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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

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Abstract. Bedrock relief with the basics (subdivision and thickness) of the overlying Quaternary sequence was studied by means of seismo-acoustic profiling beneath the Suur Strait in the West Estonian Archipelago. Reaching ca 15–20 m below sea level (b.s.l.) in the watershed area in the NE corner of the Gulf of Riga, the bedrock surface beneath the strait drops along two channels, divided by the islet of Kesselaid rising ca 15 m above sea level (a.s.l.), into a large depression more than 60 m b.s.l. in the interior of the Väinameri. A similar setting indicates that the low-lying bedrock surface between the Estonian mainland and the islands of Muhu and Saaremaa was formed by combining erosions of preglacial river(s) and Pleistocene glaciers. The large depression NW of the islet of Kesselaid possibly represents a section of an east-west running preglacial river, heavily reworked by Pleistocene glaciers. Although supported by preliminary data from the Soela Strait, the latter opinion still needs additional profiling between the islands of Hiiumaa and Saaremaa. The thickness of the Quaternary sequence around the strait follows the general height and ruggedness of the bedrock surface; it is occasionally missing in the nearshore bedrock plateaus (submarine alvars) and reaches ca 50 m in the depression NW of Kesselaid.

Keywords: Bedrock relief, Quaternary sequence, West Estonian Archipelago, Suur Strait, Silurian Klint.

INTRODUCTION

The bedrock relief around the Baltic Shield–East European Platform transect has numerous major and minor striking features. However, being buried under Quaternary sediments and inundated in large areas by the Baltic Sea, this rugged bedrock surface with its outstanding individual relief entities remains largely unnoticed. The most prominent feature is undoubtedly the bedrock depression concealed beneath the Baltic Sea, with its branching northern gulf sections (Bothnia, Finland and Riga). The most eye-catching relief entities onshore are obviously the preglacial terraced escarpments emerging in the platform cover, the Baltic and the Silurian klints, which besides picturesque coastal sections in Estonia and Sweden exhibit an excellent cuesta-relief on the seafloor beneath the central Baltic Sea (Tuuling and Flodén 2001, 2016; Tuuling 2017).

Alongside the conspicuous klint scarps towering more than 50 m above the sea, the unevenness of the bedrock relief in Estonia becomes occasionally evident in the present river valleys. Following the ancient valleys, cut deep into the platform cover, the modern rivers exhume preglacial incisions from the soft Quaternary cover, exposing bedrock walls, in places tens of meters in height. However, the Pleistocene glaciers have mainly moulded the final shape of the present bedrock surface. Besides general erosion and levelling, the advancing glaciers often reworked (deepened, enlarged and flattened) former preglacial incisions and klint escarpments. All in all, based on the drillings, the highest bedrock level in Estonia (166 m a.s.l. in the Haanja elevation) exceeds its lowest measured value (143 m b.s.l. in the Harku and Abja buried valleys) by more than 300 m, whereas the thickest penetrated Quaternary sequence (207 m) occurs in the Abja buried valley (Tavast and Raukas 1982).

Unlike the mainland, where bedrock is reached by more than 5000 boreholes and thus its relief is reasonably well mapped (Tavast and Raukas 1982), the knowledge about the bedrock surface in the Estonian submarine territories is still rare and chaotic. Most of the marine geological studies performed offshore have focused on the bottom sediments (Lutt 1985; Lutt and Raukas 1993). The primary method of studying the lithological boundaries beneath the seafloor, seismo-acoustic profiling, has enabled tracing of bedrock surface only in suitably deep waters further off the Estonian coast (Lutt and Raukas 1993; Tuuling and Flodén 2001, 2016). The high noise ratio, induced by pulse ringing multiples, has hampered tracing the contact between the bedrock and the incumbent Quaternary sediments in the shallow-marine areas.

Equipped with various modern seismo-acoustic devices mountable on a trailer-movable boat, the Estonian Geological Survey launched geological mapping of Estonian nearshore territories in 2019. For the first time, the applied seismo-acoustic equipment enabled widespread tracing of the bedrock surface in the shallow-marine areas. The Suur Strait in the West Estonian Archipelago (Fig. 1) was chosen as a pilot study area due to a possible bridge/tunnel construction across this water divide. This paper outlines the submarine bedrock relief and generalises the basics of the Quaternary sequence between the Estonian mainland and the islands of Muhu and Saaremaa in the West Estonian Archipelago (Fig. 1).

STUDY AREA

A group of four larger islands (Saaremaa, Hiiumaa, Muhu and Vormsi) and numerous smaller islets emerging from the Baltic Sea offshore West Estonia form the West Estonian Archipelago (Fig. 1A). The islet-rich water expanse that separates the Estonian mainland from its two largest islands, Saaremaa and Hiiumaa, and opens through narrow passages northwards/westwards into the northern/central Baltic Sea and southwards into the Gulf of Riga, is called Väinameri (Fig. 1A). As suggested by its name (Väinameri – “Sea of Straits” in English), there are numerous straits separating individual islands and islands from the mainland in the West Estonian Archipelago (Fig. 1). Dissecting the Estonian mainland from Muhu Island, the Suur Strait (“Big Strait” in English) forms the south-eastern branch of the Väinameri that continues southwards to the NE corner of the Gulf of Riga squeezed between the Estonian mainland and the Kübassaare Peninsula protruding from Saaremaa (Fig. 1). Towards the north, the Suur Strait opens into the interior of the West Estonian Archipelago, where the Väinameri branches into its northern (between the mainland and Hiiumaa), western (between Saaremaa and Hiiumaa) and eastern (deep into the continent indented by the Bay of Matsalu) sections.

Our study area is a water span of about 35 km long and 6–20 km wide, embracing the Suur Strait with the adjacent NE corner of the Gulf of Riga and the nearby segment in the interior of the Väinameri (Fig. 1). This area includes two larger (Kesselaid and Viirelaid) and several smaller groups of islets (NW of Kesselaid and the Virtsu Peninsula). These minor land patches, surrounded by non-navigable shallow water, interrupt the continuity of the profiling and dissect the seismo-acoustic profiles into numerous shorter and longer sections.

METHODS AND DATA

Different types of seismo-acoustic sound transmitters (boomer, chirp, pinger) with various frequency spans were run simultaneously by using Meridata Ltd.’s *software MD DSS Multi-Mode Sonar System* to maximise the information from the sub-bottom sediments and rocks. In summers 2019–2021, the SE–NW elongated study area was covered by an orthogonal set of slightly NW–SW oriented seismo-acoustic lines 1 km, in places even 500 m apart (Fig. 1B). Besides that, several profiles with varying azimuths and lengths were run lengthways in the study area.

The boomer-type sound transmitters “C-Boom” and “Sig-France” were run in 2019 and in 2020/2021, respectively, at 400 voltage and 0.5–2 kHz frequency span using *Meridata Collecting software ver. 5.2*. An 8-element hydrophone streamer “C-Phone” received the reflected signal. To minimise the propeller noise of the boat engine, both the transmitter and receiver were run 20 m behind the boat, moving at a speed of about 4 knots.

A low-frequency transducer Model T335 by Neptun Sonar Ltd. was used to generate a seismo-acoustic impulse with a chirp-type sound source. The generated pulse trigger interval, length and delay were 250 ms, 0.3 ms and 0 ms, respectively. The sample rate and the trace length of the receiver were 20 kSPS and 150 ms, respectively. The adjusted waveform parameters at maximum (100%) power were the following: start frequency 9.6 kHz, end frequency 2.4 kHz and pulse length 3 ms.

The acoustic signal reflected from the geological boundaries was digitally recorded in the boomer (BMR) and chirp (CHP) files that were later processed (pulse parameters), interpreted and exported to an XYZ data file using *Meridata Processing software ver 5.2*. In calculating the depth of the basement surface, the estimated average velocities of the seismo-acoustic pulse in the seawater, in the Quaternary sediments above and within the glacial till layer were 1500 m/s, 1650 m/s and 1750 m/s.

