Application of till geochemical and indicator mineral data to the interpretation of the thick till sequence at Muhos, northern Finland

J. P. Lunkka¹, V. Peuraniemi*¹ & T. Nikarmaa¹
¹Department of Geosciences, University of Oulu, Linnanmaa, PO Box 3000, Finland
*Corresponding author (e-mail: vesa.peuraniemi@oulu.fi)

ABSTRACT: Recent drilling at Muhos, northern Finland has revealed an exceptionally thick Quaternary sediment cover, overlying the unmetamorphosed Neoproterozoic Muhos Siltstone Formation in the Oulujoki River Valley. Here we report preliminary petrographical, geochemical and heavy mineral results from four till units from the Muhos drill-core.

The drilling site is located at 27 m asl, c. 1 km south of Oulujoki River and 30 km SE from the city of Oulu and the present shore of the Bothnian Bay of the Baltic Sea. The drilling at this site was performed with a GM 200 GTT drilling platform using 1-m long sample tubes (HDPV, diameter 5 cm) inside the stainless steel cover tubes. The coring penetrated down to the siltstone bedrock 54 m below the ground surface and the sediment core recovery was over 75%. The sedimentary sequence from the ground surface down to the local siltstone bedrock consists of four till units interbedded with sand/silt/clay beds. The upper two till beds, Mu-1 and Mu-2, are interpreted as being deposited during the Weichselian Glaciation between 115 000–10 000 years ago, the third till bed Mu-3 during the Saalian and the lowest till bed, Mu-4, during the Saalian or pre-Saalian glaciations, i.e. till beds Mu-3 and Mu-4 prior to c. 130 000 years ago.

Petrography of the coarse fraction, geochemistry of the fine fraction and heavy minerals of the sand fraction were studied from all four till units and the Muhos siltstone samples. Coarse and fine fractions were separated by dry-sieving. The fine fraction was analysed by XRF and AAS. The mineralogical composition of the heavy fraction was studied by FESEM+EDS and SEM+EDS.

The lowest till bed Mu-4 can be divided into three subunits. On the basis of clast content, geochemistry of till fines the ice movement direction was from the NW or NNW during the deposition of the lowermost brown and red till units. The composition of the upper grey unit of till bed Mu-4 shows that the ice flow direction was from the WNW. Petrographical composition of till beds Mu-3 and Mu-2 indicates that the ice flow again was from the NW whereas the petrographical composition of the uppermost till bed Mu-1 suggests that the ice flow during this deposition phase was from the WNW. Younger till beds studied have in part also some reworked and re-deposited material from the older till beds.

KEYWORDS: till stratigraphy, till geochemistry, heavy minerals, Muhos Formation, provenance area

SUPPLEMENTARY MATERIAL: The percentages of the rock types in pebble and gravel fraction, XRF and AAS analysis of the samples and identified mineral species of the heavy sand fraction are available at: http://www.geolsoc.org.uk/SUP18659

Recent core drillings in the area of the Muhos Siltstone Formation, 30 km SE from the city of Oulu, northern Finland, revealed an exceptionally thick Quaternary sediment sequence. The sequence at Muhos was drilled in 2006 by the Geological Survey of Finland in co-operation with the Department of Geosciences, University of Oulu and the drilling campaign was a part of a larger project to study the glaciation history of Northern Ostrobothnia. The sediment cover in the Oulujoki Valley including the Muhos area is several tens of metres and in places even more than 130 metres. This makes the Oulujoki Valley a unique area in Finland since the Quaternary sediments in the area are much thicker than in the rest of Finland (Fig. 1).

Sediment sequence at Muhos drill-core consists of four till beds (Mu-1–Mu-4) and sand/silt/clay interlayers that occur between the till beds (Fig. 2). Age determinations using the Optically Stimulated Luminescence (OSL) dating method had earlier been made on two samples from the sand layer between till beds Mu-2 and Mu-3 and they yielded ages of 107 and 110 ka,
respectively. In addition, two samples from the sand layer between till beds Mu-3 and Mu-4 gave ages of 137 and 146 ka. Based on these dating results, the till beds Mu-3 and Mu-4 were interpreted to represent till beds that were deposited during the Saalian glaciation and till beds Mu-1 and Mu-2 were most likely deposited during middle and late Weichselian glacial events (Lunkka et al. 2010).

Multiple till sequences deposited during the Weichselian glaciations are found in many sites in southern, central and northern Finland (cf. Lunkka et al. 2004; Johansson et al. 2011) but observations on pre-Weichselian till beds are relatively rare. However, till beds deposited during the Saalian glacial stage have been found in the areas of weak glacial erosion in northern Finnish Lapland (Hirvas 1991) and in Ostrobothnia, western Finland (e.g. Nenonen et al. 1991; Salonen et al. 2008) and for example in the meteorite impact crater in Lappajärvi, western Finland, 300 km to south of the Muhos site (Salonen et al. 1992).

The purpose of the present work is to characterize the petrography and geochemistry of four different till beds found in the Muhos drill-core in order to: (1) determine the provenance areas of till beds; and (2) study the ice movement directions during different glacial phases which would shed light on the glaciation history of Finland and Northern Ostrobothnia.

