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Corresponding author:
Igor Tuuling
igor.tuuling@ut.ee

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The bedrock relief below the Väinameri, in a shallow-marine branch of the central Baltic Sea offshore Estonia

Igor Tuuling[a,b], Sten Suuroja[a], Anu Veski[a], Markus Ausmeel[a,b], Martin Liira[a,b] and Kalle Suuroja[a]

[a] Geological Survey of Estonia, F. R. Kreutzwaldi 5, 44314 Rakvere, Estonia

[b] Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14a, 50411 Tartu, Estonia

ABSTRACT

This paper represents one output of the extensive seismo-acoustic profiling performed by the Estonian Geological Survey in the Väinameri, the shallow sea in the West Estonian Archipelago, during the geological mapping conducted in 2019–2022. Based on recordings from boomer-type sound transmitters, this study describes and analyses the bedrock relief to assess a prior suggestion that there exists a NE–SW trending pre-Quaternary river valley traversing the Väinameri, extending across the central Baltic Sea. The bedrock relief map and 3D model reveal a valley-like structure with distinctive cuesta elements crossing the central Väinameri. The cuesta plateau, along with the cuesta escarpment (Silurian Klint) that emerges faintly in the Bay of Matsalu, has been substantially reshaped by Pleistocene glaciers around the Muhu depression in the very centre of the Väinameri and is best preserved between Saaremaa and Hiiumaa islands. The general drainage pattern also points towards a fluvial erosion component in shaping the bedrock depression below the Väinameri. Despite that, the age and genesis of this valley-like feature with the Silurian Klint below the Väinameri remain open. The hypothesis that a pre-Quaternary Eridanos River System might have eroded these bedrock structures contradicts the altitude of the klint base below the Baltic Sea, which remains far below the presently estimated reach of the Eridanos fluvial erosion. Further studies are needed to specify the possible genesis and age of the klints and buried bedrock valleys in Estonia, which, in many aspects, reveal the characteristics of pre-Quaternary fluvial denudation rather than Pleistocene glacial erosion.

Introduction

When the Geological Survey of Estonia initiated the geological mapping of the Väinameri in 2019, in a shallow-marine branch of the central Baltic Sea offshore Estonia (Figs 1, 2), no data (depth, configuration, genesis, etc.) existed on the bedrock depression below this sea. Nevertheless, based on some indirect evidence emerging around the Väinameri, several authors (Kvasov 1975; Tavast and Raukas 1982; Raukas and Tavast 1984; Tuuling and Flodén 2016; Tuuling 2017) suggested that there might exist a deep pre-Quaternary river valley crossing east to west across the central Väinameri and dividing the two largest islands in the archipelago, Saaremaa and Hiiumaa. One indication supporting this hypothesis was the general geological background, as outcrop bands of easily erodible clay-rich Silurian limestone units (Velise, Rumba and Jaani formations) extend eastwesterly across the central Väinameri (Fig. 2). Furthermore, along these bands and intruding deeply into the West Estonian Lowland, there emerges Bay of Matsalu, a prolongation of the modern River Kasari, which along with its delta branches is located above the buried valley-like pre-Quaternary bedrock incisions (Tavast and Raukas 1982; Geoportal of Estonian Land Board; Fig. 2).

Another argument backing the proposed river valley between Saaremaa and Hiiumaa is the notable bedrock escarpment known as the Silurian Klint, which extends from the northern coast of Saaremaa to the Swedish island of Gotland (Fig. 1). The outlines of the Silurian and Baltic klints were ascertained already on the first bathymetric maps of the Baltic Sea (Büchting 1918). However, an excellent cuesta landscape in the bedrock relief, featuring an asymmetrical cuesta valley between these klints, was contoured below the central Baltic Sea only when applying

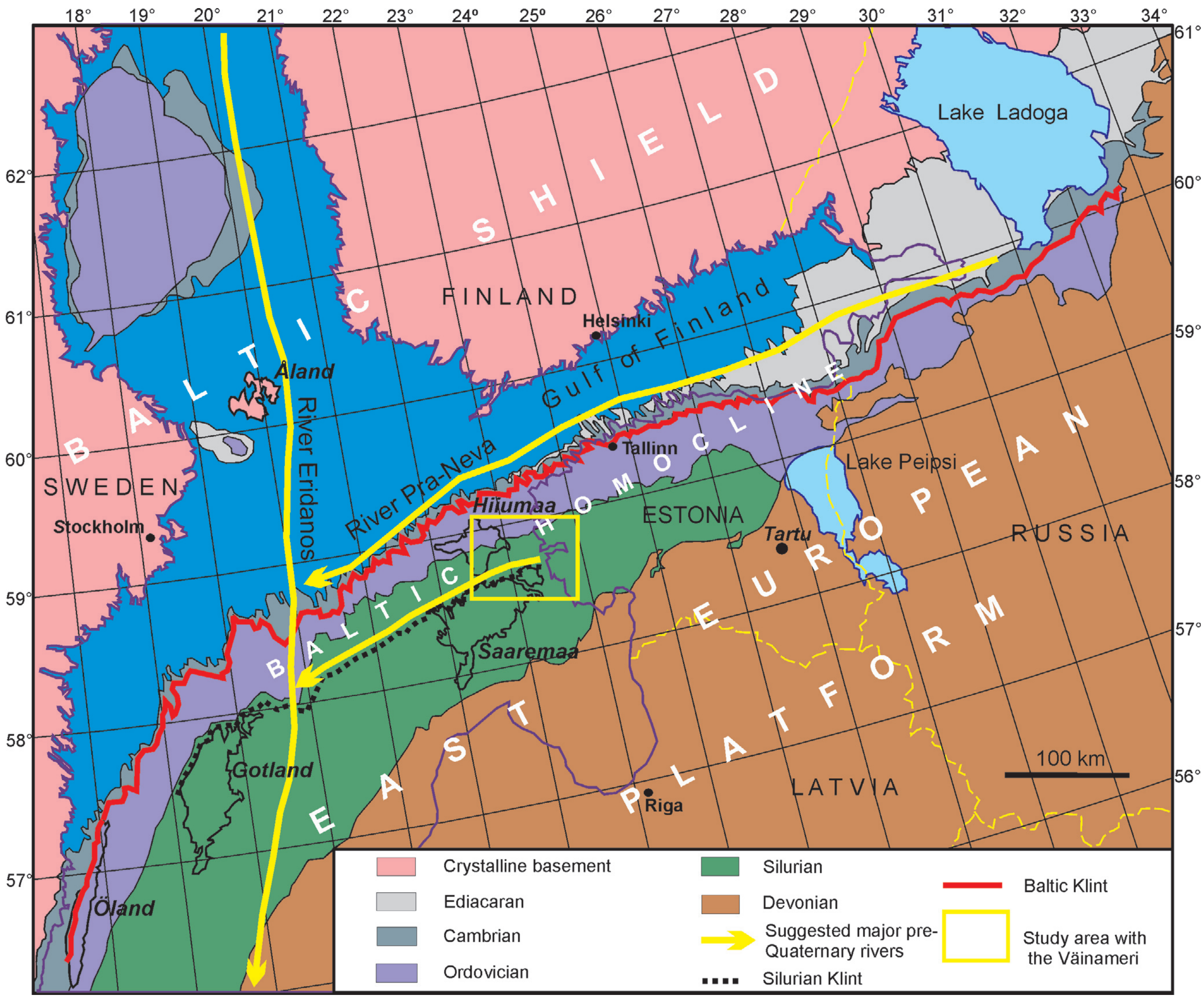

Fig. 1. Regional geological and structural setting of the study area with the Väinameri in the West Estonian Archipelago (framed area enlarged in Fig. 2) and the set of the suggested pre-Quaternary rivers eroding the Baltic and Silurian klints (modified after Tuuling 2017).

continuous seismic reflection profiling (see fig. 6 in Tuuling and Flodén 2016).

