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INFLUENCE OF THE BEDROCK TOPOGRAPHY ON OIL SHALE MINING IN NORTH-EAST ESTONIA

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According to the zonation of the Estonian bedrock topography, presented on the basis of relative and absolute heights and taking into consideration the lithological composition of the bedrock, Estonian oil shale deposit is located in the Viru-Harju Plateau including the Pandivere Elevation and Ahtme Eminence. The plateau has a thin Quaternary cover, mainly a few metres in thickness. The oil shale basin is dissected by linear structures and ancient buried valleys, which complicate oil shale mining. The buried valleys are eroded into the commercial oil shale beds and serve as natural boundaries between mining and exploration fields. Ancient buried valleys were mainly formed in the Late Paleogene when the Earth's crust was much higher than at present due to the riftogenesis in the North-Atlantic region. They were overdeepened in the Pleistocene by glaciers. Probably, some valleys are glacial in origin. There are seven bigger valleys (Loobu, Haljala, Selja, Kunda, Pada, Purtse and Vasavere) located in the study area. The valleys contain big reserves of building sand and gravel, and high-quality underground water. Tectonic features, human impact and karst phenomena play an essential role in the formation of the chemical composition of water, especially at local and regional scales.

Introduction

The handling of oil shale mining with minimum losses and in the most efficient way is a complicated task and needs serious scientific generalisations. Most of the Baltic Oil Shale Basin, covering an area of ca 50 000 sq km, is situated in North-East Estonia with part of it extending eastward into Russia. The whole basin is intersected by ancient buried valleys and structural disturbances [1] (Fig. 1). Joint zones are often karstified. Even the dead tectonic structures as joints are highly conductive to the denudation and dissolution processes. However, it should be mentioned that the direction

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and formation of buried valleys has not been influenced by main flexural disturbances as seen in Fig. 1.

The buried valleys in the Viru-Harju limestone plateau are eroded deeply into the commercial oil shale beds and serve as natural boundaries between different mining and exploration fields [2]. Based on buried valleys, the Estonia oil shale basin was divided into the western, central and eastern parts (Fig. 1).

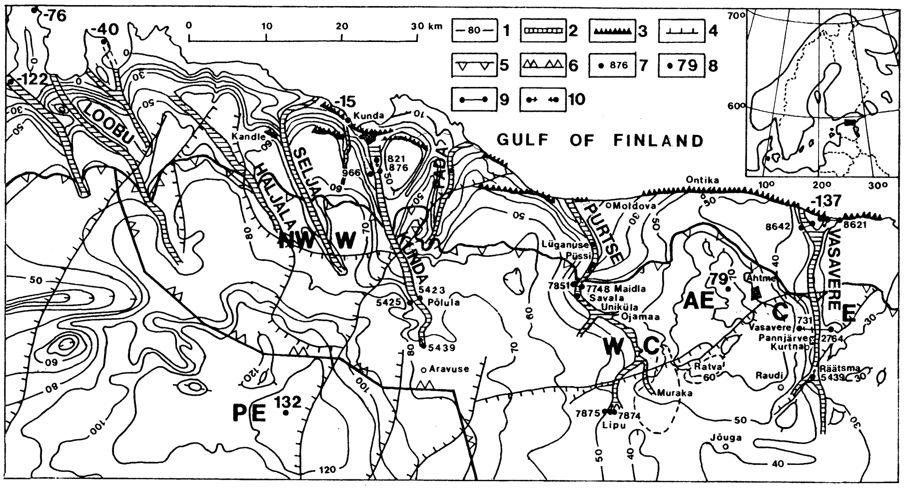


Fig. 1. Bedrock topography of NE Estonia. Legend: 1 – contour on top of bedrock, interval 10 m, 2 – buried valley, 3 – klint, 4 – flexure above a basement fault, 5 – up-dip limit of the oil shale seam, 6 – southern boundary of the mine fields, 7 – borehole, 8 – borehole and bedrock altitude, 9 – location of the cross section, 10 – location of the longitudinal section.
PE – Pandivere Elevation, AE – Ahtme Eminence. Parts of the Estonian Oil Shale Deposit: NW – north-western, W – western, C – central, E – eastern.
Data from the Institute of Geology at Tallinn University of Technology and Geological Survey of Estonia.

As a consequence of gravity and magnetic interpretations, E. Pobul and H. Sildvee [3] came to the conclusion that in Estonia old faults subdivide the Precambrian basement into a considerable number of blocks, part of which were re-activated in the cratonic stage of the development of Earth`s crust. According to Sildvee and Miidel [4], the recent local movements, as established by repeated levelling data, are frequently related to older fault zones. In other cases, recent movements appear to have developed quite independently of older structures.

