Distribution of rock fragments, grain size and chemical elements in tills in the Lake Mjøsa area, East Norway

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The Lake Mjøsa area in eastern Norway forms an interesting case to study glacial erosion, transport and deposition because bedrock lithology (source of till) is relatively well known and the Geological Survey of Norway (NGU) has a large number of till samples from the area. Late Precambrian sandstones dominate bedrock lithology in the north-northeastern parts of the area. In the central eastern areas the Cambro–Silurian rocks (predominantely shales) are found. Towards the south and west in the field area, the Precambrian crystalline rocks and Permian rocks dominate the bedrock lithology. Tills in the area often have a sandy-silty matrix, but with a high clay content in areas close to the lakes Mjøsa and Randsfjorden. In this paper we analyse a large number of till samples according to clast provenance and main cations, and show that late Precambrian sandstone often is transported long distances (50–80 km), and are deposited mainly in the upper part of the till stratigraphy. On the other hand, the lowermost part of the till sequence often closely reflects the underlying bedrock. This is particularly true in easily eroded terrain (Cambro–Silurian shales), with mostly short transported till. It is a complex problem to do mineral prospecting using till as a proxy for the underlying bedrock, and a thorough knowledge of glacial history and till stratigraphy is essential for successful interpretation of prospecting data.

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Introduction

Petrographic and geochemical analyses of tills are often used in mineral exploration, where geochemical anomalies in the till are used to trace the source mineralization (e.g., Hirvas 1989, Klassen and Thompson 1993). However, the method is problematic since the genesis of till through erosion, crushing and jostling of bedrock is complex (Haldorsen 1982), and till transport pathways often are unknown. Research during the last few decades has shown that glacial dispersal patterns not only reflect the last ice-flow direction, but that composite ice movement through several glacial stages are commonplace (e.g., Klassen and Thompson 1989, Kleman 1992, Parent et al. 1996). In short, an intimate knowledge of Quaternary ice-flow patterns and till sedimentology is needed to successfully utilize mineral prospecting using till as a bedrock proxy.

An ideal case to test some of these problems is the Lake Mjøsa area in east Norway (Figure 1). This area exhibits a wide spectrum of bedrock lithologies and is partly overlain by thick sequences of glacial till. Throughout the years 1972 to 1985, the Geological Survey of Norway (NGU) performed extensive Quaternary geological mapping of the area resulting in a number of Quaternary maps at the scale 1:50,000 (Follestad 1973, 1974, 1977, Follestad and Østmo 1977, Aa 1979, Rye 1979, Sveian 1979, Bargel 1983, Kjærnes, 1984a, Olsen, 1985a,). Additional maps at scale 1:20,000 were also compiled (Follestad 1976a, b, c, d, 1979, Rye 1976, 1978, Follestad and Rye 1976, Sveian 1976, Goffeng and Follestad 1979, 1981a, b, c, d, 1982, Olsen et al. 1979, Olsen 1980, Olsen and Follestad 1982) (Figure 1). Furthermore, detailed petrographic and geochemical characterization (150–200 samples for each map sheet) of glacial till was performed. This extensive data set has the potential to show some of the behavior of clasts and chemical elements through erosion and transport of glacial till. The properties and spatial distribution of sediments in relation to underlying lithology in this area, could thus help improve models used in mineral prospecting.

