BOREAL ENVIRONMENT RESEARCH 22: 277–298
ISSN 1797-2469 (online)

Helsinki 2 June 2017

GIS-based 3D sedimentary model for visualizing complex glacial deposition in Kersilö, Finnish Lapland

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Received 19 Jan. 2017, final version received 19 Apr. 2017, accepted 28 May 2017

Åberg A.K., Salonen V.-P., Korkka-Niemi K., Rautio A., Koivisto E. & Åberg S.C. 2017: GIS-based 3D sedimentary model for visualizing complex glacial deposition in Kersilö, Finnish Lapland. *Boreal Env. Res.* 22: 277–298.

Complicated Quaternary sediment strata have been preserved within the ice-divide zone of northern Finland because of weak glacial erosion. Geographic Information System (GIS) databases, 3D modelling and ground penetrating radar surveys were used to construct the 3D structure of unconsolidated sediments and bedrock topography for Kersilö, Sodankylä, to provide information for freshwater management and environmental studies in the mineral exploration area. The model was created using a combination of explicit and implicit modelling covering an area of 10.5 km^2. The surficial deposits in the study area are a few metres thicker than their average thickness in northern Finland. They include three till units and four sandy or gravelly units. Fluvial action has repeatedly deposited sorted sediments in the channel valley of the Kitinen river. Basins in the bedrock have preserved thick sediment packages (> 15 m), indicating that the bedrock topography controls the sedimentary features. Aquifers in the area are small and disconnected, and perched aquifers exist due to the low hydraulic conductivity of interlayered tills.

Introduction

It has long been known that Quaternary deposits in central Lapland represent complicated strata displaying a variety of geological events and phenomena. Studies of their characteristic features also have a long history. The first recorded observations on weathered bedrock in Finnish Lapland date back to the beginning of the 20th century (Rosberg 1908). The complicated glacial history was evidenced by discoveries of multiple till sections all over central Lapland that were reported, for example, in studies by Kujansuu (1967), Korpela (1969), Hirvas *et al.* (1977), Hirvas (1991) and Sarala *et al.* (2015). A very active research phase took place in the 1970s, when the Geological Survey of Finland (GTK) started extensive field campaigns for ore prospecting, including targeted geochemical sampling and systematic test pit examinations; about 1400 test pits were dug and studied (Hirvas *et al.* 1977, Pulkkinen 1983).

During the last glaciation, the Weichselian, central Lapland was most of the time part of a continental ice-divide zone characterized by frozen-bed conditions (Kleman and Glasser 2007), weak glacial erosion (Penttilä 1963, Kujansuu 1967) and deposition by meltout processes

Editor in charge of this article: Heikki Seppä

(Johansson *et al*. 2011). This led to the preservation of geological features such as abundant weathered bedrock, relict landscapes, numerous till units and interbedded unconsolidated sorted sediments comprising gravels, sands, silts and even organic sediments [e.g. Helmens *et al*. (2000), Hättestrand and Stroeven (2002), Helmens *et al*. (2007), Sarala *et al*. (2016)].

Overall, on average the unconsolidated sediments that lie above the solid crystallised bedrock in Finnish Lapland are very thin, and typically < 6 m (Maijanen *et al*. 2008). Tills were mostly deposited during the Weichselian glaciation, but a few till units have been proposed to be correlated with the Saalian glaciation (Hirvas 1991). More than half of the interglacial-type subtill sediment sites found in Finnish Lapland are located within the municipality of Sodankylä (Hirvas 1991), where our study area was located.

Recent studies indicate that the Weichselian glaciation in northern Finland consisted of at least four glaciation events interrupted by ice-free interstadials (Johansson *et al*. 2011, Salonen *et al*. 2014, Lunkka *et al*. 2015). The most notable ice-free depositions in central Lapland are located at Naakenavaara and Tepsankumpu in Kittilä (Hirvas 1991), Rautuvaara in Kolari (Lunkka *et al*. 2015) and Sokli in Savukoski (Helmens *et al*. 2000, Helmens *et al*. 2007) (Fig. 1). Naakenavaara has been interpreted to represent the Holsteinian interglacial or even an older ice-free event (Hirvas 1991, Aalto *et al*. 1992, Saarnisto and Salonen 1995), and the Rautuvaara site was previously known as a type section for the northern Fennoscandian late Middle and Late Pleistocene deposition (Hirvas 1991). However, it has recently been denoted as a Weichselian site (Lunkka *et al*. 2015).

A systematic analysis of GIS-formatted databases can be used to interpret geological structures and can be applied to investigate large-scale sedimentary systems (Wycisk *et al*. 2009, Johnson *et al*. 2015, Sarala *et al*. 2015). The 3D shape and continuity of geological structures can be accurately studied by combining modern computer programs, LiDAR (Light Detection and Ranging) elevation models and geophysical information, such as ground penetrating radar (GPR) data, with more traditional mapping methods. This makes it possible to calculate the volumes of sediments and apply the information in groundwater studies (e.g. Wycisk *et al*. 2009).

In Finland, shallow glacial drift aquifers provide the majority (ca. 70%) of the public water supply. Since groundwater flow is dependent upon the thickness and internal structure of the sediments and the topography of the underlying bedrock, 3D geological modelling [e.g. Ross *et al*. (2005), Skyttä *et al*. (2015)] has been used to characterize the subsurface architecture and complexity of aquifers for hydrogeological modelling and water management. Moreover, there is an ongoing general re-evaluation of aquifers in Finland based on a new aquifer classification (Act on Water Resources Management 1263/2014).

Our study site in Sodankylä (northern Finland) is the target area of intensive exploration activity due its ore potential. A Cu-Ni sulphide deposit named Sakatti (Brownscombe *et al*. 2015) has been discovered. Therefore, new, additional drilling data were available and there was also interest in studying the water resources prior to possible mining activities.

Bearing all this in mind, the first aim of this study was to apply a combination of tools to depict and visualize the complicated sediment architecture and associated sedimentary environments within the ice-divide zone of Finnish Lapland. This combination of a new 3D model and a GIS database enabled new interpretations of sediment thicknesses, sedimentary basins and the distribution of sediments. Another goal was to evaluate the applicability of large, old target geochemical sampling data in the present 3D modelling approach. The more specific objective of this study was to examine how 3D modelling can be applied to construct the complicated sediment package that has been deposited in the Sodankylä study area, and how this model can be introduced into aquifer characterization and classification, as well as freshwater management in the area.

Study area and geological setting

The Kersilö study area in the municipality of Sodankylä (northern Finland) covers an area of 20 km by 18 km (X: 482 000–500 000,

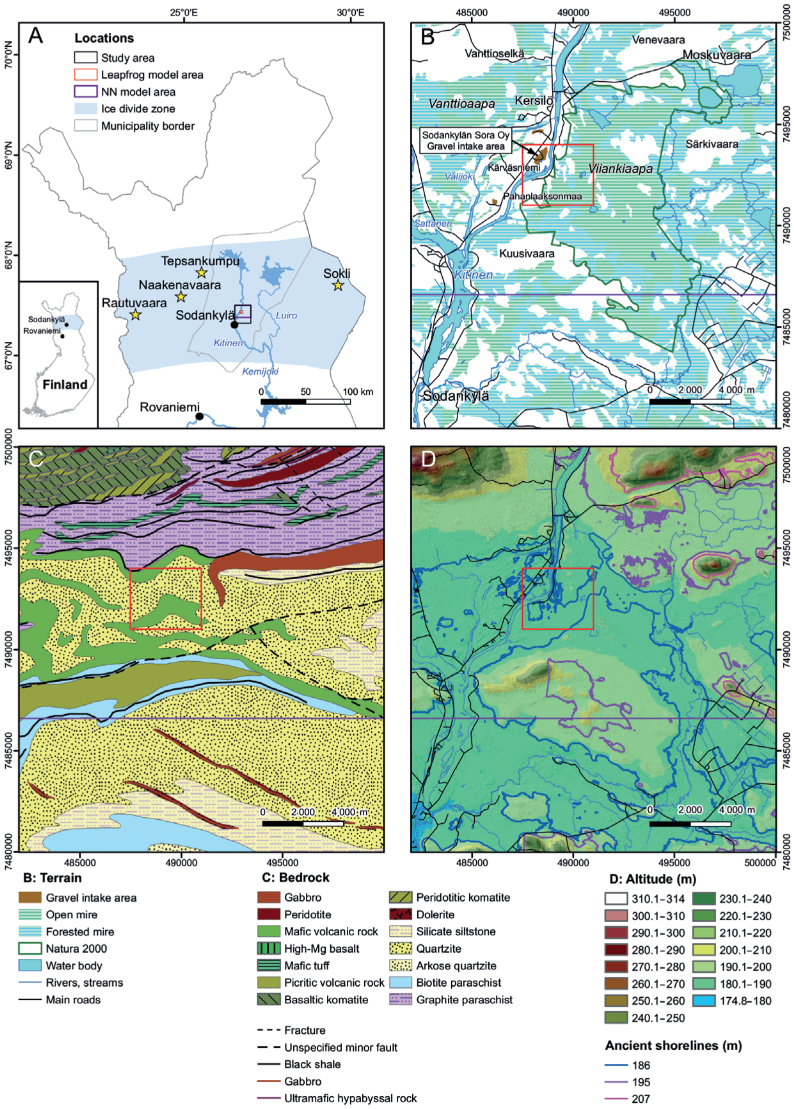


Fig. 1. (**A**) Location of the study area. Stratigraphical sites mentioned in the text are marked with yellow stars. (Sources: rivers (EU water formations) © Finnish Environment Institute (SYKE), modified and reproduced with permission from the copyright owner; administrative borders © National Land Survey of Finland, modified and reproduced with permission from the copyright owner). The ice divide zone is modified after Johansson *et al.* (2011) and Hirvas (1991). (**B**) The study area and 3D detailed model area. (Source: terrain elements (1:100 000/1:250 000) © National Land Survey of Finland, reproduced with permission from the copyright owner). (**C**) A bedrock map of the Kersilö area. (Source: bedrock map (1:200 000) © Geological Survey of Finland, modified and reproduced with permission from the copyright owner). (**D**) The topography and ancient shorelines of the Kersilö area. Shorelines: Phases 1 (207 m) and 5 (195 m) of Moskujärvi ice lake, Ancylus Lake 186 m (Johansson and Kujansuu 2005). (Sources: terrain elements (1:100 000/1:250 000) © National Land Survey of Finland, reproduced with permission from the copyright owner; LiDAR DEM © National Land Survey of Finland, modified and reproduced with permission from the copyright owner.