**STUDY AREA**

**Bedrock geology**

The bedrock in the Muhos drilling site consists of unmetamorphosed sedimentary rocks, originally deposited in a downfaulted deep rift valley system (Kesola 1985; Honkamo 1988; Laitakari 1998). The maximum thickness of the Muhos Formation is 1000 m. The upper layers of the Muhos Formation were probably deposited during the Neoproterozoic, the estimated age being c. 650–570 Ma (Tynni & Donner 1980) while the age estimates for the lower parts of the Muhos Formation are 1200 Ma (Tynni & Uutela 1984) – 1400 Ma (Simonen 1980). The colour of the siltstone ranges mostly from red to brown (80–90% from the total Formation) and in some parts also narrow grey intervals occur (Simonen 1960). Siltstone is interbedded with coarser layers of sandstone (Enkovaara et al. 1953; Simonen 1960, 1964). The siltstone is overlain by Quaternary glacial and postglacial deposits.

The bedrock north and northwest of the Muhos Formation consists of Paleoproterozoic granites and schists. The main rock types of the schist area are mica schist and gneiss, black schist, dolomitic limestone and skarn (Kesola 1985; Honkamo 1988). Mafic metavolcanics and quartzites also occur in the central part of the schist area. Further to the north from the schist area, bedrock consists of Archean gneissic granitoids (Honkamo 1988) (Fig. 1).

**Quaternary geology**

The study area is located in the area of the former glaciation centre, and therefore the area has been repeatedly covered by the Scandinavian Ice Sheet during the Pleistocene. Based on the directional data of bedrock striations and glacialic landform patterns (e.g. drumlins) found in the area, two distinctively separate ice flow directions have been recognized. The earlier, presumably pre-Weichselian, ice flow direction was from NW to SE and the younger ice flow direction representing the deglacial Late-Weichselian phase of the Oulu ice lobe was from WNW to ESE (Aario & Forsström 1979; Aario & Peuraniemi 1990; Bergel et al. 1999; Pasanen & Lunkka 2008).

The topography of the study area is relatively flat and the glacigenic till deposits occur mainly as a cover moraine (Aario 1984). Glacialic landforms in the area include small drumlin fields and hummocky moraine trains. Some hummocky moraines can be classified as hummocky disintegration moraines and some as Rogen moraines (Aario & Peuraniemi 1990). Drumlin ridges are oriented WNW-ESE representing the youngest ice flow direction. The moraine ridges in the Rogen fields are oriented SSW-NNE, i.e. transverse to the youngest ice flow direction. There are no previously published results on detailed till stratigraphy in the area. Glaciofluvial deposits occur as discontinuous eskers chains, oriented WNW-ESE. After the last deglaciation, the Muhos area was submerged by the Ancylus Lake (highest shore level at c. 210 m asl) and the Litorina Sea (highest shore level at c. 100 m asl) stages of the Baltic Basin. Varved clay and silt were deposited during
the Ancylus Lake stage and gyttja- and sulphide-bearing clay and silt were deposited during the Litorina Sea stage. As a result of postglacial land uplift, the glacial and glaciofluvial formations were affected by littoral processes during the lake and sea stages of the Baltic Basin (Aario 1984) and gravelly and sandy beach deposits were formed in many places. Shortly after the emergence of the area above the contemporary water level, aeolian dunes were formed on the surface of the glaciofluvial formations while postglacial peat accumulation on the lower ground has continued throughout the Holocene.

**MATERIAL AND METHODS**

The hole drilled in the Muhos Siltstone Formation is 54 m deep from the ground surface and it is located c. 1 km southwest from the contact with the granite bedrock (Fig. 1). The drill-core (diameter 5 cm) was drilled using GM 200 GT pneumatic drilling platform with 1-m long sample tubes (HDPV) inside stainless steel cover tubes. The entire sediment sequence from surface to bedrock was cored and the sediment core recovery was over 75%. The core was stored and logged at the University of Oulu.

The glacial sediment sequence of the drill-hole consists of four till beds separated by interlayers of sand and silt. The lowest 0.5 m of the hole was drilled into the weathered Muhos Formation siltstone. The four till beds were intersected in the drill-hole with till bed Mu-1 being the uppermost till, and till bed Mu-4 being the lowermost till. As mentioned above, the till beds are interpreted to have been deposited during the Saalian and the Weichselian glaciations. Originally the four separate till beds were characterized on the basis of colour, texture and structure. Each till bed consists of one or more till units within one till bed. These till units within one till bed differ visually from each other by grain-size or/and colour and the units examined in this paper are highlighted in grey and red tones in Figure 2.

