REFRACTION SEISMIC SOUNDINGS ON THREE CRAG AND TAIL RIDGES IN CENTRAL FINLAND

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In this study we describe the materials and thicknesses of tills in three crag and tail ridges located in Central Finland. According to the refraction seismic soundings the tills above the groundwater table are loose and sandy and their average seismic velocities are from 900 to 1200 m/s. The tills below the groundwater table are compact and sandy and their average seismic velocities are from 2000 to 2200 m/s. Below the highest shoreline of the Baltic Sea the tills are overlain by from 1 to 3 m thick shore deposits (washed tills). Their seismic velocities are from 330 to 870 m/s. The depth of the groundwater table in the ridge tails varies from 1 to 24 m. The tills are 55 m at their thickest. They may be even thicker than that, perhaps 85 m.

Key words: seismic surveys, refraction methods, drumlins, till, thickness, groundwater, Quaternary, Laukaa, Hankasalmi, central Finland

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Introduction

There are thousands of subglacially streamlined landforms in Central Finland, especially in the eastern part. Most of them are crag and tail ridges and belong to the Keitele-Pieksämäki drumlin field (see Glückert 1973, Mäkelä 1985, 1988). The size of the crag and tail ridges varies widely: length from 0.1 to 7 km, width from 0.1 to 2 km and height from 1 to 120 m.

Crag and tail ridges are elongate landforms which have a knob of bedrock (crag) at the stoss side and a streamlined slope (tail) at the lee side. The tail generally consists of till.

The Geological Survey of Finland has done seismic soundings on drumlins (e.g. Haavisto-Hyvärinen 1987, Haavisto-Hyvärinen *et al.* 1989, Salmi *et al.* 1991). The purpose of these soundings was to investigate the soil and groundwater conditions of the drumlins. The soundings were mainly done with an explosive seismic equipment.

In this study we wanted to find out how thick the tills of the crag and tail ridges can be. We also hoped to get information about the soil and groundwater conditions of the crag and tail ridges. We were also interested in finding out the reliable depth of penetration of our hammer seismic equipment. It is generally believed that the maximum reliable depth of penetration is not more than 10 m (e.g. Peltoniemi 1988). Recent studies show, however, that it is possible to get information about soil conditions 30 meters below the ground surface or even deeper (e.g. Mäkelä *et al.* 1990, Ristaniemi *et al.* 1991).

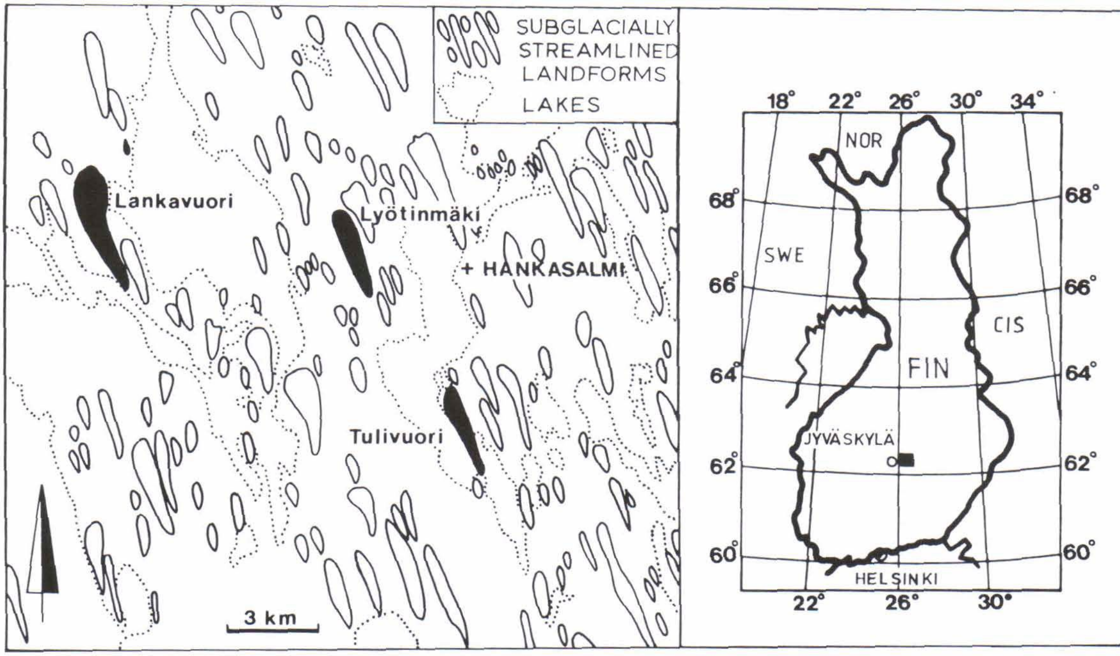

Fig. 1. The location of the study area.