Y: 7 500 000–7 480 000 in EUREF-FIN TM35 coordinate system; *see* Fig. 1). The study area is a relatively flat undulating peneplain at an altitude of 180–200 m above sea level (a.s.l.), but a few higher hilltops dominate the northernmost part: Vanttioselkä (314 m), Venevaara

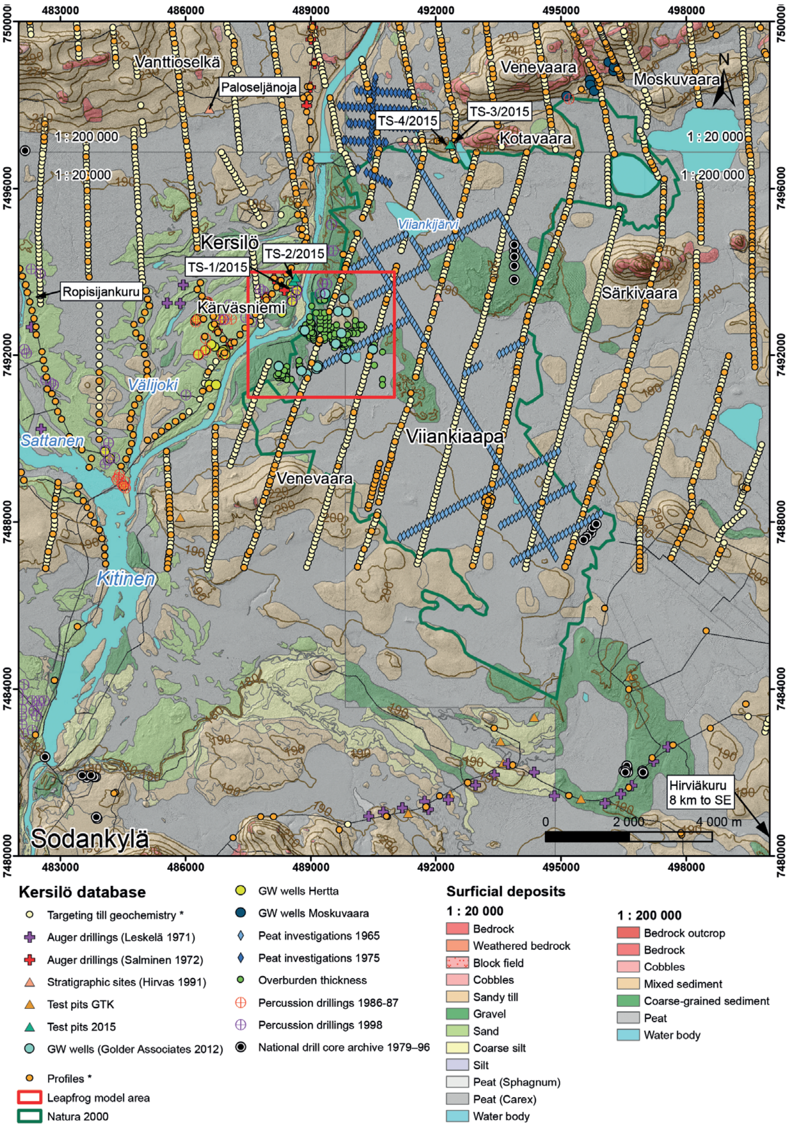


Fig. 2. The coverage of the Kersilö database on a map of surficial deposits (1:20 000 and 1:200 000; source © Geological Survey of Finland, modified and reproduced with permission from the copyright owner). The reference for each original database is mentioned in Table 1. The Paloseljänoja site was used as a reference for preliminary stratigraphy. Test sites TS-1/2015 and TS-2/2015 were studied during a field campaign in 2015. *Full profiles in the targeting till geochemistry database. (Sources: contours (1:100 000) © National Land Survey of Finland, reproduced with permission from the copyright owner; targeting till geochemistry and National drill core archive © Geological Survey of Finland, Modified and reproduced with permission from the copyright owner).

(273 m) and Särkivaara (286 m) (Fig. 1B). The mean elevation is 192 m a.s.l. and in most of the area (~93%) it is less than 210 m a.s.l.. The Kitinen river runs through the terrain from north to south. The lowest areas, below 180 m, are located in the Kitinen valley in the SW corner of the study area.

Surficial deposits

The whole of the study area has been mapped for its Quaternary deposits. The first mapping was conducted by Kujansuu (1966) at the scale of 1:400 000. Since then, two updated maps have been compiled for the Sodankylä region. Väisänen and Maunu (2004) prepared a map of surficial deposits at the scale of 1:20 000, and Räisänen (2014) updated the most recent Quaternary map, applying the advantages of LiDAR DEM (digital elevation model generated with LiDAR), at the scale of 1:25 000.

Surficial deposits in the study area consist mainly of till, sand, gravel and peat. Extensive sand and gravel deposits cover the Kitinen river valley and the Kärväsniemi area (Fig. 2). The hills Vanttioselkä, Venevaara and Särkivaara are covered by till (Fig. 2). Bedrock outcrops are common, especially in the northern part of the study area on the slopes of the hills. Another distinctive feature is the abundance of weathered bedrock sites in the area (Hirvas *et al*. 1977, Gustavsson *et al*. 1979).

Peat extensively covers the flat floodplains outside the river valley (Lappalainen 1970). The average peat thickness is 2.3 m (max. 5.7 m). Peatlands lie at altitudes of 180–200 m a.s.l., and rarely reach the altitude of 207 m, which was the highest level of the Moskujärvi ice lake (Johansson and Kujansuu 2005) (*see* Fig. 1D).

Bedrock

The bedrock of the study area had been mapped by Mikkola (1937) at the scale of 1:400 000, and later at the scale of 1:100 000 by Tyrväinen (1983), and at the 1:200 000 scale (digital map) by the Geological Survey of Finland (Fig. 1C). The bedrock of the study area is Precambrian and mainly consists of rocks belonging to the Karelian supergroup (Simonen 1980, Hanski and Huhma 2005), which are a part of the Palaeoproterozoic Central Lapland Greenstone Belt. Mafic and ultramafic volcanic rocks dominate the western and northwestern parts of the Kersilö area (Fig. 1C). The belt also includes quartzites, micashists, peridotites and gabbros. A notable structural feature of the bedrock is the almost west-to-east lineation in fractures and foliation (Tyrväinen 1980, Räsänen 2008), which is also visible in aeromagnetic anomaly maps of the area (Peltoniemi 1988, Airo 2005).

Glaciation history of the Sodankylä area

Recent studies suggest that the Scandinavian Ice Sheet (SIS) covered the study region at least two and perhaps even four times during the Weichselian glaciation (Johansson *et al*. 2011, Lunkka *et al*. 2015). New optically stimulated luminescence (OSL) age determinations by Sarala *et al*. (2015) indicate that SIS reached the area during the Early Weichselian, as indicated by a delta-like landform deposited on the western side of the rivers Kitinen and Sattanen. However, no confirmed evidence of Middle Weichselian deposits was found in the Sodankylä region (Hirvas 1991, Sarala *et al*. 2015).

Indications of at least two ice-free events have been detected in Sodankylä, both interpreted to be of Eemian age. The Paloseljänoja site (Hirvas 1991, Eriksson 1993) is located close to the village of Kersilö and hosts an interglacial gyttja layer underlain by a thin silt layer and two till units. The gyttja was deposited *in situ* and its pollen content suggests a late Eemian origin (Hirvas 1991). The pollen stratigraphy of the Paloseljänoja gyttja correlates with the Tepsankumpu interglacial (Hirvas 1991). Another site with interglacial-type subtill gyttja layers has been observed in the northern part of the Viiankiaapa mire (Fig. 1B) (Hirvas 1991).

According to Hirvas (1991), most interglacial deposits in Lapland are located within the borders of Sodankylä municipality (*see* Fig. 1), and interglacial deposits are often deposited at lower altitudes than interstadial deposits. In addition, the average thickness of interglacial deposits is greater than that of interstadial deposits. Being older, the interglacial deposits often lie much deeper than the interstadial deposits.

Deglaciation

Deglaciation of the Sodankylä region was described by Johansson and Kujansuu (2005). They determined that the Sodankylä area, including the Viiankiaapa mire, was a part of Moskujärvi ice lake (Fig. 1D), which covered an area of over 400 km^2 approximately 10 400 years ago. The ice lake was at its maximum level at 207 m a.s.l. as the ice margin withdrew from the present Viiankiaapa basin. In its oldest phase, the Moskujärvi ice lake drained towards the Luiro valley in the east. Later, as a result of glacier melting, the drainage direction turned southwards through Hirviäkuru gorge (8 km south of the study area), and the ice lake level lowered to 195 m. This is indicated by the level of the Matarakoski delta, which was deposited ca. 10 300 years ago (Johansson and Kujansuu 2005).

Later, after the glacier had melted from the study area, Viiankiaapa became connected to

Ancylus Lake ca. 10 300–10 200 years ago. The highest shoreline at that time was at 186 m (Johansson and Kujansuu 2005).

Material and model input data

Two types of input data were used for this study: (1) two GIS databases: the Kersilö database created as a part of this study and containing available percussion and auger drilling data from the study area (*see* Table 1), and the BOT (base of till) database courtesy of AA Sakatti Mining Oy which included unconsolidated sediment thickness information; and (2) data from a ground-penetrating radar (GPR) survey.

Altogether, 45 km of GPR survey profiles were acquired during this study. In addition to the Kersilö database, four new study sections, TS-1, TS-2, TS-3 and TS-4, were excavated during the field campaign in August 2015. TS-1 and TS-2 are located in a gravel intake area in Kärväsniemi (Fig. 2). The other two test pits are located in near Kotavaara. Descriptions of their lithology were included in the Kersilö database.

Ground penetrating radar (GPR) measurements

A GPR survey was performed within the current study to evaluate the continuity of the sediment layers and the bedrock surface. Acquisitions were conducted during field campaigns in spring and autumn 2015. GPR survey lines were located in the central part of the study area (Fig. 3: profiles used in modelling are indicated with pink and violet lines), and most of the profiles were measured along unpaved forest roads. The GPR surveys were performed by MALÅ Ramac ProEx, with 50 MHz and 100 MHz unshielded rough-terrain antennas. A GPS attached to a backpack for carrying the MALÅ control unit was used for positioning. The heights corresponding to the GPS coordinates were extracted from the LiDAR DEM elevation model. Before interpretation, the GPR data were processed with a conventional processing sequence that included amplitude, time-zero and topographic corrections, as well as various filtering steps. Velocities of 0.1 and 0.075 m ns^{-1} were used for time-to-depth correction. These velocities were

Table 1. The Kersilö database and BOT (base of till; source: AA Sakatti Mining Oy) data points (Fig. 2) that include all previous information on surficial deposits and the bedrock surface located within the area X: 482 000–500 000 and Y: 7 500 000–7 480 000.

	Observations	Data points[1]	Profiles	Source
Targeting till geochemistry	1936	3906	608	Gustavsson *et al.* 1979
Stratigraphic sites	2	11	2	Hirvas 1991
Auger drillings	22	60	22	Leskelä 1971
Auger drillings	12	20	12	Salminen 1972
Test pits GTK	12	27	12	Hirvas *et al.* 1977
Test sites 2015	4	18	4	This study
Groundwater wells	24	69	24	Golder Associates Oy
Groundwater wells (HERTTA database)[2]	38	38	1	HERTTA database[3]
Groundwater wells Moskuvaara[2]	12	27	12	Lapin ELY-keskus
Peat investigations 1965	311	311		Lappalainen 1970)
Peat investigations 1975	91	91		Lappalainen and Pajunen 1980
Overburden thickness	161	161		AA Sakatti Mining Oy
Percussion drillings 1998	49	152	49	Lapin ympäristökeskus
Percussion drillings 1986–1987	20	39	20	Lapin vesi- ja ympäristöpiiri
National drill core archive 1979–1996	36	36		Geological Survey of Finland
BOT observations	2181	2263		AA Sakatti Mining Oy
Total	4911	7229	766	

[1] Total sample (data point) count.