The sound pulse induced by a chirp-type transmitter with a resolution of ca 10 cm usually penetrated only the soft Baltic Sea sediments (Fig. 2A). With a boomer-type transmitter, the expected maximum resolution in the layered Baltic Sea sediments reached 20 cm (Fig. 2B). However, in order to penetrate the basal layer of the

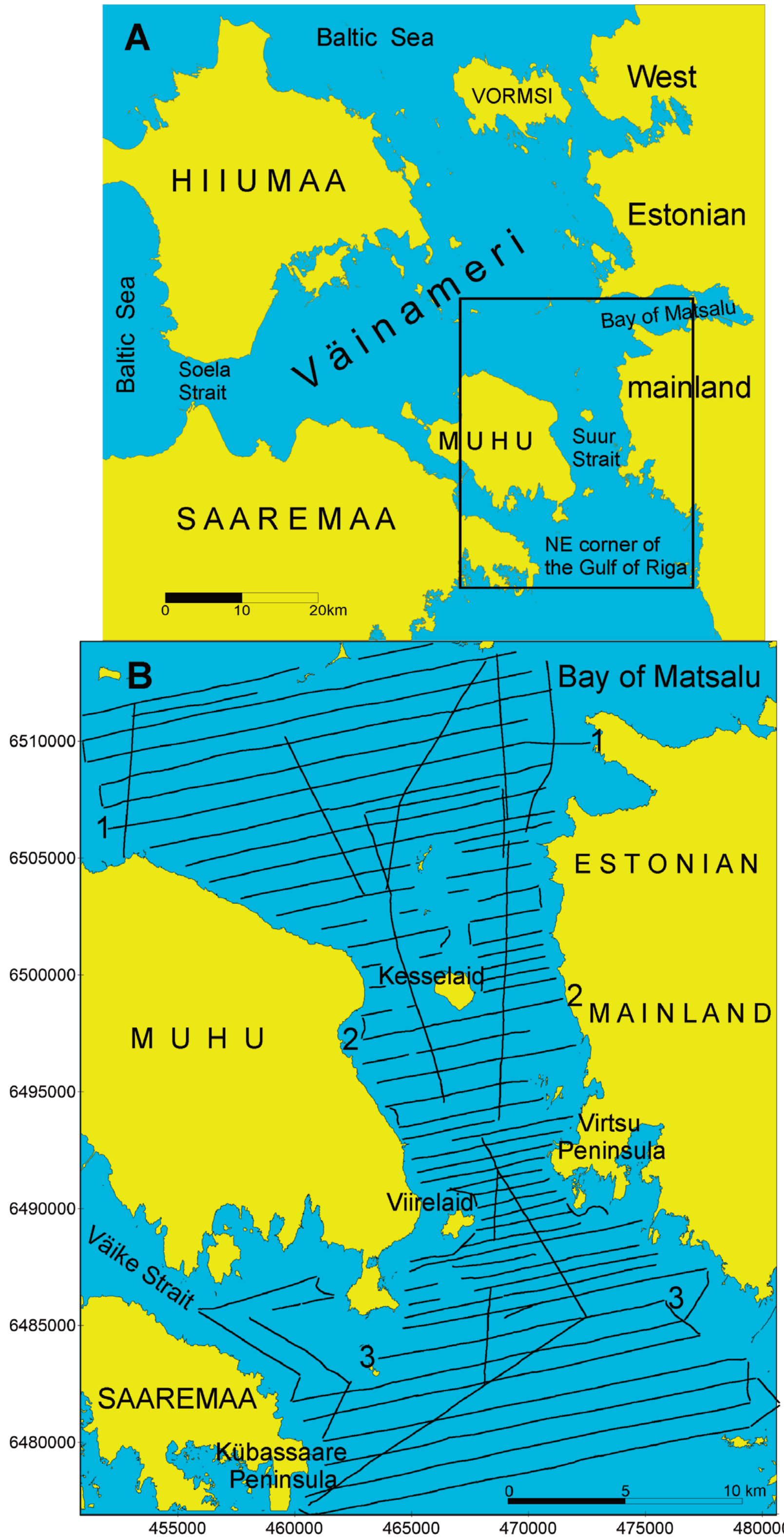

Fig. 1. (A) Väinameri in the West Estonian Archipelago with the framed study area; (B) Enlarged study area (marked with the Estonian Coordinate System 1997-EPSG:3301), showing the set/sections of the seismic lines providing bedrock surface data used in the compilation of the maps and 3D model (Figs 4, 5, 10). Numbered profiles 1–3 indicate locations of the seismic lines shown in Figs 2, 7, 8.

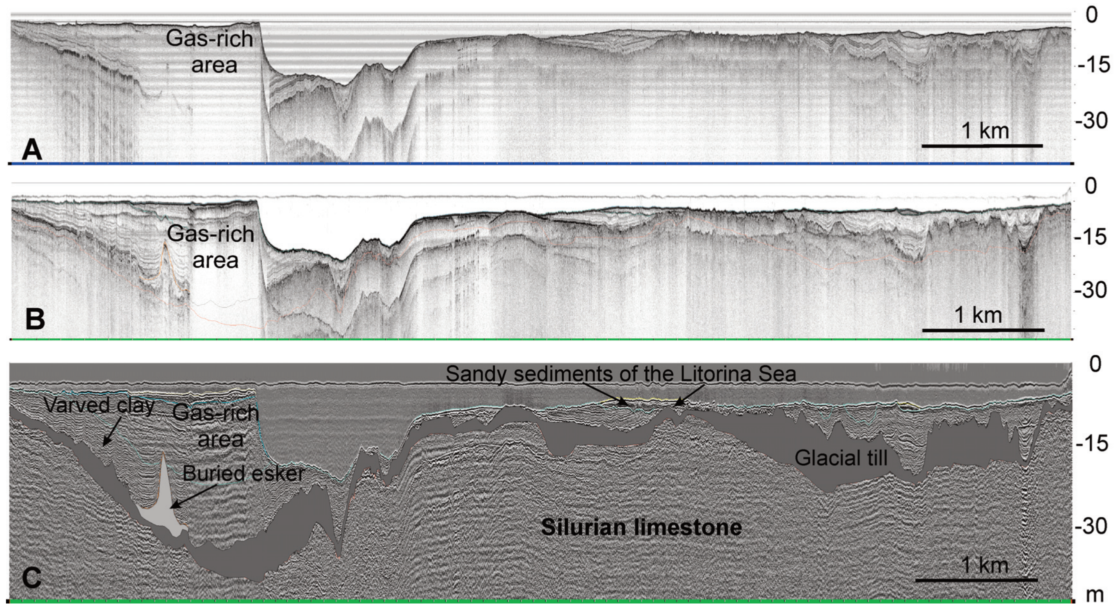

Fig. 2. Examples of the recordings of a profile south of Kesselaid (Profile 2 in Fig. 1B) based on the different seismo-acoustic sound sources and pulse frequencies: (A) – high-frequency chirp, (B) – boomer with the full frequency band and (C) – boomer with the filtered high-frequency portion. For interpretation of this profile, see Fig. 7B.

Quaternary sequence, the compact Lateglacial till, which overlies the bedrock in broad areas, the boomer sound pulse was filtered (to cut off its high-frequency spectrum) before interpretation (Fig. 2C). Exceptionally, due to the gas-rich Quaternary sequence, which is impenetrable for the seismo-acoustic pulse, some sections of the profiles W–NW of Kesselaid (Figs 1B, 2) did not yield any data on the bedrock, and thus on the thickness of the glacial till layer. The bedrock relief and the thickness of the Quaternary sequence are mainly based on the data generated by a boomer-type sound source, while the high-frequency chirp recordings were useful for subdividing and characterising the Baltic Sea sediments above the glacial till (Fig. 2).

BEDROCK RELIEF

Taking into consideration the thicknesses/attitudes of different Silurian stratigraphic units exposed on the surrounding mainland and the depth of the bedrock surface beneath the sea, the erosional cut between the Estonian mainland and the islands of Muhu and Saaremaa reaches the easily erodible clayey limestones and marls of the Raikküla (Nurmekund Formation), Adavare (Rumba and Velise formations) and Jaani stages (Jaani Formation) (Fig. 3). Exceptionally, in the areas of a high-seated bedrock, i.e. within the nearshore strips, around the Kesselaid elevation and in the NE corner of the Gulf of Riga, the cut in the bedrock terminates in the dolomitised reef limestone of the Jaagarahu Stage (Muhu Formation). The Rootsiküla (Sakla Formation) and Paadla (Paadla Formation) stages are exposed around the southernmost margin of our study area (Fig. 3).

The low-frequency spectrum of the boomer-induced sound pulse enabled to identify the bedrock surface along most of the performed profiles except for a small gas-rich area immediately W–NW of Kesselaid (Figs 1B, 2). The bedrock relief map and 3D model (Figs 4, 5) were compiled based on the generated XYZ database using the *Golden Software Surfer ver. 12*. To facilitate the description of the 3D model, appropriate colour scales were applied for different height ranges to accentuate the main trends and features of the bedrock relief beneath our study area.