Investigation sites

We chose three crag and tail ridges as investigation sites by basic map (1:20 000) interpretation. These crag and tail ridges are in Hankasalmi and Laukaa communes and their names are Lyötinmäki, Tulivuori and Lankavuori (Fig. 1). These crag and tail ridges had passable roads and their large size suggested that their tills might be thick.

Lyötinmäki is a three kilometre long crag and tail ridge. The width and height of its stoss side are 0.7 km and 75 m, respectively (Fig. 2). The crag is partly exposed. The tail flanks are covered by shore deposits (washed till) which lie below the highest shoreline of the Baltic Sea (about 146 m a.s.l., Ristaniemi 1985, 1987). These shore deposits are marked with sand pits.

Tulivuori is distinctly lower than Lyötinmäki but in other respects of the same size. The crag is partly exposed. The crag summit is about 35 metres above the surrounding area (Fig. 3) and it is below the highest shoreline of the Baltic Sea (141 m a.s.l.). There are shore deposits (washed till) of the Ancient Lake Päijänne on the tail flanks below 101 m a.s.l. (Ristaniemi 1987).

Lankavuori is a large crag and tail ridge to the west of Lake Kynsivesi. It is 4 km in length and about 1 km in width. The crag is partly exposed and its summit is more than 110 m above the water level of Lake Kynsivesi. The tail is from 30 to 40 m above the surrounding area (Fig. 4). On the tail flanks there are shore deposits (washed till) with small sandpits. The highest shoreline of the Baltic Sea is about 155 m a.s.l. (Ristaniemi 1985, 1987).

Methods

In this study we used a 12-channel hammer refraction seismograph Geometrics ES-1225 (Fig. 5). This seismograph is equipped with a digital memory which enables stacking of more than one

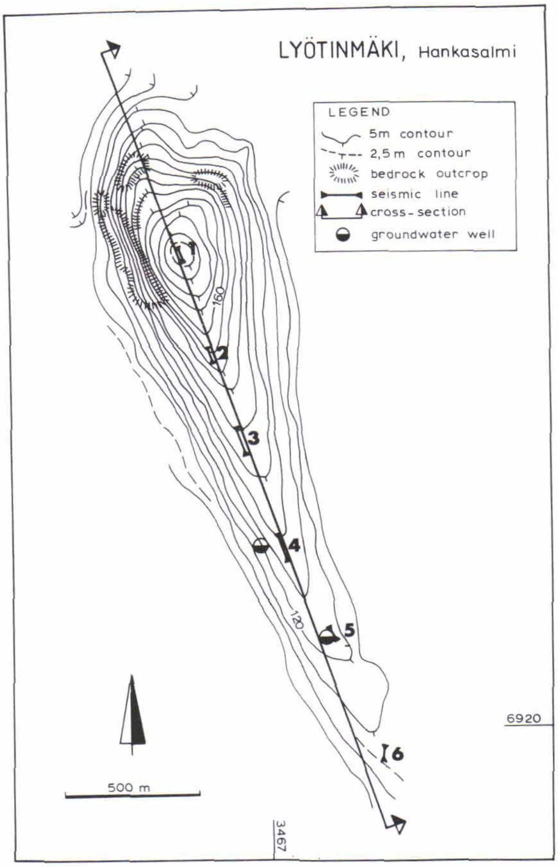

Fig. 2. The crag and tail of Lyötinmäki.

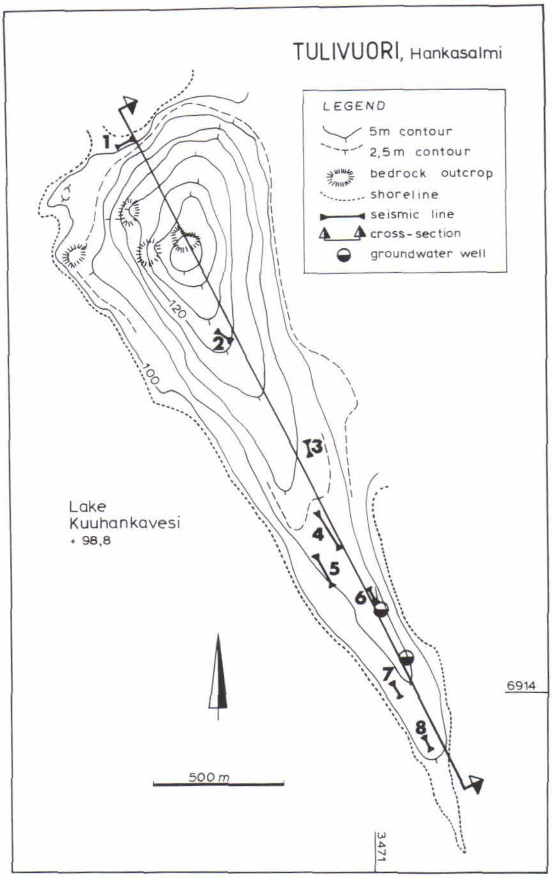

Fig. 3. The crag and tail of Tulivuori.