[2] Four wells are located outside the study area.

[3] http://www.syke.fi/fi-FI/Avoin_tieto/Ymparistotietojarjestelmat [in Finnish].

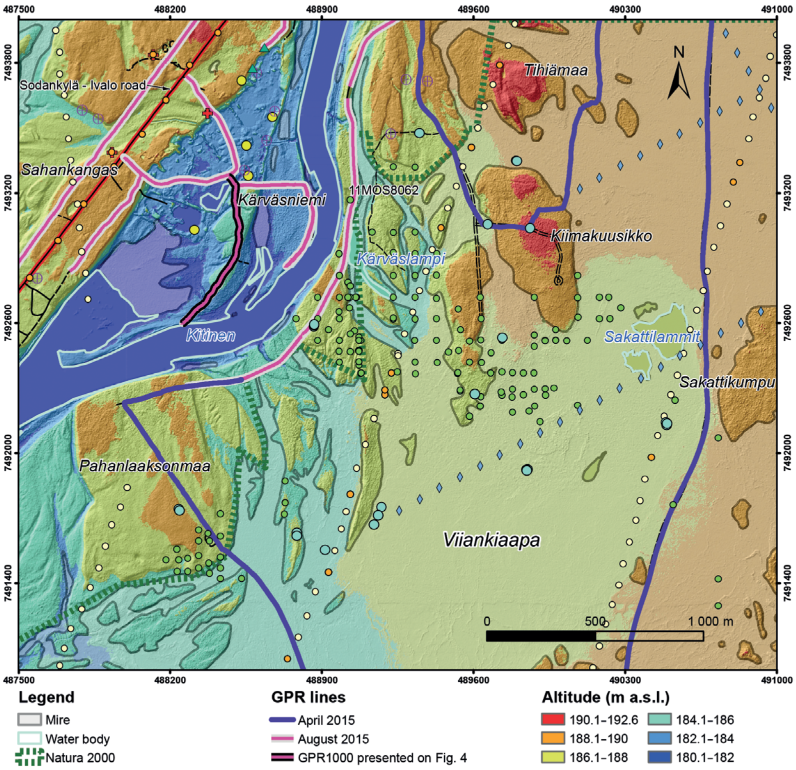


Fig. 3. The 3D model area with topography. GPR lines are marked with pink and violet lines. An explanation of the data points is provided in Fig. 2. (Sources: waterbodies (1:100 000) and roads (1:20 000) © National Land Survey of Finland, reproduced with permission from the copyright owner; conservation area and mire (1:100 000) and LiDAR DEM © National Land Survey of Finland, modified and reproduced with permission from the copyright owner.

determined using reference information from the drill cores located along the GPR profiles. For this study, the GPR data were used to interpret the bedrock surface and to verify the lateral distribution of stratigraphical units and their contact surfaces observed in the test sections and drill cores. For example, survey profile GPR1000 (Fig. 4) had a distinct signal of the bedrock surface and groundwater table, but it also indicated sedimentary features such as foresets.

Modelling methods

Leapfrog modelling

Two models with different distributions were generated in this study. The first was a full 3D model that included sediment units that exist in the vicinity of Kersilö, the bedrock surface and a model of the Kitinen river. This model (3 × 3.5 km; *see* Figs. 1 and 2) was generated with the software Leapfrog Geo® (ARANZ Geo). The second model was a GIS-based model of the bedrock surface and sediment thickness that was generated in a larger distribution (13.4 × 18 km).

Here, Leapfrog modelling was performed with a combination of explicit (traditional manual method of wire framing and digitising) and implicit modelling. Leapfrog Geo is an implicit model software package and is aimed at faster implicit modelling. Leapfrog uses geological data from drillings. These data are used to create contact surfaces that define the outlines of modelled units (*see* Lemon and Jones (2003) for further information). Leapfrog Geo uses the FastRBF™ (ARANZ Geo) interpolation method, in which the linear interpolant was chosen for interpolation of the contact surfaces. However, due to the uneven distribution of the data points in the Kersilö database within the Leapfrog model area and missing sediment information for over half of the data points, explicit modelling was used to enforce the modelling. Explicit modelling is used in software such as CAD (computer-aided design), where the modeller has to manually

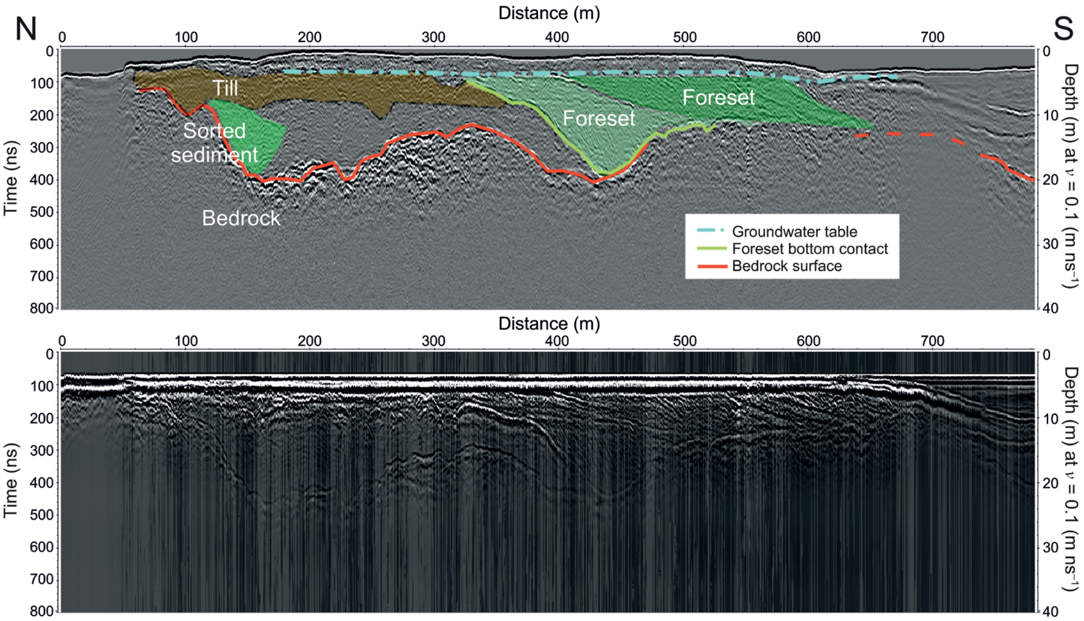


Fig. 4. An example of interpretation of GPR (above) and raw data (below) along profile GPR1000 (its location is shown in Fig. 3). The contact marked with a red line was used for bedrock surface modelling and the contact marked with a lime green line was used to model a contact of the sediment units 'middle sorted' and 'lowest sands and gravels'.

draw outlines for the modelled units. Combining the advantages of both styles, it was possible to generate a model of the surficial deposits and the bedrock surface in the Leapfrog model area.

For the purpose of Leapfrog modelling, the content of the Kersilö database was modified to some extent. The altitude of drilling from the ground surface was calculated from the LiDAR DEM. Some combinations and simplifications were made during the process. In some cases, information from two sub-databases of the Kersilö database were combined. The locations of the auger drilling data from Salminen (1972) are based on a targeting till geochemistry study, so their information was combined for Leapfrog modelling. If data points sharing the same location contained contradicting information, the location having more detailed sediment information or deeper drilling was chosen for the modelling. Due to the requirement for information on the bedrock in the modelling, a 1-m extra layer of bedrock was added to overburden thickness data as well as to the BOT drilling data (*see* Table 1) that included information on confirmed bedrock.

The area with the densest network of observations was chosen for the 3D modelling. The modelled area was 3 km by 3.5 km (10.5 km^2) and located within the coordinates X: 487 500–491 000 and Y: 7 491 000–7 494 000 (EUREF-FIN coordinate system). The model has a 10-m horizontal resolution. LiDAR elevation data from the National Land Survey of Finland were used to simulate a complete surface of the modelled area with a 2-m resolution. Overall, 2600 observations were used in modelling, of which half did not contain any sediment information and could only be used for bedrock surface modelling.

The sediment units chosen for the model were based on field observations from Kärväsniemi gravel pit sites TS-2/2015 and TS-1/2015 and the Paloseljänoja site from Hirvas (1991). As the geological data originated from different periods and multiple studies with various objectives and levels of detail, some generalization of the sediment stratigraphy was necessary. Sand and gravel units were always combined as sorted sediment layers. The top deposits included fines, sands, gravels and cobbles that overlie till layers.

Each of the subtill sand and gravel layers flanked by the same two till units were combined into one. Bedrock, peat and the Kitinen river were represented as single units in the 3D model. For modelling purposes, weathered bedrock was added to sediment units.

The units of the Leapfrog model and their relative chronology from the youngest to the oldest were as follows: Kitinen river, peat, top deposits, upper till, middle sorted deposits, middle till, lower sorted deposits, lower till assemblage, lowest sands and gravels, weathered bedrock, and bedrock.

The Leapfrog model was created in four steps. The bedrock surface model was generated as the first step, followed by the creation of surficial deposits, peat and Kitinen river models.

Leapfrog has two suitable contact types for modelling unconsolidated sediment units: the deposit type contact and erosion type contact. The erosion type (cuts an older contact) was used to model the bedrock surface and the bottom of the Kitinen river. All other contacts were created with the deposit type contact, which does not intersect the contact below.

The bedrock surface was generated using the Kersilö and BOT databases as input data combined with bedrock surface information derived from the GPR survey. Explicit modelling (manually drawn polylines) was used to cover the areas where topography or drilling data, with no confirmed bedrock observation, might indicate rough topography of bedrock. Manually edited areas are an estimation of the possible altitude of the bedrock, hence they should be treated as uncertainties in the model. Since the landscape often slightly follows the depressions of the solid rock, areas lacking drilling data were estimated using the shapes of the ground level (DEM) combined with information on bedrock surface interpretations from GPR lines. The bedrock surface from the Leapfrog model and the thickness of surficial deposits are shown as DEM in Figs. 5 and 6.

The next step was the generation of surficial deposit models. Altogether, three till layers (upper till, middle till and lower till assemblage) and four different sorted sediment layers (top deposits, middle sorted deposits, lower sorted deposits and lowest sands and gravels) and weathered bedrock were modelled. Explicit modelling was mainly used to depict all the modelled units. The Kersilö database was used as a reference in drawing the polylines reflecting the contacts between different sediment units. The most informative GPR profiles, such as line GPR1000, were also used as a reference in modelling the thickness of the sediment layers (Fig. 4).

