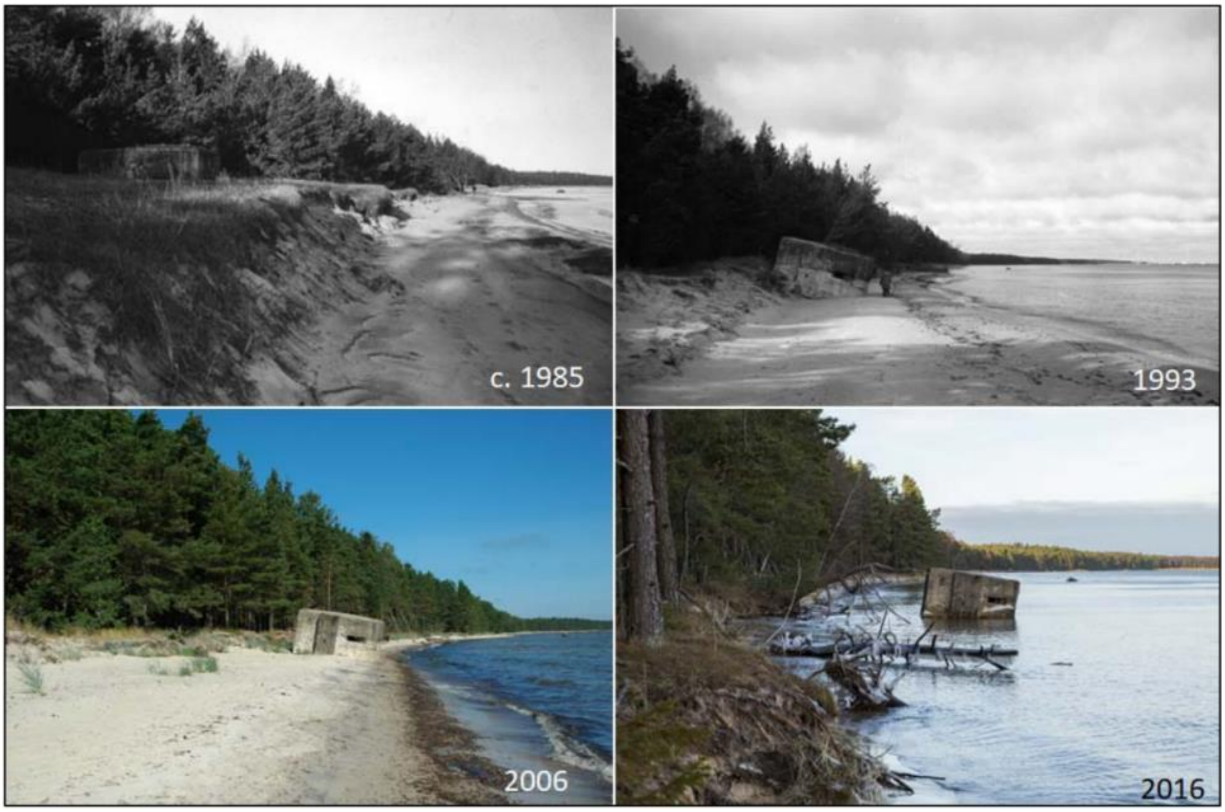


Figure 29. Wave erosion at the western coast of Tareste Bay due to sediment deficit caused by the Lehtma harbour constructions which cut the natural longshore sediment drift (R. Noormets).

References:

Anderson A, Ratas U, Rivis R, Palginõmm V (2012) Relationship between coastline changes and dynamics of coastal ecosystems of Tahkuna Peninsula, Estonia. IEEE/OES Baltic International Symposium (BALTIC), Klaipeda, Lithuania, pp. 1-6

Buynevich IV, Tõnisson H, Suursaar Ü, et al. (2023) Diverse erosional indicators along a rapidly retreating Holocene strandplain margin, leeward Hiiumaa Island, Estonia. Baltica, 36 (1), 79–88

August 30, Hiiumaa Island – Pärnu

Stop 16: Erratic boulder field at the slope of Kärdla impact structure rim

Large erratic boulders carried by continental glaciers are inseparable part of former glacial areas, incl. the Estonian landscape. Due to the closeness of crystalline basement of the Fennoscandian Shield and the glaciation centre, a moving glacier was able to tear off and transport huge monoliths. When the ice melted, the boulders were placed on completely different sedimentary bedrock in Estonia, which makes them easily recognizable. This inspired scientists in the 19th century with the idea of continental glaciation and served as one evidence for the glacial theory.