Similar to the Baltic Klint, which borders the northern Estonian coast and crosses the southern slope of the Baltic Shield, and which was thought to be eroded by a large late Cenozoic river, the Pra-Neva, the Silurian Klint was tied to a coeval pre-Quaternary river further south (Martinsson 1958; Ignatius et al. 1981; Puura 1980; Tavast and Raukas 1982; Raukas and Tavast 1984; Tuuling and Flodén 2001, 2011, 2016; Noormets and Flodén 2002; Puura et al. 2003; Tuuling 2017; Figs 1, 2). Both klint-sculpturing rivers flowed apparently into the Eridanos, a large sub-meridional river close to the eastern coast of Sweden. The Eridanos River System, which drained the Baltic Shield through the present Baltic Sea (Fig. 1) during the late Cenozoic, deposited a Miocene to Early Pleistocene fluvio-deltaic package, containing sediments of Fennoscandian origin and fossils from the drainage area of the Pra-Neva, across northern Poland and Germany to the present North Sea (Overeem et al. 2001; Rhebergen 2009). However, the idea that the terraced cuesta relief below the central Baltic Sea has been shaped by pre-Quaternary rivers has been increasingly contested by the hypothesis that it was gouged by the erosion of the Pleistocene ice sheet (Amantov et al. 2011; Hall and van Boeckel 2020).

The interpretation of the first set of seismo-acoustic profiles covering the southeastern branch of the Väinameri, the Suur Strait (Fig. 2), revealed two distinct channels falling towards the central Väinameri, most likely the beds of tributaries once flowing into the proposed E–W trending palaeoriver (Tuuling et al. 2022). The current study, comprising profiling data from all four years (2019–2022), enables for the first time to outline the entire bedrock depression below the Väinameri and analyse the details of the bedrock relief more closely, including altitude values with trends and most significant relief features within its different branches. These data, in turn, allow us to ascertain the extent to which the general morphology of the bedrock surface below the Väinameri, with its drainage pattern, supports the idea of a possible palaeo-river valley traversing east to west across the West Estonian Archipelago.

Thus, this paper aims to deliver and describe novel data on the bedrock relief below the Väinameri to advance and encourage further studies and discussions on the significant incisions, klints, and buried valleys eroded into the Estonian

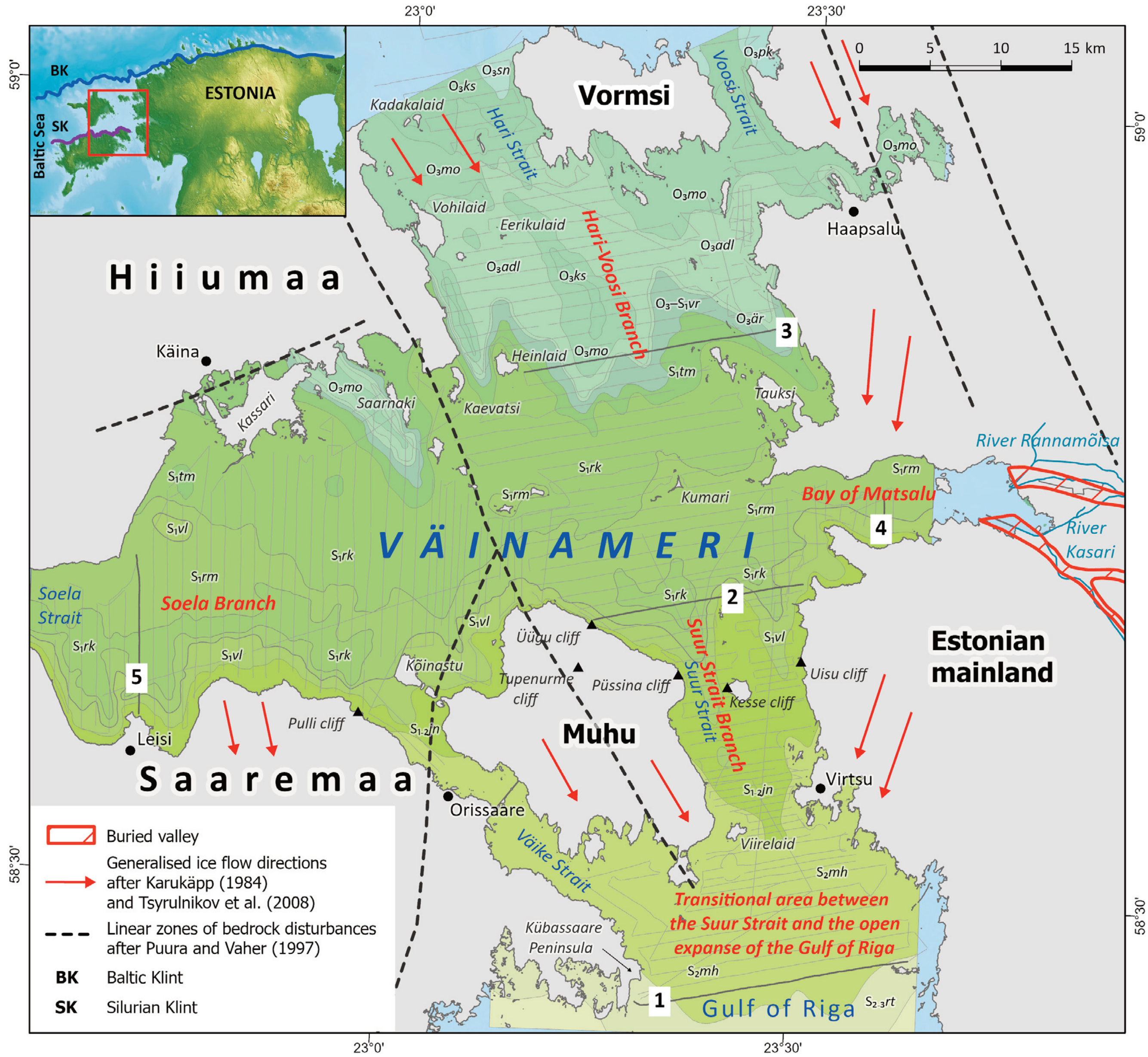

Fig 2. Composed geological map of the Väinameri with a set of seismo-acoustic survey lines (weak lines) covering different branches of the Väinameri. **1–5** – interpreted seismo-acoustic lines in Figs 6–10. Indexes of the outcropping Ordovician and Silurian formations (Fm): S_{2-3}*rt* – Rootsiküla Fm, S_1*mh* – Muhu Fm, S_{1-2}*jn* – Jaani Fm, S_1*vl* – Velise Fm, S_1*rm* – Rumba Fm, S_1*rk* – Raikküla Fm, S_1*tm* – Tamsalu Fm, O_3–S_1*vr* – Varbola Fm, O_3*är* – Ärina Fm, O_3*adl* – Adila Fm, O_3*mo* – Moe Fm, O_3*ks* – Kõrgessaare Fm, O_3*sn* – Saunja Fm.

bedrock. An approach that suggests the klint escarpments and deep valley-like bedrock incisions with their intricate patterns resembling river sets are the result of Pleistocene glaciers rather than palaeo-rivers would cardinally change the prevailing understanding among Estonian geologists. The timing and genesis of the formation of the klints and buried valleys in Estonia certainly require separate studies with more profound discussions, weighing all possible pro and contra arguments concerning the possible roles of palaeo-rivers and Pleistocene glaciers. This discussion, however, remains outside the scope of this paper.

Study area

A group of four larger islands (Saaremaa, Hiiumaa, Muhu, and Vormsi) and numerous smaller islets emerging from the northern Baltic Proper offshore western Estonia form the West Estonian Archipelago (Figs 1, 2). The islet-rich water expanse that separates the Estonian mainland from its two largest islands, Saaremaa and Hiiumaa, and opens through straits northwards and westwards into the northern and central Baltic Sea and southwards into the Gulf of Riga is called the Väinameri (Estonian for *sea of straits*; Fig. 2).