The peat model was generated as a uniform organic deposit without any internal structures. Peat was modelled with two distributions: one for the Leapfrog model and another was the whole peat model of Viiankiaapa (Fig. 7A and K). First, manually drawn contours were generated with ArcMap covering the Viiankiaapa mire. These contours were used as an input for the natural neighbour interpolation method (Sibson 1981), and after this, the resulting raster was subtracted from the surface DEM to obtain altitudes of lower contact of peat instead of depths. Simultaneously, N–S direction polylines were generated to model the 3D peat deposit in Leapfrog. The interpolated raster surface that represented the lower contact of peat was used as a layer onto which the N–S direction polylines were set to obtain their elevation in Leapfrog. The final editing was manually conducted by extending the polylines in the western part of the Leapfrog model area where peat is presented in the surficial deposits map of GTK (base map of Fig. 2). The final surface of the lower peat contact was generated with FastRBF™ interpolation of Leapfrog from the edited polylines.

The Kitinen river was included in the model. A cross-section of the Kitinen river from an unpublished dataset courtesy of Kemijoki Oy was used to model the bottom of the river channel, and it was combined with the mapped edges of the river. The river bottom was also used as an additional reference for the bedrock surface in the vicinity of former rapids, which had disappeared due to regulation and damming of the river.

After the generation of sediment contact surfaces, the lower peat contact, the bedrock surface and the Kitinen river model were combined to form the final Leapfrog model.

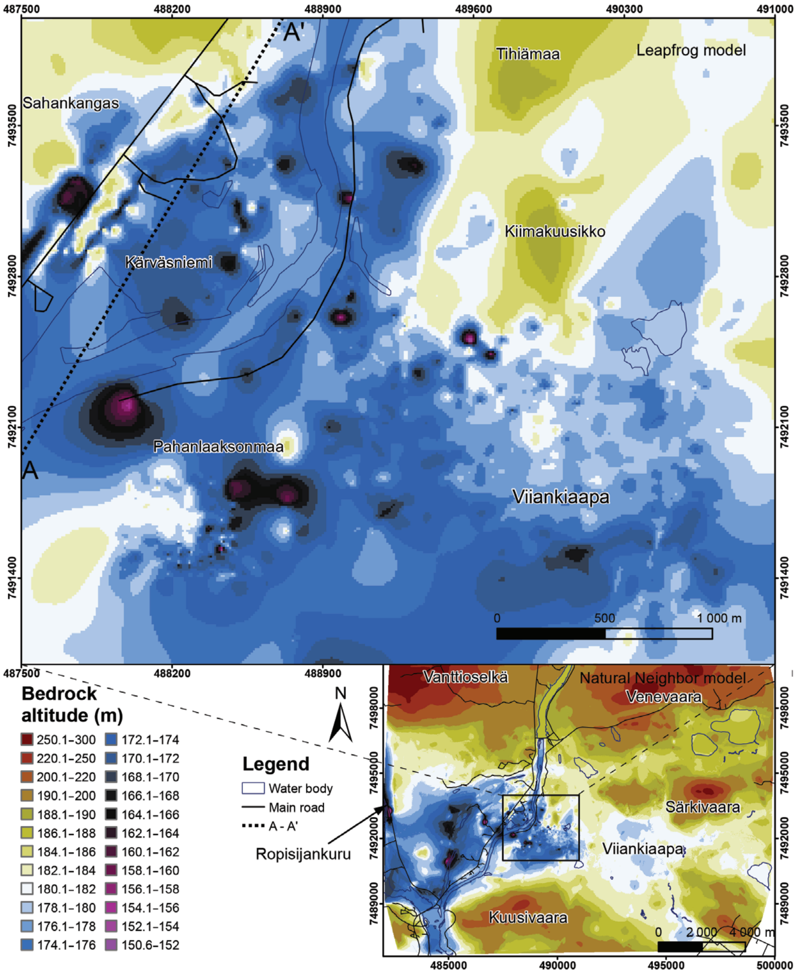


Fig. 5. The Leapfrog-modelled bedrock surface represented as DEM (above) and expanded NN interpolated bedrock surface map (below). The NN bedrock surface altitude was calculated by subtracting the NN sediment thickness model (*see* Fig. 6) from the LiDAR DEM. In the lower picture, the Leapfrog model lies atop the NN model. Cross-section A–A' is shown in Fig. 8. (Sources: waterbodies (1:20 000) and main roads (1:100 000) © National Land Survey of Finland, Reproduced with permission from the copyright owner).

Natural neighbour model of the unconsolidated sediment thickness and bedrock surface

In addition to the Leapfrog-based 3D model, an ArcMap-based unconsolidated sediment thickness model was generated to cover the whole study area (13.4 × 18 km, 241.2 km^2) (Fig. 1). The model coverage was limited to Y: 7 486 600 due to scarcity of data from the southern part of the study area. The natural neighbour (NN) method (Sibson 1981) was used to estimate the thickness of unconsolidated sediments in ArcMap. The NN model was generated using the Kersilö and BOT databases only to provide an overview of the unconsolidated sediment thickness. It was subtracted from the LiDAR DEM to obtain the bedrock surface elevation model for the whole study area.

Results

Bedrock surface DEMs

The altitude of bedrock topography varies from 190 to 148 m (mean = 177.5 m) in the detailed Leapfrog model area (Fig. 5). The highest altitudes are in the NW part in Sahankangas and on the hills (Kiimakuusikko and Tihiämaa). The lowest elevations are in Kärväsniemi, Pahanlaaksonmaa and in the middle parts of the modelled area. They form a visible depression that dominates the bedrock topography and is connected

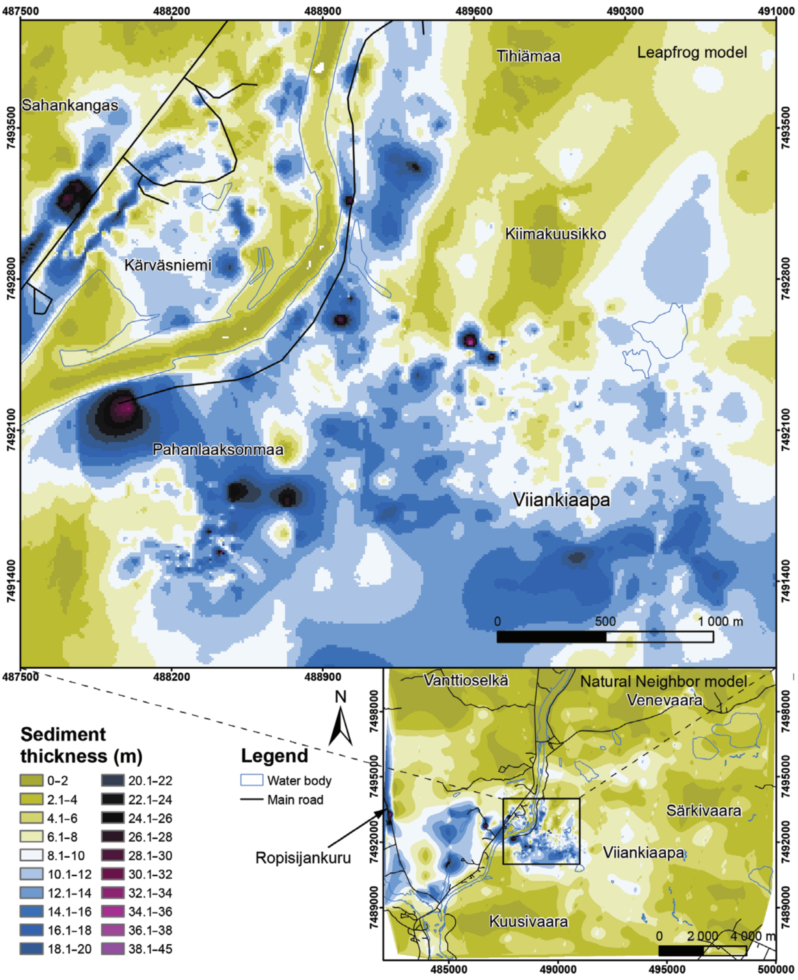


Fig. 6. Leapfrog-modelled sediment thickness map (above) and expanded NN interpolated sediment thickness map (below). The input data of the NN model were from the Kersilö database, excluding the peat thickness (*see* Table 1 for references). The drilling depth was assumed to correspond to the bedrock surface. In the lower picture, the Leapfrog model lies atop the NN model. (Source: waterbodies (1:20 000) and main roads (1:100 000) © National Land Survey of Finland, reproduced with permission from the copyright owner).

to the river valley, where the altitude is 178 m or less. A visible N-shaped depression is located beneath the eastern corner of Sahankangas. A depression around Pahanlaaksonmaa is visible in the model and it continues towards the Kitinen river (Fig. 5). The dominant W–E lineation of the bedrock (Tyrväinen 1983), which could be seen as W–E orientation of elevated areas, is not evident in the Leapfrog bedrock model due to the small size of the selected area (10.5 km^2).

In the NN model area, the topography of bedrock surface varies between 142 and 300 m (mean = 190 m). The W–E lineation is clearer in the NN model, which is indicated as lower altitudes in the middle parts and as the shape of the hill tops such as Särkivaara and Kuusivaara, which are elongated in a W–E direction (Fig. 5).

Table 2. Unconsolidated sediment thickness (m) from the Kersilö database and BOT within two distributions based on the drilling depth. Abbreviations: *n* = number of observations.

Distribution	*n*	Mean	Mode	SD	Range
NN model	4868	6.99	6.7	4.3	0–45
Leapfrog model	2561	8.95	9	4	0–45

Sediment thickness distribution

The thickness of the sedimentary package, including unconsolidated sediments and peat (*see* Table 2), was calculated using both models, and with two databases (Kersilö and BOT database) combined with two distributions (Leapfrog model and NN model). In the Leapfrog model, the thickness of the sedimentary package vary between 0 and 41 m (mean = 9.1 m, SD = 4.2 m). The sedimentary package is the thickest (41 m) in the surroundings of Pahanlaaksonmaa (Fig. 6). The sedimentary package is the thinnest in the river channel, where it is often absent, and on the till-covered hills Tihiämaa and Kiimakuusikko, where it is generally < 4 m. The preliminary thickness distribution of depositional units is shown in Fig. 7.

The mean sediment thickness calculated using the NN model was 4.9 m (SD = 3.0 m). The unconsolidated sediment thickness of the flat mire-covered plains varies from a few to ten metres. The thickest areas are in the valleys of the Kitinen river and the Välijoki and in the western part covered by the Viiankiaapa mire. In the NNW–SSE-oriented depression near Ropisijankuru there is also a notably thick (up to 33 m) package of sands (Fig. 6). The thinnest sediment layers are on the till-covered hills of Vanttioselkä, Venevaara, Särkivaara and Kuusivaara, being generally < 2 m.