A zoologist/palaeontologist of Tartu University, E. Eichwald (1795-1876), reached the conclusion that the boulders in Estonia originate from Scandinavia and were brought here by marine ice (1846). In 1853, he was the first in the Baltic and Russia to consider that at least northern Estonia was once covered by an active glacier. While the Stockholm Royal Society accepted the glacial theory already in 1864, it didn't find acceptance in Germany and Russia. Thus, many outstanding geologists (incl. G. Helmersen and C. Shmidt) went to Sweden to learn about the glacial phenomena. As a result, they rejected the hypotheses of glacial drift and considered the distribution of erratic boulders and formation of 'boulder clay' to be caused by the continental ice sheet reaching here from Scandinavia.

According to some sources, there are only a few gigantic erratic boulders with a perimeter of more than 25 m in Northern Europe, outside Estonia. However, in Estonia *ca* 1800 large boulders have been documented, 395 of them protected as natural monuments:

Perimeter	number of boulders	Perimeter	number of boulders
>25 m	96/110	16-20 m	363
20-25 m	186	10-16 m	~1200

Based on the mineral content and texture it is possible to distinguish more than fifty types of boulders in Estonia. Some of them originate from clearly marked places **(indicator boulders)**, for example, the Vyborg rapakivi, and the Hoglandian and Ålandian quartz-porphyries.

We will visit the NE slope of the Kärdla impact structure rim with more than 80 boulders (8 boulders >10m perimeter) on the 0.5 ha area. Such a concentration of large boulders is rare but not unique. Along the coastline, zones or lines of erratic boulders are common but they might mark also the orientation of cracks in former ice sheet. In some locations, sharp-edged gigantic boulders of the same type suggest that a large block has been crushed into smaller blocks.

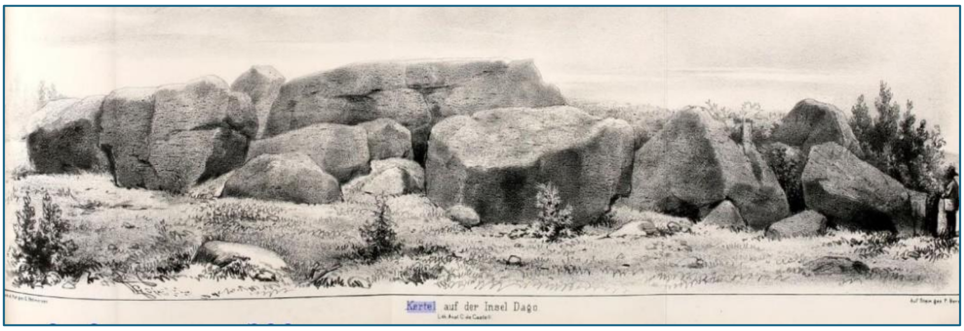


Figure 30. A drawing by G. Helmersen of a boulder field at Paluküla, Hiiumaa Island, published in 1882.

References: *Gudelis V (ed.) (1965) Crystalline indicator boulders in the East Baltic area. Mintis, Vilnius.*
Raukas A (1995) Estonia – a land of big boulders and rafts. Guestiones Geographicae. Sp. Issue 4, 247-253.

Stop 17: The Kärdla impact structure

The Kärdla meteorite crater is one of the six impact structures discovered in Estonia. Four of them (Kaali, Ilumetsa, Tsõõrikmäe, Simuna) are small (up to 110 m in diameter) and relatively young (formed after Pleistocene glaciation), while the remaining two (Kärdla and Neugrund) are considerably larger (4 and 7 km in diameter) and older (455 and 530 Ma).