The bedrock depth in the area covered by the seismo-acoustic profiles (Fig. 1B) varies from 5 to 60.9 m b.s.l. However, as the bedrock rises gradually towards the mainland, in many places its surface forms a shallow seafloor near the coastline. Based on the depth of the bedrock and dominating relief features with the orientation of their isolines, our study area can be broadly divided into three sections (Figs 4–6):

(1) The highest and widest – a bowl-shaped plateau in the NE Gulf of Riga between Saaremaa and the Estonian mainland (Figs 4, 5, 6B);
(2) The narrowest – the Suur Strait squeezed between the Estonian mainland and Muhu Island, dominated by

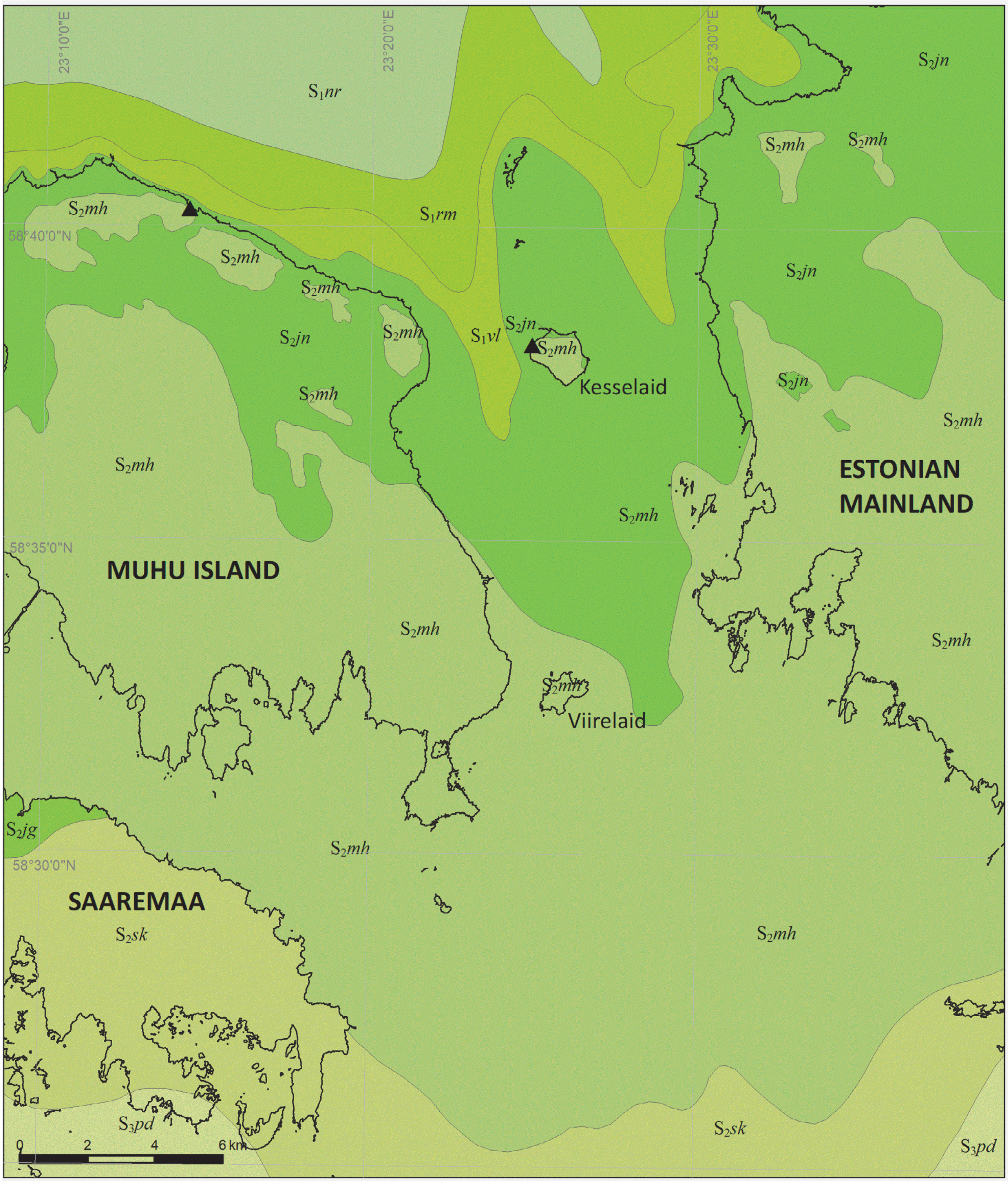

Fig. 3. Geological map of the Suur Strait with adjacent onshore areas. Indexes mark the following Silurian formations: S_{1nr} – Nurmekund Formation, S_{1rm} – Rumba Formation, S_{1vl} – Velise Formation, S_{2jn} – Jaani Formation, S_{2mh} – Muhu Formation, S_{2jg} – Jaagarahu Formation, S_{2sk} – Sakla Formation, S_{3pd} – Paadla Formation.

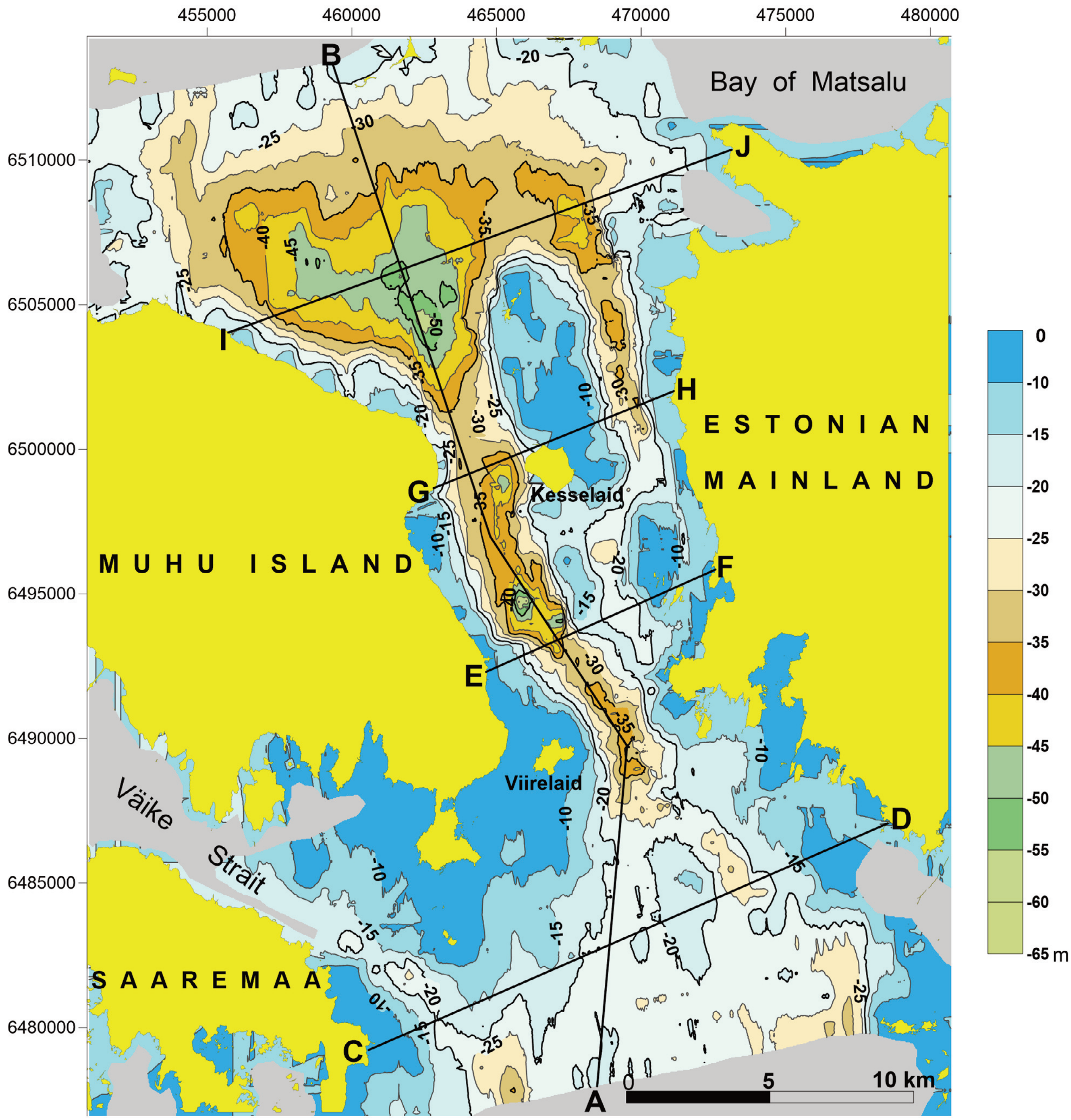

Fig. 4. Bedrock relief map of the study area with lines of the cross-sections shown in Fig. 6.

two channels descending towards the central part of the Väinameri divided by an elevation around the islet of Kesselaid (Figs 4, 5, 6C, D);

(3) The deepest – a depression (part of a more significant depression/channel?) around the Suur Strait–interior Väinameri transect between the northernmost part of Muhu Island and the Estonian mainland with the Bay of Matsalu (Figs 4, 5, 6E).