Samples were collected from the drill-core after it was split in half. Each till sample was collected over a 15- to 20-cm interval. There were 40 samples from till beds and four samples from the Muhos siltstone. The same methods were used to analyse the till samples as well as siltstone samples obtained from the Muhos Formation. The flow sheet (Fig. 3) shows how the samples were processed. The following three grain-size fractions were separated from each till sample by dry-sieving:
The pebble and gravel fraction (> 0.6 mm) was separated and used for stone counts. The percentages of the rock types (granite, mica schist and gneiss, siltstone, quartzite, mafic volcanics and granitoids) found in each sample were classified into lithological groups and counted for every sample and every till unit and compared for the different units in each till bed. A maximum of 100 stones were counted (if found) from each sample with the aid of a stereomicroscope. Data are reported as frequency percentage. Also the clast-shape and roundness were determined on a scale from 1 to 5, where class 5 is the most rounded (Hirvas et al. 1977).

The fine fraction (< 0.06 mm) of the till samples was used for X-ray fluorescence (XRF) and atomic absorption spectrometry (AAS) analyses to reveal the chemical composition of the till fine fraction. The total concentrations of 44 elements were determined by XRF (Bruker AXS S4 Pioneer) at the Department of Electron Microscopy, University of Oulu. Concentrations of Co, Cu, Ni, Pb, Zn, Fe, Mn and Ag were determined from a 500-mg sample by flame AAS (Varian Spectr AA-300) following a total dissolution with HF-HClO4-HNO3-HCl. Concentrations of Au were determined from a 1-g sample by graphite furnace AAS (HCl-HNO3 dissolution, precipitation with SnCl2 and Hg2NO3, HCl dissolution, HNO3 dissolution). AAS analyses were carried out in the Department of Geosciences, University of Oulu.

A total of 200 mineral grains were systematically identified and the percentages of the different mineral species from a total of 200 grains were calculated from the heavy mineral fraction of every sample by a rapid SEM scan (QEMscan) (Zeiss ULTRA plus, resolution 1.0 nm/15 kV). Minerals were identified using the MinIdent-programme. The samples of the same till unit are combined in the results. The heavy fraction contains also some light minerals because the heavy liquid used was not that dense.

After this procedure, the 20 samples obtained were once more combined to 10 samples. This group comprised one sample from the Muhos Formation siltstone, three from till bed Mu-1, one from till bed Mu-2, one from till bed Mu-3 and four from till bed Mu-4. The sample interval was selected on the basis of colour of the sample and the element content determined earlier by XRF. These 10 distinct samples were ground and mounted on carbon film and studied by scanning electron microscopy and energy dispersive spectroscopy (SEM+EDS) in the Department of Electron Microscopy, University of Oulu.

A total of 200 mineral grains were systematically identified and the percentages of the different mineral species from a total of 200 grains were calculated from the heavy mineral fraction of every sample by a rapid SEM scan (QEMscan) (Zeiss ULTRA plus, resolution 1.0 nm/15 kV). Minerals were identified using the MinIdent-programme. The samples of the same till unit are combined in the results. The heavy fraction contains also some light minerals because the heavy liquid used was not that dense.

Single mineral grains, not ground, mounted on carbon film, were also identified and photographed in three-dimensions.
using Scanning Electron Microscopy (SEM) with energy-dispersive X-ray spectrometry (EDS). The equipment used was the JEOL JSM-6400, with a resolution of 3.5 nm/35 kV. The intention was to study the surface features, shape and weathering stage of different mineral grains.

**RESULTS**

**Lithostratigraphy of the Muhos drill-hole**

The lithostratigraphy of the Muhos drill-hole is shown in Figure 2. There are four different till beds in the strata. All till beds in the core contain only few clasts and their size ranges from pebbles to cobbles (from 4 mm to a maximum of 6 cm). Till bed Mu-1 extends from c. 9–16.6 m below the ground surface (bgs). Till bed Mu-1 is grey, loose and sandy (clay fraction 3–5%) and it includes few clasts, mostly mica schist. However, the clast content increases in the lower part of the till bed where clasts are mostly granite. Till bed Mu-2 occurs between 17.14 m to 19 m bgs. The colour of till bed Mu-2 ranges from grey to light brown. This till bed is sandy (clay fraction 8%) and more compact than till bed Mu-1 above. The clasts size is small as in all till beds.

Till bed Mu-3 extends from c. 28 m to 38 m bgs. The colour of this till unit is mostly dark grey but it also includes intervals of red till in its upper part. The till is sandy (clay fraction 7–8%), compact and hard and includes only few small clasts. Till bed Mu-4 extends from c. 39 m to 53.4 m bgs. The composition of this till bed is highly variable. It includes grey, red and dark brown till varieties and the clasts are abundant particularly in the red part of the till bed. The red and dark brown till are very hard and densely packed and their matrix is relatively fine. The dark brown till has an especially high content of organic material (0.8%) and clay fraction <0.0002 mm (19–43%). The matrix of the upper, grey part of the till bed is coarser than that of brown and red parts of the till bed.

The Muhos Siltstone Formation was reached at 53.4 m bgs. Its colour is dark red and brown and it consists of weathered siltstone. Within the weathered siltstone there are some granite clasts, probably derived from adjacent granite bedrock.

