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Structure and origin of the Vaivara Sinimäed hill range, Northeast Estonia

Rein Vaher, Avo Miidel and Anto Raukas

Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; rein.vaher@gi.ee, avo.miidel@gi.ee, anto.raukas@gi.ee

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Abstract. The distribution, structure and origin of the hill range of Vaivara Sinimäed and bedrock folds are discussed. Many narrow (150–500 m), east- to northeast-trending folds with 1–10 km long axes are found in the studied area. Anticlines resulting from diapiric processes are prevailing. Cambrian clay-, silt- or sandstones are cropping out in the centre of the anticlines. Terrigenous outcrop zones are surrounded by Middle Ordovician carbonate rocks, which enabled us to use low-resistivity anomalies for tracing the distribution of the proven anticlines. The Vaivara Sinimäed, a 3.3 km long and 200–300 m wide range of three elongated hills, rise 20–50 m above the surrounding land. The tops of Tornimägi, Põrguhauamägi and Pargimägi hills are 69, 83 and 85 m a.s.l., respectively. Two saddles between the hills are on the level of 50–55 m a.s.l. Uplift of Middle Ordovician carbonate rocks at Pargimägi Hill is mostly due to the thickening of Cambrian claystone. Its core, and most likely also the cores of Tornimägi and Põrguhauamägi hills, consist of squeezed-out and folded sedimentary bedrock, diapirs, which are probably of glaciostatic origin. The dominant glaciotectonic feature is a glacial erratic. The surrounding bedrock and cores of the hills are covered with a thin blanket of Quaternary deposits: till, glaciofluvial gravel and sand, glaciolacustrine silt and clay. The Vaivara Sinimäed as a whole represent a diapir, modified by glaciers.

Key words: Northeast Estonia, diapir, glacial erratic, ice-marginal formation, hill, Quaternary deposits.

INTRODUCTION

As a part of the vast East European Plain, Estonia is characterized by a rather flat surface topography with small relative and absolute heights. Structurally, it lies mostly within the boundaries of the southern slope of the Fennoscandian (Baltic) Shield. The dominant macrostructures of glaciotectonic origin are thrust faults along which sheets have been displaced in front of the advancing glacier (van Gijssel 1987). Thrust faults are very rare in Estonia, but glacial erratics are often found. Glaciotectonic structures may be created in the substratum under ice or in the foreland region in front of the ice cover. In most cases in Estonia they seem to have been dragged along in the lower part of the glacier and left behind when they were released from the ice by basal melting. Ridges, hills and composite massifs composed of Quaternary deposits appear to be the most common glaciotectonic landforms in Estonia (Rattas & Kalm 1999).

The hill range of Vaivara Sinimäed (*Blue Hills*) is located in the northeasternmost part of Estonia (Fig. 1). A 3.3 km long and 200–300 m wide range of three elongated hills rises 20–50 m above the surrounding land, forming, besides the Baltic Klint, a most prominent land form in northeastern Estonia. Since the beginning of the previous century, a number of researchers have studied these hills (Hausen 1913; Granö 1922; Jaansoon-Orviku 1926; Tammekann 1926; Stumbur 1959; Sammet 1961;

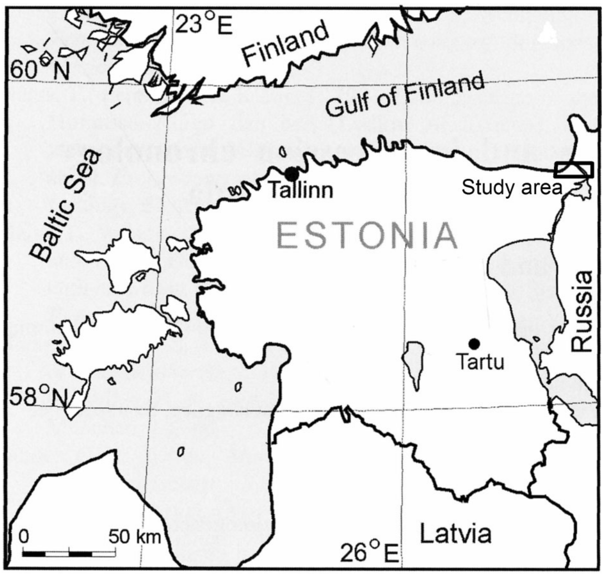

Fig. 1. Location of the study area in northeastern Estonia.

Miidel et al. 1969; Raukas et al. 1971; Malakhovskij & Sammet 1982; Rattas & Kalm 2004; Suuroja 2005, 2006). They have posed several hypotheses about the structure (push moraine, large sedimentary bedrock erratics, horst, fold or diapir) and origin (glaciotectonic, glaciostatic or tectonic) of the Vaivara Sinimäed. This paper is based on our interpretation of the available drilling and electrical-resistivity data, aimed at solving these problems.

MATERIALS AND METHODS

Numerical data (location and altitude of the borehole mouth, thickness of sediments and rocks) of 570 boreholes and results of resistivity prospecting were obtained from unpublished reports stored in the Depository of Manuscript Reports of the Geological Survey of Estonia (GSE) and Estonian Land Board. The data were interpreted manually by interpolating between higher and lower values, and contour maps were drawn taking the resistivity maps into account. Electrical mapping in 1961–1965 for locating anticlines was made by the GSE in the resistivity profiling and sounding technique with the Schlumberger array AMNB where the separation between the current electrodes on profiles was AB = 60 m, and between the potential probes MN = 15 m. Resistivity data were surveyed at traverse spacing of 250 m in 25 m steps along the line of the array. Ten boreholes were drilled and a 60 m long trench was dug out for interpretation of resistivity anomalies. Additional resistivity measurements were made in 2007–2008 as profiling with axial dipole-dipole array ABMN, where AB = MN = 20 m and the distance between the inner electrodes BM = 40 m, and sounding with the Schlumberger array.