Ancient valleys in the bedrock vary in depth and morphology. The valley slopes can be very gentle (up to 10^o), gentle (10–15^o), steep (15–20^o) or very steep (more than 20^o). In all North-Estonian valleys traces of glacial erosion are observable, because during the Pleistocene glaciations these valleys were oriented in the direction of the ice movement. For the most part, the valleys are 0.3–1.5 km wide and sometimes (Vasavere valley) more than 100 m deep. The contemporary river drainage is supposedly inherited from the ancient pre-Quaternary fluvial system [5]. The ancient valleys on the limestone plateau are filled with deposits of different genetic types, mainly glaciofluvial (32.4%) and glaciolacustrine (29.4%). Till (23.1%) covers the bottommost part of the valleys. Holocene deposits (15.1%) form the surficial layers [6].

Main outlines of the bedrock topography

The Estonian bedrock topography is cuesta-like and more complicated in southern Estonia. The maximal amplitudes of absolute heights of the bedrock surface are close to those of the modern topography, being lowest in the ancient valleys (Harku valley –145 m) and highest in the Haanja Heights (+166 m). According to the modern zonation of the bedrock topography [5], the Estonian Oil Shale Deposit belongs to the Viru-Harju Plateau where the average heights range from +40 to +60 m. Higher parts of the plateau are known as the Pandivere Elevation (absolute height up to +132 m) and Ahtme Eminence (up to +79 m). Different tadpole and whaleback forms, ranging from a few metres to ten metres in height, are sculptured in the more or less flat bedrock surface. Morphologically, such small bedrock protuberances can be rounded, oval, elongated or irregular, sometimes even compound where two or more smaller hillocks overlie a longer protuberance [7].

The sedimentary bedrock strata have a regular southward inclination (7–15', azimuth 179^{o}) and Palaeozoic layers form a gently dipping homocline. Several escarpments of erosional origin, locally known as klints (North-Estonian, West-Estonian and Upper-Devonian) and smaller scarps have been formed in accordance with lithological differences and tectonical structures in the bedrock. The northern edge of the Viru-Harju Plateau falls abruptly to the Gulf of Finland, forming the steep North Estonian Klint – the middle part of the 1200-km-long Baltic Klint [8]. In some places it is identified as a system of terraces separated by smaller escarpments. The absolute height of the klint is about 68 m near Kandle and 56 m at Ontika. The klint is dissected by ancient and modern river valleys and divided into klint bays and peninsulas. Klint bays were repeatedly widened and deepened by glaciers.

The bedrock topography has developed under the effect of different geological processes. In the course of long-term pre-Quaternary continental period, the development of bedrock surface was controlled by erosional-denudational processes and by the beginning of the Pleistocene a complicated bedrock topography with much higher altitudes than nowadays had formed. In the Pleistocene, the bedrock topography was significantly levelled by the glaciers. According to the calculations by Issachenkov [9] and Makkaveyev [10], the Pleistocene glaciers had removed a layer of rocks up to 50–60 m in thickness, in the ice lobe depressions, e.g. the Peipsi depression, the thickness of the removed layer could have reached even 100 metres. In the Holocene the bedrock surface was affected by the wave action during the various stages of the Baltic Sea and different terrestrial geological agents. In recent times, human impact has been the main factor changing the bedrock.

Our data show that the structure of the Quaternary cover and the thickness and composition of deposits depend greatly upon the bedrock topography, which exercises a clear influence on the distribution of different landforms [11]. In the study area, end moraines are frequent on the proximal slopes of bedrock elevations blocking the movement of glaciers and causing the accumulation of glacial deposits. Eskers are often associated with valleys. Iisaku-Illuka – the biggest esker in the area – is located above a branch of the Vasavere buried valley at Jõuga. Kames are also attributed to the depressions in the bedrock surface. For instance, the Kurtna (Illuka) Kame Field has formed above the deep ancient Vasavere valley. This is a typical marginal formation with an asymmetric cross section, and a relatively high, straight and abrupt ice contact slope in the west and gradually lowering and undefined slope in the east. The relief is varied due to numerous glaciokarstic hollows. Thirty-nine lakes of varying shape, size, drainage catchment, hydrological regime and trophic level occur in this 30 sq km hilly area.

Structure and morphology of ancient valleys in the Estonian oil shale deposit.

There are seven bigger ancient valleys in the study area (Fig. 1) [12]: Loobu (330–360^{o} NW, length 16 km, width 1–1.5 km), Haljala (320–330^{o} NW, length 8 km, width 0.7–1.0 km), Selja (330–340^{o} NW, length 13 km, width 0.8–1.0 km), Kunda (340–350^{o} NW, length 20 km, width 0.5–1.5 km), Pada (350° NW – 10° NE, length 5 km, width 0.3–0.5 km), Purtse (330^{o} NW – 70^{o} NE, length 22 km, width 0.3–1.2 km) and Vasavere (350^{o} NW – 20^{o} NE, length 17 km, width 0.5–1.5 km). The present paper focuses on the three longest and structurally most complicated valleys – Kunda, Purtse and Vasavere. The paper is based on the data comprised in numerous mapping, exploration and prospecting reports of the Geological Survey of Estonia.