**Petrography of the coarse fraction**

The majority of pebbles in all till beds are composed of granite and mica schist (Fig. 2). The very angular pebbles in the uppermost grey unit of till bed Mu-4 are composed nearly totally of granites (98–100%). The lower red and brown units in till bed Mu-4 are composed of granite, mica schist, mafic volcanics, siltstone and a small amount (2.1–4.8%) of quartzite. Granitoid rocks from the basement gneiss area occur only in the red unit of till bed Mu-4. The gneissic granitoid pebbles in the red unit indicate that the ice has transported the granitoid pebbles at least 60 km from the source area to the NW. Some of the clasts of mafic volcanics, granitoids and quartzites in the red till unit in till bed Mu-4 are slightly more rounded than clasts in the upper till beds, which also may indicate a longer transport distance. Pebbles of mafic volcanic rocks and siltstone occur also in till bed Mu-3 but these rocks were not found in till bed Mu-2. Mica schist, granite and small amount of quartzite pebbles are angular or sub-angular and constitute the pebble fraction in till beds Mu-1 and Mu-2. In addition, some lithic clasts of mafic volcanics were also found in till bed Mu-1.

**Chemical composition of the fine fraction**

The siltstone in the Muhos Formation area is unmetamorphosed, unlike the bedrock around that area which is composed of igneous granite and metamorphosed mica schist, quartzite, dolomite and volcanoclastic. In the samples analysed from the Muhos Formation siltstone S, Ba, Rb, V, Ga and Cs contents are high. Similarly, metal contents, especially Fe and Mn, but also Al, Mg, Co, Cu, Ni and Zn are also elevated while Zr, Mo and Na contents are quite low. Chemical composition of the siltstone samples is similar to earlier data from brown siltstone samples in a deep drill-hole nearby (Lokka 1950). The Muhos Formation siltstone is rich in clay minerals that absorb many metals and elements. Gallium, Rb and Cs are typical elements in mica minerals that are abundant in the siltstone. Sulphur is typical in baryte mineral and in sulphide minerals. Plenty of baryte grains were found in siltstone samples when they were observed three-dimensionally.

Aluminium, Fe, Mg, Pb, Zn, Ni, Cu and S contents in till bed Mu-4, especially in its lower brown unit, are higher than in other till beds (Fig. 4). The same elements are also at a higher level in the samples analysed from the siltstone samples of the Muhos Formation. Sodium contents are higher in till beds Mu-1 and Mu-2 while Ba, P, Zr, Pb and Zn contents are elevated in the upper grey unit of till bed Mu-4 when compared to other till units. Iron, Mn, Pb, Ni, Cu and Zn contents decrease upwards in the sediment sequence but are the highest in the lower part of till bed Mu-1. Potassium contents are highest in the Muhos Formation siltstone, in till bed Mu-4, in the upper part of till bed Mu-2 and in the lower part of till bed Mu-1.

In many samples analysis the concentration of metallic elements (e.g. Cu, Ni, Zn, Fe, Al) increases downwards towards the base of the sediment sequence. Concentrations of Si and Na are lower in the basal parts of the till units and in the siltstone of the Muhos Formation. The three units in till bed Mu-4 with different colours differ from each other also by their geochemical signatures (Na, Mg, Zr, P, S, Zn, Cu, Ni, Pb, Fe, Mn). The Cu content is relatively low in all till beds; the maximum value is 16 ppb in till bed Mu-1. Contents of Fe are high in the dark brown and grey till units and in the bottom part of the red unit of till bed Mu-4 and also at the base of the grey till bed Mu-1.

**Heavy minerals**

The heavy mineral content of the 0.06–0.6 mm fraction of the Muhos Formation siltstone is relatively low compared to a heavy mineral content of the till beds. Heavy minerals in the siltstone mainly consist of apatite, tourmaline, pseudorutile, garnet, amphibole and sphaene (Table 1). A lot of barite grains were found in the three dimensional images by SEM (Fig. 5). Many of the heaviest mineral grains were composite grains of barite and some other minerals like albite. MinIdent analysis of the Muhos siltstone gives no barite grains as identified minerals but the analysis shows 27 unidentified mineral grains that are composed of high amounts of S and Ba and therefore they can be identified also as barites. Barite grains were abundant also in till beds Mu-4 and Mu-3 as independent minerals and their number increases towards the base of the sediment sequence in the 3D-observations by the SEM. This may indicate that barites in the till beds originate from the Muhos Formation siltstone. Magnetite, ilmenite, pyrite and chloropyrite were found as separate heavy grains (Fig. 6). Magnetite is a very common heavy mineral in the Muhos Formation siltstone samples as it was separated using a hand magnet from the heavy fraction. On average the amounts of magnetite in the Muhos Formation siltstone (>15 weight% of the heavy mineral fraction) is almost twice the amount of magnetite found in till beds (maximum 10.8 weight% of magnetite) (Table 2). Muhos siltstone samples are mainly composed of light minerals such as mica, feldspar, quartz, calcite, chlorite, illite and kaolinite-serpentinite.

When comparing the mineral content of the Muhos Formation to the mineral content of the rock-types in the
surrounding area, some typical minerals for different rock types can be listed. Common minerals in mica schist are quartz, plagioclase and biotite. Common accessory minerals are garnet, apatite, muscovite, chlorite and potassium feldspar. Typical minerals in volcanic rocks are hornblende, plagioclase, chlorite, quartz. Chlorite occurs especially in the contact zone between volcanic rocks and mica schist.