Despite significant differences, the bedrock relief in the nearshore areas has mainly similar architecture, both along the Estonian mainland and the islands of Saaremaa and Muhu. Close to the coastline, the bedrock mostly starts with a strip having a flattened or slightly undulating surface (Fig. 6B–E). This strip might become hardly distinguishable along the western coast of the Suur Strait when a large channel gets very close to Muhu Island

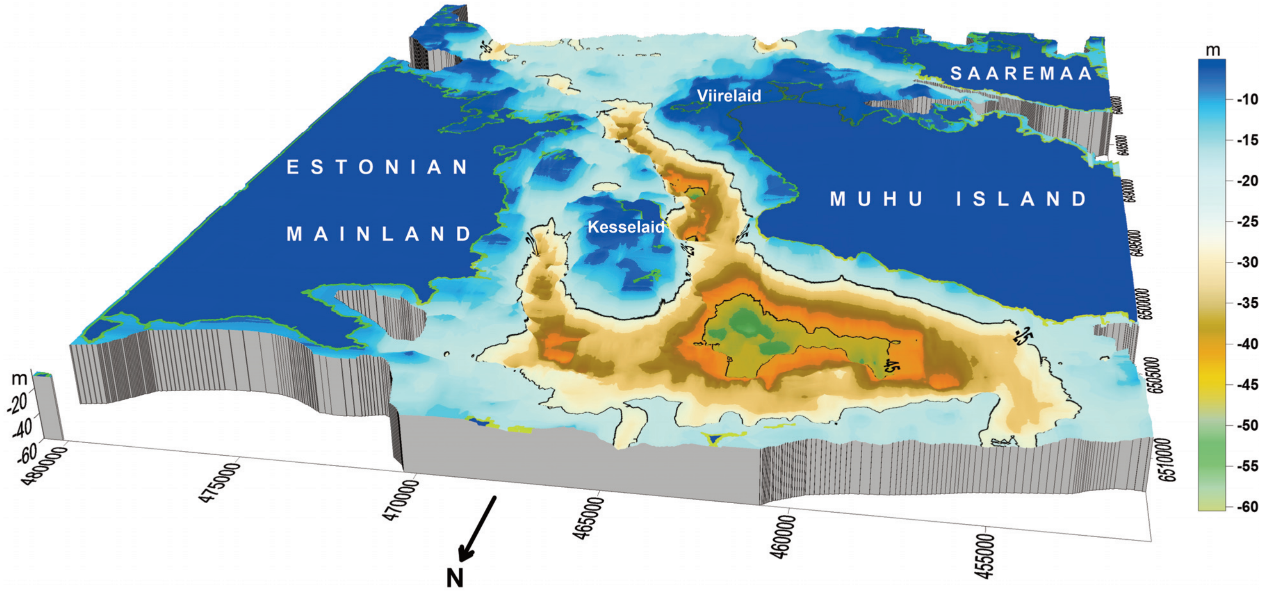

Fig. 5. Perspective look at our study area from the SSW (interior of the Väinameri) depicted on the bedrock relief model showing a depression NW of Kesselaid, channels in the Suur Strait divided by the Kesselaid elevation and a high-seated concave watershed plateau in the NE corner of the Gulf of Riga.

(Fig. 6C, D). Further off the coast, these flattened strips become sloping sections (Fig. 6), the tilt and width of which depend on the specific characteristics of the bedrock relief (amount of erosion, ruggedness, depth values, etc.) in the most eroded central part of the study area (Figs 4–6).

The NE corner of the Gulf of Riga between the Estonian mainland and the north-easternmost corner of Saaremaa

The Gulf of Riga inundates a vast depression carved mainly by Pleistocene glaciers. The bottom of the gulf with the underlying bedrock surface descends from the surrounding mainland alongside a thickening Quaternary sequence towards the central deep of the gulf around Ruhnu Island (Tsyrulnikov et al. 2008, fig. 2). The coring data combined with the seismo-acoustic profiling proved that about 30–35 km south of Saaremaa the bedrock surface, overlain by ca 40 m thick Quaternary sequence, drops about 50 m b.s.l. (Tsyrulnikov et al. 2012). However, in the NE corner of the Gulf of Riga, the bedrock surface lowers towards the Väinameri, i.e. in the opposite direction (Figs 4–6). Thus, the submarine area flanked by the SE corner of Saaremaa and the Estonian mainland likely represents a former preglacial watershed between the present Gulf of Riga and the Väinameri. In fact, signs of a possible watershed area appear already at the southernmost margin of our bedrock relief map. The contours which delimit the S–SE descending valleys emerge in the Väike Strait (“Small Strait” in English) that separates the islands of Saaremaa and Muhu, as well as the nearby Estonian mainland (Figs 4, 5, 6B).

Following the depth isolines on the map (Fig. 4) and the height distribution in the profile (Fig. 6B), the bowl-shaped bedrock profile in the north-easternmost corner of the Gulf of Riga is divided into three portions:

(1) The above-described flattened narrow strips along the coasts of Saaremaa and the Estonian mainland;
(2) The more extensive plateau-like section in the central part with a slightly undulating bedrock relief;
(3) The sloping transects between these two smoothed areas giving the bedrock surface between Saaremaa and the Estonian mainland a concave configuration (Fig. 6B).

The depth of the bedrock within the nearshore levelled margins, generally descending towards the central plateau, reaches about 10–15 m b.s.l. (Fig. 4). The width of this mainland bordering zone remains primarily within 3–5 km. However, southeast of Muhu Island and around the islet of Viirelaid, where the sloping section is very vaguely developed or virtually missing (Fig. 4), the nearshore levelled area extends up to a 10 km broad Viirelaid plateau. The sloping transect reaching the central plateau covers mainly the depth span of 10–20 m b.s.l. and is in the southernmost part of our study area on both sides of the strait, mostly a few km to 5 km wide (Figs 4, 6B). However, the sloping section narrows towards the

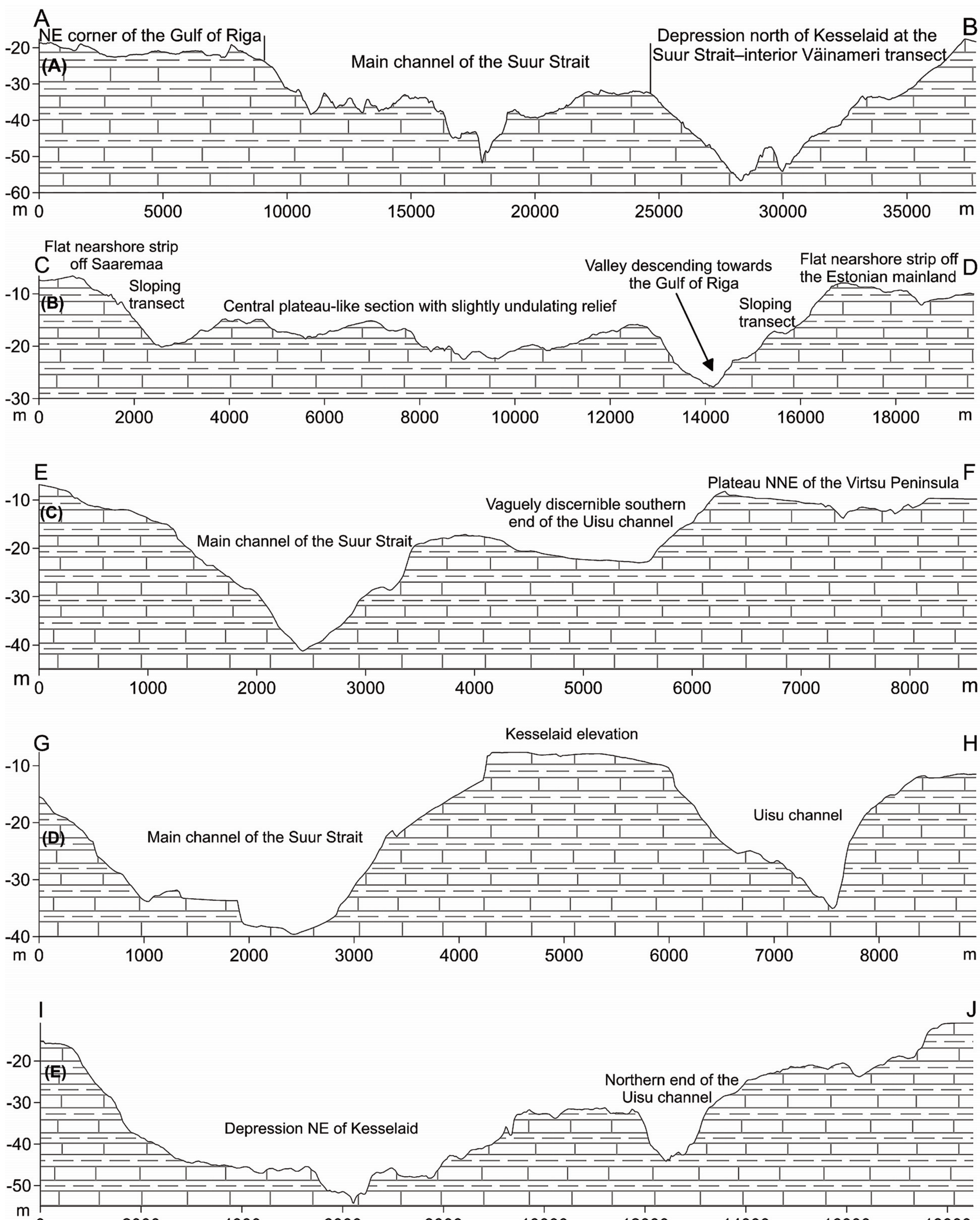

Fig. 6. Cross-sections of the bedrock relief showing the main relief features in different parts of our study area. For locations of the profiles, see Fig. 4.