signal from an impact point. This means that the signals can be added to each other so that a series of identical weak signals can produce a strong final signal.

The seismic soundings were done with an in-line profiling method. Most of the seismic lines were on roads or paths on the top of the ridges (Figs. 2, 3 and 4). Some lines were continuous whereas others were sporadic. The geophones were arranged at intervals of 5 m, which means that the length of a single line was 55 m. This 5 metre interval gives more exact information on soil and groundwater conditions than, for instance, a 10 metre interval. The offset impact points were generally 30 and/or 55 m beyond the ends of the lines. Some offset impact points were 70 and 90 m beyond the ends of the lines. The longest distance between an impact point and the nearest geophone was 125 m. Because of the remote location of the investigation sites and the fine weather, the background noise was minimal. Therefore, we could use maximum signal gains in the soundings. The soundings were done in August and September 1990 and in October 1991.

The seismic data was preliminarily interpreted in the field with a programmable pocket calculator. We picked up the travel time values (breaks) from the seismograph screen and drew the time-distance graphs by hand. The thicknesses of the soil layers at the ends of the seismic lines

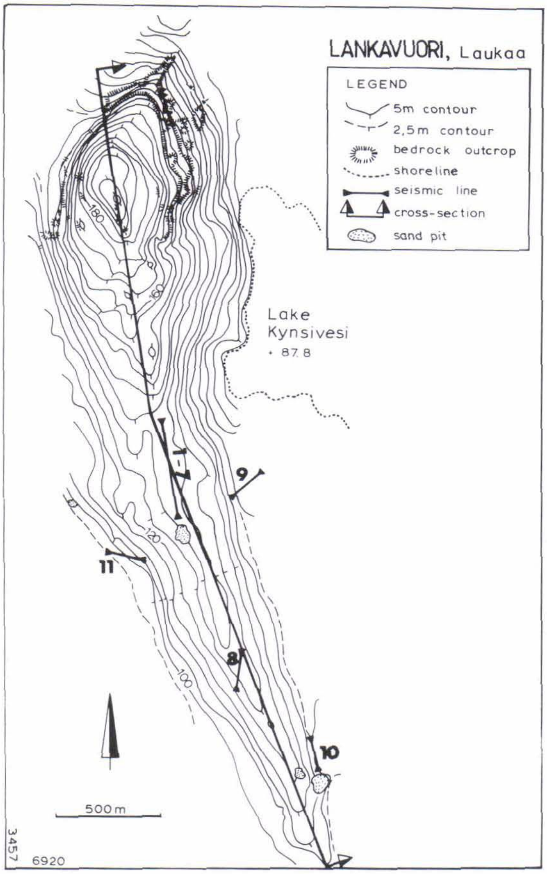

Fig. 4. The crag and tail of Lankavuori.

Fig. 5. The 12-channel hammer refraction seismograph.

were calculated with the intercept time method. The true velocities of the soil layers and those of the bedrock were calculated, if possible, with the mean-minus-T -method (e.g. Mäkelä 1989, Sjögren 1984).

If the depth of the bedrock could not be directly calculated with the data from the end impact points, it was undirectly calculated with the data from the offset impact points. These calculations, however, require reliable bedrock travel times from the offset impact points. The data from these offset impact points were appended on the time-distance graphs of the end impact points as a function of the distance between the ends of the seismic lines and the offset impact points. This method can only be applied in areas where soil conditions do not vary significantly. Despite these restrictions, this method generally gives reliable information on the depths of bedrock (e.g. Saarenketo 1988).

Sometimes we received no bedrock travel time signals, not even from the offset impact points. In these cases the minimum depths of bedrock were calculated by appending imaginary bedrock velocity lines to the ends of the time-distance curves of the real data. When the bedrock velocities could not be calculated, we used 4000 m/s as a bedrock velocity in our calculations. This value was chosen because it does not give too large soil thicknesses (Sjögren 1984).

The seismic results have not been checked with drillings for technical reasons. To control our interpretations we measured the groundwater levels of the wells situated on the ridges.