Granites are composed mainly of quartz, potassium feldspar, plagioclase and biotite and as accessories muscovite, chlorite, apatite, zircon, monazite and sphene.

Tremolite and diopside are typical minerals in skarn rocks. Pyrite and chalcopyrite are common also in hydrothermal veins in schists and in contact metamorphic rocks. Pyrite occurs as an accessory mineral in granite and chalcopyrite sometimes in volcanic rocks. Tourmaline occurs in Muhos siltstone but also in pegmatite granites.

The mineralogy of the Muhos Formation is poorly known because there are only few previous studies. Pyrite, chalcopyrite, calcite and carbonate have been found also prior to this study (Väyrynen 1954; Tynni & Siivola 1966).

Amphiboles (hornblende, tschermakite, edenite, tremolite/actinolite) are the most common heavy minerals in the 0.06–0.6 mm fraction of all the till beds, except in the upper grey
Table 1. Mineralogical composition of the heavy sand fraction of till beds Mu-1 – Mu-4 and Muhos siltstone

| Mineral        | Till bed Mu-1 (samples M1–15) | Till bed Mu-2 (M16–21) | Till bed Mu-3 (M22–24) | Till bed Mu-4: grey (M25–26) | Till bed Mu-4: red (M27–35) | Till bed Mu-4: dark brown (M36–40) |
|----------------|-------------------------------|------------------------|------------------------|-------------------------------|-------------------------------|-------------------------------|
|                | Mineral %                     | %                      | %                      | Mineral %                     | %                            | %                            |
| Amphibole      | 62.2                          | 70.4                   | 63.1                   | 47.7                          | 14                           | 45.7                          |
| Epidote        | 11.6                          | 12.8                   | 9.6                    | 5.6                           | 5.1                          | 3.2                           |
| Pyroxene       | 4.7                           | 5.1                    | 7.1                    | 5.1                           | 5.1                          | 5.1                           |
| Sphene         | 3.8                           | 4.1                    | 3.5                    | 2                            | 2                            | 2                             |
| Garnet         | 3                             | 2                      | 2.7                    | 12.8                          | 3                            | 1.6                           |
| Apatite        | 2.4                           | 2                      | 3.2                    | 4.6                           | 4.6                          | 4.6                           |
| Feldspar       | 2.1                           | 1                      | 2.7                    | 3                            | 3                            | 3                             |
| Ilmenite       | 2                             | 1                      | 2.7                    | 3                            | 3                            | 3                             |
| Quartz         | 1.4                           | 2                      | 1.6                    | 1.3                           | 1.3                          | 1.3                           |
| Mica           | 1.1                           |                        |                        | 3                             | 3                            | 3                             |
| Spinel         | 0.9                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Maghemite      | 0.9                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Hematite       | 0.6                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Pyrite         | 0.6                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Rutile         | 0.6                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Chlorite       | 0.5                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Zirkon         | 0.5                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Pseudorutilite | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Prehnite       | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Brookite       | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Calcite        | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Sepiolite      | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| Axinite        | 0.2                           |                        |                        | 0.5                           | 0.5                          | 0.5                           |
| **Total**      | **100**                       | **100**                | **100**                | **100**                       | **100**                      | **100.2**                     |

| Mineral        | Muhos siltstone (M41–44) | %                            |
|----------------|---------------------------|------------------------------|
| Mica           | 28.1                      |
| Feldspar       | 12.6                      |
| Quartz         | 11.1                      |
| Apatite        | 8.1                       |
| Calcite        | 7.4                       |
| Chlorite       | 5.9                       |
| Turmaline      | 4.4                       |
| Illite         | 3.7                       |
| Pseudorutilite | 3.7                       |
| Kaolinite-Serpentine | 3                        |
| Garnet         | 2.2                       |
| Zeolite        | 2.2                       |
| Chlortonite    | 1.5                       |
| Amphibole      | 1.5                       |
| Sphene         | 0.7                       |
| Anatase        | 0.7                       |
| Cordierite     | 0.7                       |
| Polygonskite   | 0.7                       |
| Stilpnomelanine| 0.7                       |
| Pyroxene       | 0.7                       |
| **Total**      | **99.6**                  |
Fig. 5. Composite grain of barite and albite from Muhos siltstone. Left: SEM, secondary electron image; right: SEM, backscattered electron image.

Fig. 6. Pyrite grain from till bed Mu-4 (upper left), SEM, secondary electron image. Pyrite grain from till bed Mu-1 (upper right), SEM, secondary electron image. Light pyrite cube from Muhos siltstone (lower left), SEM, backscattered electron image.