Väinameri, and its width drops below 1 km at the Gulf of Riga–Suur Strait transect.

Within the central plateau, the bedrock surface undulates largely at around 20 m b.s.l. (Figs 4, 6B). However, at the southern border of our study area, where valleys descending towards the Gulf of Riga emerge along its margins, the bedrock surface in the central plateau drops >30 m b.s.l. (Figs 4, 6B). The width of the central plateau, reaching ca 12–15 km near its broadest southern margin, decreases rapidly northwards where the plateau, about 2–3 km wide, eventually transfers to the main channel of the Suur Strait (Figs 4, 5, 6A).

The Suur Strait

The Suur Strait has the most rugged and rapidly varying bedrock relief (Figs 4, 5, 6C, D). The width of its levelled or slightly undulating nearshore margins, drawn along the –15 m isoline, remains mostly below 1 km; however, around Viirelaid and north of the Virtsu Peninsula it may exceed 4–5 km or become hardly distinguishable off Muhu Island in the northern part of the strait (Figs 4, 6C, D). The bedrock relief in the middle of the Suur Strait is dominated by two SE–NW trending channels descending towards the interior of the Väinameri, separated by an elevation around the islet of Kesselaid (Figs 4, 5, 6C, D). These channels gradually widen towards the northern border of the strait and are smoothly transformed, alongside the declining Kesselaid elevation between them, into a depression, indenting from the interior of the Väinameri to the Suur Strait (Figs 4, 5, 6E).

The larger main channel passes through the Suur Strait and is more than 20 km long. Its southern end at the Gulf of Riga–Suur Strait transect is more clearly outlined along the –25 depth isoline, in the middle of the strait about 5–6 km SE of Viirelaid (Fig. 4). However, a few kilometres NE of Viirelaid, this channel bends towards the NW and continues close to the eastern coast of Muhu Island. Beyond the islet of Kesselaid, the main channel retreats from the NW bending coastline of Muhu Island, widens and merges gradually with the depression at the Suur Strait–interior Väinameri transect. Along the –15 m depth isoline, the width of the main channel extends slightly more than 2 km in its narrowest southern part, reaches up to 3 km for most of its middle section and widens up to 6 km right before dropping into the deepest (>60 m b.s.l.) point of the depression NW of Kesselaid. Although the main channel generally lowers towards the Väinameri, it has a few locally isolated deepened sections (Figs 4–6A). Limited depths in the bedrock relief gauged by the pressure of the subglacial waters are a well-known phenomenon (Bennett and Glasser 2009). However, an elevated section of the main channel directly NW of Kesselaid (Figs 4–6A) may be due to the lack of gridding data, as around this area the sound pulse of the boomer did not penetrate the gas-rich Quaternary sequence (Figs 1, 2).

The vague contours of a smaller channel (called the Uisu channel after a bedrock cliff onshore) emerge along the –20 depth isoline directly NW of the Virtsu Peninsula, where it delimits the 3–4 km wide Virtsu plateau with a slightly undulating bedrock relief on the mainland side of the strait (Figs 4, 5, 6C). However, about 2–3 km SE of Kesselaid, this channel turns towards the mainland, starts to deepen and continues close to the northeastern coast of the Suur Strait (Figs 4, 5, 6D). Thus, the contours of the Uisu channel along the –25 m depth isoline are more sharply outlined first NW of Kesselaid, i.e. in the northern part of the Suur Strait. As a result, the length of the northerly descending section with a depth exceeding 25 m b.s.l. is more than twice shorter at the Uisu channel compared with the main channel (Fig. 4). The vaguely formed southern section of the Uisu channel is less than 1 km wide. Its deeper and sharper northern section (measured along the –15 m depth isoline) is about 2 km wide near Kesselaid and broadens up to 5 km right before the Uisu channel drops into the depression at the Suur Strait–interior Väinameri transect.

The bedrock elevation between the Uisu and the main channels reaches its maximum height, about 15 m a.s.l., on the islet of Kesselaid. The Kesselaid elevation is best outlined along the –15 m depth isoline, whereas its shape becomes particularly distinctive and accentuated NW of Kesselaid, where the channels delimiting the elevation reach their maximum depth (Fig. 6D). South of Kesselaid, where the distance between the channels shortens considerably and the Uisu channel is very vaguely developed, the contours of the Kesselaid elevation disperse and its precise outlining becomes impossible. Measured along the –15 m depth isoline, the SE-NE trending Kesselaid elevation is about 9 km long and up to 3.5 km wide at its most extensive section NW of Kesselaid (Fig. 4).

The depression at the transition from the Suur Strait to the interior of the Väinameri

The depression shared by the Suur Strait and the interior of the Väinameri covers the northern part of our study area. In fact, the interior of the Väinameri embraces only the northern slope of this depression, dropping from 20 down to 45 m b.s.l., as its deepest portion remains clearly within the Suur Strait between Muhu Island and the Estonian mainland (Figs 4, 5, 6E). The deepest values occur around its southern border, where the depression transfers to the main channel (>60 m b.s.l.) and the Uisu channel (>40 m b.s.l.) of the Suur Strait. However, the preliminary mapping data suggest that the depression at the transition between the Suur Strait and the Väinameri

(Figs 4, 5, 6E) is likely a part of a longer E–W trending channel/valley passing through the Väinameri. Namely, a few seismo-acoustic profiles from the Soela Strait (Fig. 1A) reveal that an even deeper depression emerges further west between Hiiumaa and Saaremaa. Moreover, this depression resembles an asymmetrical cuesta valley; the cuesta plateau slanting southwards from Hiiumaa ends with a scarp (or system of scarps) along the northern coast of Saaremaa. Thus, the depression at the Suur Strait–interior Väinameri transect may represent a section of this cuesta valley heavily reworked by southerly advancing Pleistocene glaciers.

Quaternary sediments

A detailed seismo-acoustic study combined with a sampling of the Quaternary sequence using a 6-m-long Kullenberg corer was performed by a Swedish–Estonian team in 2004 about 50 km south of our study area in the middle of the Gulf of Riga (Kalm et al. 2006; Tsyrulnikov et al. 2012). Based on the descriptions of the corings, a generalised lithostratigraphic section was compiled and juxtaposed with the nearby seismo-acoustic recordings. The established seismo-acoustic-lithostratigraphic correlation scheme (see fig. 2 in Tsyrulnikov et al. 2012) enabled to follow the distribution and thicknesses of different Quaternary units in the seismo-acoustic recordings across large areas. The seismo-acoustic signature from the central part of the Gulf of Riga mainly coincides with that of our study area. Thus, the same correlation scheme was applied, and the same Quaternary units were distinguished around the Suur Strait.

Thickness and subdivision

The bedrock is overlain by a compact layer of Lateglacial till throughout the study area (Figs 7, 8). However, occasionally the till is missing within the nearshore shallow-marine limestone plateaus, where the thickness of this unit decreases to zero. The maximum thickness of