GEOLOGICAL BACKGROUND

The studied area covers about 150 km^2 in northeastern Estonia (Fig. 1). Structurally it belongs to the Russian Platform, East European Craton. The ~ 1.88 Ga crystalline basement is formed of Palaeoproterozoic Svecofennian orogenic rocks (mostly Al-rich gneisses). The gentle (10′) southeast-dipping top surface of the basement lies at a depth of 200 to 240 m below sea level (b.s.l.). The basement is overlain by an up to 260 m thick sequence of subhorizontally layered 470–600 Ma old Neoproterozoic and Palaeozoic sedimentary rocks (Table 1). Detailed information on local stratigraphy is available in Raukas & Teedumäe (1997).

The Ediacaran, Cambrian and Lower Ordovician sections are dominated by sandstone, siltstone and claystone. The Middle Ordovician is represented by carbonate rocks (mostly limestone and marlstone). The regional low-angle (8–11′) southerly-dipping homoclinal structure of the sedimentary bedrock is diversified by local folds (generally diapirs). The most prominent bedrock and land surface feature is the 20–35 m high west–east-ranging Baltic Klint where Cambrian and Ordovician strata crop out. South of the klint the bedrock lies mainly 25–35 m above sea level (a.s.l.).

The Quaternary is represented by mostly 1–5 m thick accumulations of glacial (Pleistocene) and post-glacial (Holocene) deposits (till, clay, silt, sand, gravel, pebbles and boulders, peat). The plain south of the klint lies mainly 30–35 m a.s.l. Besides the Baltic Klint, three ridges of the Vaivara Sinimäed rising 20–50 m above the surrounding land are most noticeable landforms in the area.

Table. 1. Sedimentary bedrock of the area (Raukas & Teedumäe 1997; Ogg et al. 2008)

System	Series	Regional Stage	Lithology	Thickness, m
Ordovician	Upper	Uhaku	Limestone, marlstone	0–16
		Lasnamägi	Limestone	0–9
		Aseri	Limestone	2–3
		Kunda	Limestone	6–9
		Volkhov	Limestone, dolostone	2–3
	Lower	Billingen	Limestone, sandstone	0.3–1.2
		Hunneberg	Siltstone	
		Pakerort	Sandstone, argillite	2–5
Cambrian	Furongian			
	Terreneuvian	Dominopol′	Sandstone, siltstone	15–43
		Lontova	Claystone	72–107
Ediacaran		Kotlin	Sandstone, siltstone, claystone	109–133

DIAPIRS

A number of narrow (150–500 m) east- to northeast-trending folds are found in the study area (Fig. 2), whereas anticlines are prevailing (Vaher & Mardla 1969). Most of the fold axes are 1–3 km long, but some extend to 10 km. Cambrian claystone or siltstone (predominantly), or Cambrian and Lower Ordovician sandstone (rarely)