Results

Lyötinmäki

The supra-aquatic summit of Lyötinmäki is capped by a soil layer which is from 2 to 4 m thick (L1, Table 1, Fig. 6). The seismic soundings suggest that the layer contains no groundwater. At the lee side of the crag the thickness of soil in-

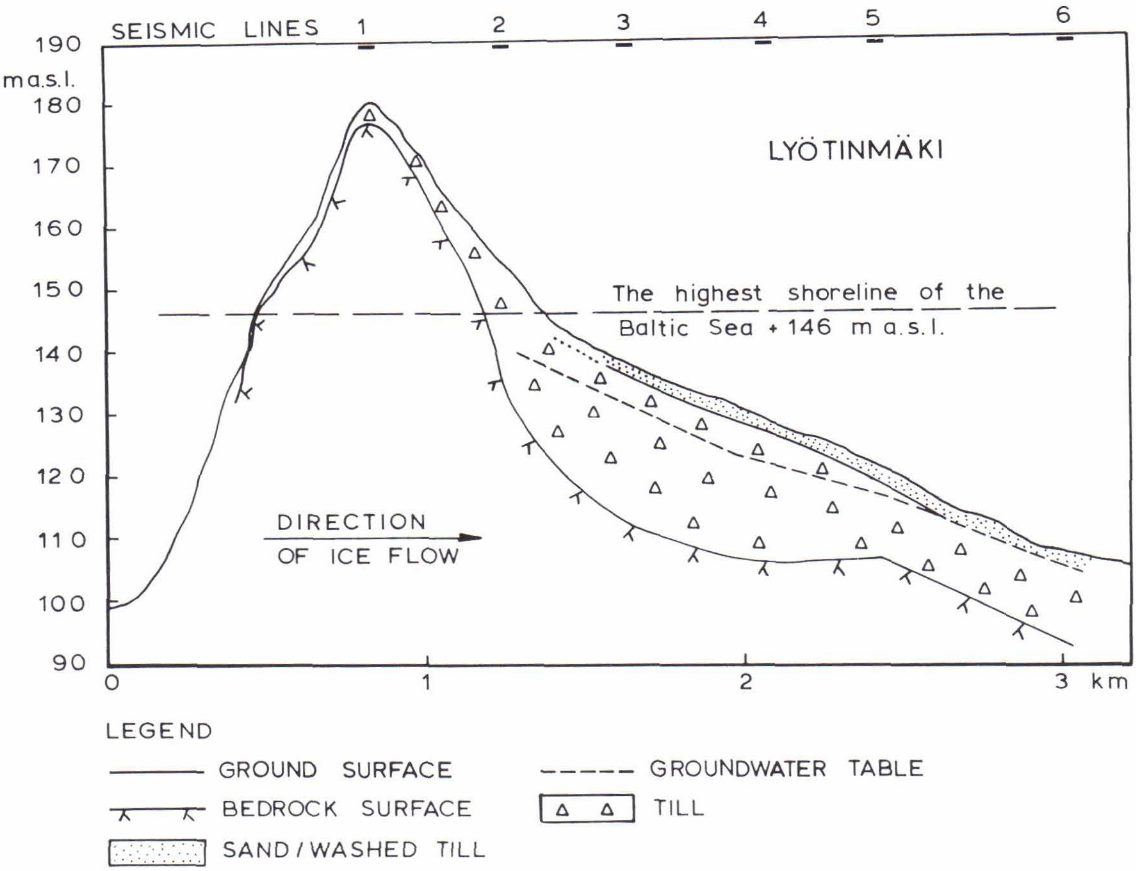

Fig. 6. The cross-section of Lyötinmäki.

creases clearly. The bedrock is at a depth from 20 to 24 m and the depth of the groundwater table is from 11 to 13 m below the seismic line 2. Leewards from the seismic line 3 the seismic soundings showed a 2 metre thick surface layer (seismic velocity from 330 to 510 m/s). The seismic velocity of the unsaturated layer below the surface layer is from 870 to 1200 m/s. The seismic velocity of the saturated layer varies from 1900 to 2200 m/s (seismic lines 3 – 6). At the end of the tail the groundwater table is from 1 to 3 m below the ground surface. The groundwater level of the well situated here is 1.4 m below the ground surface.

The bedrock is at its deepest from 20 to 26 m below the ground surface between the seismic lines 2 and 4. The lee side of the crag (L2) is clearly more fractured (seismic velocity 3100 m/s) than the stoss side (L1, 4650 m/s).