Kunda valley

The 27-m-long Kunda valley starts from the eastern slope of the Pandivere Elevation (Fig. 1). The valley is of SE–NW orientation following the direction of the prevailing joint set in the bedrock [13, 14]. In the southern part, it crosses commercial phosphorite beds at the heights of 30–32 m (in the SW slope) and 32–34 m (in the NE slope) and divides the Rakvere phosphorite deposit into the West-Kabala and East-Kabala mining fields [2].

In the Kunda klint bay the Kunda buried valley cuts through Middle and Lower Ordovician hard carbonate rocks into Lower Ordovician and Lower Cambrian terrigeneous rocks. In the south, the valley is in Upper and Middle Ordovician carbonate rocks. Rocks of the Middle Ordovician Kunda Stage crop out in the deepest parts of the valley.

According to gravimetric studies, the Kunda buried valley starts south of the Aravuse village where it forms three ca a-kilometre-wide valley-like landforms below the kame fields and mires. Some 1–1.5 km northwards, the 0.6–0.7-km-wide flat-bottomed main valley is already 26–36 m deep. The valley bottom is there at a height of 34–36 m above sea level. A kilometre farther north, the width of the valley is 0.3–0.4 km on the bottom, and 1.5–2.5 km from rim to rim. The depth has decreased to 27 m. The next and deepest 7-km-long segment of the valley extends as far as the Tallinn–Narva railway. Within this segment, both the depth of the valley and thickness of the Quaternary deposits are at their greatest reaching 68.4 m in borehole 1740 (Fig. 2c). The valley bottom is 8.3 m below sea level. The depth of the valley is prevailingly 50–55 metres, the width 0.5 to 1.4 km on the bottom and 2.0–2.8 km from rim to rim. North of Tallinn–Narva railway, the valley floor rises and the depth of the valley decreases; however, at the site of Sämi glaciofluvial delta the valley is still more than 40 m deep (borehole 1563, Fig. 2c). Immediately south of the town of Kunda it is 25–30 m deep (Fig. 2a), the width of the upper part is 1.1 km (in the south), up to 1.5 km (in the north) and 0.3–0.7 km on the valley floor. The bottom of the valley is 15–22 m a.s.l. The above suggests that the longitudinal profile of the valley is uneven (Fig. 2c). Probably, the valley deepens southward. The valley does not reach the Gulf of Finland, but ends abruptly on the southern boundary of the town of Kunda as evidenced by the uninterrupted character of the North Estonian Klint in the town of Kunda, but also west and east of it. Hence, the Kunda buried valley is either a closed valley-like landform or a valley opening to the south and having a length of 25–30 km. The contemporary Kunda valley was formed in the Holocene above the ancient one. This is most clearly revealed between Sämi and Põlula where the recent valley marks the location of the ancient buried valley. The distribution of Quaternary sediments along the valley suggests that a great part of the valley, especially its deepest segment, is filled with loamy carbonaceous till with a maximum thickness of 56.6 m (Fig. 2). In the deepest segment its average thickness is 40–45 m, and only 15–16 m in the northernmost part. The till is overlain by glaciolacustrine sands, silts or varved clays, up to 25 m in thickness. Southwards the thickness decreases. In the southernmost part of the valley, the till is overlain by glaciofluvial sandy-gravelly sediments, up to 20 m thick. In the cross-section the thickness of the till is usually greater in the middle part of the valley and it decreases laterally. Occasionally, till has accumulated mostly on one slope, particularly in the case of asymmetric cross-section (Fig. 2b).