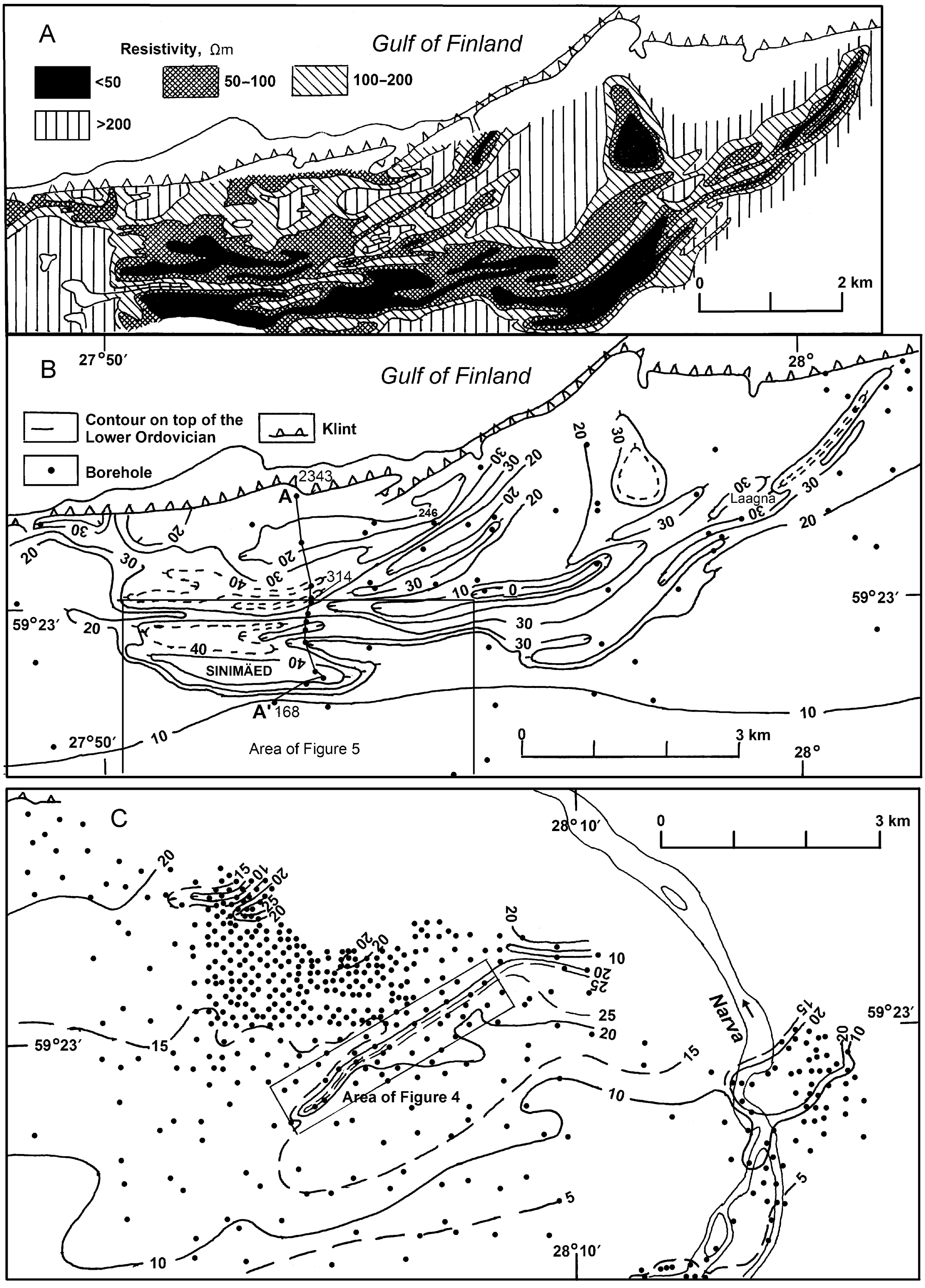

Fig. 2. Diapirs, northeastern Estonia: resistivity (**A**) and structure (**B**, **C**) maps (modified after Vaher & Mardla 1969). For cross section along line A–A′ see Fig. 3B.

crop out on the bedrock surface in the centre of the anticlines. The zones of clastic rocks are surrounded by an outcrop area of Middle Ordovician carbonate rocks, which allowed us to use the low-resistivity anomalies for tracing the distribution of the proven (by drilling) anticlines. Electrical resistivity of rocks varies from 20 Ωm for claystone, 100–150 Ωm for silt- and sandstone up to 1000 Ωm for carbonates. In boreholes (b.h.) Nos 29, 117 and 314 (Fig. 3) above the outcrop area of siltstone and claystone the resistivity is 40–75 Ωm. A resistivity anomaly as low as 30 Ωm occurs in b.h. 310, caused by 26 m thick till filling a depression on the bedrock surface. Thus, unambiguous interpretation of resistivity anomalies is possible only after checking their source by drilling.

The northwestern limb of one anticline was studied in 1965 in a specially excavated trench (line B–B′ in Fig. 4B, D) where the dip of the Middle Ordovician carbonate strata increases gradually towards the centre of the structure until reaching 40°. Carbonate rocks were eroded from the central part of the anticline, and the exposed Cambrian sandstone beds are vertical in the middle of the structure. The southeastern limb of a similar anticline was partly exposed in a trench at the Narva-Kalmistu site where the dip of the Middle Ordovician carbonate strata and the Cambrian siltstone beds measured by Orviku (1930) was 20° and 55°, respectively.

In b.h. 314 (Fig. 3) the Ediacaran strata are practically undisturbed above the basement of normal altitude. The claystone of the overlying Lontova Stage is disturbed by numerous slickensides increasing upwards in number. Siltstones of the Dominopol′ Regional Stage are severely disturbed and nearly three times as thick as normal. Evidently, the claystone was locally squeezed upwards along the lines of minimum resistance forming a diapir (Vaher & Mardla 1969; Puura & Vaher 1997).

MORPHOLOGY AND STRUCTURE OF THE VAIVARA SINIMÄED

The 3.3 km long and 200–300 m wide range of three elongated hills (Fig. 5), named the Vaivara Sinimäed after blue-looking forest that once covered them, rises 20–50 m above the surrounding land. The tops of the Tornimägi (*Tower Hill*), Põrguhauamägi (*Hell Pit Hill*) and Pargimägi (*Park Hill*) (Fig. 6) ridges are 69, 83 and 85 m a.s.l., respectively. Two saddles between the hills are on the level of 50–55 m a.s.l. A glaciofluvial plain, some 8 km^2 in area and 35–45 m a.s.l., lies to the south of the hills. A clear scarp at an altitude of 34–37 m a.s.l. and a fragmentary one at an altitude of 39–42 m a.s.l can be followed at the southern border of the plain.