Tulivuori

The summit of Tulivuori, which is more than 10 m below the highest shoreline of the Baltic Sea, is partly exposed. On the tail there is a surface layer between the seismic lines 2 and 8. Its thickness varies from 1 to 3 m and seismic velocity from 340 to 510 m/s (Fig. 7). The seismic velocity of the unsaturated layer below the surface layer varies from 750 to 1350 m/s (Table 2).

Table 1. The seismic results of Lyötinmäki (.... = groundwater table).

Seismic line	Seismic velocity m/s	Thickness m	Interpretation
1	V1 470 – 870	2.5 – 3.9	Till
	V2 4650	depth 2.5 – 3.9	Bedrock
2	V1 430 – 820	1.2 – 4.3	Till
	V2 870 – 1020	8.2 – 10.2	Till
	....	....	....
	V3 1710 – 2050	9.5 – 11.0	Till
	V4 3100	depth 20.5 – 24.0	Bedrock
3	V1 390 – 510	2.1	Sand/washed till
	V2 1100 – 1200	4.8	Till
	....	....	....
	V3 2200	19.3	Till
	V4 4000	appr. depth 26.1	Bedrock
4	V1 500	1.4	Sand/washed till
	V2 920 – 1050	4.9	Till
	....	....	....
	V3 1900	15.6	Till
	V4 3400	depth 22.0	Bedrock
5	V1 330 – 450	1.8 – 2.6	Sand/washed till
	....	....	....
	V2 1350 – 1580?	2.1 – 14.0?	Sand/loose till?
	V3 2200	9.8	Till
	V4 4000	appr. depth 14.4 – 15.8	Bedrock
6	V1 360 – 460	2.5	Sand/washed till
	....	....	....
	V2 2000	12.3	Till
	V3 3700	depth 14.7	Bedrock

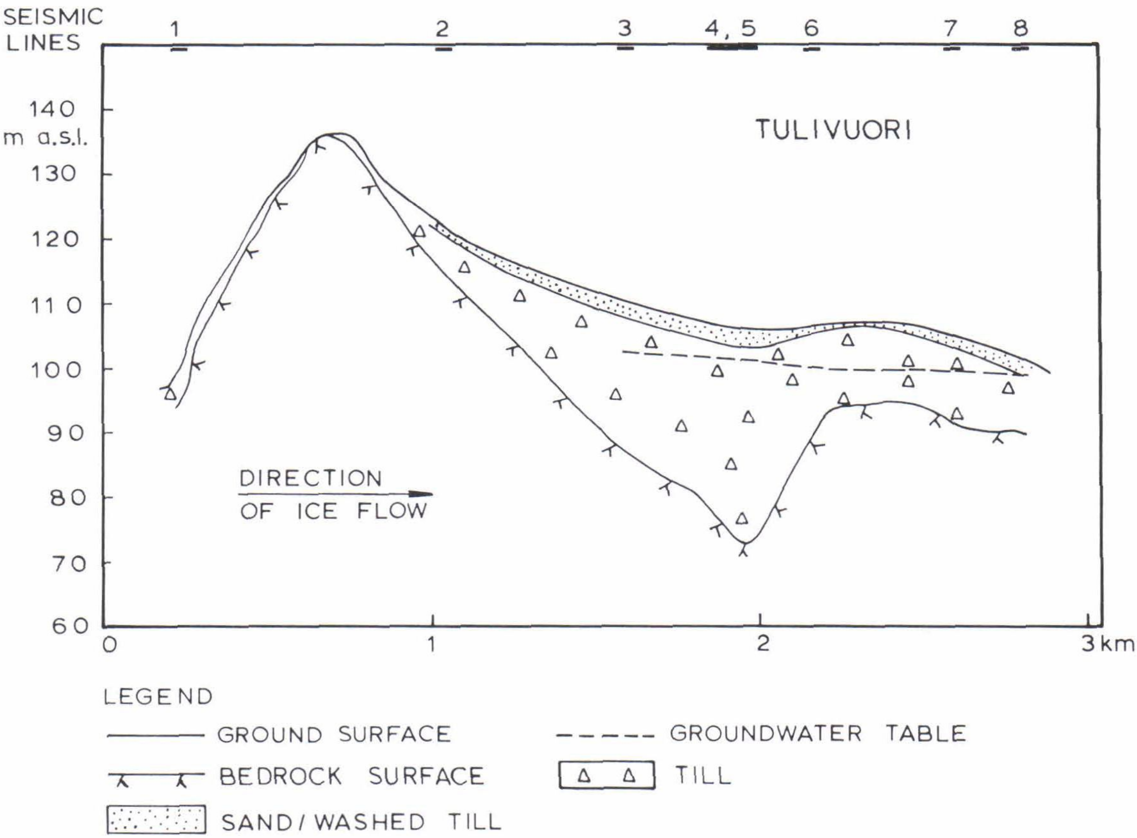

Fig. 7. The cross-section of Tulivuori.