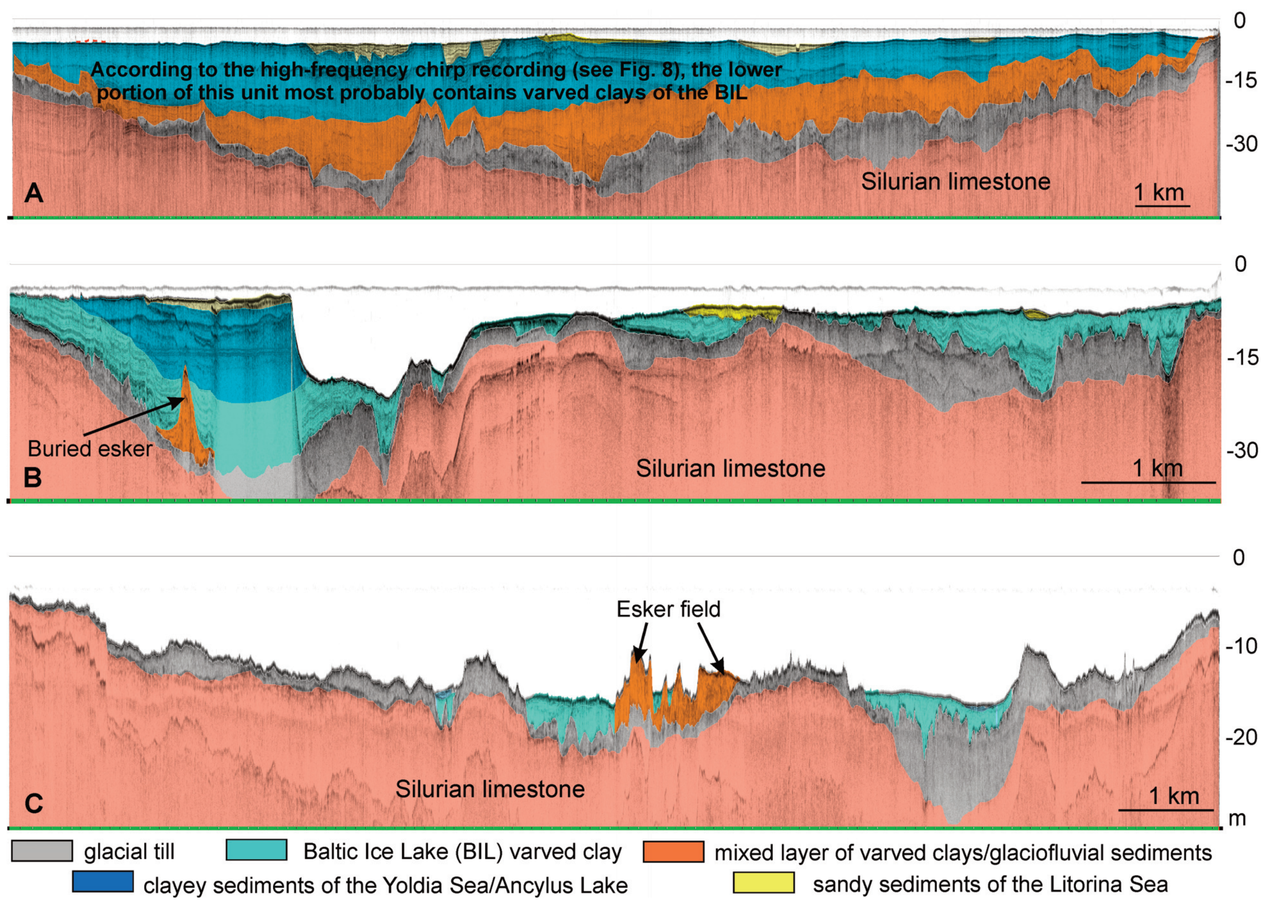

Fig. 7. Interpreted boomer-type seismo-acoustic profiles from the northern (A), middle (B) and southern (C) parts of our study area (for the locations, see profiles 1, 2, 3 in Fig. 1B, respectively). For the location of the esker field in profile C, see rectangle B in Fig. 9.

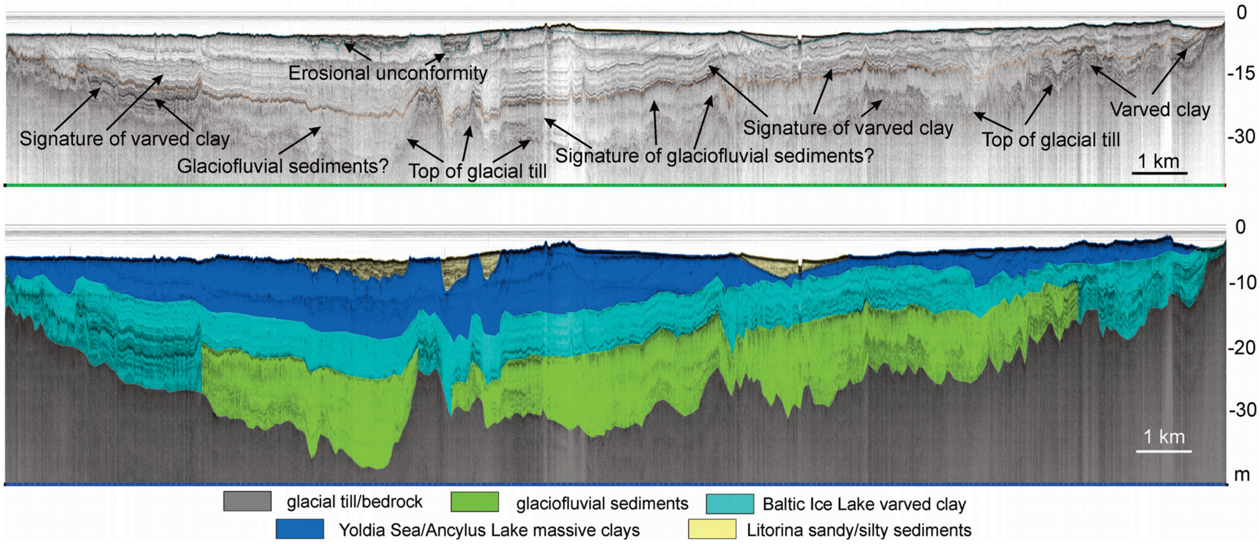

Fig. 8. High-frequency chirp recording NW of Kesselaid (for the location, see profile 1 in Fig. 1B) shows varying/mixed seismo-acoustic signatures in the layer overlying the till. Signature of massive or weakly layered sediments (outwash of the glaciofluvial sediments?) is occasionally mixed/replaced and covered with the fine-layered sections/patches (Baltic Ice Lake varved clays).

the till can reach 15 m in larger bedrock depressions (Fig. 7B, C). Further off the coastline, the till layer is overlain by the varved clays of the Baltic Ice Lake (Fig. 7). The latter unit crops out widely within the NE corner of the Gulf of Riga, where its thickness varies from zero to 5 m around the highest and the lowest areas of the undulating glacial till surface, respectively (Fig. 7C). Around the Suur Strait, the thickness of the varved clays increases significantly due to the general deepening and increasing ruggedness of the bedrock relief and the till surface. Its thickness increases gradually towards the deepening bedrock channels of the strait and a large depression NW of Kesselaid (Fig. 7B, C). As the exact upper boundary of the varved clays in the seismic recordings is ambiguous, its estimated thickness in the areas covered by the younger sediments of the Yoldia Sea and Ancylus Lake exceeds slightly 20 m (Fig. 7B).

Along with the accumulation of the varved clays, glaciofluvial sediments with eskers or esker fields were occasionally formed around the Suur Strait. In several profiles traversing the large depression NW of Kesselaid, the layer of the glacial till between Muhu Island and the Bay of Matsalu becomes overlain by a unit, the seismic signature of which is atypical for the varved clays (Figs 7A, 8). Thus, instead of a fine-layered reflector-rich unit, a massive sequence of unlayered/unsorted sediments arises around the northern half of this significant bedrock depression. Still, in high-frequency chirp profiles, patches with very weak indications of layering do occasionally emerge within this unit that decreases in thickness and is replaced towards the mainland by a typical signature of the varved clays (Fig. 8). Furthermore, this massive unit is buried under the finely layered varved clay sequence (Fig. 8). Considering the bedrock relief, the mixed unit of the varved clays/glaciofluvial sediments covers the northern slope of the depression NW of Kesselaid, i.e. where this depression transfers to the northern branch of the Väinameri. The latter branch was obviously one of the main pathways of the southerly advancing Late Weichselian glaciers (Karukäpp 2004; Tsyrulnikov et al. 2008). The limited distribution, the massive internal structure and its coevalness with the varved clays of Baltic Ice Lake suggest that this massive reflector-free unit likely represents some kind of glaciofluvial outwash deposited in a former bedrock depression, eroded in front of a northerly retreating glacier.

Significant eskers/esker fields emerge around our study area in two districts. A buried esker that arises in a seismic line between Kesselaid and Muhu Island (Figs 2, 7B) continues southwards in four successive profiles. This esker's 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 (Figs 7C, 9). As most of these eskers crop out on the seafloor, their emergence in a detailed sea bottom multibeam map is striking (Fig. 9A–D). The length of these eskers remains within the limits of 1 km, as their height rarely exceeds 10 m.