The Kärdla impact structure was formed at 455 Ma (Upper Ordovician), in a shallow epicontinental sea some tens of kilometres from the land and erosion area. The iron-rich projectile, about 200 m in diameter, approached from the west at an angle of 30–45°. The impactor penetrated about 50-m-thick water layer and the sedimentary cover and exploded in the uppermost part of the crystalline basement. A complex crater, *ca* 4 km wide and 500 m deep, with a central uplift rising of 130 m from the crater floor, was formed. The highest point of the rimwall is 110 m above the target level. The rimwall is cut by at least two resurge-excavated gullies. The variable height of the rimwall results from the obliqueness of the impact. Because the crater and its surroundings were buried directly after the impact, the whole complex of impact-related sediments is preserved there. They are recovered by 160 wells, six of which penetrate the entire complex of impact breccias inside the crater.

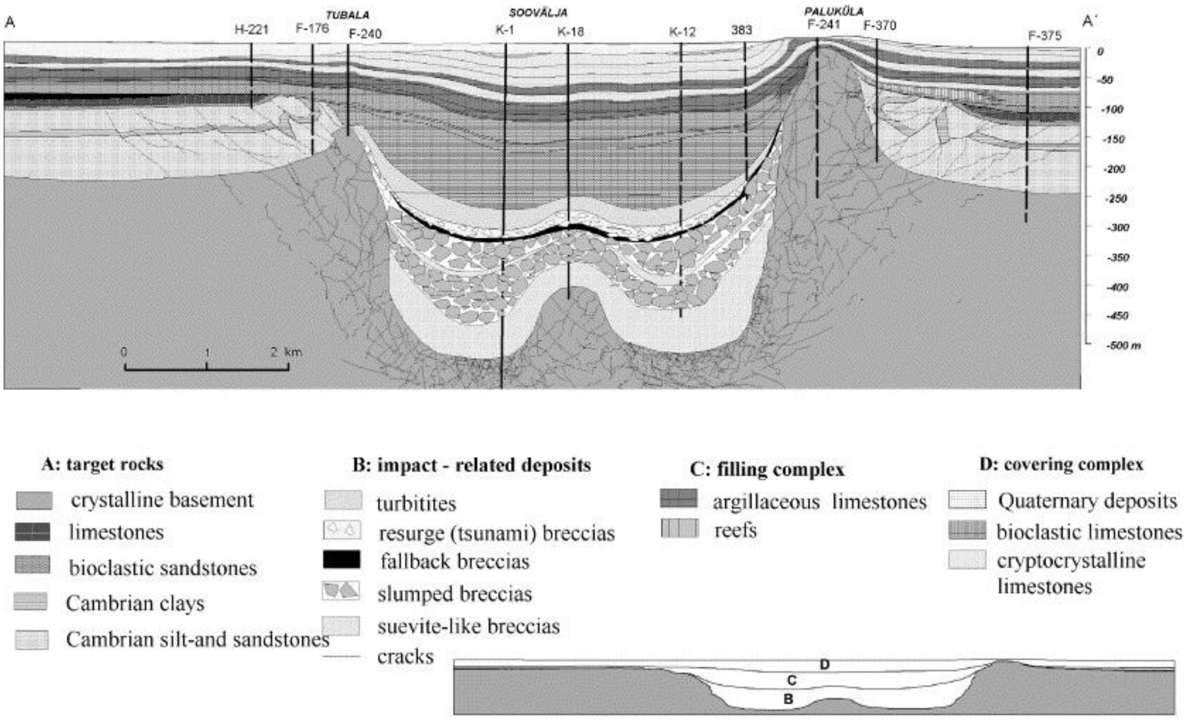


Figure 31. West–east cross-section A–A' of the Kärdla crater (Suuroja et al. 2002)

References:

Suuroja K, Suuroja S, All T, Flodén T (2002) Kärdla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. Deep-Sea Research Part II: Topical Studies in Oceanography 49, 2, 1121−1144.

Suuroja S, Suuroja K, Flodén T (2013) A comparative analysis of two Early Palaeozoic marine impact structures in Estonia, Baltic Sea: Neugrund and Kärdla. Bulletin of the Geological Society of Finland 85, 79−97.