The Väinameri consists of two SE–NW and SW–NE crossing sections, intersecting around the centre of the sea, NE of Muhu Island (Fig. 2). This creates four elongating branches:

1. The NW branch, including the Hari and Voosi straits, separates Hiiumaa from the Estonian mainland;
2. The SE branch, featuring the Suur Strait, separates Muhu from the Estonian mainland;
3. The SW branch with the Soela Strait divides Hiiumaa and Saaremaa;
4. The NE branch encompasses the Bay of Matsalu, which intrudes the Estonian mainland (Fig. 2).

Thus, excluding the Bay of Matsalu, the outward extents of the other branches are determined by the straits, the boundaries of which also confine the expanse of the Väinameri and, hence, the limits of our study area. The Soela Strait restricts the westerly extent of the SW (Soela) branch between Saaremaa and Hiiumaa. The northern boundary of the NW (Hari–Voosi) branch coincides with the parallels drawn from the NW and NE corners of Vormsi Island towards Hiiumaa and the Estonian mainland, respectively. However, in the SE (Suur Strait) branch, our study area was exceptionally extended beyond the limits of the Väinameri, typically drawn along the parallel between the SE corner of Muhu Island and the Estonian mainland. Instead, extending the study area to the latitude drawn from the SE corner of the Kübassaare Peninsula, we also embraced a narrow between Saaremaa and the Estonian mainland that forms a transitional area between the Suur Strait and the open expanse of the Gulf of Riga further south (Fig. 2).

General structural setting with the main bedrock relief features

Estonia, including the Väinameri, is located in the NW corner of the East European Platform, where the faintly southerly sloping package of Ediacaran-Silurian layers, exposed across the southern slope of the Baltic Shield, forms the Baltic Homocline (Tuuling 2017; Fig. 1). The depression of the Väinameri is eroded into Ordovician-Silurian limestone and dolostone layers (Fig. 2) with highly varying clay content and resistance to erosion. These layers slant slightly to the SSE (at an angle of about 10–15', with a strike of about 85–90°).

The northern margin of the Baltic Homocline, its erosional transect to the Baltic Shield, is marked by cuesta terraces that form one of the most striking bedrock landforms in the NW corner of the East European Plain. These terraces, cut into the Ediacaran-Silurian rocks, descend stepwise to the Palaeoproterozoic crystalline rocks exposed on the southern slope of the Baltic Shield below the Baltic Sea (Lutt and Raukas 1993; Tuuling and Flodén 2016; Tuuling 2017; Fig. 1). Although the sea inundates a more significant part of this cuesta landscape, two of its most prominent entities, the escarpments of the Baltic and Silurian klints, which are exhumed and refreshed by the abrasion of the sea, occasionally emerge onshore along the northern coasts of the Estonian mainland and Saaremaa Island, respectively (Figs 1, 2). Thus, the submerged Baltic Klint passes close to the northern border of the Väinameri, west of the Estonian mainland. At the same time, the Silurian Klint, with its onshore sections, crosses the central part of the Väinameri and contours furthermore several segments of its bedrock depression (Fig. 2).

Another group of significant relief features incised into the Estonian bedrock, interpreted as pre-Quaternary river valleys according to the present knowledge (Tavast and Raukas 1982; Raukas and Tavast 1984; Vaher et al. 2010), are primarily hidden below a thick Quaternary cover. Similar buried valleys with varying orientations and patterns resembling river sets are frequent and, in places, partially exhumed by modern rivers in northern and southern Estonia, where the general bedrock altitude and ruggedness surpass these of the West Estonian Lowland (Tavast and Raukas 1982; Vaher et al. 2010). Originating from a suggested watershed area around central Estonia, the buried valleys in northern Estonia mostly descend northwards towards the suggested River Pra-Neva (Fig. 1), whereas in western and southwestern Estonia, they drop predominantly towards the W (Väinameri) and SSW (Gulf of Riga), respectively (Tavast and Raukas 1982, fig. 42). The buried valleys, enlarged and often overdeepened by Pleistocene glaciers, can exceed 2 km in width. Their deepest points were ascertained in drill cores, reaching 143 m below sea level (b.s.l.), in locations such as Harku and Abja valleys in northern and southern Estonia, respectively (Tavast and Raukas 1982).

Materials and methods

To penetrate the glacial till layer spread across the Väinameri and reach the bedrock surface, the current study is predominantly based on seismo-acoustic profiling data collected with boomer-type sound transmitters. The transmitters C-Boom and SIG France SIG Pulse S1 were run at 400 volts in 2019 and 2020–2022, respectively, producing an impulse with a frequency range of 0.4–12 kHz. The reflected signals were received by the hydrophone streamers C-Phone with eight elements and SIG France SIG16 with 16 elements. To minimise the propeller noise of the boat engine, the transmitters and receivers were towed 20 m behind the boat, which moved at a speed of about 4 knots. The equipment on the sea was operated using the Finnish firm Meridata's software package MDCS (Meridata Collecting Software) v. 5.2.

The main set of seismo-acoustic profiles 1 km apart was oriented approximately crosswise to the SE–NW and SW–NE trending sections of the Väinameri. Thus, the N–S profiles covered the Soela and the Bay of Matsalu branches, while the SW–NE profiles traversed the Suur Strait and the Hari–Voosi branches (Fig. 2). Several extensive profiles, trending variously across different branches, complement the main set. Additionally, numerous short profiles with changing trends were run around the frequent islets and in the nearshore shallow water areas due to navigational restrictions.

The processing and filtering of the pulse parameters to enhance the quality of the recordings before interpretation, as well as the interpretation of the profiles, were performed with the MDPS (Meridata Processing Software) v. 5.2. This software also enabled the creation of an XYZ data file (containing points with geographic coordinates and the absolute height of the bedrock surface) for contouring the bedrock surface. As boomer-type sound transmitters bring forward, in most cases, only two distinctive Quaternary units, the glacial till and the set of the Baltic Sea (Baltic Ice Lake, Yoldia Sea, Lake Ancylus, and Litorina Sea) sediments (Figs 7–9), seismic wave velocities of 1800 and 1650 m/s were applied, respectively, for these units to calculate the altitude of the bedrock. When varved clay from the Baltic Ice Lake or sandy-silty units from the Litorina Sea emerged in the boomer-generated profiles (Figs 5, 6), sound wave velocities of 1600 and 1650 m/s were used, respectively, for these units.

Outlines of the bedrock relief below the Väinameri

The filtered low-frequency spectrum (0.5–2 kHz) of the boomer-induced sound pulse enabled following the bedrock surface along most profiles, except in areas with impenetrable gas-rich sediments in the northern and central parts of the Suur Strait and Soela branches, respectively. Based on the MDPS-generated XYZ database, a map and a 3D model (Figs 3, 4) were drawn using the ArcGIS Pro software to describe the framework of the bedrock depression along with the more significant relief features below the Väinameri.

To estimate the likely spilling patterns and water accumulation sites within this depression, and to assess the probability of a hypothetical pre-Quaternary river set with a NE–SW trending larger river traversing the central Väinameri, the changes and general trends of the bedrock relief altitudes across its different branches will be examined below. In doing so, we have to bear in mind that the initial pre-Quaternary bedrock surface below the Väinameri was reshaped, to a greater or lesser extent, by the NNW–SSE advancing glaciers that crossed this area during the Pleistocene (Karukäpp 2004; Tsyrulnikov et al. 2008; Karpin et al. 2021, 2023; Greenwood et al. 2024; Szuman et al. 2024; Fig. 2). However, the estimation that the average depth of glacial erosion in the sedimentary bedrock around the Baltic Sea basin amounted to 40 m over the last 1 Ma (Hall and van Boeckel 2020) raises a question whether the pre-Quaternary fluvial component in shaping the bedrock depression below the Väinameri (if it existed) has been preserved at all.