Table 2. The seismic results of Tulivuori (.... = groundwater table).

Seismic line	Seismic velocity m/s	Thickness m	Interpretation
1	V1 390	1.7	Sand/washed till
	....	....	....
	V2 2100	3.1	Till
	V3 4000	appr. depth 4.7	Bedrock
2	V1 490–510	1.4	Sand/washed till
	V2 750–940	5.2	Till
	V3 2750	depth 6.6	Bedrock
3	V1 350–460	2.4–2.6	Sand/washed till
	V2 1200–1220	5.1–5.3	Till
	....	....	....
	V3 2040–2060	12.0–13.5	Till
	V4 5400	depth 19.7–21.2	Bedrock
4	V1 430	2.1–2.5	Sand/washed till
	V2 1200	2.8	Till
	....	....	....
	V3 1730–2000	23.0–26.0	Till
	V4 2700	depth 28.0–30.0	Bedrock
5	V1 490–500	2.9	Sand/washed till
	V2 1150–1350	3.3	Till
	....	....	....
	V3 2150	25.0–26.0	Till
	V4 4000	appr. depth 32.0–33.0	Bedrock
6	V1 360	1.2	Sand/washed till
	V2 860	6.1	Till
	....	....	....
	V3 1930	appr. 6.5	Till
	V4 4000	appr. depth 13.7	Bedrock
7	V1 340–390	2.0–2.1	Sand/washed till
	....	....	....
	V2 1300–1750	3.7–6.4	Sand/loose till
	V3 2460	6.1–6.5	Till
	V4 4000–4900	depth 12.0–15.0	Bedrock
8	V1 350	2.5	Sand/washed till
	....	....	....
	V2 1680	9.7	Sand/loose till
	V3 4000	appr. depth 12.2	Bedrock

The seismic velocity of the saturated layer varies from 1730 to 2460 m/s. In the seismic line 7 there is an additional layer (seismic velocity from 1300 to 1750 m/s) below the groundwater table. The gradient of the groundwater table of Tulivuori is lower than that of Lyötinmäki.

The soil is at its thickest between the seismic lines 4 and 5. The bedrock is 33 m below the ground surface at its deepest. The bedrock rises sharply in the lee side of the ridge. This can also be seen in the field as a slight rise of the tail. The contours of the basic map, however, do not show this in any way. The groundwater levels of the wells in the tail of Tulivuori coincide with the water levels obtained by the soundings.

The lee side of the crag (L2) is very fractured and probably weathered (seismic velocity 2750 m/s).

Lankavuori

All the seismic lines are below the highest shoreline of the Baltic Sea. The seismic lines 1–8 are on the top of the ridge and the lines 9–11 are