Stop 18. Palivere ice-marginal formations and distribution of eskers in Estonia

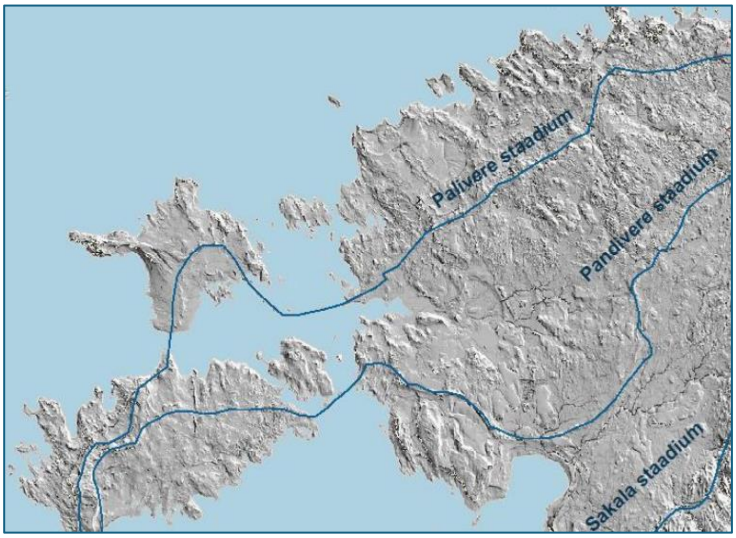


Figure 32. The ice marginal formation zones of the last glacier in W Estonia (Kalm, 2012).

The glacier began to retreat from the NW Estonia *ca* 13.8 yrs ago. A new temporary advance of ice occurred *ca* 13.2 yrs ago, which led to the formation of the Palivere ice-marginal zone. The zone stretches from Lahemaa in N Estonia to the Sõrve Ps in Saaremaa, passing through Tallinn, Palivere and Hiiumaa, and can only be traced in Estonia, as it is not traceable in the Baltic Sea. Its further course is therefore hypothetical and has been correlated with both, the Vimmerby (GI 1d *ca* 14 ka BP) and the Levene marginal formations (GS-1b *ca* 13.3 ka) in Sweden (Saarse *et al*. 2012). The different options are on the table because the changes in the ice cover were not consistent on the different shores of the Baltic Sea (Raukas, 1992).

The ice-marginal formations of the Palivere zone are represented by end-moraines on the islands, marginal eskers at Palivere (NW Estonia), and glaciofluvial deltas in N Estonia. The term "***marginal eskers***" stands for a specific type of glaciofluvial delta, that is narrower than deltas and has a ridge-like morphology and asymmetric cross profile (Raukas 1992). Palivere glaciofluvial deposits form an asymmetric marginal ridge with the gradual transition to the glaciolacustrine plain at the distal direction. Gravelly deposits display a diversity of grain size and many glaciotectonic deformations. Glaciofluvial deposits cover the older clayey diamiction and varved clays which, together with glaciotectonic deformations, support the theory of glacier readvance. Readvance is also supported by the lithology of tills that are rich in rapakivi from SW Finland, granites from Åland and olivine diabases from Satakunta. These could also be found in the earlier Pandivere zone. Thus, the accumulation of tills in the earlier Pandivere stage was affected by S to SW oriented ice flow, but the flow during the later Palivere was SE-E. Although, it is still not clear how far the ice margin retreated before the readvance.

At the site, we will also discuss the mapping of eskers in Estonia and the role of the bedrock in the esker formations as these are located mostly in the northern part of Estonia and are associated with the Ordovician and Silurian carbonaceous bedrock. Bedrock valleys and eskers are arranged in a sub-parallel pattern reflecting former meltwater flow towards the ice margin. Several esker systems are confined to the valley limits following either the valley floors or lying upon their shoulders. Thus, the initial focus of meltwater may have been controlled by the location of the bedrock valleys.