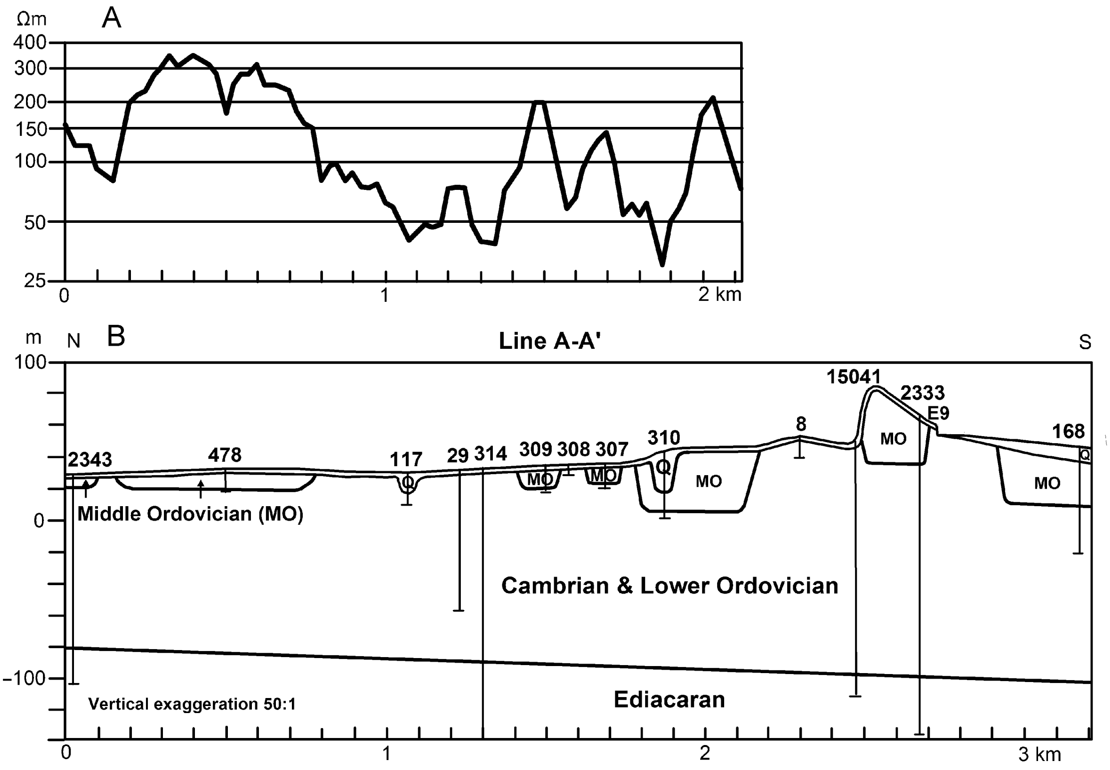

Fig. 3. Diapirs, northeastern Estonia: resistivity curve (**A**) and cross section (**B**) (modified after Vaher & Mardla 1969). For location of the cross section along line A–A′ see Fig. 2. Notation: Q, Quaternary; MO, Middle Ordovician; E, exposure.

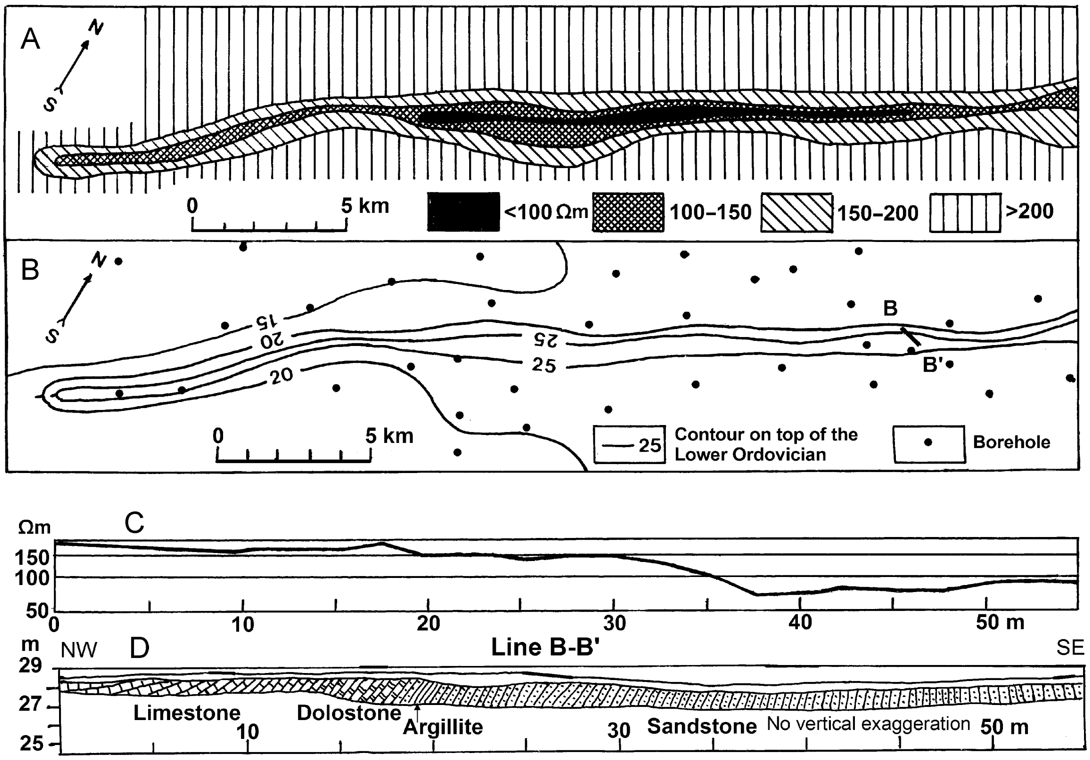

Fig. 4. A diapir, northeastern Estonia: resistivity (**A**) and structure (**B**) maps, resistivity curve (**C**) and cross section (**D**).

Possibly these are coastal scarps of the Baltic Ice Lake, with the heights at Laagna (Fig. 2B) and Vaivara (6 km west of b.h. 168) of 38 and 38–39 m (stage BI), and 32–33.5 and 33–34 m a.s.l. (stage BIII), respectively (Saarse et al. 2007). The westernmost and lowest **Tornimägi** Hill is 800 m long and rather narrow (up to 200 m). The western half of the steeper northern hillside includes an up to 15 m high vertical wall: an exposure of Middle Ordovician limestone (from Kunda to Uhaku regional stages) (Suuroja 2005). The altitude of the top of the Kunda Regional Stage on this wall (Fig. 5, exposure 1) is 45.25 m a.s.l. (Jaansoon-Orviku 1926). The normal position of that surface in b.h. 168 is 18.1 m a.s.l., i.e. 27 m lower. Figure 7A shows a section of an exposure (Fig. 5, exposure 2) of Lower and Middle Ordovician rocks on the western hillside. The Lower Ordovician sandstone strata at the northern end of the exposure are vertical. Clear traces of ice pressure are observed here: the upper parts of the vertical beds below the till are turned to the south according to ice movement (Fig. 8). The adjacent slightly wavy Middle Ordovician beds are close to vertical. The middle part of the exposure consists of mostly shattered limestone strata dipping 60–70° SSE. An overturned syncline occurs in the southern part of the exposure (left half of Fig. 9). The right half of Fig. 9 shows a flat anticline. The central **Põrguhauamägi** Hill is 800 m long and 300–400 m wide. An oval depression (Fig. 5, exposure 3) about 300 m long, 150 m wide and 20 m deep, called Põrguauk (*Hell Pit*), is observed on the top of the hill. The southern slope of the depression is an exposure of south-dipping (60°) Middle Ordovician limestone, with the Uhaku Regional Stage on the top edge (Suuroja 2005, 2006). On the eastern side of Põrguhauamägi a 4 m high exposure (Fig. 5, exposure 4) of Cambrian sandstone was seen in 1924. In the eastern part of the southern hillside (Fig. 5, exposure 5) limestone of the Aseri Regional Stage and on the southwestern hillside (Fig. 5, exposure 6) in several 2 m deep trenches south–southwest-dipping (65°) limestone (from Volkhov to Lasnamägi regional stages) was exposed (Jaansoon-Orviku 1926). The easternmost and highest **Pargimägi** Hill (Fig. 6) is 2300 m long and 400–500 m wide. Middle Ordovician limestone of the Uhaku Regional Stage crops out on top of the hill (Suuroja 2005). Several blindages (Fig. 5, exposure 7) were dug out of the limestone of the Lasnamägi Regional Stage in the northeastern hillside; here the limestone strata dip 20° SSE (Jaansoon-Orviku 1926). In three boreholes an outcrop of Cambrian siltstone (Dominopol′ Regional Stage) was found on the northern (Fig. 5, b.h. 2 and 8) and northeastern (Fig. 5, b.h. 15041)