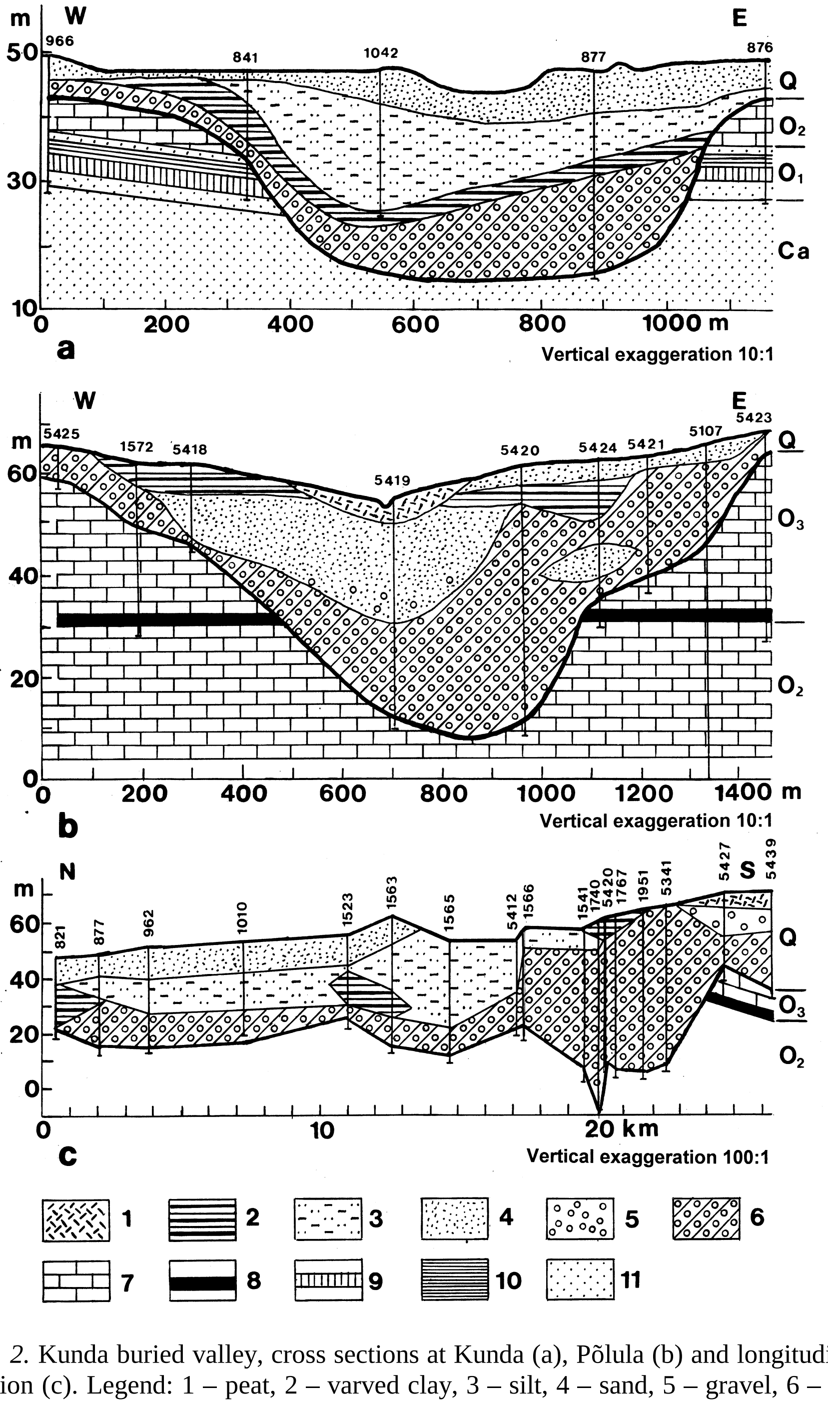


Fig. 2. Kunda buried valley, cross sections at Kunda (a), Põlula (b) and longitudinal section (c). Legend: 1 – peat, 2 – varved clay, 3 – silt, 4 – sand, 5 – gravel, 6 – till, 7 – carbonate rocks, 8 – oil shale seam, 9 – Dictyonema argillite, 10 – claystone, 11 – sand- and siltstone. Q – Quaternary, O_1, O_2, O_3 – Lower, Middle and Upper Ordovician, Ca – Cambrian, NP_3 – Ediacara. Data from the Geological Survey of Estonia.

Purtse valley

The Purtse (Savala) buried valley is situated 20–30 km east of the Kunda buried valley (Fig. 1). The southern part of the valley is cut into Middle Ordovician carbonate rocks. In the deeper parts, the rocks of the Aseri Stage crop out on the valley floor. Relevant data on the northern part are absent but, in all likelihood, the valley reaches the Lower Cambrian terrigeneous rocks.

The beginning of the Purtse buried valley is not known, but evidently it starts under the Muraka and Ratva mire massif. At a distance of only a few kilometres from the mire edge, in the vicinity of Lipu Village (Fig. 3b), a flat and wide valley-like formation is seen on the bottom of boreholes. Its floor is at a height of 23 m a.s.l. The valley is 0.4 km wide and 13 m deep. With respect to the surrounding low elevations, the valley cuts to a depth of 27–29 m and is more than 2 km wide. It continues in the same way downstream up to Ojamaa Village, where its depth increases to 35 m (absolute height of the bottom 10 m). The ca 60-m-wide valley is asymmetric; its eastern slope is much steeper than the western slope. Morphologically, a similar valley is traceable up to Maidla Village. Only the depth slightly increases reaching 39 m in the vicinity of Maidla Village (the bottom is 0.5 m b.s.l., Fig. 3a). Here the width of the valley decreases to 300 m. The segment of the valley between Maidla Village and the sea is poorly studied. There are only a few poorly described boreholes, according to which the valley depth is up to 40 m and its bottom is close to sea level [15, 16]. At the same time, the course of the valley to the sea is not clear. If the valley opens at the Gulf of Finland at all, it must take place east of the recent Purtse valley, probably near Moldova Village.