References: *Raukas A (1992) Ice marginal formations of the Palivere zone in the eastern Baltic. Sveriges Geologiska Undersökning 81, 277–284; Saarse L, Heinsalu A, Veski S (2012) Deglaciation chronology of the Pandivere and Palivere ice-marginal zones in Estonia. Geological Quarterly 56, 353-362.*

Stop 19. Varved clays and varve chronology for western Estonia

Concern about current climate change has raised the number of publications dealing with varved sediments giving rise to the term 'recent varves' for those forming today, and 'paleovarves' for those from the Holocene and Pleistocene. Work on paleovarves has advanced in the use of the varve sequences to constrain chronologies and to further our understanding of Pleistocene climate as well as non-climatic events associated with deglaciation.

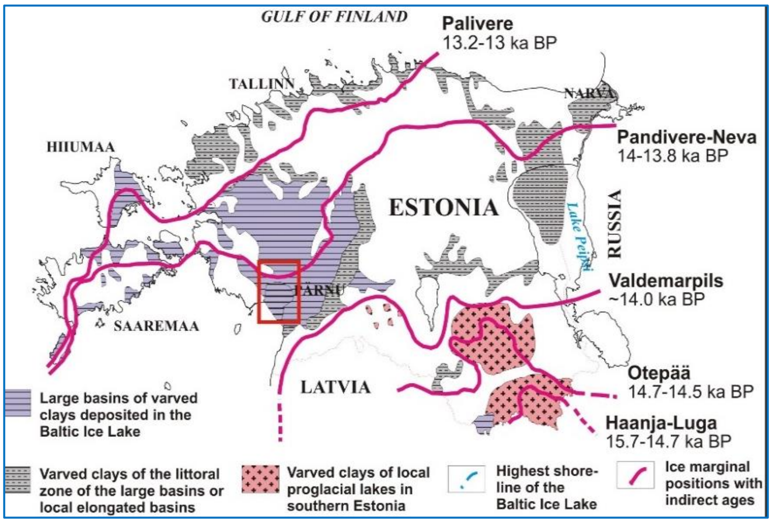


Figure 33. Distribution of varved clays in Estonia.

The decay of Late Weichselian ice from Estonian territory between 14.7–12.7 ka BP was followed by extensive proglacial bodies of water, which developed in accordance with the receding ice margin and opening of new drainage roots. This is reflected in a wide distribution of varved clays with their characteristic summer (silty) and winter (clayey) layers which are interpreted to reflect seasonal variations in sedimentary environment in proglacial lake.

Varved clays in western Estonia forming two large basins, namely Pärnu and Vigala, were deposited in the Baltic Ice Lake. Up to 30 m-thick cover of clay is characterised by distinct lamination of seasonal layers. Local varve chronology for Pärnu comprises of 584 yrs and for Vigala basin 532 consecutive varve years (Hang & Kohv, 2013). As two basins are separated by *ca* 15 km till terrain no good visual correlation between those was possible. Therefore, we exploited numerical techniques to assist in finding possible correlations. Raw varve thickness series were normalised to remove sedimentary signal assumed mostly to reflect the proximity to melting glacier. This signal (general trend) was calculated and extracted from the raw series. Residual series were log-transformed to stabilize variance, and the log-transformed series were smoothed with 21 yr window median filter. The cross-correlation function suggested the best fit if normalised Vigala series is lagged +140 yrs. Thus, the earlier magnetostratigraphic data (Hang et al. 2011) from two clay sections from Pärnu and one from Vigala basin were connected. Strong eastern shift in declination is correlated with similar data from regional declination curves (Bakhmutov & Zagniy 1990; Saarnisto & Saarinen 2001) between 13.9-13.3 ka BP. This correlation places the stagnation of the ice margin at the Pandivere-Neva line to *ca* 13.9-13.8 ka BP and supports the recent AMS dates from N Estonia suggesting the age of Pandivere-Neva formations there to be 14.0–13.8 ka cal yrs BP (Vassiljev & Saarse 2013).

References: *Hang T, Kohv M (2013) Glacial varves at Pärnu, southwestern Estonia: a local varve chronology and proglacial sedimentary environment. GFF, 135, 273−281.*

Arrival in Pärnu at the latest at 6 PM