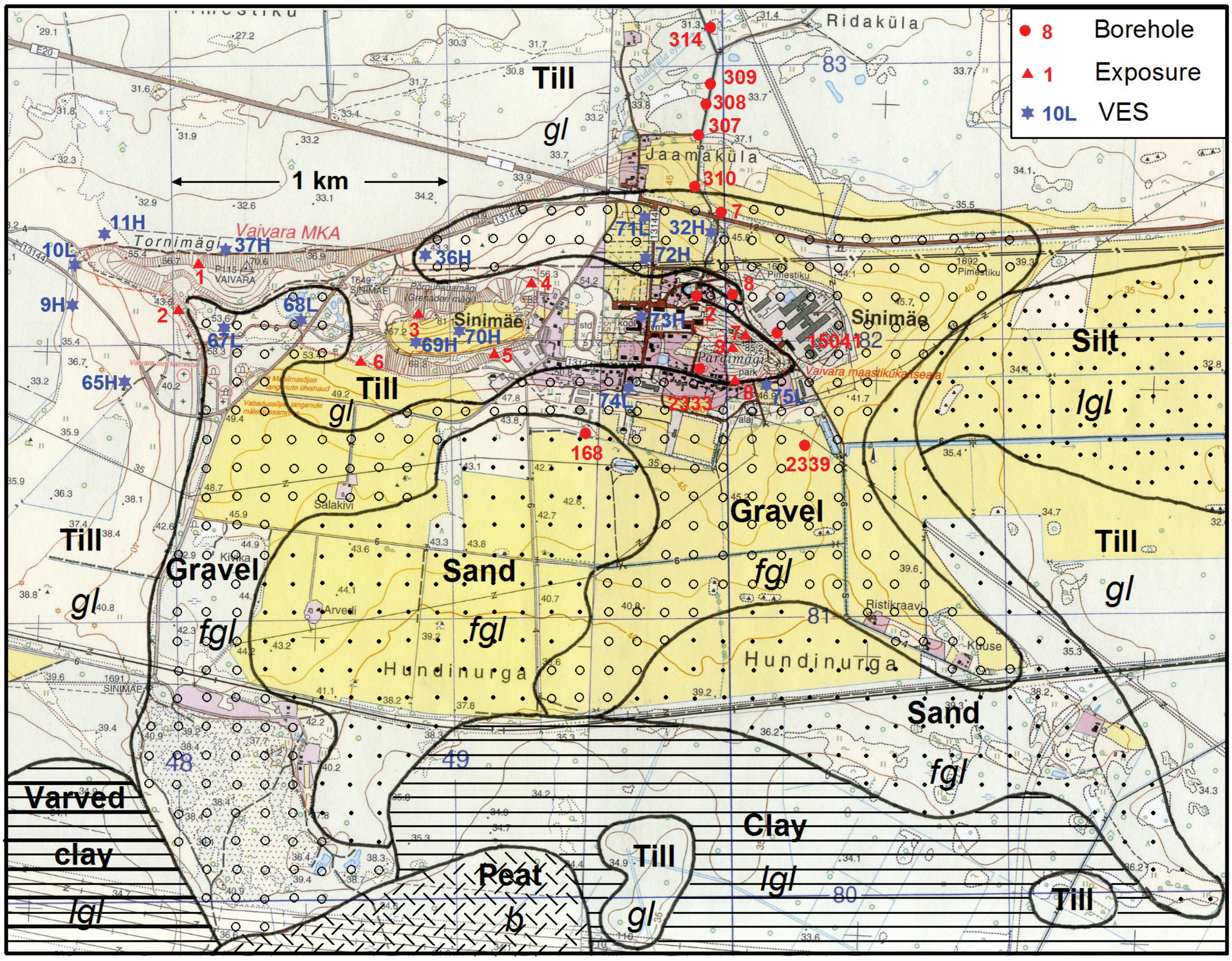

Fig. 5. The map of Quaternary deposits of the Vaivara Sinimäed and surroundings (modified after Miidel et al. 1969). Notation: *gl*, glacial; *fgl*, glaciofluvial; *lgl*, glaciolacustrine; *b*, bog; VES, vertical electrical sounding: H, high-resistivity curve; L, low-resistivity curve. Map topography is based on Estonian Basic Map 1 : 20 000, sheets Vaivara 65.81 (2002) and Auvere 65.82 (2007), Estonian Land Board, General Staff of the Estonian Defence Forces.