The Purtse buried valley is meandering, which is not typical of the other valleys in northern Estonia (Fig. 1). The meridionally running valley changes its course and trends NE–NW, regaining thereafter its meridional direction (Fig. 3c). Somewhat north of Lipu Village, there is an up-to-10-m-deep tributary valley of south-east orientation. Contrary to the Kunda valley, the longitudinal profile of the Purtse valley is falling more or less steadily downstream (Fig. 3c).

The geological structure of the Purtse buried valley is rather complicated. The thickness of the Quaternary deposits increases rather regularly from 26 m in the vicinity of Lipu Village up to 41–42 m near Maidla Village (Fig. 3). Characteristically, there are at least two, probably three till beds. Two till beds occur at Lipu (thicknesses 8 and 6 m from top downwards), Ojamaa (3 and 7 m), and Uniküla (each about 10 m thick). In the vicinity of Maidla Village, there are evidently three till beds (thickness from top downwards 4.7 and 3 m). At Linnasaare, downstream from Lipu Village, there is only one till bed, 17–18 m in thickness, which at Ojamaa falls again into two parts. Above and between till beds, there are glaciolacustrine sands, silts or varved clays with a rather changeable thickness. At Ojamaa Village the thickness of sand between the till beds is ca 20 m. At Uniküla and Maidla the varved clays underlying the lower till are 11–13 m thick.

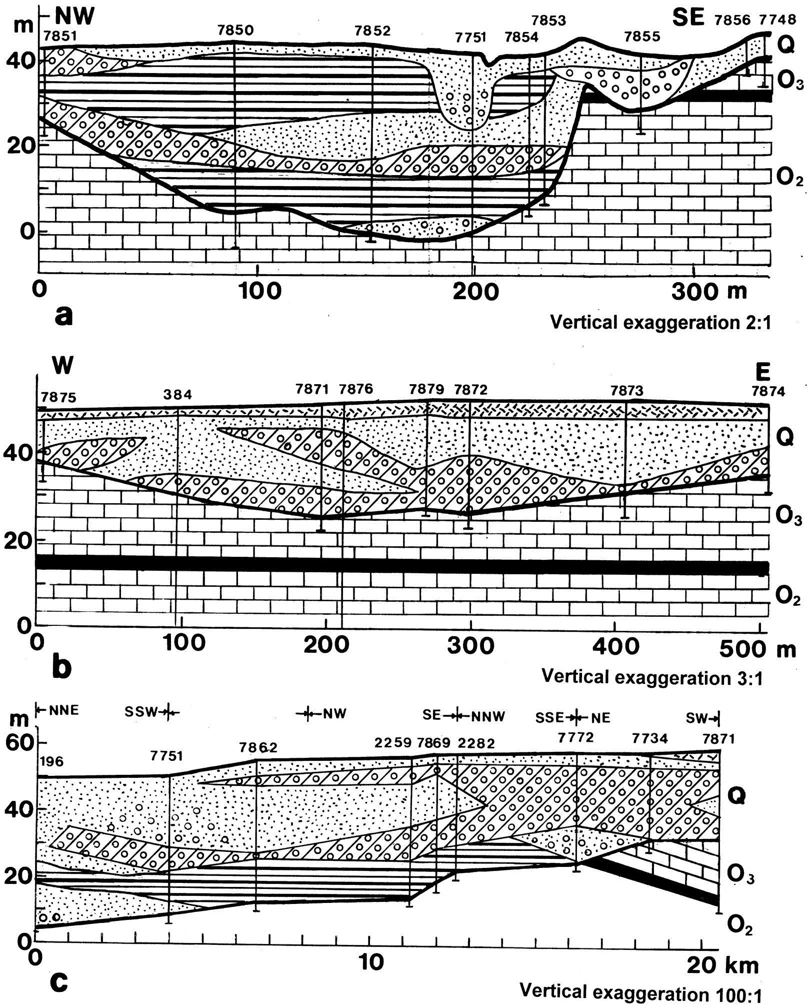


Fig. 3. Purtse (Savala) buried valley, cross sections at Maidla (a), Lipu (b) and longitudinal section (c). For legend see Fig. 2. Data from the Geological Survey of Estonia.

The Purtse buried valley was stratigraphically studied by Elsbet Liivrand [16] in Püssi, Lüganuse and Savala boreholes. Two different periglacial strata, separated by a till bed, are characterized by different pollen and spore compositions. The lower Lower-Weichselian bed in the Püssi section was formed under cold and humid climatic conditions and the upper Middle-Weichselian bed in the Savala section under a cold and dry climate, but in warmer conditions than the Püssi bed. They both represent Early- and Middle-Weichselian ice free intervals characterized by a specific periglacial spore and pollen composition. According to E. Liivrand [16], the Savala spectra represent one of the warmest Middle-Weichselian intervals and can be correlated with the Peedu and Tõravere sections in South Estonia.