According to the Kersilö and BOT databases, from which the southern part of the study area (south of Y: 7 486 600) was excluded due to scarcity of data, the average thickness the sedimentary package is 7 m. Within the distribution of the Leapfrog area, the average thickness is 9 m (Table 2), which corresponds to the average thickness obtained from the Leapfrog model. The thicknesses of 2 m and 9 m are most frequent in the databases (Table 2).

The unconsolidated sediments of the Leapfrog model include recent top deposits (three till layers and three subtill sorted sediment layers; *see* Fig. 7). According to the model, the volume of the unconsolidated sediment is 0.096 km^3 of surficial deposits within a 10.5 km^2 area (Leapfrog model), of which 59% of the volume is till and is 32% is sorted sediment; and the volume of peat is 0.0083 km^3 (9% of the volume). According to the NN model, the volume of surficial deposits in the 241.2 km^2 area is 1.2 km^3. The volume of Viiankiaapa peat (0.0603 km^3) in the NN modelled peat layer is an underestimation as compared with the value of 0.0907 km^3 given by Lappalainen and Pajunen (1980) who calculated the volume of the Viiankiaapa mire using the same data (from the years 1965 and 1975) as those used in our study.

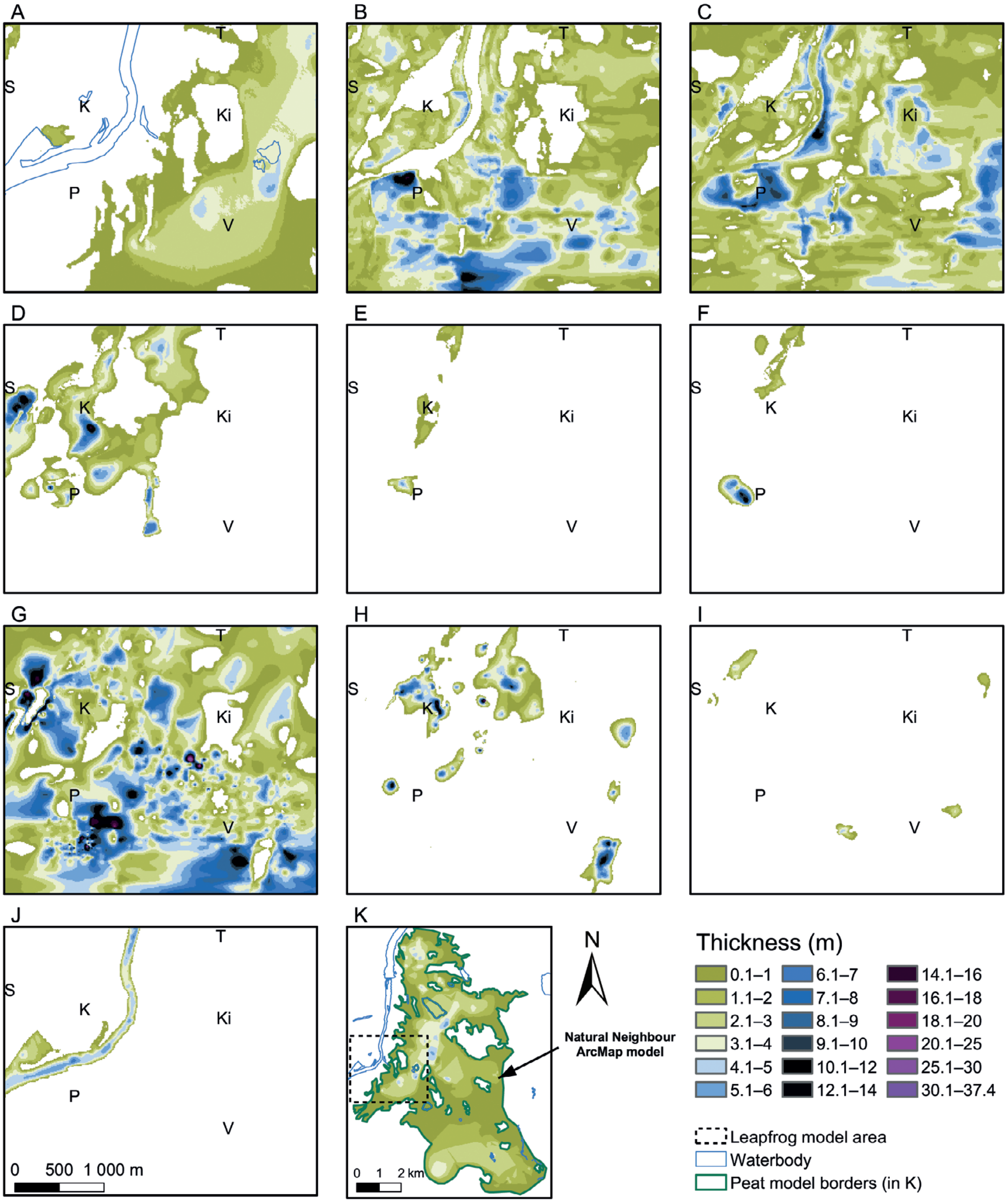
The distribution of unconsolidated sediments in the Kersilö area is uneven. The SE and E parts of the modelled area are covered by peat. Top deposits, which consist of sands and gravels, cover almost the whole model area (75% coverage) (Fig. 7B), but the eastern part is overlain by peat of the Viiankiaapa mire. Upper till is distributed almost everywhere (84% coverage; Fig. 7C), and it is partly exposed through top deposits. Middle sorted deposits (Fig. 7D) exist in the Kärväsniemi foreland and the Kärväsniemi gravel intake area, as well as on the eastern side of the Kitinen river between the river and till-covered Kiimakuusikko. In general, middle till and lower sorted deposits have a similar N–S-oriented distribution (Fig. 7E and F) measured in the Kärväsniemi foreland and Kärväsniemi gravel intake area, but lower sorted deposits are thicker and have a wider distribution. They both also continue towards the south to Pahanlaaksonmaa, but are absent from the eastern part of the model area. Lowest sands and gravels (Fig. 7H) are distributed in the Kärväsniemi gravel intake area, but also along the eastern flank of the Kitinen river. The most widely distributed layers are top deposits and the lower till assemblage (Figs. 7G, 8 and 9).

Weathered bedrock is scattered, and five main areas can be identified from the model (Fig. 7I). Altogether, the study area includes 208 weathered bedrock observations and 81 observations that contain information on subtill sediments (91 samples in total).

Discussion

Reliability of the Leapfrog model regarding bedrock surface and sediment thickness

The reliability of the Leapfrog model was evalu-



Ki = Kiimakuusikko, K = Kärväsniemi, P = Pahanlaaksonmaa, S = Sahankangas, V = Viiankiaapa

Fig. 7. The thickness of modelled units modelled with Leapfrog Geo: (**A**) peat, (**B**) top deposits, (**C**) upper till, (**D**) middle sorted deposits, (**E**) middle till, (**F**) lower sorted deposits, (**G**) lower till assemblage, (**H**) lowest sands and gravels, (**I**) weathered bedrock, (**J**) Kitinen, and (**K**) peat (whole Viiankiaapa). The peat model (**A** and K**)** was generated with two extents. The peat thickness of the Viiankiaapa mire was modelled with manually drawn depth contours and with NN interpolation from the contours (**K**). Unpublished peat investigations by the Geological Survey of Finland from 1965 and 1975 were used as a reference. The Leapfrog peat model (**A**) was modelled with polylines in Leapfrog Geo and the ArcMap-modelled peat layer (**K**) served as basis for the editing polylines. (Source: waterbodies (1:100 000) © National Land Survey of Finland, reproduced with permission from the copyright owner).

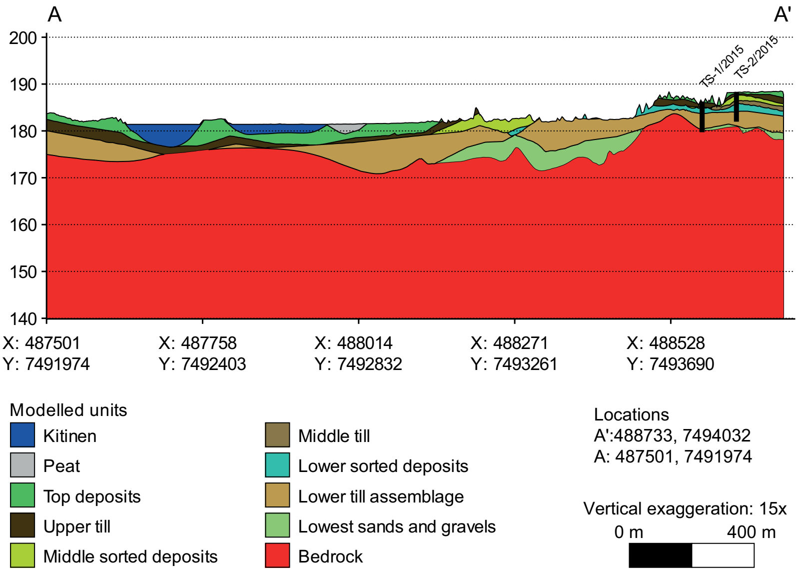


Fig. 8. A cross-section of the 3D model for the Kersilö area. The location of the cross-section is shown in Fig. 5. The reference sections TS-1 and TS-2 from the 2015 field studies are marked with black bars.

ated using reliability classes. The input data for the model were subjectively classified into six reliability classes concerning the model of bedrock altitude and surficial sediment thickness (Fig. 10 and Table 3). The most reliable drillings are those reaching bedrock, hence they were placed in reliability class 1. The most reliable GPR profiles were placed in class 2, and the GPR profiles with more uncertainties were placed in class 3. The data from drilling that did not extend to the bedrock surface were placed in class 4. The peat investigations of 1975 and 1965 were used to estimate the bedrock topography. They were placed in class 5, as they provide an indication of the rough bedrock topography only. The Kersilö database points that had missing depth information were placed in class 6 and they were not used in the modelling.

The classified Kersilö database points, BOT database points and GPR lines were interpolated with the NN method to visualize the reliability of the bedrock model (Fig. 10). The reliability of the model was highest near class 1 drillings. The interpolated surface of reliability classes (Fig. 10) indicates that the most reliable parts of the model are located in the Kärväsniemi gravel intake area, in the middle of Pahanlaaksonmaa and in the western corner of the Viiankiaapa mire. The class 2 GPR survey lines represent the topography of the bedrock surface well. Along these lines, the contact to bedrock was interpretable as a clear reflected signal. The velocities for time-to-depth conversion of the GPR profiles were determined using reference information from the drill holes located along the GPR profiles. The GPR profiles of class 3 did not contain as clear a reflected signal from the bedrock contact as the profiles in class 2 (i.e., the interpretation is to be considered less certain). Most of the model area, however, is included in reliability class 4, in which the bedrock altitude is less reliable.

The highest uncertainties recorded are in the NE corner of the detailed model area, where drilling data are scarce and the model probably overestimates the altitude of the bedrock surface north of the N-shaped depression due to the lack of reference data there.

The reliability surface (Fig. 10) does not consider the fact that the morphology of surficial deposits somewhat follows the rough topography of the bedrock, which generally improves the reliability of the model.