The massive, vaguely laminated clayey sequence above the varved clays distinguishes the combined Yoldia Sea/Ancylus Lake unit (Figs 7, 8). This unit occurs mainly in the areas with sufficiently deep bedrock values north

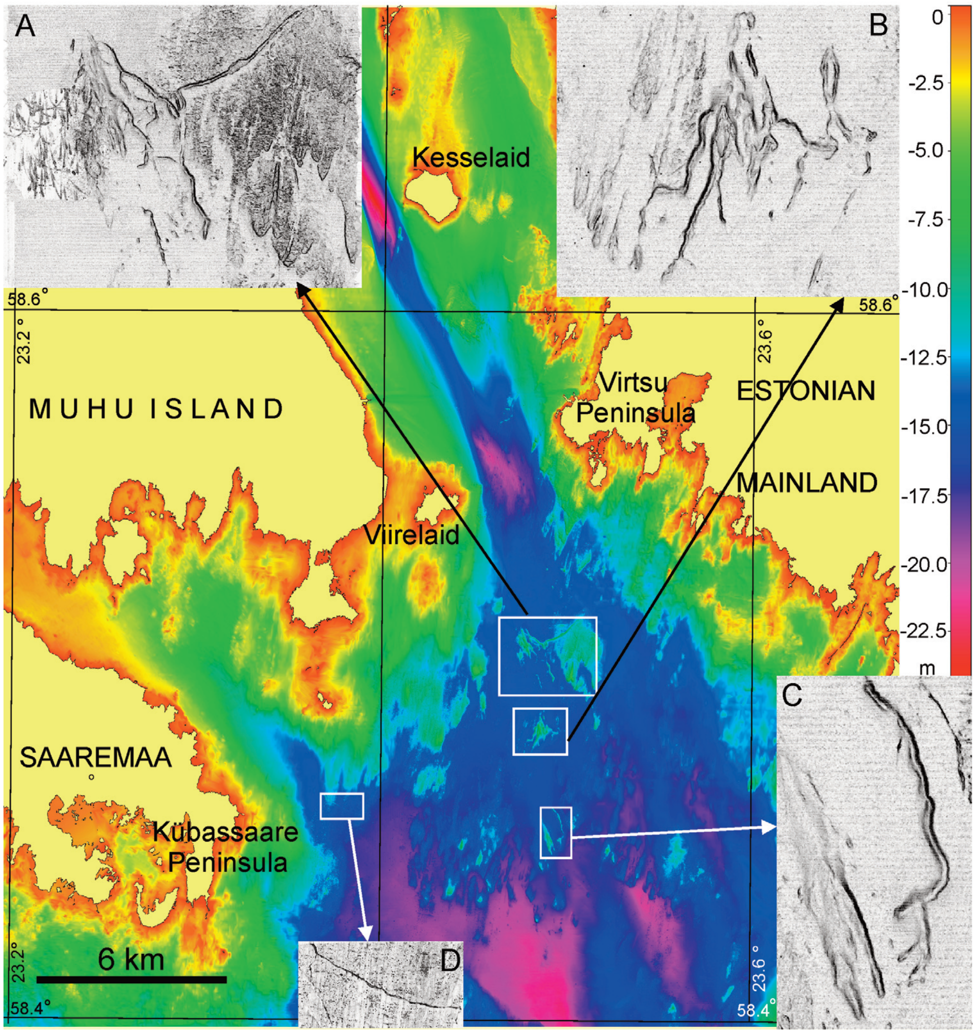

Fig. 9. Eskers/esker fields (with enlargements) exposed on the bathymetry map of the NW corner of the Gulf of Riga. The map/enlargments were compiled by the Estonian Maritime Administration using the multibeam technique.

of Viirelaid. The Yoldia Sea/Ancylus Lake sediments constitute, alongside the Baltic Ice Lake varved clays, a substantial part of the deposits filling up and levelling the bedrock channels in the Suur Strait and the large depression NW of Kesselaid. The estimated thickness of this unit above the deepest bedrock areas can occasionally exceed 15 m. In the northernmost part of the study area, around the depression NW of Kesselaid, a distinct unconformity surface appears in some places in the uppermost Quaternary sequence (Figs 7, 8). According to the study on the Gulf of Riga (Tsyrulnikov et al. 2012), this erosional surface marks the upper boundary of the Yoldia Sea/Ancylus Lake unit that underlies a silty/sandy sequence with clayey interlayers of the Litorina Sea. The thickness of the latter unit remains mainly within a few meters, occasionally reaching slightly >5 m.

The general thickness of the Quaternary sequence

The thickness map of the Quaternary sequence around the Suur Strait (Fig. 10) reveals that the amount of the amassing sediments is directly dependent on the available accumulation space determined by the general depth and ruggedness of the underlying bedrock surface. Thus, as the sediments produced were constantly shifting towards negative topography features such as depressions, valleys, channels, furrows, etc., the thickness map of the Quaternary sediments of the study area (Fig. 10) largely follows the outlines of the underlying bedrock relief map (Fig. 4). The thickness of the Quaternary sequence in the high-seated areas with less rugged relief remains predominantly below 5 m. Such thickness prevails in the nearshore flattened areas and plateaus, covers most of the

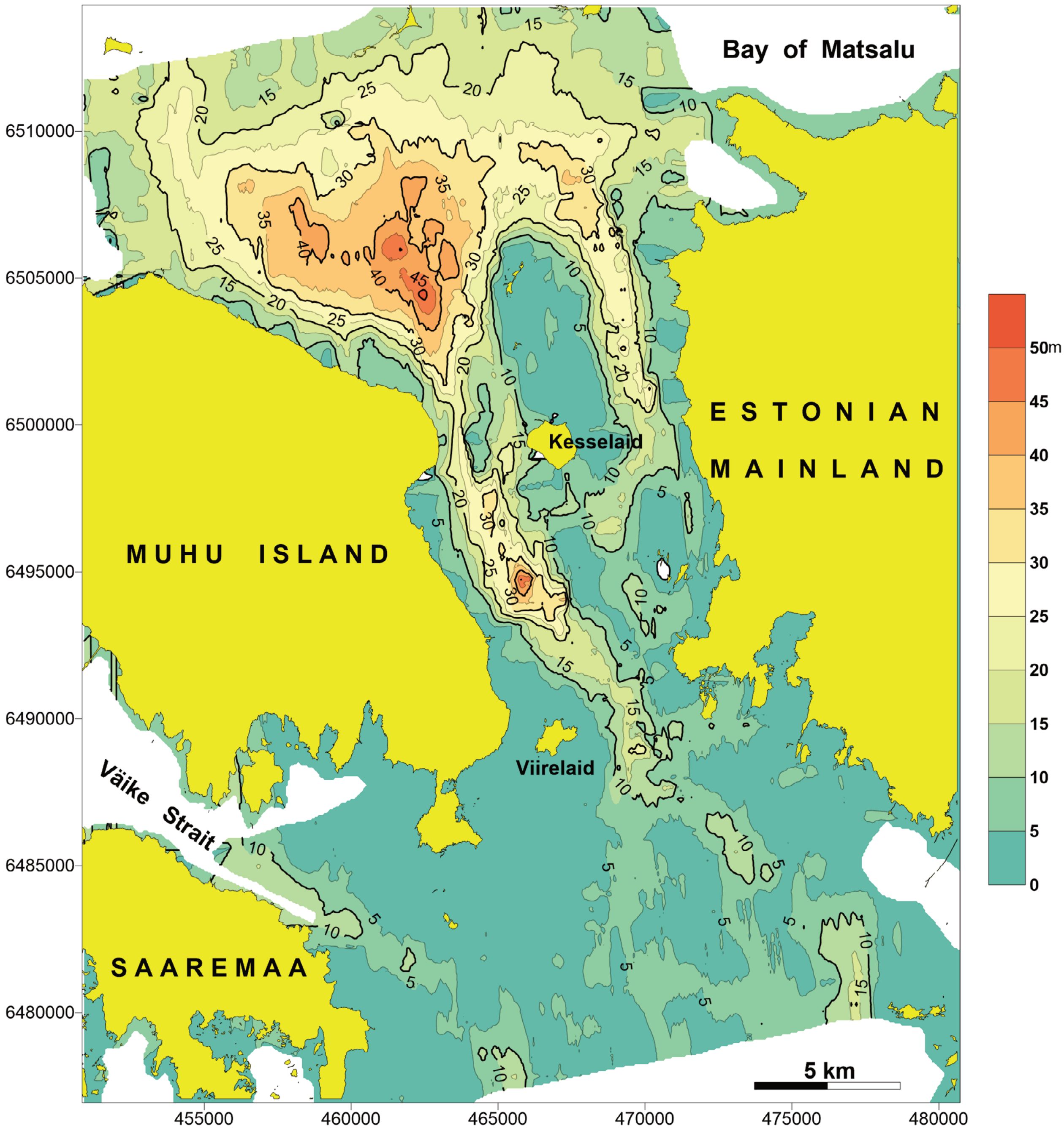

Fig. 10. Thickness map of the Quaternary cover.