Vasavere valley

The Vasavere buried valley is eroded into the carbonate rocks of the upper part of the Middle Ordovician Haljala Stage. The central parts of the valley, which are situated under the Kurtna Kame Field, expose carbonate rocks of the Middle Ordovician Kunda Stage. The longitudinal profile of the valley bottom is uneven and, therefore, younger rocks up to the Uhaku Stage are occasionally exposed. In the Ahtme tectonic structure in the vicinity of Ahtme mine, the valley floor is in the clayey rocks of the Lower Cambrian Lükati Formation. But only 5 km father north, after a higher part composed of the rocks of the Uhaku Stage, the valley cuts into the Lower Cambrian terrigeneous rocks. In the vicinity of Voka Settlement the valley floor is already in the clastic rocks of the Ediacaran Kotlin and Gdov formations (Fig. 4).

The ca 26-km-long meridional Vasavere buried valley starts from the southern boundary of the Kurtna Kame Field in the vicinity of Raudi Village. According to some data, there are several branches. One of those, established by borehole data, is ca 4 km long, 300 m wide and 8–10 m deep. At the beginning of the valley, its bottom is 30–37 m a.s.l. The depth of the valley increases rapidly northward. For instance, the height of the bottom is +11 m in the vicinity of Lake Räätsma, a kilometre farther north – near Lake Nõmme – it is +2 m, and in the area of Pannjärv sandpit –4 m. In the vicinity of Vasavere Village, there is an elongated closed depression on the bottom where the bedrock is at a height of –17 m (Fig. 5a). Three similar depressions occur farther north. In one of those, which is situated close to the Ahtme tectonic structure, the bedrock surface is 28.5 m b.s.l. Relative height between the valleys and adjoining elevations reaches 56 m. The depth of the valley increases especially rapidly in Cambrian terrigeneous sedimentary rocks (Fig. 4) where its bottom is 137 m b.s.l. In the Voka settlement at the sea, the valley is 174 m deep. Some 4.5 km to the south, the depth is still rather great, but does not exceed 60 m. Thus, the longitudinal profile of the valley is irregular in shape (Fig. 5b).

The valley starts and ends with several branches. Some 3–4 km before the sea the valley branches: the southern branch runs to Toila, the eastern one to Voka (Figs. 1 and 4). The bottom of the western part is 43 m a.s.l. in the downstream area.

The cross-section of the valley is prevailingly asymmetric (Fig. 5a), except the segment close to the Gulf of Finland (Fig. 4). Usually, the western slope is higher, but gentler. In accordance with this, the incutting is different with respect to the surrounding topography. The calculations based on the left (western) slope yield 50–65 m for the depth of the valley, while those based on the right (eastern) slope suggest that the depth won’t occasionally amount to 30 m, although in some cases it may even reach 45 m. In the