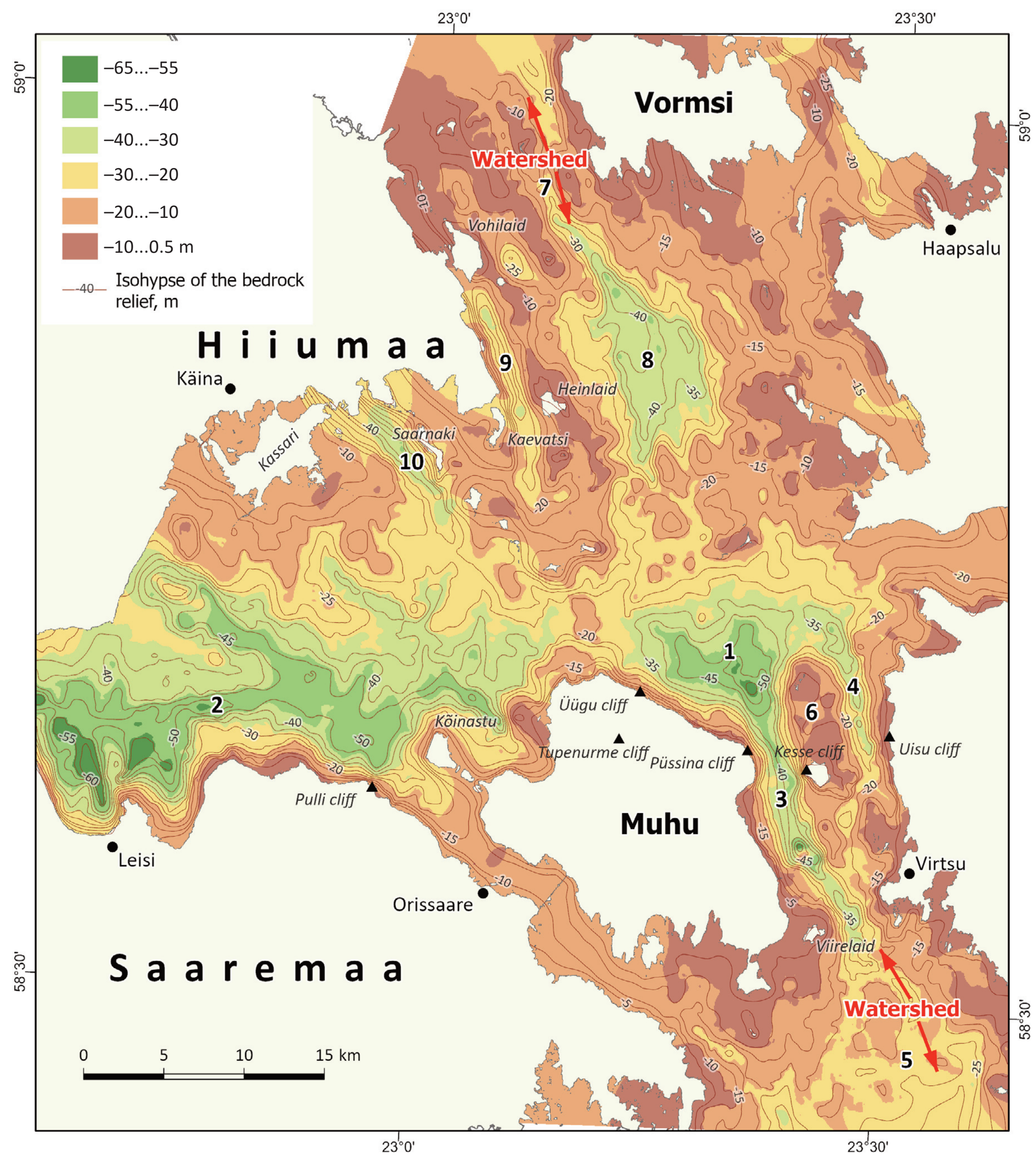

Fig. 3. Bedrock relief map of the Väinameri, created with the ArcGIS Pro software, featuring a coloured height scale, numbered significant relief features, and watershed areas mentioned in the text. **1** – Muhu depression, **2** – channel of the Soela Strait, **3** – main channel of the Suur Strait, **4** – Uisu channel, **5** – plateau-like transitional area in the NE Gulf of Riga, **6** – Kesselaid elevation, **7–8** – mixed channel-depression shaped zone in the Hari–Voosi branch, **9** – Vohilaid channel, **10** – Õunaku channel.

Framework of the bedrock relief

The map and the 3D model (Figs 3, 4) show the general changes and prevailing trends in the bedrock relief altitudes across the Väinameri. The greatest bedrock depths below this sea align along its NE–SW extending Bay of Matsalu and the Soela branches, where two remarkable relief features emerge, falling to ca 60 m b.s.l. (Figs 3, 4). The first one is the Muhu depression, a significant bedrock hollow in the centre of the Väinameri that converges around the junction of its four differently trending branches. The second one is the channel of the Soela Strait that denotes a complex-shaped bedrock groove running close to the northern coast of Saaremaa. This deep NE–SW oriented zone bisects the SE–NW trending section of the Väinameri into the Suur Strait and Hari–Voosi branches (Fig. 2), with oppositely leaning bedrock relief features, both falling, with a lesser or greater clarity, towards the Muhu depression in the central Väinameri (Figs 3, 4).

The Suur Strait branch

Based on the general bedrock relief characteristics and features, the Suur Strait branch, extending beyond the limits of the Väinameri, reveals two distinctive units: the transitional area in the NE Gulf of Riga and the Suur Strait itself (Figs 2, 3). The first unit is distinguished by a plateau-like expanse with a slightly undulating bedrock relief (around 20–25 m b.s.l.) between the Estonian mainland and Saaremaa, flanked by a weakly expressed channel on its NE and SW sides, where depths can drop to ca 30 m b.s.l. (Tuuling et al. 2022; Figs 3, 5). However, a closer look reveals that the NW and SE segments of these plateau-edging channels gradually deepen towards the Suur Strait and the central Gulf of Riga, respectively. Thus, this plateau-like area likely represents a palaeo-watershed between the Väinameri and the main depression of the Gulf of Riga (Fig. 3).

The Suur Strait discloses two bedrock channels descending gradually towards the Muhu depression, separated by an elevation rising ca 15 m above sea level (a.s.l.) on the islet of Kesselaid (Figs 3, 4, 6). The larger one, the main channel of the Suur Strait, runs close to Muhu Island and emerges as a bedrock groove descending to ca 30 m b.s.l. near the NW margin of the plateau-like transitional area in the NE Gulf of Riga. Passing the 20-km long SE–NW trending Suur Strait, the main channel descends to ca 50 m b.s.l. at its intersection with the Muhu depression (Figs 3, 4, 6). The depth of the shorter, about 10-km long Uisu channel, which arises near the Estonian mainland in the NE part of the strait, ranges from 20 to 35 m b.s.l. (Figs 3, 4, 6).

The Hari–Voosi branch

Compared to the Suur Strait, the more than two times broader NW branch of the Väinameri, which includes Vormsi Island that splits the northern part of this branch into the Hari and Voosi straits, discloses a more variable bedrock relief. Based on the distribution of bedrock relief altitudes and trends, the Hari–Voosi branch can be broadly divided into two sections (Figs 3, 4, 7):

1. Near the shore, slanting faintly towards the centre of the branch, there are 5–15 km wide bands, where the bedrock surface undulates largely around 10–20 m b.s.l.;
2. Deeper into the branch, extending from the Hari Strait to the Muhu depression, there is a zone with mixed channel-depression shaped, 1–10 km wide segments, where the bedrock relief falls largely 25 m b.s.l.