The bedrock surface model was constructed with an assumption that the depths of the drillings represent the bedrock surface or are close to it. Thus, the bedrock surface model represents the minimum thickness of surficial deposits. However, the high density drilling areas and GPR survey lines indicate high diversity

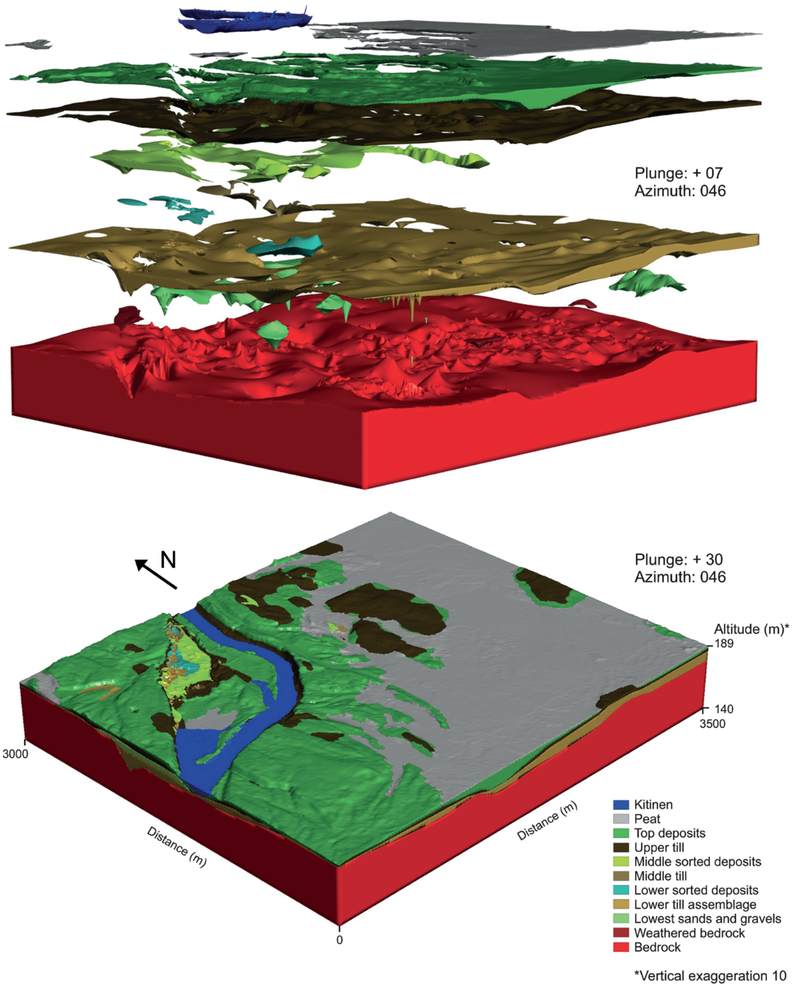


Fig. 9. A 3D Leapfrog model (below) with sediment units discussed in the text and an exploded view of the model (above). The location of the model area is shown in Fig. 1.

in the thickness of surficial deposits over short distances (< 20 m), leading to the fact that the interpolation in Leapfrog may also overestimate the thickness of surficial deposits in some parts.

Bedrock surface features

The topography of the modelled bedrock surfaces (Leapfrog and NN) shows certain distinct features that can be connected to the geology of the area. The modelled bedrock surfaces were compared with bedrock map of GTK and the aeromagnetic map. Some interpretations of basins and eminences were made (Fig. 11) based on the altitude of the bedrock surfaces. There is an east–west trend in structural elements of the bedrock (Tyrväinen 1980, 1983), which is also visible in large-scale features of the LiDAR DEM (Fig. 1D). The west to east lineation is visible in the bedrock surface models as the distribution of lowland area with altitudes < 186 m a.s.l. (Fig. 11). The models also indicate that the lineation of bedrock changes its direction to north–south in the vicinity of the Välijoki (Fig. 11). The elevated areas relate to gabbroic rocks in the north and to intermediate volcanic rocks in the south, which are more resistant to glacial erosion than black shales and peridotitic rocks occupying the central parts of the area.

It can also be noted that the river valley of Kitinen cuts through the area (Fig. 11, river influence area), and it appears to have caused overdeepening of the erosion level, especially in the central-western part of the area, where the bedrock surface is at its lowest level.

The basin from Pahanlaaksonmaa towards the Kitinen river (Fig. 11) indicates a weakness area in the bedrock that may be related to bedrock fracture zones.

Sediment thickness

The sediment thickness generally varies within 0–15 m. It is more than 15 m in 4% of observations within the NN model distribution (Kersilö and BOT databases) and in 6% of observations within the Leapfrog model distribution. The thick sediment package (> 15 m) in the Leapfrog model corresponds to fracture zones or depressions in the bedrock (altitudes < 172 m a.s.l.). The sediment thicknesses of less than 6 m also correspond to higher altitudes of the bedrock surface (> 182 m a.s.l.), except for the basin of the Kitinen river. The average thickness of the Leapfrog model area (9.1 m) is deposited

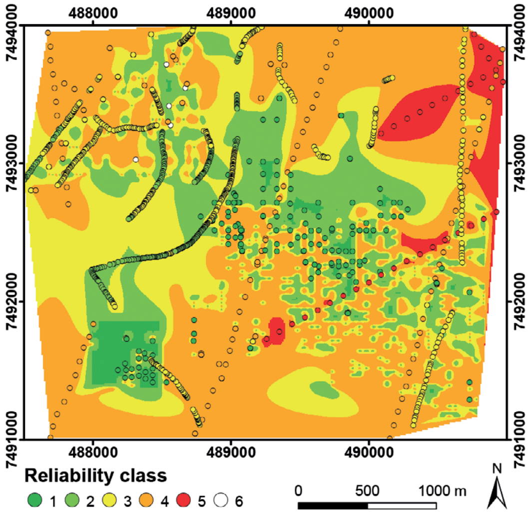


Fig. 10. Reliability of the databases used in modelling presented as an NN interpolation surface. Observation points of the Kersilö database and GPR survey are indicated with circles. BOT data points used in the analyses are not visible. Class 6 was not used in the interpolation. The reliability classes are explained in the text and in Table 3.

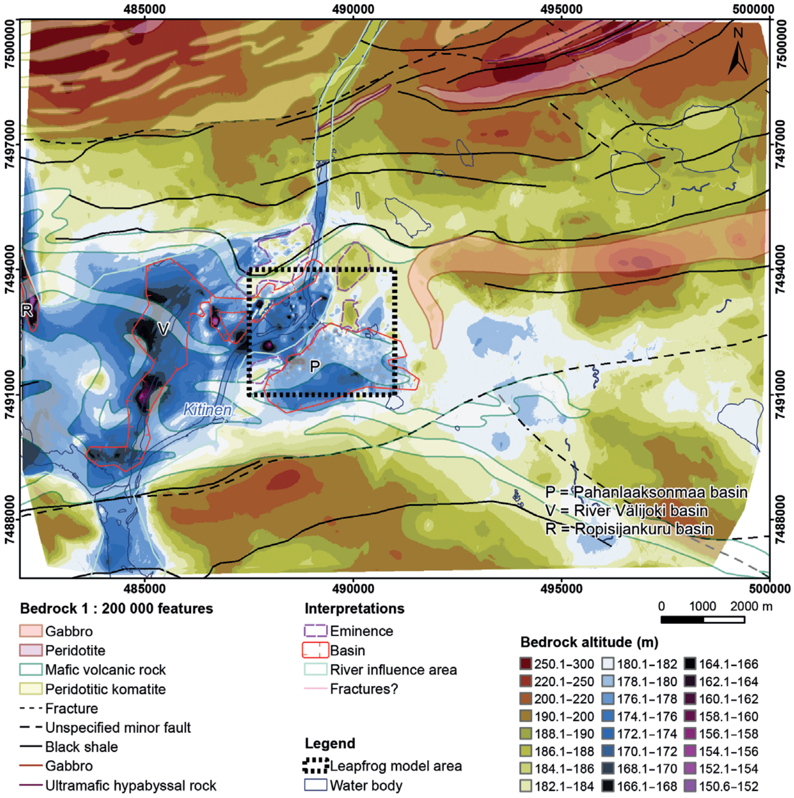


Fig. 11. The Leapfrog-modelled bedrock surface and NN bedrock surface model. Interpretations of bedrock surface features are based on comparing the distribution of the altitudes of the models with the bedrock map (1:200 000) and aeromagnetic data of Finland. Basin areas mentioned in the text are marked with initials. (Source: bedrock map (1:200 000) © Geological Survey of Finland, modified and reproduced with permission from the copyright owner).

at altitudes of 172–180 m. In the NN model, sediment thicknesses of less than 6 m are deposited at altitudes of about 182 m a.s.l. and above. There is a higher frequency of < 5 m thicknesses in the whole database as compared with that in the database distributed within the Leapfrog model area. This is due to the drilling method used for targeting till geochemistry samples, but also indicates thinner sediment packages in the surroundings of the Leapfrog model area.

The measured sediment thickness of the sediment thickness models is 1–3 m greater in this study than the average (6 m) reported in Lapland (Maijanen *et al*. 2008). In the Leapfrog model area, the average thickness is greater than in the whole study area. This is also visible in the map of superficial deposit thickness in Finland at the scale of 1:1 000 000 by GTK, in which the thickness is 30 m. The range in that map is 1–30 m, which is close to the range obtained from this study, but the lateral distribution of sediment thickness is different. This is probably because the GTK map has a coarser grid size (50 × 50 m) compared to that used in current study (10 × 10 m). The distribution of thick sediments (> 10 m) in the GTK map corresponds to areas with a bedrock altitude smaller than 180 m a.s.l.

The gravelly areas in the map of Sarala *et al*. (2015) correspond to the thick sediment deposits and often are 10 m thick, except in the Kärväsniemi gravel intake area, where the sediments have been partly excavated. The sand-covered areas in the river valleys (Kitinen, Välijoki and Sattanen) correspond to a thicker overburden. This is also evident in other valleys in Lapland, which usually have a preglacial origin and are filled with multiple layers of till and fluvial sediments (Korpela 1969, Lappalainen 2004). Exceptionally, some sections of the Kitinen river have eroded the valley down to the bedrock close to rapids. Similarly, sediments deposited prior to the late Weichselian are preserved in the Kemijoki valley (Korpela 1969).

The thickness of sediments reflects the fact that the Kersilö area is covered by sediments from many successive depositional events. The surficial sand and gravels (Sarala *et al*. 2015) are underlain by alternating glacial and fluvial sediments. The distribution of thick sediment packages corresponds to observed depressions in the bedrock topography. This indicates that the lower parts in the bedrock relief have sheltered sediments from erosion.

The calculated volumes of tills (59%) and sorted sediments (32%) and of surficial sediments are close to the proportions of sediment samples calculated from the Kersilö database, of which 60% are till and 26% are sorted sediments. Within the Leapfrog model distribution, the sediment samples consist of 45% till and 36% sorted sediments. This indicates that there might be more sorted sediments in the model area than the Leapfrog model represents. However, there is possibly a lack of some sediment types in the Kersilö database, which reflects the uneven distribution of drilling data.