Fig. 7. Ilmenite grains from till bed Mu-1 (left), SEM, secondary electron image and from till bed Mu-4 (right), SEM, backscattered electron image.
Application of till geochemical and indicator mineral

unit of till bed IV where the content of mica is 50% of the 200 heavy mineral grains examined in MinIdent analysis by SEM. Epidote, sphene, ilmenite (Fig. 7), magnetite, apatite, pyroxene (diopside, enstatite, augite) garnet (almandine) occur in all till beds with amounts of few percent to 10% of the 200 heavy mineral grains examined. Barite occurs in till beds Mu-3 (found only in 3D by the SEM) and Mu-4 (0.8–1.6 % of 200 grains examined), pyrite only in till beds Mu-1 (0.6%) and Mu-4 (0.5–1.6%) and chalcopyrite (Fig. 9) in the brown unit of till bed Mu-4 (0.5%) (Figs. 6, 8, 9). One chromite grain was found in the brown unit of till bed Mu-4. The chemical composition of that chromite grain (Cr₂O₃ 48.14%, MgO 9.66%, Al₂O₃ 15.33%, FeO 24.4%) is quite similar to that of the chromites of the Kemi chromium ore deposit (cf. Alapieti et al. 1989).

In some samples of till bed Mu-4 and the Muhos Formation siltstone, strange-looking slab- or ribbon-like Na-W bearing minerals were found (Fig. 10). They were interpreted as synthetic minerals precipitated from heavy liquid (Na-heteropolytungstate). It is assumed that despite thorough washing of the heavy fraction after separation there may be traces of the heavy liquid left that crystallize and form synthetic minerals.

---

Table 2. Magnetite content (wt. %) in the heavy sand fraction of the till and siltstone samples

| Till bed | Sample | Magnetite weight% (of the heavy mineral fraction) |
|----------|--------|---------------------------------------------------|
| Mu-1     | M1–2   | 8                                                 |
|          | M3–4   | 3.1                                               |
|          | M5–6   | 2.2                                               |
|          | M7–8   | 3.5                                               |
|          | M9–12  | 6.9                                               |
| Mu-2     | M16–18 | 6.3                                               |
|          | M19–21 | 2.6                                               |
| Mu-3     | M22–23 | 8.9                                               |
|          | M24    | 7.1                                               |
| Mu-4 (grey) | M25–26 | 0.8                                               |
| (red)    | M27    | 2.4                                               |
|          | M28–30 | 6.7                                               |
|          | M31–32 | 10.8                                              |
|          | M33–34 | 7.2                                               |
|          | M35    | 6.4                                               |
| (dark brown) | M36–38 | 6.7                                               |
|          | M39–40 | 7.2                                               |
| Muhos F. | M41–42 | 8                                                 |
|          | M43–44 | 26.2                                              |

Fig. 8. Barite grains (in the middle of the figure) from till bed Mu-4, SEM, secondary electron image.

Fig. 9. Chalcopyrite grain (in the middle of the figure) from till bed Mu-4, SEM, secondary electron image.
DISCUSSION

Petrographical, geochemical and heavy mineral composition of till beds Mu-1–Mu-4 in the Muhos drill-core show that till beds differ markedly from one another. These compositional differences are likely to result from different provenance areas due to diverse ice flow directions during the Saalian and Weichselian glaciations. Previous results using directional evidence from striations, streamlined subglacial landforms and measurements carried out from glaciotectonic structures indicate that the youngest ice flow direction over the present study area was from the W or WNW and an older ice movement direction from the NW or NWW (Aario & Peuraniemi 1990; Bergel et al. 1999; Pasanen & Lunkka 2008). Although the youngest westerly ice flow direction is normally related to the last deglaciation, there is no firm evidence into which ice flow phase the oldest ice flow direction relates to.

In the present study, clasts of mafic volcanics, quartzite and gneissic granitoids, elevated contents of Mg, Fe, Ni, Cu and Zn in the brown and red units of till bed Mu-4 show that the ice movement direction was most likely from the NW or NWW during the deposition of these till units. Finding of chromite grains in the brown unit also supports this conclusion, because the nearest chromite deposit occurs in the Kemi ultramafic intrusion, which is situated 125 km to NW from the Muhos drilling site (Alapieti et al. 1989). The surrounding bedrock areas have been thoroughly examined and no other chromite deposits or ultramafic intrusions have been found in the area.

Influence of local Muhos siltstone is seen as siltstone clasts from till bed Mu-4. The coarse fraction of the grey unit of till bed Mu-4 contains more micas than amphiboles, which is opposite as compared to lower red and brown till units of till bed Mu-4. This evidence seems to indicate that the ice flow direction during the deposition of the grey till unit of till bed Mu-4 shifted from the NW to the WNW when the ice flowed across the extensive granite area (Fig. 1).

Petrographical composition of till bed Mu-3 is quite similar to that of the red unit of till bed Mu-4. This similarity can be interpreted to indicate that ice flow direction during the erosion/transportation/deposition of the both till units was from the NW. Alternatively, reworked material from older till beds could have been incorporated into the younger till bed Mu-3.

Till bed Mu-2 has a high amount of mica schist in the coarse clast fraction. On the basis of this, it seems that the ice still has flowed from the NW across the schist area.

The amount of granite clasts increases considerably in the coarse fraction of till bed Mu-1 and this increase indicates that ice flow changed again and the ice was flowing from the WNW across the area underlain by granite bedrock. Some pyrite grains found in till bed Mu-1 could be re-deposited material from till bed Mu-4.