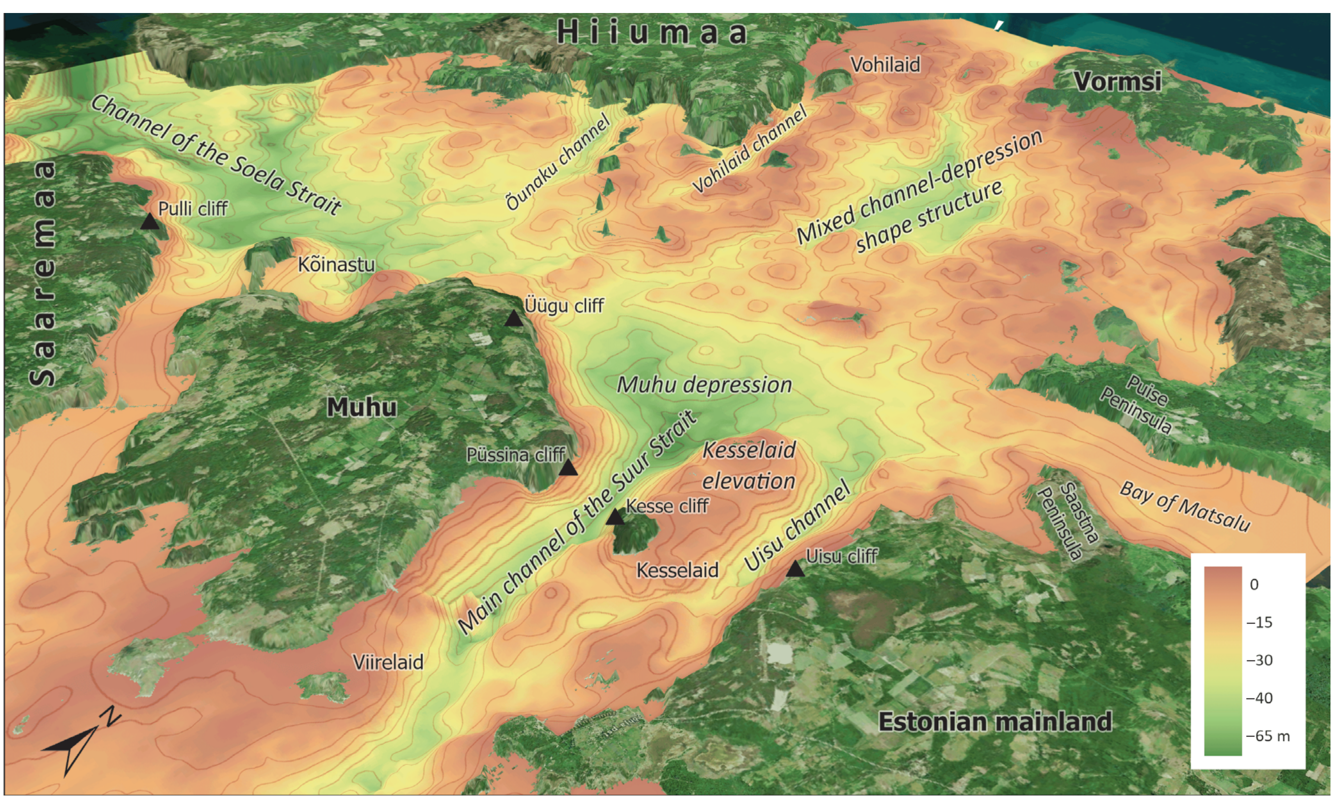

Fig. 4. 3D model of the bedrock relief, created with the ArcGIS Pro software, featuring a coloured height scale and the most prominent relief features below the Väinameri, shown in a perspective view from the SE.

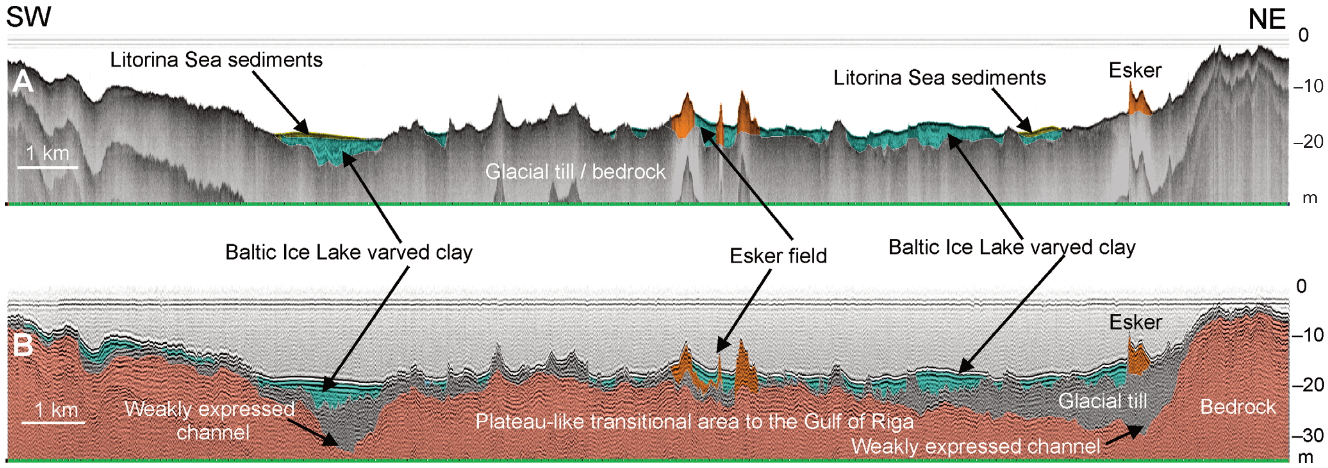

Fig. 5. Interpreted seismo-acoustic profile across the plateau-like transitional area in the NE Gulf of Riga with adjacent weakly expressed channels, recorded with the chirp-type (**A**) and boomer-type (**B**) sound transmitters. For location, see profile 1 in Fig. 2.

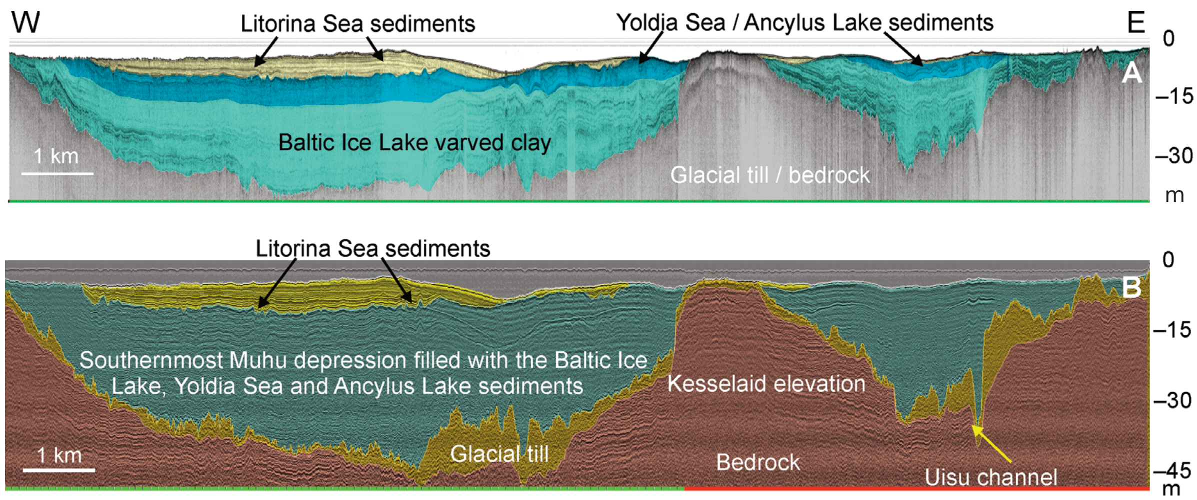

Fig. 6. Interpreted seismo-acoustic profile across the Muhu depression and the Uisu channel divided by the Kesselaid elevation, recorded with the chirp-type (**A**) and boomer-type (**B**) sound transmitters. For location, see profile 2 in Fig. 2.