Fig. 6. A view of Pargimägi Hill. Photo by A. Miidel.

hillsides. Five vertical electrical soundings (VES) on the southern hillsides (Fig. 5, VES 10L, 67L, 68L, 74L and 75L) belong to a low-resistivity zone which corresponds to an outcrop area of Cambrian silt- and sandstones. This is proved by an exposure (Fig. 5, exposure 8; Fig. 10) of Cambrian sandstone on the southern hillside. According to the gamma-ray log and drill core of b.h. 2333 on the southwestern hillside, the Phanerozoic sequence (from the Uhaku Regional Stage on top to the Ediacaran System on the bottom) is normal. The top of the Lower Ordovician lies here at about 36 m a.s.l., i.e. about 28 m higher than the position of that surface in drill cores at the northern (b.h. 310) and southern (b.h. 168 and 2339) feet of the hill (7.9, 8.7 and 8 m a.s.l., respectively). The mode of occurrence of Ediacaran

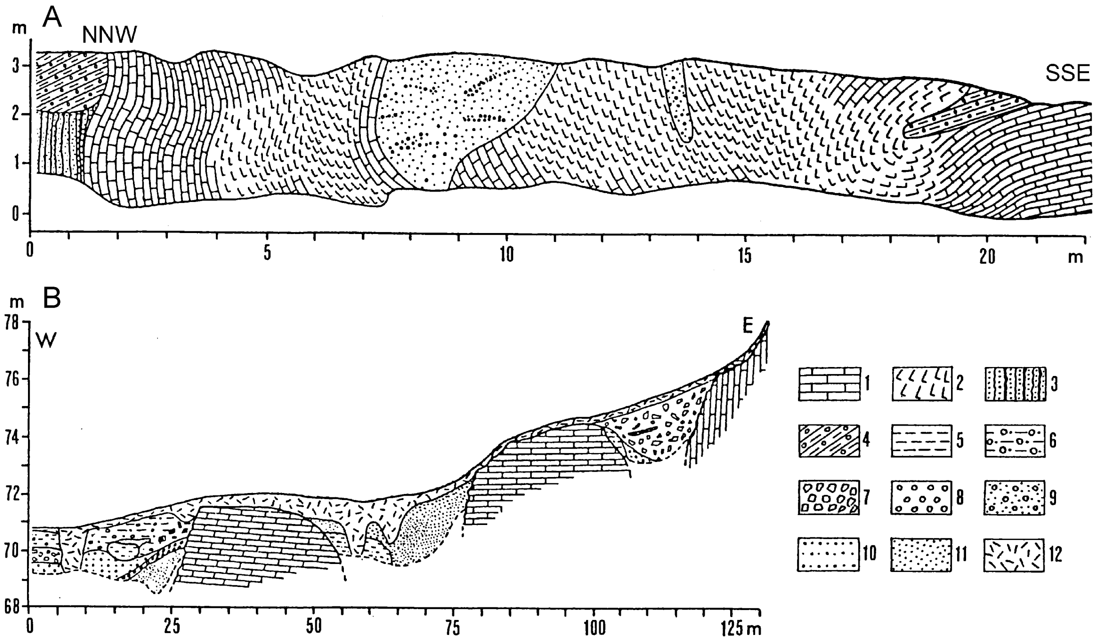

Fig. 7. Vertical sections of the exposures at Tornimägi (**A**) and Pargimägi (**B**) (from Miidel et al. 1969): 1, limestone; 2, shattered limestone; 3, sandstone with graptolite argillite interbeds; 4, till; 5, green clayey till; 6, brown sandy till; 7, grey carbonaceous till; 8, pebbles; 9, glaciofluvial gravel and pebbles; 10, sandy gravel; 11, cross-bedded sand; 12, soil. For location of exposures 2 (at Tornimägi) and 9 (at Pargimägi) see Fig. 5.

Fig. 8. Sandstone with graptolite argillite interlayers of the Pakerort Regional Stage on the western side of Tornimägi Hill. The topmost part is inclined towards the direction of the glacier movement and covered with stratified lodgement till. Photo by A. Raukas.

rocks is normal. The thickness of Cambrian claystone (Lontova Regional Stage) is 107 m, i.e. 25 m greater than in the normal b.h. 246 (2 km to the northeast, Fig. 2). So, uplift of the Middle Ordovician carbonate rocks here is mostly caused by the thickening of Cambrian claystone during diapiring processes.

Fig. 9. Glacially folded and densely fissured carbonate rocks on the western side of Tornimägi Hill. Photo by A. Miidel.

Fig. 10. An exposure of Cambrian sandstone (exposure 8, see Fig. 5) on the southern side of Pargimägi Hill. Photo by A. Miidel.

QUATERNARY DEPOSITS

Quaternary deposits are represented mainly by the till of the last (Late Weichselian) glaciation, distributed in all three hills and to the north and west of them. In the east and south the area is covered with glaciofluvial (coarse sand, gravel and pebbles) and glaciolacustrine deposits (sand, silt and clay) (Fig. 5). Glaciofluvial deposits are spread also at the proximal side of Põrguhauamägi and Pargimägi hills. A small settlement exists at Pargimägi and therefore there are more drillings than in other hills. The thickness of Quaternary deposits in the upper part of Pargimägi is only half a metre, increasing up to 10 m on the hillsides. Among these deposits up to 7 m thick till is prevailing. Figure 7B demonstrates an exposure (Fig. 5, exposure 9) of Quaternary deposits on the western hillside. The section of this exposure shows three about 25 m long limestone erratics being 10–15 m apart. Limestone strata of two erratics are nearly horizontal, but vertical in the eastenmost one. Four limestone erratics of the same size, with dip of the strata 45°S, 22°NE, 25°S and 16°SSW, were found also on the southern hillside. The composition of material between bedrock erratics is changing rapidly.