The NN peat thickness model (Fig. 7K) of Viiankiaapa underestimates the volume of peat

Table 3. Explanation of the reliability classes.

Class	Reliability	Use	Altitude error	Notes
1	Good	Real altitude	< 1m	Drillings that reach the bedrock or confirmed bedrock
2	Good	Real altitude	±1–3 m	GPR profiles with a good bedrock surface reference
3	Average	Real altitude	±1–5 m up to 9 m	GPR profiles with a bedrock surface reference, less reliable
4	Average	Rough bedrock topography	More than 1 m to unknown	Drillings that did not reach the bedrock
5	Poor	Rough bedrock topography	More than 1 m to unknown	Used as a reference for relief, but indicate poor estimation of the bedrock surface altitude
6	Not evaluated	Not used		Not used in the model

(0.06 km^3) as compared with the estimation of 0.09 km^3 by Lappalainen and Pajunen (1980). The average thickness of peat in the NN model (Fig. 7K) is 1.3 m (SD = 1.1 m), while according to Lappalainen and Pajunen (1980) the average thickness of peat in Viiankiaapa is 2.7 m. The difference in the volumes and average thicknesses indicates that the distribution areas of < 1 m were modelled too extensively during manual contour generation. Furthermore, the actual distribution of Viiankiaapa mire continues about 2 km southwards from the NN peat model limit, which also reduces the overall volume.

Depositional elements

Our modelling demonstrates that the distribution of mires is determined by the topography of the underlying sediments and bedrock. In the Viiankiaapa mire, the thickest peat layers (≥ 4 m) are oriented in a SW–NE direction (Fig. 7). This would indicate the continuum of the basin from Pahanlaaksonmaa towards the middle parts of the mire. Another thick peat area (> 4 m) also exists in the northern corner of the mire west of Moskuvaara. A thinner peat cover (≤ 1 m) occupies the southern half of the mire, except for the southernmost areas with thicker (2–4 m) peat layers.

The thickness of sorted deposits varies between 0 and 16 m. The average thickness of top deposits is 2.6 m (SD = 1.9 m) and it appears to increase southwards, where there is a bedrock basin. The average thickness of top deposits in the Leapfrog model may be too great, since the field studies in Kärväsniemi indicate that they are thinner (< 1 m). The average thickness of the subtill deposits (middle sorted deposits, lower sorted deposits and lowest sands and gravels) is 2.5 m (SD = 2.1 m). The thickest subtill sorted deposits (reaching over 10 m) are located in Pahanlaaksonmaa and Sahankangas (Fig. 7D and F) and in the western part of Viiankiaapa (Fig. 7H).

Top deposits — varying from 1–5 m in thickness — are represented by glaciofluvial sands and gravels forming outwash plains on both sides of the Kitinen river (Fig. 7B). The outwash plains are visible in the LiDAR DEM, which also indicates the typical braided river topography. Possible older fluvial deposits exist beneath the upper till unit, and were exposed in the Kärväsniemi gravel pit area, where they are modelled as middle sorted deposits (Fig. 7). The three subtill sorted sediment units (middle sorted deposits, lower sorted deposits and lowest sands and gravels) were deposited near the river, which indicates that they are fluvial in origin. Sorted deposits also occur beneath the Viiankiaapa mire.

The thickness of till units varies between 0 and 37 m. The thickest till unit according to the Leapfrog model is the lower till assemblage, which represents the basal till in the model. The mean thickness of the lower till assemblage is 3.5 m, with a standard deviation of 2.5. The thickest till deposits are in the Pahanlaaksonmaa area, where they are over 15 m thick. There are also at least 10-m-thick till deposits in bedrock depressions. The basal till unit named as the lower till assemblage is assumed to correspond to till bed III in Hirvas (1991), which is found in the Paloseljänoja site. The lowest part of the lower till assemblage is massive and dense and can therefore be compared to massive grey till in Keivitsa (Hirvas *et al*. 1994). The grey till is the lowermost of two basal till beds deposited in the area (Hirvas *et al*. 1994). The uppermost till unit, upper till (mean thickness = 2.4 m, SD = 1.8 m), is the thickest on the eastern flank of the Kitinen river, reaching over 10 m. The model may overestimate the thickness of upper till on the flanks of the Kitinen river, since the thicknesses found at the test sites of this study were < 1 m. According the Leapfrog model, the mean thickness of middle till is 1.0 m (SD = 1.0 m) which is probably an overestimate due to a bulge in the model of the middle till in Pahanlaaksonmaa (Fig. 7L).

The till geochemistry data can be used for constructing 3D models and evaluating groundwater reservoirs. The 22 observations with 110 sediment samples within the Leapfrog model area offered information on the stratigraphic order of sediment units. The rest of the till geochemistry data offered information on sediments at the bottom of the drilling. Within the Leapfrog model area, the data were obtained from drilling with a Cobra percussion borer and auger drilling. The drillings located parallel to the Sodankylä–Ivalo road (*see* location in Fig. 3) were drilled with the auger drilling method, the rest being percussion drillings. The auger drillings are reliable for identifying the sediment, but the exact contact of the units may be uncertain. Sediment samples cored with percussion drilling were small, but observations with multiple samples were usable for investigation of the sediment structure.

Evaluation of aquifers in the study area

Ongoing evaluation of groundwater reservoirs in Finland is based on a new aquifer classification (Act on Water Resources Management 1263/2014). The previous classification by Britschgi *et al*. (1996) contained three classes of aquifers (I–III) following their importance for water supply management and protection. The new assessment of the aquifers contains three classes: 1, 2 and E. Aquifers in class 1 are important for water supply, those in class 2 are suitable for water supply, and class E aquifers support valuable terrestrial or surface water ecosystems (Act on Water Resources Management 1263/2014). Previously mapped class III will be reassessed and either removed from the classification or updated to class 1, 2 or E. Most of the aquifers within the study area belong to class III, and as such require an evaluation. We incorporated the aquifer information into our depositional model in order to evaluate the geological setting connected to the particular aquifers.

There are six classified aquifers within the study area (Fig. 12, the outdated classification (Britschgi *et al*. 1996) is in parentheses): Moskuvaara (III), Kersilönkangas (III), Ahvenjärvenkangas (II), Pahanlaaksonmaa (III), Hietakangas (III) and Myllymaa (II). This study suggests that most of the aquifers are not uniform groundwater reservoirs, and perched groundwater exists on top of the (upper) till bed due to its relatively low hydraulic conductivity. The classified aquifers Pahanlaaksonmaa and Kersilönkangas consist of alternating till and sorted sediment units, which makes their hydraulic conductivity heterogeneous and relatively low. The Kärväsniemi gravel intake area also has a low hydraulic conductivity due to the alternating till and sand/gravel units.

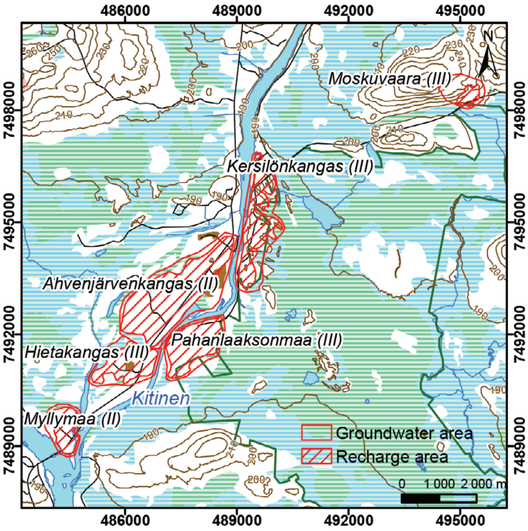


Fig. 12. Administrative groundwater areas in Sodankylä near Kersilö village. (Sources: administrative groundwater areas (II and III) © Finnish Environment Institute (SYKE), modified and reproduced with permission from the copyright owner; terrain elements © National Land Survey of Finland, modified and reproduced with permission from the copyright owner).

Ahvenjärvenkangas is an outwash plain covered with sand (Sarala *et al*. 2015). According to our 3D model, the topmost sandy layer of Ahvenjärvenkangas may form a uniform groundwater reservoir due to its thickness and continuity, but the continuum of the sediment structures needs further research. Hietakangas has thick sediment deposits reaching over 20 m in its eastern part. The structure in the GPR survey indicates that the groundwater reservoir is connected to the thick sandy and gravelly layers. However, the Kersilö database and GPR survey indicate that there are thick till deposits (reaching 8 m) in the middle part of the reservoir. This makes Hietakangas a less uniform reservoir and lowers the hydraulic conductivity of the reservoir. Myllymaa has a simpler structure. It has a sandy cover (around 2–11 m thick) and basal till under it, which allows a reasoned definition of the aquifer. The Moskuvaara groundwater reservoir is mainly till. Around 200 m from the border of the reservoir is a complex structure of alternating till and gravel according to sediment data in the targeting till geochemistry database (Table 1). If this sediment structure continues towards the

Moskuvaara reservoir, it indicates that Moskuvaara contains poorly connected water lenses. Our study indicates that Myllymaa and Sahakangas would be placed in class 2. Hietakangas may also remain in class 2. Moskuvaara may be omitted from the new classification. Pahanlaaksonmaa and Kersilökangas may also be omitted from the new classification due to unfavourable internal structures of sorted sediments.

Conclusions

The conclusions of this study and interpretations of the 3D detailed model of Kersilö can be summarized as follows:

- In the Kersilö area, the locations of the thickest sediments (> 15 m) correspond to sites with a deepened bedrock surface. This indicates that the depressions in the bedrock have affected sedimentation and sheltered the sediments from glacial erosion.
- At least three till units and four sorted sediment units were deposited within the Kersilö area during the latest glaciation. The sediment package commonly consists of recent top deposits, two till units and two interbedded sorted sediment units. All interpreted units were observed together only in the Kärväsniemi gravel intake area of Sodankylän Sora Oy. The eastern side of the Kitinen river has three or four sediment units consisting of a thin subpeat sand layer and one or two till units underlain by it.
- Due to the heterogeneity of sediment units, aquifers are poorly connected and complex in the Kersilö area. Till units with low hydraulic conductivities conceal perched aquifers.
- Aquifers in the Kersilö area were evaluated on the basis of the 3D structure of sediments, and their classification was adjusted to correspond to a new aquifer classification introduced in Finland.
- Knowledge of the 3D structure of sediments helps to better understand the hydrogeological settings and it can be applied in 3D hydrogeological modelling, as well as in planning possible mining activities at the study site.
- The old target geochemical sampling data represent a valuable dataset in the present 3D modelling approach. However, our 3D simulation of the Leapfrog model area underestimates surficial deposit thickness and bedrock surface altitude. On the contrary, in the areas with sparse geological data, the interpolation overestimates the thickness due to the uneven lateral distribution of the input data and high variability in the sediment thickness and bedrock surface altitude within short distances.
- The Leapfrog model could be imported into the groundwater flow model in order to characterize the inner structure and heterogeneity of the aquifer. Our modelling methods can be applied in the mapping of freshwater supplies within the Nordic countries and other glaciated areas.