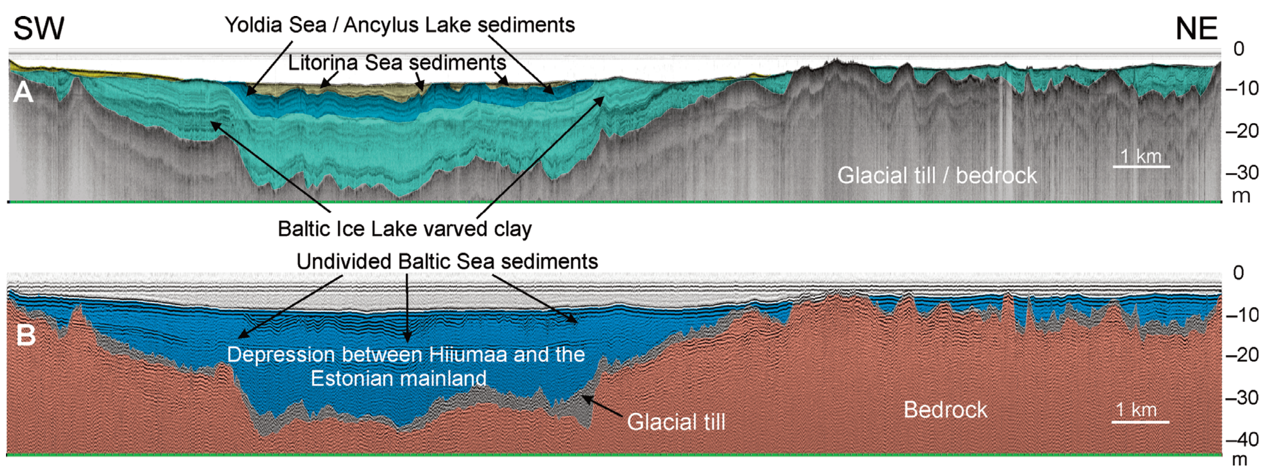

Fig. 7. Interpreted seismo-acoustic profile across the bedrock depression between Hiiumaa and the Estonian mainland in the Hari–Voosi branch, recorded with the chirp-type (**A**) and boomer-type (**B**) sound transmitters. For location, see profile 3 in Fig. 2.

However, unlike the channels in the Suur Strait, the bedrock relief along the deeper mixed-shaped zone does not steadily descend towards the centre of the Väinameri in two occasions. First, this trend overturns in the bedrock channel that passes through the Hari Strait, as the NW segment of this channel deepens towards the northern Baltic Sea (Figs 3, 4). Thus, this channel crosses the watershed area between the Väinameri and the northern Baltic Sea (Fig. 3). Second, the SE segment of this channel, descending towards the central Väinameri, broadens to up to 10 km and forms an isolated depression, dropping >40 m b.s.l. midway between Hiiumaa and the Estonian mainland (Figs 3, 4, 7). The latter depression

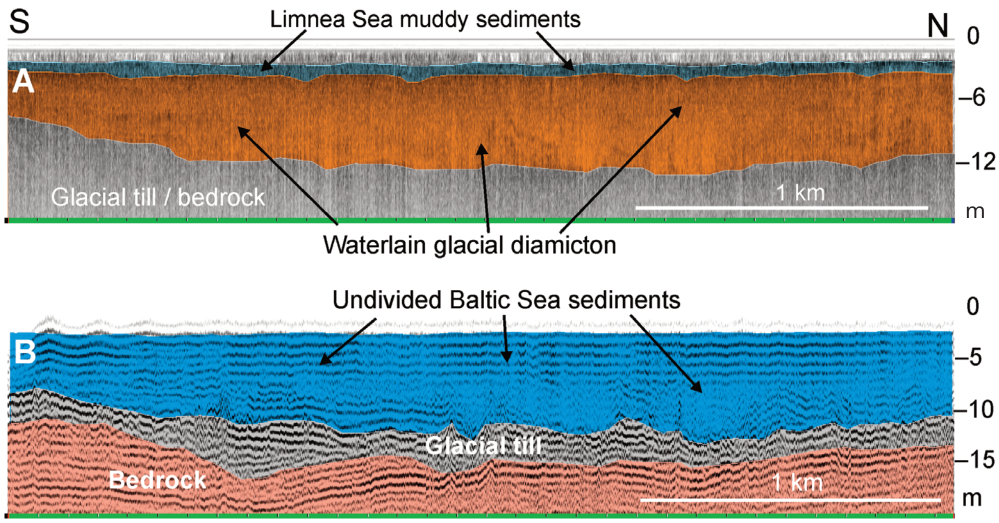

Fig. 8. Interpreted seismo-acoustic profile across the Bay of Matsalu, showing the slightly sloping bedrock surface towards the Saastna Peninsula, recorded with the chirp-type (**A**) and boomer-type (**B**) sound transmitters. For location, see profile 4 in Fig. 2.

is separated from the Muhu depression by a bedrock area, which is up to 8–10 km wide and rises to 15–25 m b.s.l., and has a hardly discernible channel-like feature (Figs 3, 4).

The Bay of Matsalu

The bedrock altitudes in the shortest and narrowest Bay of Matsalu branch, cut deeply into the Estonian mainland, remain predominantly above –20 m b.s.l. (Figs 3, 8), being thus largely similar to those typical of nearshore areas bordering other branches of the Väinameri. However, the bedrock relief section across this narrow NE–SW trending branch reveals a more profound central part slanting slightly towards the Saastna Peninsula, bordered by steeper shoreward sections (Figs 3, 4, 8). Thus, a weakly expressed channel-like feature emerges in the middle of the Bay of Matsalu that descends gradually towards the central Väinameri and opens into the Muhu depression (Figs 3, 4). Comparing the bedrock altitudes on the neighbouring peninsulas, the SE border of this channel in the proximity of the Saastna Peninsula is slightly steeper than the NW border near the Puise Peninsula (Figs 3, 4).

The Soela branch

Compared to the previously described three branches, where the bedrock relief with channels or channel-like features lowers, with a lesser or greater clarity, towards the Muhu depression in the central Väinameri, the complex NE–SW trending bedrock channel passing the Soela branch descends in the opposite direction towards the western margin of the Väinameri. The gradual descent of this channel towards the central Baltic Sea begins from an elevation several kilometres wide, rising up to –20 m b.s.l., which separates the Soela branch from the Muhu depression (Figs 3, 4). A steep, occasionally terraced narrow slope with the Silurian Klint and a gradually southwards descending rugged plateau-like area border the channel of the Soela Strait from the south and north, respectively. The latter plateau-like slope, descending from Hiiumaa towards Saaremaa, with some NW–SE trending grooves, embraces the larger part of the Soela branch.

Discussion

The likely spilling trends in water drainage scenarios

The distribution of the bedrock altitudes, their changes and trends allow tracking down the most likely water spilling trends, their accumulation sites, and thus the general drainage pattern across the different branches of the Väinameri.

In the Suur Strait branch, a vital role in water spilling is played by the transitional plateau-like area in the NE Gulf of Riga between the Estonian mainland and Saaremaa Island (Figs 2, 3). The oppositely falling channels bordering the SE and NW segments of the plateau suggest that this area acted as a watershed, dividing water drainage between the central depression of the Gulf of Riga and the main channel of the Suur Strait (Figs 3, 4). Within the Suur Strait, waters from its nearshore marginal areas and the slopes of the Kesselaid elevation spilt into the strait passing two channels, and flowed straight into the Muhu depression. Though not so explicitly expressed, water also spilt towards the Muhu depression via the Bay of Matsalu (Figs 3, 4).

Unlike in the Suur Strait, the bedrock relief trends in the Hari–Voosi branch reveal that, due to a significant central depression, there is no forthright water drainage into the Muhu depression. The presence of an up-and-down profile along the mixed channel-depression shaped zone midway the Hari–Voosi branch raises a question about the possible role of Pleistocene glaciers in reshaping the initial bedrock surface designed by pre-Quaternary rivers below the Väinameri. Above all, how and when were the significant isolated bedrock depressions along the NW–SE trending section of the Väinameri in the Hari–Voosi branch and around the very centre of the Väinameri (Muhu depression) formed? Theoretically, they might have even been of pre-glaciation origin. However, similar depressions in the bedrock, scraped by glaciers or induced by pressurised subglacial meltwaters, are a well-known phenomenon (Bennett and Glasser 2009).