Two types of tills could be distinguished. The upper till is greyish-brown or grey, in places containing yellowish loamy sand with poorly rounded carbonate clasts 8–40 cm in diameter. The content of rough material (over 10 mm in diameter) is up to 60%. Even rather large crystalline boulders were found (Fig. 11). The crystalline clasts represent Vyborg rapakivi, Suursaari quartz porphyries and helsinkites, showing ice movement from north to south (Miidel et al. 1969). The lower loamy till (at least 3.6 m thick) is greenish or bluish-grey with violet streaks and interlayers, resembling blue claystone of the Cambrian Lontova Regional Stage. Both till beds are highly deformed. The upper till is underlain by 1.5–4.9 m thick sand, silt or clay void of organic matter. Therefore it is not possible to date Quaternary deposits more exactly than to the Late Weichselian.

On the southern hillsides the upper limit of coarse-grained glaciofluvial delta deposits (pebbles, gravel and coarse sand, Fig. 12) lies at 50 m a.s.l., marking, according to Ramsay (1929) and Vassiljev et al. (2005), the level of the Baltic Ice Lake stage AI. The layers of delta deposits are dipping to the south at an angle of 8–24°. The grain size and sorting coefficient of the deposits are diminishing southwards (Miidel et al. 1969). South of Pargimägi, the delta diverges into two branches, with 3–9.6 m thick deposits of variable composition. The 2–2.5 m thick coarse-grained deposits are underlain by loam, sandy loam and sand. An up to 3 m thick layer of variegated sand can also be seen above loamy material or inside the loamy bed in the form of lenses. To the south of Põrguhauamägi, up to 5.5 m thick fine sand covers the undulating till bed.

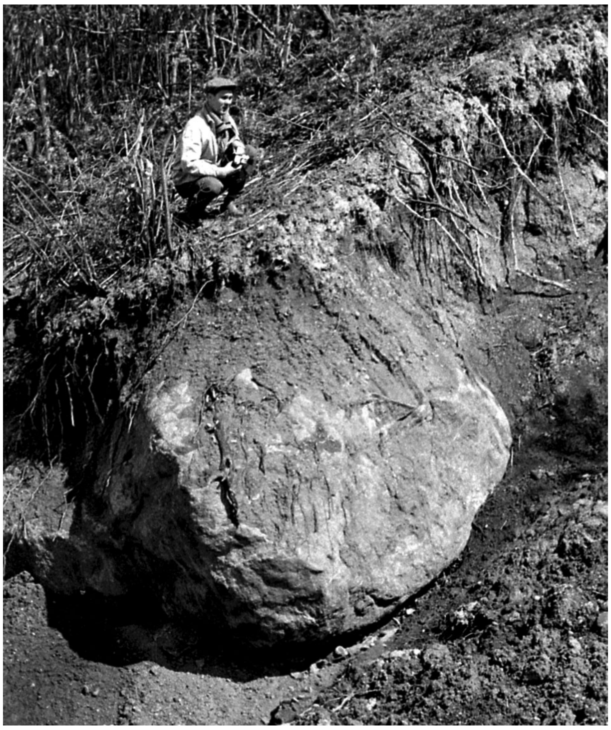

Fig. 11. A large boulder in the distal part of Tornimägi Hill. Photo by A. Raukas.

Fig. 12. Inclined bedrock strata in the distal part of Tornimägi Hill are covered with gravel and pebbles, which are poorly sorted and stratified. Photo by A. Miidel.

The area south of Tornimägi is rather well investigated. Here the till is covered by gravelly-pebble deposits of the glaciofluvial delta, which are cemented in the proximal part, resembling a conglomerate. The thickness of deposits is growing southwards from 2.5 to 7 m, whereas up to 4 m thick coarse deposits cover up to 3 m thick sand. To the south of the railway coarse-grained material is often covered with sand or loamy sand. In lateral direction the thickness of deposits is variable: 3.5–6.5 m thick fine-grained yellowish-brown sand lies on 2.5 m thick clay or loam. The whole Quaternary cover is here at least 12 m thick. The delta deposits are dominated by carbonate clasts (over 80%), and crystalline clasts have a high content of Vyborg rapakivi (some 45%). To the south glaciofluvial deposits are replaced by glaciolacustrine deposits, which are represented by loam and silt (in the east) and varved clays (in the west) (Fig. 5).

DISCUSSION

Since the beginning of the last century the majority of scientists (Hausen 1913; Granö 1922; Jaansoon-Orviku 1926; Tammekann 1926; Miidel et al. 1969; Raukas et al. 1971; Malakhovskij & Sammet 1982; Rattas & Kalm 2004; Suuroja 2005, 2006) have supported the glacial origin of the Vaivara Sinimäed, mostly interpreting them as push moraines. However, in the course of geological mapping Stumbur (1959) discovered several uplifts of Cambrian claystone (Sinimäed included). He claimed that their formation could not be explained by glacio-tectonics only, and most likely tectonic movements played the principal role. Sammet (1961) favoured a concept that these hills are seemingly a tectonic fold. Later he suggested that the Vaivara Sinimäed had much in common (erratics, folds, etc.) with Duderhoff and Kirchoff hills (near St Petersburg, Russia), formed in front of the advancing glacier (Malakhovskij & Sammet 1982).