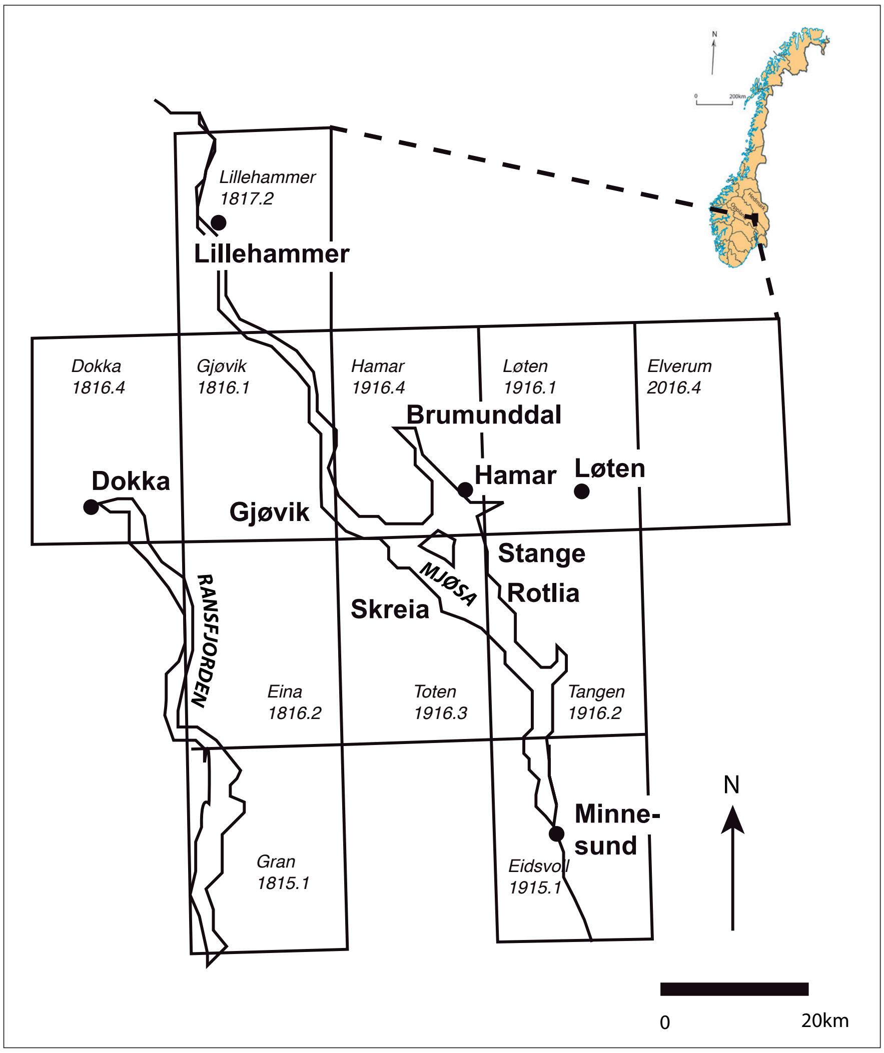

Figure 1. Location of study area. Quaternary maps used in the article, with names, are marked with boxes.

Physiographic setting and Quaternary history of the Mjøsa area

The field area is dominated by Lake Mjøsa (123 m a.s.l.), which covers an area of 368 km^2 (Figure 2). The lake is 107 km long from Lillehammer to Minnesund and 15 km wide in the Toten–Hamar area. The depression housing the lake represents the southward extension of Gudbrandsdalen valley, which also provides much of the discharge into Mjøsa. The area is surrounded by a hilly landscape where the hills reach 400–600 m a.s.l. in the areas to the northeast and to the south. The water divides against the valley of Glomma, and the valley of Dokkadalen/Randsfjorden defines the eastern and western watersheds for Lake Mjøsa. The lowland between the areas of Stange/Hamar and the Løten area reaches an altitude of 150–200 m a.s.l. and is known as the Hedemarken area.

The central parts of Norway have repeatedly been covered by ice sheets (Mangerud et al. 2011). During the last glaciation (Weichselian), the ice divide was mostly situated north of Lake Mjøsa, and hence a general ice movement towards the south dominated. Aa (1979), Sveian (1979) and Olsen (1979, 1983, 1985a, b) mapped well-defined drumlins, and, together with observations of glacial striae, these features indicate that ice moved in a south-southeastward direction in the western and central parts of the Lake Mjøsa areas during the final phase of the Weichselian glaciation. In the eastern parts of the Lake Mjøsa area, the ice-flow direction was due south (Follestad 1973, 1974). Farther to the east, in the Elverum area, Bargel (1983) also showed southward-flowing ice, more or less following the direction of the Glomdalen valley.