CONCLUSIONS

A 54-m thick Quaternary sediment sequence overlying the unmetamorphosed Neoproterozoic Muhos Siltstone Formation was drilled at Muhos, northern Finland. The sediment sequence consists of four till beds (Mu-1–Mu-4) interbedded with sand/silt/clay units. The lowermost till beds Mu-3 and Mu-4 are thought to have been deposited during the Saalian or pre-Saalian glaciations and till beds Mu-1 and Mu-2 during the middle and late Weichselian glacial events. In order to define the provenance areas of till beds and the ice movement directions during different glacial phases, petrography of till clasts, geochemistry of the fine fraction and heavy minerals of the sand fraction from all four till beds were studied.

The results show that till bed Mu-4 can be divided into three sub-units. The ice movement direction during the deposition of the lowermost brown and red till units of the till bed Mu-4 was from the NW to the SE or from the NWW to the SSE across the Muhos area. During the deposition of the uppermost grey till unit of the till bed Mu-4 the ice flow direction was from the NW to the ESE. The till beds Mu-3 and Mu-2 were deposited when the ice flowed again from the NW to the SE. The composition of the uppermost till bed Mu-1 suggests that the ice flowed from WNW–ESE during this stage.

Gneissic granitoid clasts in the red unit and a chromite grain in the brown unit of the till bed Mu-4 are the result of the long glacial transport from the NW. The younger till beds contain also some reworked and re-deposited material from the older till beds.
The results of this study partly support some earlier data on the ice movement directions in the area but also give new more detailed data on the ice flow directions during Weichselian and Saalian glacial stages in the surroundings of Muhos and Oulu. Laboratory technician Ms. Riitta Kontio has done the AAS analyses of the samples. Mr. Olli Taikina-Aho was in charge of the XRF analyses. Ms. Päivi Huhatala has given help in SEM studies. Ms. Kristiina Karjalainen has drafted the figures. We express our sincere gratitude to all these people.

REFERENCES

AARJO, A. 1984. Jääikäkkösyntyisten maaperä- ja noodosten muotoon, ominaisuu- det ja käyttöosuuus. Suomen Akatemian tutkimusprojektin loppuraportti, Oulun yliopisto, University of Oulu.

AARJO, R. & FORSSBOM, L. 1979. Deglaciation stratigraphy of Koillismaa and North Kainuu, Finland. Nords. Nordija, 13, 3.

AARJO, R. & PEURANEN, V. 1990. Secondary copper iodide in till in the Löytsönsaaret, Ylikiiminki, Finland. Applied Geochemistry, 5, 347–355.

ALAPIETTI, A., KUSMAN, J., LAHTINEN, J. & PAPINEN, H. 1989. The Kemi strataform chromitite deposit, northern Finland. Economic Geology, 84, 1057–1077.

BERGEL, T., HUHTA, P., JOHANSSON, P. et al. 1999. Maps of Quaternary Geology in Central Fennoscandia, Sheet 3: Ice-flow indicators, scale 1:1 000 000, and Quaternary Stratigraphy, scale 1:2 000 000. Geological Survey of Finland (Espoo), Norway (Trondheim) and Sweden (Uppsala).

ENKOVANKA, A., HURMI, M. & VÄYRYNEN, H. 1953. Bedrock map of Oulu and Toroni areas. Geological map of Finland 1:400 000. Geological Survey of Finland, Helsinki.

HERVÄ, H. 1991. Pleistocene stratigraphy of Finnish Lapland. Geological Survey of Finland, Bulletin, 354.

HERVÄ, H., ALPETT, A., PEULKENIN, E., PURANEN, R. & TYNNI, R. 1977. Raportit malminetsintää palvelevasta maaperätutkimuksesta Pohjois-Suomessa vuonna 1972–1976. Geological Survey of Finland, Report of Investigation, 19, Espoo.

HÖNKANEN, M. 1988. Bedrock map of Haukipudas and Kiiminki areas. Geological map of Finland 1:100 000, sheets 2533 and 3511. Geological Survey of Finland, Espoo.

JOHANSSON, P., LUKKA, J.P. & SABAL, P. 2011. The Glaciation of Finland. In: EDLERS, J., GIBBARD, P.L. & HUGHES, P.D. (eds) Quaternary Glacialites – Extent and chronology. Developments in Quaternary Science. Elsevier, Amsterdam, 15, 105–116.

KESÖLÄ, R. 1985. Bedrock map of Oulujoki area. Geological map of Finland 1:100 000, sheet 3422. Geological Survey of Finland, Espoo.

KORPELA, K. 1977. On the engineering geological properties of the Muhos silstone. Tunnon ylipyisten maaperätutkimuksen asiaston julkaisusarja, 31.

LAFIKARI, I. 1998. Peruskallion myöhemäiset kehitysteinteet. In: LEHTINEN, M., NURMI, P. & RAMO, T. (eds) Suomen kalliopeita: 5000 vuotta kalliomaalla. Suomen Geologinen Seura, Helsinki, 309–325.