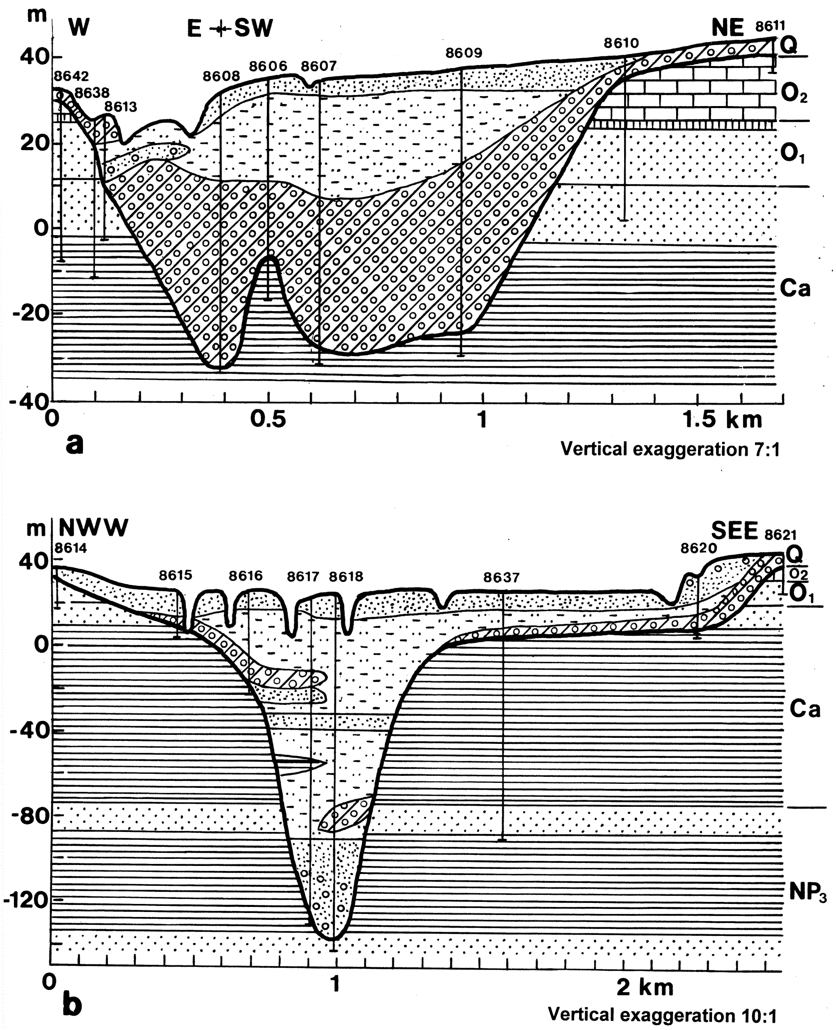
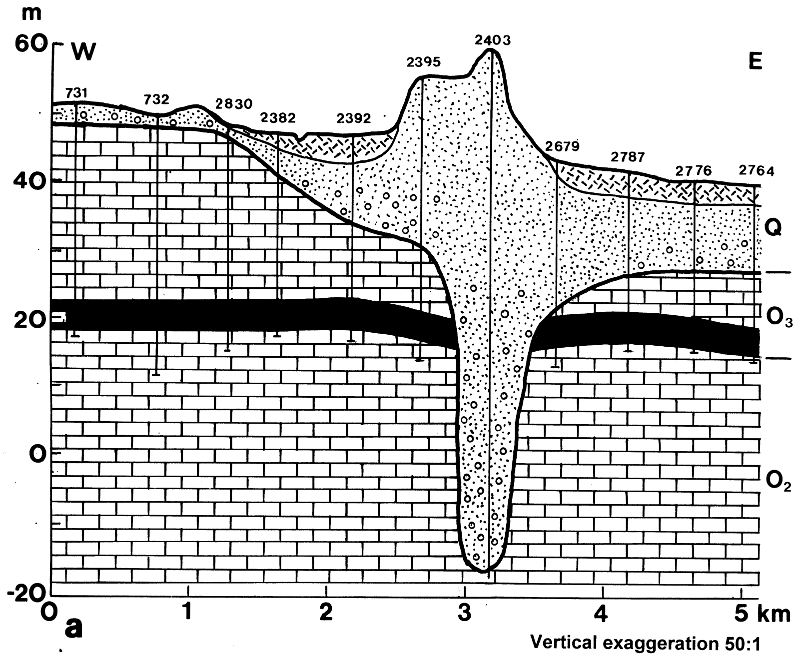


Fig. 4. Vasavere buried valley, cross sections at Voka: western branch (a) and eastern branch (b). For legend see Fig. 2. Data from the Geological Survey of Estonia.

vicinity of the Gulf of Finland, the cross-section of the valley is symmetric. The width of the valley is rather stable, being 2.5–3.5 km on the rim. In the vicinity of Lake Räätsma it decreases to 2.0–2.5 km. Before the valley falls into two branches, it is only a kilometre wide. The width of the valley bottom ranges between 100–500 m.

The thickness of the Quaternary deposits is rather changeable. At the beginning of the valley it is 10–12 m, but within the kame field the total thickness of the Quaternary deposits and kame-forming ones, exceeds 75 m, being 45–50 m on an average (Fig. 5b). In the deep valley at Voka, in the



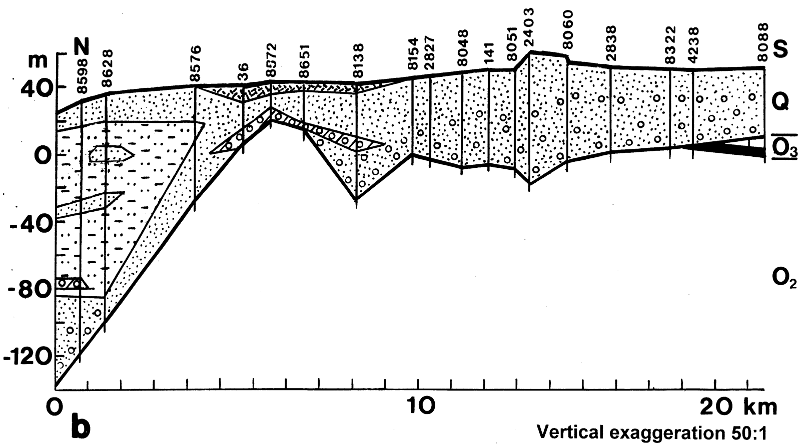


Fig. 5. Vasavere buried valley, cross section in the Kurtna Kame Field (a) and longitudinal section (b). For legend see Fig. 2. Data from the Geological Survey of Estonia.

vicinity of the Gulf of Finland, the Quaternary deposits are already 146 m thick. In the westernmost branch of the valley, south of Toila, they are 64 m thick (Fig. 4).