Earlier glacial phases are not well documented in the geomorphological and stratigraphical record of the area. However, since the field area is situated relatively close to the southern margin of the Scandinavian glaciations, it is inferred that southward ice movement has been dominating throughout much of the Quaternary. From general knowledge of ice-sheet build-up and decay it is plausible that east-southeasterly ice movement, with a mountain-centered ice divide to the west, dominated in the early Quaternary (2.6–0.7 Ma) (Kleman et al. 1997, Fredin 2002, Mangerud 2011).

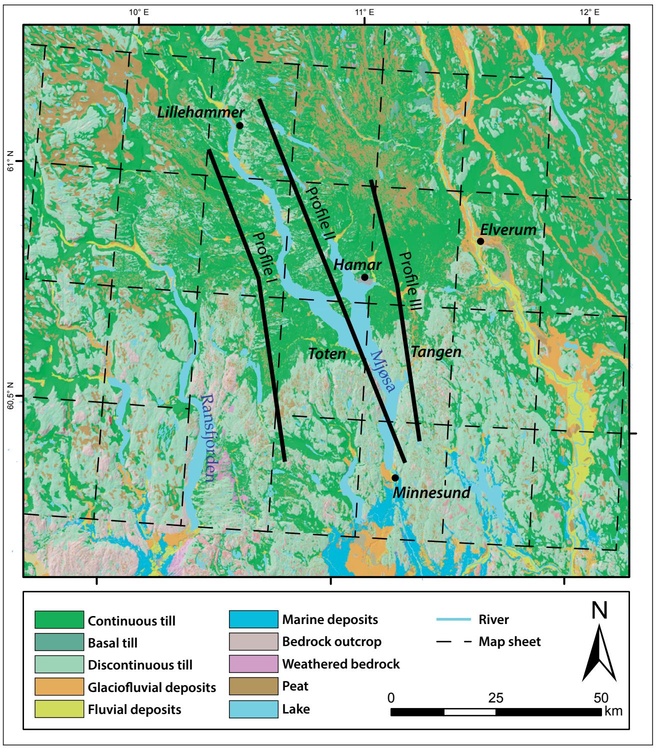

Figure 2. Published Quaternary geological maps at the scale of 1:50,000 extracted from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/). The locations of profiles (I, II and III) in Figure 12 are indicated by lines.

Methods

Mapping of Quaternary deposits is based on procedures developed at NGU (Bergstrøm et al. 2001), where sediments are classified according to their genesis. Mapping was conducted using aerial photographs and extensive field observations. Together with surficial mapping and stratigraphic description, more than 2000 soil samples were collected, whereof 1278 were samples from till.

The till samples were analyzed according to grain size, clast lithology and main cations at the NGU laboratory in Trondheim. Grain-size analysis was performed using sieves and sedimentation techniques, and the proportions of Gravel (19.0–2 mm), Sand (2–0.063 mm), Silt (0.063–0.002 mm) and Clay (< 0.002 mm) were measured. Clast lithologies in tills were determined together with NGU bedrock mappers operating simultaneously in the field area (Bjørlykke, 1979).

Concentration of main metallic cations (Pb, Cu, Cd, Zn, Co, Ni, V, Ag, Mn and Fe) in glacial till was determined through digestion of the sample in HNO_3 and measurement of the solution using Atomic Absorption Spectroscopy (AAS). All these analytical data are unpublished or only partly found in Quaternary map descriptions from NGU. However, recently all data were digitized into an ESRI ArcMap geodatabase (Electronic Supplement) for analysis and visualization using ArcGIS (version 10.1).

Quaternary deposits in the Lake Mjøsa district

A continuous till cover drapes the landscape east and northeast of Hamar and southwest of Gjøvik and Toten villages (Figure 2). Here, the till morphology is fairly smooth, exhibiting a typical rolling moraine landscape. In areas with large bedrock structures, e.g., as in the Stange area, distinct folds of Silurian limestone are oriented with fold axes trending E–W. These bedrock structures dominate the morphology in parts of the landscape. Over the ridges (folds) the till cover is discontinuous or thin, otherwise it often exhibits great thickness (5 m or more) in the Hedemarken area (Follestad 1973, 1974, Rye 1979).