LOKKI, L. 1950. Chemical Analyses of Finnish Rocks. Bulletin Commission Géologique de Finlande, 151.

LUKKI, J.P., JOHANSSON, P., STARINISI, M. & SALASMAA, O. 2004. Glaciation of Finland. In: EDLERS, J. & GIBBARD, P.L. (eds) Quaternary Glacialites – Extent and Chronology. Part 1: Europe. Elsevier, Amsterdam, 93–100.

LUKKI, J.P., BREILING, O., PUTKINEN, N. & ESKOLA, T. 2010. Sediment sequence at Muhos, central western Finland – a window to the Pleistocene history of the Scandinavian Ice Sheet. APEX Fourth International Conference and Workshop, Iceland 2010 – Arctic Palaeoclimates and chronologies. Höfn, Iceland, May 26th–30th 2010. Abstract Volume, 53–56.

NENONEN, K., ERIKSSON, B. & GRÖNLUND, T. 1991. The till stratigraphy of Ostrobothnia, western Finland, with reference to new Eemian interglacial sites. In: ANDERSEN, B.P. & KÖNGING, L.-K. (eds) Late Quaternary Stratigraphy in the Nordic Countries 150 000-15 000 B.P. Striae, 34, 65–76.

PAASinen, A. & LUKKA, J.P. 2008. Glaciotechnic deformation of till covered glaciofluvial deposits in Oulu region, Finland. Bulletin of the Geological Society of Finland, 80, 89–103.

SALINEN, V.-P., ERIKSSON, B. & GRÖNLUND, T. 1992. Pleistocene stratigraphy in the Lappajärvi meteorite crater in Ostrobothnia, Finland. Boreas, 21, 253–269.

SALONEN, V.-P., KAAKINEN, A., KULTI, S., MEHTINEN, A., ESKOLA, K.O. & LUKKI, J.P. 2008. Middle Weichselian glacial event in the central part of the Scandinavian Ice Sheet recorded in the Hütta pit, Ostrobothnia, Finland. Boreas, 37, 58–54.

SIMONEN, A. 1960. Pre-Quaternary rocks in Finland. Bulletin de la Commission Géologique de Finlande, 191.

SIMONEN, A. 1964. Kallioperä. In: RANKA, K. (ed.) Suomen geologia. Kirjakyhýmä, Helsinki, 49–124.

SIMONEN, A. 1980. The Precambrian in Finland. Geological Survey of Finland, Bulletin, 304. Espoo.

TYNNI, R. & DONNER, J. 1980. A microfossil and sedimentation study of the Late Precambrian formation of Hailuoto, Finland. Geological Survey of Finland, Bulletin, 311.

TYNNI, R. & SHIVAK, J. 1966. On the Precambrian microfossil flora in the silstone of Muhos, Finland. Bulletin de la Commission Géologique de Finlande, 222, 127–133.

TYNNI, R. & UTTELA, A. 1984. Microfossils from the Precambrian Muhos formation in Western Finland. Geological Survey of Finland, Bulletin, 330. Espoo.

VAUGHAN, D.J., SWEENEY, M.A., FRIEDCHIC, G., DREBIE, R. & HARBANČK, C. 1989. The Kupferschiefer: an overview with an appraisal of the different types of mineralization. Economic Geology, 84, 1003–1027.

VÄYRYNEN, H. 1954. Suomen Kallioperä. Otava, Helsinki.

Received 4 January 2012; revised typescript accepted 3 October 2012.
Earthworks in Europe
Edited by T A Radford
This book provides an overview of developments in the design and construction of earthworks predominately associated with transport infrastructure. It includes case studies from across Europe and covers a range of topics including the suitability of materials; geotechnical risk and performance; asset management as well as environmental impact and climate change.
ISBN: 978-1-86239-352-3 | Hardback | 185 pages | Publication date: 10 December 2012
List price: £75.00 Fellow’s price: £37.50 Other societies price: £45.00  Online Bookshop Code: SPE26

Sustainable Development and Management of the Shallow Subsurface
Author/Editors C C D F Van Ree, E F J De Mulder and H R G K Hack
This book focuses on the development and management of structures and resources in the shallow subsurface, which plays a key role in human life, and addresses sustainable use in the past, present and future. It is aimed at all those involved in subsurface construction: providing an overview of technical aspects and also legal, governmental and policy-making issues.
ISBN: 978-1-86239-343-1 | Hardback | 192 pages | Publication date: 17 October 2012
List price: £75.00 Fellow’s price: £37.50 Other societies price: £45.00  Online Bookshop Code: MP5DM

Hot Deserts: Engineering, Geology and Geomorphology:
Engineering Group Working Party Report
Edited by M J Walker
This volume provides an authoritative and comprehensive, state-of-the-art, international review and handbook on hot desert terrains, their geomaterials and influence on civil engineering site investigation, design and construction. It is an essential reference book for professionals that will also be a valuable textbook for students and be digestible to the non-specialist.
ISBN: 978-1-86239-342-4 | Hardback | 440 pages | Publication date: 28 March 2012
List price: £100.00 Fellow’s price: £50.00 Other societies price: £60.00  Online Bookshop Code: SPE25