Kesselaid elevation and is widespread in the NE corner of the Gulf of Riga. The distribution of the Quaternary sequence with a thickness of more than 5 m is primarily confined to the elongated channels/valleys and depressions in the central/northern part of the study area. A similar picture emerges faintly in the NE corner of the Gulf of Riga, where a 5 m isopach delimits the above-described valley-like features around the Väike Strait and along the margins of its central plateau (Figs 4, 6B, 10). However, the role of the rugged and low-lying bedrock relief in accumulating the sediments throughout the Quaternary period is very sharply accentuated within the channels in the Suur Strait and the depression NW of Kesselaid. They are all excellently outlined in the thickness map of the Quaternary sequence (Fig. 10). Towards the bottom of the channels the Quaternary sequence reaches a thickness of 30 m, and in the main channel of the Suur Strait occasionally even 40 m. However, the thickest Quaternary sequence, ca 50 m, is observed in the area where the main channel of the Suur Strait enters the depression NW of Kesselaid (Fig. 10).

DISCUSSION

In general, having Ordovician/Silurian limestone cores, the islands and many islets of the West Estonian Archipelago represent supramarine land patches dissected from the Estonian mainland by a complex pattern of bedrock relief. So far, almost nothing has been known about the bedrock relief, its features beneath the Väinameri. Still, many authors have supported the hypothesis of a deep preglacial buried valley running beneath the Bay of Matsalu and between Hiiumaa and Saaremaa, a westerly continuation of the present valley of the Kasari River (Kvasov 1975; Tavast and Raukas 1982, fig 42; Tuuling 2017). One of the main reasons for such a prediction were the cliffs of the Silurian Klint that occasionally emerge around the Suur Strait and along the northern coast of Saaremaa. The continuation of the Silurian Klint beneath the central part of the Baltic Sea, where it represents a steeper bank of an asymmetrical cuesta valley, suggests that the river passing through the Väinameri is only a section of a large tributary of the Eridanos, which once ran along the Swedish east coast (Overeem et al. 2001; Tuuling and Flodén 2016; Tuuling 2017). For verifying this concept, the Suur Strait along with the adjacent Väinameri section is one of the critical areas, and the knowledge about the nature of its bedrock relief is of paramount importance.

The map of the bedrock relief (Fig. 4) reflects the outlines of the preglacial landscape scenery around the Suur Strait, reworked to a lesser or greater extent by Pleistocene glaciers. The southerly advancing glaciers that repeatedly crossed this area adjusted their pathways to the former bedrock relief, often preferring the existing river valleys. Similar adjustments are particularly well accentuated at the remarkable preglacial klint escarpments and are best revealed at the Baltic Klint along the North-Estonian coast. Deep into the mainland penetrating notches in the Baltic Klint, klint bays according to Tammekann (1940), are mostly former river valleys widened by glaciers (Tuuling and Flodén 2016). This is probably also the case around the Suur Strait, which once embedded a preglacial river running from the watershed area around the NE corner of the Gulf of Riga towards the depression NW of Kesselaid. The rapidly rising southern slope of the latter depression towards the northern branch of the Väinameri (between Hiiumaa and the Estonian mainland) hampers the possible northwards course of this river. According to the preliminary bedrock depth data from the Soela Strait, the river that followed the main channel of the Suur Strait seems to be more likely a tributary of a larger east-west running stream. Glacier erosion created a significant bedrock depression at the confluence of these two rivers (that became partly filled with glaciofluvial sediments) and the picturesque cliff sections around the northernmost part of the Suur Strait (Muhu Island, Kesselaid and Uisu).

CONCLUSIONS

Characterising the bedrock relief and Quaternary sediments around the Suur Strait, we conclude the following:

1. The bedrock depression/channel separating the Estonian mainland from the islands of Muhu and Saaremaa has been formed by combined erosion of a preglacial river and Pleistocene glaciers.
2. Following the general depth and ruggedness of the bedrock relief, the submarine area between the Estonian mainland and the islands of Muhu and Saaremaa is divided into three sections: (1) The high-seated (15–20 m b.s.l.) and least rugged NE corner of the Gulf of Riga, (2) The Suur Strait – dominated by two large channels (where the bedrock drops in places down to 50 m b.s.l.) separated by the Kesselaid elevation (with the highest point of ca 15 m a.s.l.), (3) The deepest area around the significant depression NW of Kesselaid, where the Suur Strait transfers to the interior of the Väinameri and the bedrock surface drops below 60 m b.s.l.
3. The less rugged NE corner of the Gulf of Riga between Saaremaa and the Estonian mainland forms a preglacial watershed area in the bedrock relief that separates the Väinameri from the Gulf of Riga.
4. The bedrock channels beneath the Suur Strait most probably represent former preglacial river valleys that ran from the high-seated watershed area in the NW corner of the Gulf of Riga to a vast bedrock depression in the interior of the Väinameri.
5. The large depression NW of Kesselaid, in the interior of the Väinameri, is likely a part/section of a larger east-west running channel, a former preglacial riverbed, which has been heavily reworked by the erosion of Pleistocene glaciers.
6. Additional data are needed from the northern (between Hiiumaa and mainland), and particularly from the eastern (Bay of Matsalu) and western branches (Soela Strait) of the Väinameri to verify the existence of an extensive buried valley between Hiiumaa and Saaremaa.
7. The Quaternary sequence overlying the bedrock consists of widely spread Lateglacial till and occasionally emerging glaciofluvial sediments and eskers.

8. The varved clays of the Baltic Ice Lake and the vaguely laminated massive clays of the Yoldia Sea/Ancylus Lake stages represent the sediments of the Baltic Sea, which are essentially filling up and levelling the unevenness of the underlying bedrock relief.
9. The occurrence of the sandy/silty sediments of the Litorina Sea, resting on a striking unconformity surface, is limited to a deeper bedrock area around Kesselaid and the depression north of it.
10. The total thickness of the Quaternary sequence follows the underlying bedrock relief, reaching ca 50 m at the deepest point of the depression NW of Kesselaid.

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Aluspõhjareljeefi ning Kvaternaari settekompleksi põhijooned Mandri-Eesti ning Muhumaa ja Saaremaa vahelisel alal Lääne-Eesti Arhipelaagis (Väinameres)

Igor Tuuling, Sten Suuroja ja Markus Ausmeel

Geoloogilise kaardistamise käigus kaeti Muhu- ja Saaremaa ning Mandri-Eesti vaheline Väinamere osa regulaarsete seismo-akustiliste profiilide võrguga, mis võimaldas esmakordselt kontuurida Suure väina aluspõhjareljeefi. Liivi lahe kirdesopp Saaremaa ja Mandri-Eesti vahel kujutab jäätumise eelset veelahkme ala, mille keskmes suuresti 15−25 m sügavusel paiknev aluspõhi laskub läbi Suure väina Väinamere keskosa suunas. Sealset aluspõhjareljeefi ilmestavad kaks põhjasuunas langevat orundit, mida eristab nende vahele jääv Kesselaidu ümbritsev kõrgendik. Kogu väina läbiv üle 20 km pikkune peaorund jääb selle Muhupoolsele küljele, samas kui mandrile lähemal paikneva poole lühema Uisu orundi kontuurid tulevad selgemalt esile alles väina põhjaosas. Mõlemad orundid laskuvad Kesselaiust loodesse jäävasse ulatuslikku nõkku, kus aluspõhi langeb ca 60 m merepinnast madalamale. Tuginedes esialgsetele seismoakustiliste profileerimiste andmetele laskub aluspõhi sellest nõost lääne pool, Hiiumaa ja Saaremaa vahel, veelgi sügavamale. Hiiumaalt Saaremaa suunas laskuv ning Saaremaa põhjaranniku ümbruses astangutena kerkiv aluspõhjareljeef sarnaneb asümmeetrilisele kuestaorundile. See lubab oletada, et Väinamere keskosa läbis jäätumise eelsel ajal ulatuslikum ida-läänesuunaline jõeorund, mille osa on ka Kesselaiust loodes paiknev ning Pleistotseeni liustike poolt süvendatud aluspõhja nõgu. Suure väina alused orundid on algselt ilmselt olnud Matsalu lahe Soela väina sihis kulgenud suurema

jäätumise eelse jõe lisaharud, mida hiljem on süvendanud või laiendanud Pleistotseeni liustikud. Lõplikuks tõestamiseks on vaja teha täiendavaid uurimisi nii Soela väinas kui ka Matsalu lahes.

Kvaternaariaegsete setete paksus uuritaval alal järgib suuresti aluspõhjareljeefi, olles suurem negatiivsete orundite ja nõgude kohal ning küündides Kesselaiust loodesse jäävas nõos ligi 50 m sügavusele. Suurema osa negatiivseid pinnavorme täitvatest setetest moodustavad Balti Jääjärve viirsavid (paksus kuni 20 m) ning Joldiamere ning Antsülusjärve massiivsemad savikad setted (kuni 15 m). Kesselaiu ümbruses tuleb Kvaternaari settekompleksi ülaosas kohati esile selge katkestuspind, mille peal lasuvad Litoriinamere liivakad setted (kuni 5 m). Paiguti esineb uuritaval alal glatsiofluviaalseid setteid, oose ja oosistikke.