The fact that both overdeepened depressions occur along the NW–SE trending section of the Väinameri, coinciding largely with the pathways of NNW–SSE advancing Pleistocene glaciers and the prevailing trend of fractured bedrock zones (Figs 2, 3), speaks in favour of their glacial origin. A few NW–SE trending elongated bedrock grooves with no apparent outlets – the Vohilaid and Õunaku channels in the Hari–Voosi and Soela branches, respectively – further point towards possible glacial erosion in this area (Figs 3, 4). Thus, the extensive isolated and overdeepened depressions below the Väinameri, lacking clear outlets, likely reflect neither the bedrock relief features nor the drainage pattern shaped by suggested pre-Quaternary rivers.

However, despite the genesis and age of similar depressions, the mixed channel-depression shaped bedrock zone lowering towards the central Väinameri with a watershed within the Hari Strait played a central role in accumulating and draining waters across the Hari–Voosi branch (Figs 3, 4). Even if the isolated bedrock depression between Hiiumaa and the Estonian mainland has a pre-Quaternary origin, it could not hamper the water spillage further towards the Muhu depression, located in the central Väinameri. Eventually, the water level in the lake, which would have evolved above the bedrock depression between Hiiumaa and the Estonian mainland, would have surpassed the altitude of the elevated section separating the Hari–Voosi branch from the Muhu depression (Figs 2, 3).

Thus, based on the outlines of the present bedrock relief, the water spilling across the Suur Strait, Hari–Voosi and Bay of Matsalu branches converged into the Muhu depression, located in the very center of the Väinameri. From there, the water drainage continued towards the Soela branch, possibly through a river or an overspilling lake if the Muhu depression indeed has a pre-Quaternary origin. The contours of the bedrock relief in the Soela branch (Figs 3, 4) prove that the southerly water spillage from Hiiumaa, flowing across the furrowed plateau-like area towards the channel of the Soela Strait near the northern coast of Saaremaa, prevailed here. This channel, separated from Saaremaa by a steep, occasionally terraced slope, lowers and clearly opens through the Soela Strait towards the central Baltic Sea.

Indicators of the asymmetrical cuesta valley

Before our mapping project, the only indications pointing towards a possible cuesta-type valley passing through the Väinameri were the terraced nearshore sections of the Silurian Klint along the northern coast of Saaremaa, rising mostly several meters above the sea. They are best developed and expressed further west beyond the Soela Strait, which limits the Väinameri and where one klint section in northern Saaremaa rises even 20 m a.s.l. The map and 3D model allowed, for the first time, to examine the submarine bedrock relief along the nearshore areas of the Väinameri, particularly the Silurian Klint sections around the Uisu, Kesse, Püssina and Pulli cliffs (Figs 2–4). All these cliffs arise as the uppermost supra-marine vertical segments within the steeply descending slope structures below the sea, bordering the most profound bedrock features, such as the main and Uisu channels in the Suur Strait, the Muhu depression, and the channel of the Soela Strait, all emerging around the central Väinameri.

In all, tracking down the NE–SW trending branches of the Väinameri, a similar steep, occasionally terraced submarine bedrock slope emerges faintly already near the Saastna Peninsula in the Bay of Matsalu. This slope becomes more accentuated at the submerged portion of the Kesselaid elevation and can be followed almost continuously along the northern coasts of Muhu and Saaremaa islands (Figs 3, 4, 9). An analogous steep slope (cuesta escarpment) at the base of the Silurian Klint, bordering a slightly SSE falling limestone plateau (cuesta plateau), is best developed below the central Baltic Sea (Tuuling and Flodén 2016).

Compared with the relatively well-defined cuesta escarpment, the outlines of the cuesta plateau below the Väinameri are weakly developed and hardly discernible. Similar to the cuesta escarpment, the cuesta plateau, with a bedrock surface sloping slightly towards the Saastna Peninsula, is only predictable below the Bay of Matsalu (Figs 3, 4, 8). Although the general southerly lowering relief from the Hari–Voosi branch to the Muhu depression is perceptible, it is highly

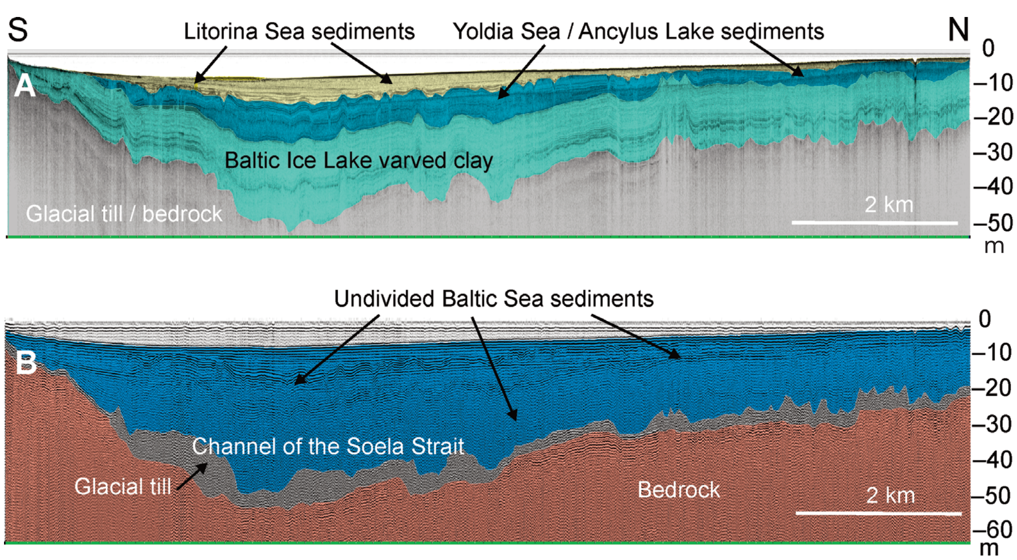

Fig. 9. Interpreted seismo-acoustic profile across the Soela branch, showing a descending cuesta plateau from Hiiumaa towards Saaremaa, the channel of the Soela Strait, and a steeply rising slope (cuesta escarpment) towards Saaremaa, recorded with the chirp-type (**A**) and boomer-type (**B**) sound transmitters. For location, see profile 5 in Fig. 2.

rugged and hardly resembles a SE falling plateau-like area (Figs 3, 4). This ruggedness supports the estimation that Pleistocene glaciers have significantly reworked the initial river-shaped bedrock relief in the Hari–Voosi branch and around the Muhu depression.

The cuesta plateau is most apparent in the Soela branch, where it emerges as a bedrock surface falling gradually from Hiiumaa towards Saaremaa, featuring a few NE–SW trending grooves (Figs 3, 4, 9). These grooves supposedly represent the beds of tributaries that once flowed into a larger stream traversing the Väinameri near the northern coast of Saaremaa. Unlike the NW–SE oriented Hari–Voosi and Suur Strait branches, the NE–SW trending Soela branch and the Bay of Matsalu were more protected from erosion caused by the SSE advancing Pleistocene ice streams, which followed the prevailing trends of linear bedrock disturbances (Fig. 2).

Conclusions

Summarising our study about the relief of the bedrock depression below the Väinameri, we conclude the following.