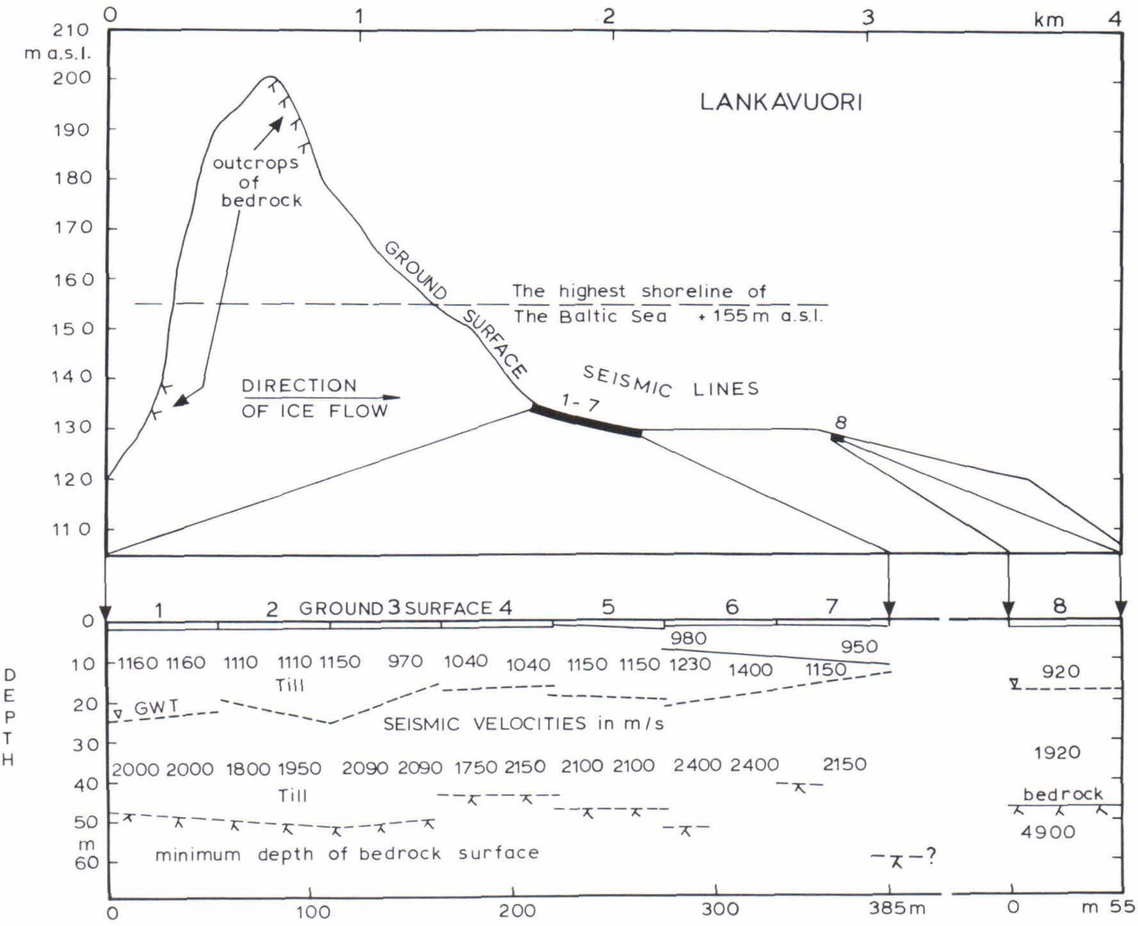

Fig. 8. The cross-section of Lankavuori.

on the flanks of the ridge (Fig. 4).

A from 1 to 2 m thick surface layer could be interpreted for all seismic lines. The seismic velocity of this layer is from 360 to 740 m/s. The surface layer is underlain by an unsaturated layer. The seismic velocity of this layer is from 970 to 1400 m/s (Fig. 8). In addition there is a layer of lower seismic velocity (from 920 to 980 m/s) below the surface layer in the seismic lines 6–8. Its thickness is from 6 to 17 m. The depth of the groundwater table in the tail is from 14 to 24 m. The seismic velocity of the saturated layer varies from 1750 to 2400 m/s.

The bedrock was not detected in the seismic lines 1–7. The calculated minimum depth of bedrock was from 41 to 60 m. The only reliable observation of the bedrock was from the seismic line 8, where the bedrock is 47 m below the ground surface (Figs. 8 and 9).

At the flanks of the ridge the bedrock was detected only in the seismic line 11. The depth of bedrock is there 55 m. This suggests that the depth of the bedrock at the top of the ridge is 85 m at its largest. This estimate is supported by the seismic soundings in the line 9, where the soil is at least 43 m thick.

Table 3. Seismic velocities m/s of soil and rock types above and below groundwater table. 1 and 2 are from Finnish studies and 3 is from Swedish studies (Lahermo & Rainio 1972).