The Vasavere buried valley is filled with glaciofluvial and glaciolacustrine deposits, mainly with sand and silt, partly with the mixture of gravel (Figs. 4 and 5). This applies, first of all, to the segment of the valley within the Kurtna Kame Field. The till forms 2–6 m thick isolated beds in the deeper parts of the valley. In the branch of the valley running through Voka Settlement, till (22.5 m) has been established in some places, but the scanty data available indicate that this branch is also filled with fine-grained glaciolacustrine sands and silts. At the same time, in the western branch till has been established in several boreholes with a maximum thickness of 43 m. The overlying glaciolacustrine silts are 25 m thick.

In the area of the Kurtna Kame Field, the valley is 1200–1300 m wide and 65 m deep. The Pannjärve sand deposit, the biggest of its kind in Estonia, with active proved reserves of 71.1 mln m^3 is located here. The high content of quartz (over 90%) makes the sand suitable for use in concrete and mortar, but also for the manufacture of silica and silicalcite products. In the Vasavere ancient valley within the Kurtna Kame Field, sand and gravel form an up to-80-metre-thick layer. The Pannjärve sand quarry (390 ha in area) was opened in 1964. Its production capacity is 1.1 mln m^3 annually, of that 0.7 mln m^3 is mined below the groundwater level.

The age of the thick sand and silt layer in the area of the Kurtna Kame Field is unclear, but most probably these deposits accumulated during the retreat of the last glaciation. Five samples collected from the medium and coarse sand in the eastern wall of the sand pit were dated by the OSL method [17]. Two samples at a depth of 5 m, with sampling points located 10 m apart, yielded the ages of 72 000 ± 11 000 and 75 000 ± 9000 OSL years. Two samples at a depth of 8 m from the ground surface, spaced 20 m apart, yielded the ages of 9800 ± 1100 and 11 500 ± 1200 OSL years and one sample from a depth of 15 m gave the age of 13 400 ± 1200 OSL years.

In the Voka outcrop near the seashore, 600 m to the east from the mouth of the Voka River, where the klint bay is 2300 m wide, the Quaternary cover in an exposure is more than 20 m thick, of that 7.5 metres are formed by fine sand and silt. In some places, the sand and silt are underlain by 22.5-m-thick grey till originating, presumably, from the last glaciation. The sandy-silty complex comprises at least 4–5 layers with soft-sediment deformation structures. Taking into consideration the bedding, stratification and grain-size of sediments, but also the height of water basins, it was assumed that these sediments were formed in an ice lake at the end of the Late Pleistocene [18]. Two OSL dates from the depths 5.5 and 12 metres gave the ages 12 530 (18 500) and 25 000 OSL years, respectively [19]. However, there are some dates considerably older, even up to 110 000 OSL years [20].

As in North-East Estonia, the deposits of the buried valleys are prevailed by glaciofluvial sand and gravel serving as a productive resource for groundwater use and supply. The Vasavere water intake is operating since 1972 with a pumping rate of up to 10 000 m^3 d-1. The groundwater of this Quaternary aquifer system is of the HCO_3-Ca-Mg-type with TDS up to 0.5 g/l [21]. The groundwater consumption from this intake exerts an obvious influence on the Kurtna area where the water level in several lakes has dropped. On the other hand, the hydrological regime in the valley has been influenced by oil shale mining. The content of sulphate in the surface and groundwater indicates directly the influence of the mining water [22]. The comparatively intensive and uneven water exchange with surrounding mines has been clearly caused by the uneven bedrock topography.

Conclusions

Buried valleys are usually treated as pre-Quaternary river valleys reworked by the Pleistocene glaciers [5]. Probably many of valleys were formed in the Late Paleogene Paleogene when the Earth's crust was much higher than at present due to the riftogenesis in the North-Atlantic region. The above-presented data show that the Kunda and Purtse valleys are of Weichselian age. The segment of the valley within the Kunda klint bay may have developed prior to the Weichselian period, while the valley in the Kurtna Kame Field and the segment running in the direction of Toila originate from the Weichselian.

The formation of the valleys is not entirely clear. But some aspects, including the absence of clearly marked valley on the Gulf of Finland's shore, irregular longitudinal profile of the buried valleys, great thickness of till or, *vice versa*, its small share, significant role of glacial meltwaters, suggest that the valleys were eroded by glaciers.

Wide and long ancient valleys intersect the whole area of the Estonian Oil Shale Deposit hampering the use of reserves and affecting the water regime. It is concluded [23] that even the palaeorecharge of the Cambrian–Ediacaran aquifer most probably occurred by subglacial drainage through tunnel (=buried) valleys during the last glaciation.

The excavation of oil shale below the groundwater level causes the latter's pollution. The ancient valleys have been studied geophysically and with borings, but the amount of drillings is not enough to establish the exact distribution of valleys and their geological structure. Taking into consideration the importance of valleys in the water supply and nature protection, the study of valleys must be intensified. The buried valleys are weakly protected against surface pollution due to the lack of topmost till and clay.

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