1. The deepest bedrock surface below the Väinameri confines into its NE–SW trending Bay of Matsalu–Soela Strait section that includes two relief features falling >60 m b.s.l.: the Muhu depression in the very centre of the Väinameri and the channel of the Soela Strait along the northern coast of Saaremaa.
2. The watersheds emerging at the NW and SE margins of the Väinameri, in the Hari–Voosi and Suur Strait branches, respectively, along with the faintly SW falling bedrock relief in the Bay of Matsalu, suggest that waters from these branches likely spilt and flowed towards the Muhu depression in the central Väinameri.
3. In the Suur Strait branch, water drainage converged into two channels gradually falling towards the central Väinameri: the main channel of the Suur Strait and the Uisu channel. These channels likely represent the beds of tributaries that flowed into the suggested larger NE–SW trending river passing through the Väinameri.
4. In the NW–SE trending Hari–Voosi branch, the initial drainage channel, eroded by a possible water stream, between the Hari Strait and the Muhu depression has possibly been reshaped by the erosion of SSE advancing Pleistocene glaciers, which created a significant isolated overdeepened depression between Hiiumaa and the Estonian mainland.
5. Pleistocene glaciers, which advanced along the Hari-Voosi and Suur Strait branches, likely also eroded the Muhu depression and thus considerably reworked the initial river valley that extends east to west across the central Väinameri, shaped by a pre-Quaternary river set.
6. Concerning the NE–SW trending cuesta valley traversing the central Väinameri, its contours are faintly discernible in the Bay of Matsalu and likely severely reshaped by Pleistocene glaciers around the Muhu depression. The outlines of the asymmetrical cuesta valley are best developed and preserved in the Soela branch, where a terraced cuesta escarpment runs along the northern coast of Saaremaa, bordering a cuesta plateau that slants faintly from Hiiumaa towards Saaremaa.
7. All in all, the drainage pattern as well as the signs of the cuesta valley emerging in the bedrock depression below the Väinameri do not contradict and rather support the suggestion of a river that, before the glacial erosion, flowed between Saaremaa and Hiiumaa and continued via the present Soela Strait further towards the central Baltic Sea.
8. Despite the conclusions that support the presence of a fluvial component imprinted into the bedrock depression below the Väinameri, with a large NE–SW trending valley traversing its central part, we have to admit that connecting these features with a pre-Quaternary Eridanos River System is still highly hypothetical. This is because the altitudes of the klint bases in the East Gotland Basin, up to 150 m b.s.l., occur far below the expected reach of fluvial erosion (Hall and van Boeckel 2020).
9. On the other hand, there are many reasons why the klint escarpments and the buried bedrock valleys in Estonia are interpreted as pre-Quaternary river-sculptured landforms. Both the Baltic and Silurian klints are divided into alternating sections with plummeting klint scarps tens of meters high, dissected by large and deep indentations or troughs (the so-called klint bays) with heavily eroded and levelled klint scarps. If the indentations are heavily crushed and eroded by southerly advancing lobes of Pleistocene glaciers, then the walls of the plummeting klint scarps reveal almost no signs of glaciotectonic activities, as we would expect from southerly advancing bulldozing and scraping glaciers or ice sheets. The rare tectonic dislocations in the klint wall are instead caused by the significant linear zones of disturbances, representing the flexural bends in the platform cover and having their roots in the basement faults (Tuuling 2017).
10. The significant valley-like, occasionally distinctive river set resembling overdeepened incisions with varying orientations in the Estonian bedrock (the buried valleys) are still poorly studied. Their morphology and distribution pattern, with a watershed-like area in central Estonia, supports the idea that these deep bedrock incisions, reworked by glaciers, rest on some palaeo-river set. However, as already pointed out above, both the klints and the buried bedrock valleys need further studies with more profound discussions on the possible role of pre-Quaternary rivers and Pleistocene glaciers in eroding these remarkable relief forms in the platform cover of Estonia.

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Väinamere, Lääne-Eesti arhipelaagi jääva Läänemere keskosa madalveelise haru aluspõhja reljeef

Igor Tuuling, Sten Suuroja, Anu Veski, Markus Ausmeel, Martin Liira ja Kalle Suuroja

Aastatel 2019–2022 aset leidnud geoloogilise kaardistamise käigus kaeti Lääne-Eesti arhipelaagi jääv Väinameri korrapärase seismo-akustiliste profiilide võrguga. Saadud andmestik võimaldas esimest korda kontuurida Suure väina aluspõhja reljeefi ning kontrollida varasemat, kaudsetele andmetele tuginevat oletust, et Väinamerd läbib Matsalu lahe Soela väina sihis kulgev pleistotseeni jäätumise eelne jõeorg.

Ordoviitsiumi–siluri kivimitesse erodeeritud Väinamere aluspõhja nõo põhijooned tulevad ilmekalt esile nii aluspõhja reljeefi kaardil kui ka 3D-mudelil. Piltlikult kahest ristuvast, NW–SE ja NE–SW orientatsiooniga segmendist koosnev Väinamere aluspõhja nõgu jaguneb nelja ilmakaarde suunduvaks haruks: SE ehk Suure väina haru, SW ehk Soela haru, NW ehk Hari–Voosi haru ning NE ehk Matsalu lahe haru. Väinamere aluspõhja nõo sügavaim osa jääb Matsalu lahe Soela väina harude joonele, kus tuleb esile kaks merepinnast enam kui 60 m madamale laskuvat struktuuri: Muhu nõgu ja Soela väina vagumus.

Suure väina, Hari–Voosi ja Matsalu lahe harude aluspõhja reljeefi ning neis esinevate reljeefivormide kõrguste leviku ja muutustrendide detailsem analüüs näitab, et kõigis neid harudes langeb reljeef Väinamere keskossa jääva Muhu aluspõhja nõo suunas. Erandina laskub Soela harus aluspõhi piki selle Saaremaa-poolsesse külge jäävat Soela väina vagumust Väinamerd läänest piiritleva Soela väina poole. Selline aluspõhja reljeefi üldpilt kinnitab, et piki Väinamere NW, NE ja SE harusid laskuvad veed koondusid esmalt madalama reljeefiga Läänemere keskossa, kust need valgusid piki Soela haru voolanud jõge edasi lääne poole. Sellise põhifooni taustal tekib aga küsimus, millise päritoluga on kaks ulatuslikku, isoleeritud, otsese väljavooluta aluspõhja nõgu: Muhu nõgu Väinamere keskmes ja Hiiumaa ning Eesti mandriosa vahele jääv nõgu Hari–Voosi harus. On tõenäone, et nimetatud, NW–SE sihis paiknevad nõod ei peegelda pleistotseeni jäätumise eelsete vooluvete toimel kujunenud aluspõhja struktuure, vaid on tekkinud Väinamerest NNW–SSE sihis üle liikunud liustike erosiooni, ennekõike nende alla tekkinud survelise sulavee kulutaval toimel. Seega viitab aluspõhja reljeef sellele, et Väinamerd läbib pleistotseenieelsel ajal tekkinud NE–SE sihiline jõeorg, mille jätkumist lääne suunas tõendab Läänemere keskosas, Siluri klindi ees esile tulev kuesta tüüpi jõeorg. Asümmeetrilise kuesta tüüpi jõeoru elemendid – järsk kuestanõlv ja lauge kuestaplatoo – ilmnevad selgelt ka Väinamerd läbiva jõeoru juures. Siluri klindi jalam ehk Väinamere alla laskuva kuestaorundi järsk nõlv tuleb ilmekalt esile piki Muhumaa ja Saaremaa põhjarannikuid, samas kui laugelt SSE sihis laskuva kuestaplatoo kontuurid tulevad esile Soela harus Hiiumaa ja Saaremaa vahel.

Vaatamata sellele, et Väinamere aluspõhja reljeefis ilmneb pleistotseeni jäätumise eelse jõe/jõevõrgu erosiooniline komponent, jääb endiselt lahtiseks selle seostamine kvaternaarieelsel ajal (miotseenis) Rootsi idaranniku lähedal voolanud Eridanose ja selle lisajõgede võrgustikuga, kuna Siluri klint ja klindi jalam jäävad Läänemere keskosas tunduvalt madalamale tolleaegsest arvatavast erosioonibaasist. See tekitab aga küsimuse Eesti aluspõhja märkimisväärsete reljeefivormide, klindiastangute ja mattunud orgude geneesist ning tekkeajast, mille täpsustamine eeldab edasisi uuringuid.