Acknowledgements: The authors thank Joanna Kuntonen-van't Riet and Janne Siikaluoma from AA Sakatti Mining Oy for delivering the data and supporting the study, the participants in the NordMin 3D modelling workshop in Trondheim (8–10 Nov. 2016) for inspiration in evaluating the bedrock surface model, Jyri Laakso and Tatu Lahtinen for their help with the GPR studies and test site interpretations, Aulis Ruotsalainen from the ELY Centre for providing drill hole data on Moskuvaara and the K.H. Renlund Foundation for making this study possible. The manuscript was greatly improved by the constructive comments of Dr. Tiit Hang and Dr. Peter Johansson.

References

Aalto M., Eriksson B. & Hirvas H. 1992. Naakenavaara interglacial; a till-covered peat deposit in western Finnish Laplands. *Bulletin of the Geological Society of Finland* 64: 169–181.

Airo M.-L. 2005. *Aerogeophysics in Finland 1972–2004: methods, system characteristics and applications*. Geological Survey of Finland (GTK), Espoo.

Britschgi R., Gustafsson J., Britschgi R. & Gustafsson J. 1996. *Suomen luokitellut pohjavesialueet*. Suomen ympäristökeskus, Helsinki.

Brownscombe W., Ihlenfeld C., Coppard J., Hartshorne C., Klatt S., Siikaluoma J.K. & Herrington R.J. 2015. The Sakatti Cu-Ni-PGE sulfide deposit in northern Finland. In: O'Brien W.D.M.L. (ed.), *Mineral deposits of Finland*, Elsevier, Amsterdam, pp. 211–252.

Eriksson B. 1993. The Eemian pollen stratigraphy and vegetational history of Ostrobothnia, Finland. *Bulletin (Geological Survey of Finland)* 372: 1–36.

Gustavsson N., Noras P. & Tanskanen H. 1979. *Seloste geokemiallisen kartoituksen tutkimusmenetelmistä*. Geologinen tutkimuslaitos, Espoo.

Hanski E. & Huhma H. 2005. Central Lapland greenstone belt. *Developments in Precambrian Geology* 14: 139–193.

Helmens K.F., Räsänen M.E., Johansson P.W., Jungner H. & Korjonen K. 2000. The last interglacial-glacial cycle in NE Fennoscandia: a nearly continuous record from Sokli (Finnish Lapland). *Quaternary Science Reviews* 19: 1605–1623.

Helmens K.F., Bos J.A.A., Engels S., Van Meerbeeck C.J., Bohncke S.J.P., Renssen H., Heiri O., Brooks S.J., Seppä H. & Wohlfarth B. 2007. Present-day temperatures in northern Scandinavia during the last glaciation. *Geology* 35: 987–990.

Hirvas H. 1991. Pleistocene stratigraphy of Finnish Lapland. *Bulletin (Geological Survey of Finland)* 354: 1–123.

Hirvas H., Alfthan A., Pulkkinen E., Puranen R. & Tynni R. 1977. *Raportti malminetsintaa palvelevasta maaperatutkimuksesta Pohjois-Suomessa vuosina 1972–1976*. Tutkimusraportti, Geological Survey of Finland.

Hirvas H., Saarnisto M., Hakala P., Huhta P., Johansson P. & Pulkkinen E. 1994. *Maaperän kerrosjärjestys ja geokemia Keivitsassa*. Geologian tutkimuskeskus, Rovaniemi. [Available at http://tupa.gtk.fi/raportti/arkisto/p23_4_014.pdf].

Hättestrand C. & Stroeven A.P. 2002. A relict landscape in the centre of Fennoscandian glaciation: geomorphological evidence of minimal Quaternary glacial erosion. *Geomorphology* 44: 127–143.

Johansson P. & Kujansuu R. 2005. *Pohjois-Suomen maaperä: maaperäkarttojen 1:400 000 selitys*. Geologian tutkimuskeskus, Espoo.

Johansson P., Lunkka J.P. & Sarala P. 2011. The glaciation of Finland. In: Ehlers J., Gibbard P.L. & Hughes P.D. (eds.), *Quaternary glaciations — extent and chronology, a closer look*, Developments in Quaternary Science 15, Elsevier, Amsterdam, pp. 105–116.

Johnson M.D., Fredin O., Ojala A.E.K. & Peterson G. 2015. Unraveling Scandinavian geomorphology: the LiDAR revolution. *GFF* 137: 245–251.

Kleman J. & Glasser N.F. 2007. The subglacial thermal organisation (STO) of ice sheets. *Quaternary Science Reviews* 26: 585–597.

Korpela K. 1969. Die Weichsel-Eiszeit und ihr Interstadial in Peraepohjola (noerdliches Nordfinnland) im licht von submoraenen Sedimenten. *Annales Academiae Scientiarum Fennicae, Series A3: Geologica-Geographica* 99: 108.

Kujansuu R. 1966. *Suomen geologinen yleiskarttakartta 37: Sodankylä maaperäkartta*. Geological survey of Finland, Rovaniemi.

Kujansuu R. 1967. On the deglaciation of western Finnish Lapland. *Bulletin de la Commission Geologique de Finlande* 232: 98.

Lappalainen E. 1970. Über die spaetquartaere Entwicklung der Flussufermoore Mittel-Lapplands. *Bulletin de la Commission Geologique de Finlande* 244: 79.

Lappalainen E. 2004. Kallio- ja maaperä sekä kasvillisuuden jääkauden jälkeinen kehityshistoria. In: Pääkkö E. (ed.), *Keski-Lapin aapasoiden luonto*, Metsähallitus, Vantaa, pp. 18–45.

Lappalainen E. & Pajunen H. 1980. *Lapin turvevarat: yhteenveto vuosina 1962–1975 Lapissa tehdyistä turvetutkimuksista*. Geologinen tutkimuslaitos, Espoo.

Lemon A.M. & Jones N.L. 2003. Building solid models from boreholes and user-defined cross-sections. *Computers & Geosciences* 29: 547–555.

Leskelä S. 1971. *Auger-kairaus Sodankylässä 5.7.–4.7.1971*. Geologian tutkimuskeskus, Espoo. [Available at http://tupa.gtk.fi/raportti/arkisto/p13_5_1_026.pdf].

Lunkka J.P., Sarala P. & Gibbard P.L. 2015. The Rautuvaara section, western Finnish Lapland, revisited: new age constraints indicate a complex Scandinavian Ice Sheet history in northern Fennoscandia during the Weichselian Stage. *Boreas (Oslo)* 44: 68–80.

Maijanen H., Salonen V.-P. & Heikkinen P. 2008. Maaperän paksuus FIRE-linjoilla Lapissa. *Geologi* 60: 157–160.

Mikkola E. 1937. *Kivilajikartta, Lehti C7, Sodankylä. Suomen geologinen yleiskartta, 1:400 000*. Maanmittauslaitoksen kivipaino, Helsinki.

Peltoniemi M. 1988. *Maa- ja kallioperän geofysikaaliset tutkimusmenetelmät*. Otakustantamo, Espoo.

Penttilä S. 1963. The deglaciation of the Laanila area, Finnish Lapland. *Bulletin de la Commission Geologique de Finlande* 203: 71.

Pulkkinen E. 1983. *Sattasen karttalehtialueen geokemiallisen kartoituksen tulokset*. Geologinen tutkimuslaitos, Espoo. [Available at http://tupa.gtk.fi/kartta/geokemiallinen_karttaselitys/gks_3714_s.pdf].

Rosberg J.E. 1908. Studien ueber Talbildungen im finnischen Lappland und dessen Umgebungen, I. Das Tal des Tulomjok. *Fennia* 24: 38.

Ross M., Parent M. & Lefebvre R. 2005. 3D geologic framework models for regional hydrogeology and land-use management: a case study from a Quaternary basin of southwestern Quebec, Canada. *Hydrogeology Journal* 13: 690–707.

Räisänen J. 2014. *Sodankylän alueen maaperäkartoitus 2013–2014 (Väliraportti)*. GTK:n arkistoraportit, Geologian tutkimuskeskus, Rovaniemi. [Available at http://tupa.gtk.fi/raportti/arkisto/52_2014.pdf].

Räsänen J. 2008. *Keski-Lapin liuskevyöhykkeen geologinen kehitys Sodankylän liuskealueella*. GTK:n arkistoraportit, Geologian tutkimuskeskus, Rovaniemi. [Available at http://tupa.gtk.fi/raportti/arkisto/k21_42_2008_25.pdf].

Saarnisto M. & Salonen V.-P. 1995. Glacial history of Finland. In: Ehlers J., Kozarski S. & Gibbard P. (eds.), *Glacial deposits in north-east Europe*, A.A. Balkema, Rotterdam, p. 626.

Salminen R. 1972. *Auger-kairaus Sodankylässä keväällä 1972*. Geologian tutkimuskeskus. [Available at http://tupa.gtk.fi/raportti/arkisto/s41_3713_1_1972.pdf].

Salonen V.-P., Moreau J., Hyttinen O. & Eskola K.O. 2014. Mid-Weichselian interstadial in Kolari, western Finnish Lapland. *Boreas (Oslo)* 43: 627–638.

Sarala P., Räisänen J., Johansson P. & Eskola K.O. 2015. Aerial LiDAR analysis in geomorphological mapping and geochronological determination of surficial deposits in the Sodankylä region, northern Finland. *GFF* 137: 293–303.

Sarala P., Väliranta M., Eskola T. & Vaikutienė G. 2016. First physical evidence for forested environment in the Arctic during MIS 3. *Scientific Reports* 6: 1–9.

Sibson R. 1981. A brief description of natural neighbor interpolation. In: Bannett V. (ed.), *Interpolating multivariate data,* John Wiley & Sons, New York, pp. 21–36.

Simonen A. 1980. *The Precambrian in Finland*. Geologinen tutkimuslaitos, Espoo.

Skyttä P., Kinnunen J., Palmu J.-P. & Korkka-Niemi K. 2015. Bedrock structures controlling the spatial occurrence and geometry of 1.8 Ga younger glacifluvial deposits — example from first Salpausselkä, southern Finland. *Global and Planetary Change* 135: 66–82.

Tyrväinen A. 1980. *Suomen geologinen kartta 1:100 000, Lehti: Sattanen kallioperäkartta*. Geologinen tutkimuslaitos, Espoo.

Tyrväinen A. 1983. *Suomen geologinen kartta 1:100 000, Lehdet 3713 ja 3714: Sodankylän ja Sattasen kartta-alueiden kallioperä*. Geologinen tutkimuslaitos, Espoo.

Wycisk P., Hubert T., Gossel W. & Neumann C. 2009. High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial megasites. *Computers & Geosciences* 35: 165–182.

Väisänen U. & Maunu M. 2004. *Maaperäkartta 1:20 000 selitys: 3714 07 Sattanen*. Geologian tutkimuskeskus, Rovaniemi.