<table>
<tr><th rowspan="2">Soil type, fraction, rock</th><th colspan="3">Seismic velocity above groundwater table</th><th colspan="3">Seismic velocity below groundwater table</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td>humus-rich topsoil</td><td>200–500</td><td></td><td>300–500</td><td></td><td></td><td></td></tr>
<tr><td>clay</td><td rowspan="2">200–700
(1500)</td><td rowspan="2">600</td><td>300–600
(1200)</td><td rowspan="2">1200–1800</td><td rowspan="2">1275–1600</td><td>1100–1600</td></tr>
<tr><td>fine, medium silt</td><td rowspan="2">500–800
(1200)</td><td rowspan="2">1200–1500</td></tr>
<tr><td>coarse silt,
fine sand</td><td rowspan="2">200–800</td><td rowspan="3">350–850
400–950</td><td rowspan="2">1200–1800</td><td rowspan="3">1350–1850
1325–2100</td></tr>
<tr><td>medium, coarse sand</td><td>300–500</td><td>900–1500</td></tr>
<tr><td>gravel</td><td>400–1300</td><td>400–1200</td><td>1200–1800</td><td>1200–2000</td></tr>
<tr><td>loose sandy till</td><td>200–1300</td><td rowspan="2">450–1300</td><td>300–500</td><td>1200–1800</td><td rowspan="2">1650–2100</td><td>1200–1500</td></tr>
<tr><td>medium dense sandy till</td><td>700–1500</td><td>400–1200</td><td>1300–2000</td><td>1200–1600</td></tr>
<tr><td>dense sandy till</td><td>1500–2200
(2700)</td><td></td><td>1600–2800</td><td>2000–2500
(2700)</td><td></td><td>1600–2800</td></tr>
<tr><td>weathered bedrock</td><td>500–1500</td><td></td><td></td><td>2700–4000</td><td>2600–3800
(4000)</td><td>3000–4000</td></tr>
<tr><td>granite, gneiss</td><td></td><td></td><td></td><td>4500–5700</td><td>4100–5300</td><td>4500–5900</td></tr>
<tr><td>mica schist</td><td></td><td></td><td></td><td>4100</td><td></td><td></td></tr>
<tr><td>amfibolite, gabbro</td><td></td><td></td><td></td><td>6000</td><td>5600–5700</td><td>5500–6000</td></tr>
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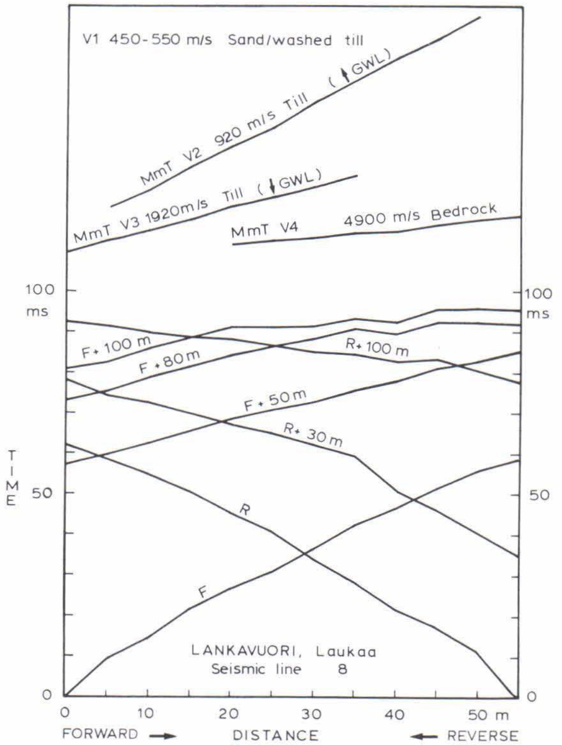

Fig. 9. The time-distance graph and the mean-minus-T -velocity curves for different layers in the seismic line 8 of Lankavuori.

Conclusions

The seismic velocities of the various layers correspond to those given in literature for sandy till (Table 3). The seismic velocities of the tills above the groundwater table are mainly from 900 to 1200 m/s. This means that the tills are comparatively loose. The seismic velocities of the tills below the groundwater table are generally from 2000 to 2200 m/s. This indicates that the tills are compact.

The seismic soundings also revealed the shore deposits on the crag and tail ridges. The thicknesses of the shore deposits vary from 1 to 3 m and their seismic velocities are from 330 to 870 m/s. The fractured bedrock at the lee sides of the crags reflects the intensity variations of the glacial erosion.

The groundwater table can lie deep below the ground surface in the tails. In Lankavuori, for instance, the calculated maximum depth of the groundwater table is 24 m. This indicates that the tills have relatively high hydraulic conductivities. These are clearly lower, however, than those of esker soils (sand, gravel). Therefore, crag and tail ridges are not suitable for large-scale water supply. On the other hand, the groundwater intake of Leivonmäki commune is constructed in a crag and tail ridge. The yield of this intake is 60 m^3/d (Keski-Suomen vesipiiri 1982). According to Salmi *et al.* (1991) the shore deposits of drumlins are in a key position when the groundwater resources are considered.

The calculated thicknesses of the tills in the ridges were 55 m at their largest. The tills in Lankavuori are probably even thicker than that, perhaps 85 m. Such great thicknesses are, however, rare in crag and tail ridges. It is likely that the tills are at their thickest in large ridges. The thicknesses of the tills decrease leewards as the ridges get lower and merge into the surroundings.

Seismic sounding is a simple and effective preliminary method to investigate soil thicknesses. It is a valuable research method especially in till areas where drillings are often hindered by compactness of till and by cobbles and boulders. On the other hand the crag and tail ridges may contain, for instance, sorted deposits or lenses. These are not detected by seismic soundings if their seismic velocities are lower than those of tills. The coarseness and sorting of tills cannot be determined exclusively by seismic soundings.

The depths of bedrock obtained in this study are, so far, the record depths of hammer refraction seismics in Finland. The interpretations have not, however, been checked with drillings. In Lankavuori the depth of bedrock must be determined by explosive refraction seismics because of the great thicknesses of the tills.

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