According to K. Orviku (Jaansoon-Orviku 1926), the assumed huge limestone erratics within the Vaivara Sinimäed were broken by ice from the edge of the North Estonian Klint and transported for 4–5 km to the south or southwest. Rattas & Kalm (2004, p. 17) reached a similar conclusion: ‘Large glacial rafts of pre-Quaternary bedrock, transported for some kilometres away from the cliff, are located at Sinimäe in NE Estonia. Three bedrock blocks of Lower Ordovician limestone form the cores of three hills at Sinimäed’. Later K. Orviku (Orviku 1960) changed his former view-point, and (based on the results of the above geological mapping) suggested that at the Vaivara Sinimäed Cambrian claystone as more plastic rock was squeezed upwards along the existing tectonic zone by ice pressure. Suuroja (2005, 2006, p. 208) assumed that ‘the Vaivara Blue Hills arose due to upward squeezing (diapiring) of Cambrian claystone (“blue clay”) within a tectonic fault zone under the pressure of a 2–3-km-thick continental glacier’.

In the present paper the diapiric origin of Pargimägi Hill has been proved for the first time. This conclusion arises from the fact that the 28 m uplift of Middle Ordovician carbonate rocks on the southwestern side of Pargimägi (b.h. 2333) is mostly due to the 25 m thickening of Cambrian claystone, while the surface of the Ediacaran rocks is at normal height of 100 m b.s.l. As seen from Fig. 3, the core of Pargimägi Hill consists of pushed-up carbonate bedrock (diapir). An unusually high altitude of the inclined Middle Ordovician lime-stone strata, observed at Tornimägi and Põrguhauamägi, may be caused by (1) huge erratics broken by ice from the edge of the North Estonian Klint or (2) diapirism. According to Suuroja (2005), the klint cannot be a source of such erratics, because carbonate rocks at the klint are about 5 m thick and the youngest limestone there is of Kunda age, while at the Vaivara Sinimäed they are over 25 m thick and the youngest one belongs to the Uhaku Regional Stage. More likely the cores of Tornimägi and Põrguhauamägi hills are diapirs as well. Three vertical electrical soundings of low resistivity on the southern side of Tornimägi Hill, indicating an outcrop area of Cambrian sand- and siltstones, support this conclusion.

Diapirs may have been formed due to diapir-inducing load caused by glacier ice and/or earlier deposited thick overburden. Although no final decision between these two alternatives is possible at present, we believe that the diapirs are very likely of glaciostatic origin. If glacier ice is involved, the diapirs were formed rather during the first glaciation than the later ones. The diapiric process and glaciotectonic disturbances may have been favoured by altitude differences in the Viru plateau and at the bottom of the Gulf of Finland, which generated the change of load and increase in the pressure on the edge of the ice cover.

Most likely the Vaivara Sinimäed developed during several glaciations. A great part of the diapirs was eroded. However, we cannot prove that two different tills belong to different glaciations. The strong influence of the last glacier on the development of the hills, giving them final shape, is clear. The diapirs are covered with a thin blanket of Quaternary deposits (mostly till). During the melting of the ice on the southern hillsides, a glaciofluvial delta was formed, passing in the south into a glacio-lacustrine plain. Thus, the assemblage of the landforms and deposits in the Vaivara Sinimäed and surrounding area resembles a complex of typical glacial marginal formations (Miidel et al. 1969). However, the diapiric core of the hills together with small thickness of the Quaternary cover shows (Fig. 3B) that the Vaivara Sinimäed cannot be considered as a classical push moraine. The glaciofluvial and glaciolacustrine landforms were probably formed near the margin of the glacier.

CONCLUSIONS

Anticlines caused by diapiric processes are prevailing among the folds of the studied area. In the centre of the anticlines Cambrian clay- and siltstone or sandstone are cropping out. They are surrounded by the outcrop area of Middle Ordovician carbonate rocks, which enabled us to use the low-resistivity anomalies for tracing the distribution of the proven anticlines.

Uplift of Middle Ordovician carbonate rocks at Pargimägi is mostly due to the thickening of Cambrian claystone, while the surface of Ediacaran rocks lies at normal height of 100 m b.s.l. It means that the core of Pargimägi Hill consists of squeezed-out and folded sedimentary bedrock (diapir). So, for the first time the diapiric origin of Pargimägi was proved. Most likely the cores of Tornimägi and Põrguhauamägi hills are diapirs as well. The Vaivara Sinimäed as a whole are a diapiric composite ridge modified by glaciers. The diapir and the bedrock of its surroundings are covered with a thin blanket of Quaternary deposits: till, glaciofluvial gravel and sand, and glaciolacustrine silt and clay. The glaciofluvial and glaciolacustrine landforms were probably formed near the margin of the glacier.

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Vaivara Sinimägede ehitus ja teke Kirde-Eestis

Rein Vaher, Avo Miidel ja Anto Raukas

On käsitletud Vaivara Sinimägede ja aluspõhja kurdude levikut, ehitust ning teket. Kurrud on ida- või kirdesihilised, 150–500 m laiad ja 1–10 km pikad. Ülekaalus on kohrud (diapiirid), mis on tekkinud varasematesse rikkevöönditesse savikivimite surumise tulemusel.

Vaivara Sinimäed on 3,3 km pikkune ja 200–300 m laiune seljak, mis koosneb kolmest piklikust künkast (Tornimägi, Põrguhauamägi ning Pargimägi). Nende tipud ulatuvad 69–85 m üle merepinna ja nende suhteline kõrgus on 20–50 m. Pargimäe tuumaks on ülespoole surutud ja kurrutatud aluspõhi (diapiir), mille Kesk-Ordoviitsiumi karbonaatsete kivimite kerge on tingitud Kambriumi savikivi ("sinisavi") paksenemisest. Tõenäoliselt on ka Tornimäe ja Põrguhauamäe tuumad diapiirid. Arvatavasti on diapiirid glatsistaatilise tekkega. Sinimägesid katavad ja ümbritsevad väikese paksusega Kvaternaari setted (rohkete rändpangastega moreen, jääjõe- ning jääjärvetekkelised kruusad, liivad ja savid).