In southern and southwestern parts of the mapped area, the till cover is discontinuous and the bedrock is frequently exposed (Figure 2). This is the case on both sides of Lake Mjøsa and in the areas east of Lake Randsfjorden. However, even in these areas some minor depressions with continuous cover of till occur, e.g., in the map sheets of Tangen (1916 II) and Gran (1815 I).

Stratigraphic sections from different parts of the field area (Follestad 1973, 1974, 1977) often show that vertical variations in clast lithology might be significant. Thus, Late Precambrian sandstones might occur in the uppermost part of the profiles, while clasts of local origin are more frequently represented lower in the section, close to the till–bedrock contact. Also, grain size varies predictably in sections, where the upper till sequence commonly has a gravelly to sandy matrix, while a sandy to silty matrix is frequently observed close to the bedrock contact. Clay-rich, stiff till is found in areas close to Lake Mjøsa. It is traditionally named the Mjøsa clay, which is an informal term used in this area for a till with a high content of clay. The matrix of this till likely was formed by erosion of older marine clays deposited during the middle and late part of the last glaciation (Olsen 1985b, Olsen and Grøsfjeld, 1999).

Grain-size distribution

The grain-size distribution of till samples (less than 19 mm) is shown in the Electronic Supplement and Figures 3 and 4. Gravel is the dominant grain size in most of the till samples and can in some cases reach >60% (by weight) of the material less than 19 mm (Figure 3). The median value for the till samples vary between 0.015–6 mm and 0.04–7 mm, as reported by Follestad (1973, 1977) and Bargel (1983). Sveian (1979) and Olsen (1985 a, b) reported similar grain-size median values from till samples in the Gjøvik and Lillehammer areas.

In some samples the content of fines (silt and clay) can constitute as much as 40% of the material (less than 19 mm). Around Stange, Skreia and Randsfjorden the clay fraction commonly reaches 30% (Figure 4). This is explained by incorporation of older clay material, deposited in the Lake Mjøsa and Lake Randsfjorden basins in an ice-free environment (Follestad 1973, 1977). During the middle and late Weichselian glaciation, advancing glaciers are thought to have eroded and incorporated

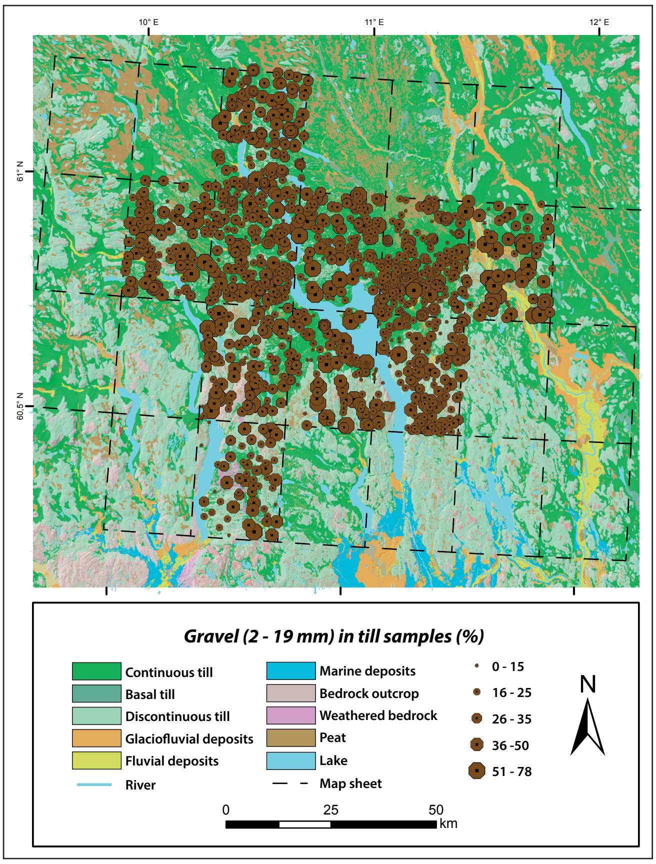

Figure 3. Spatial distribution of gravel (2–19 mm) in surficial till samples.

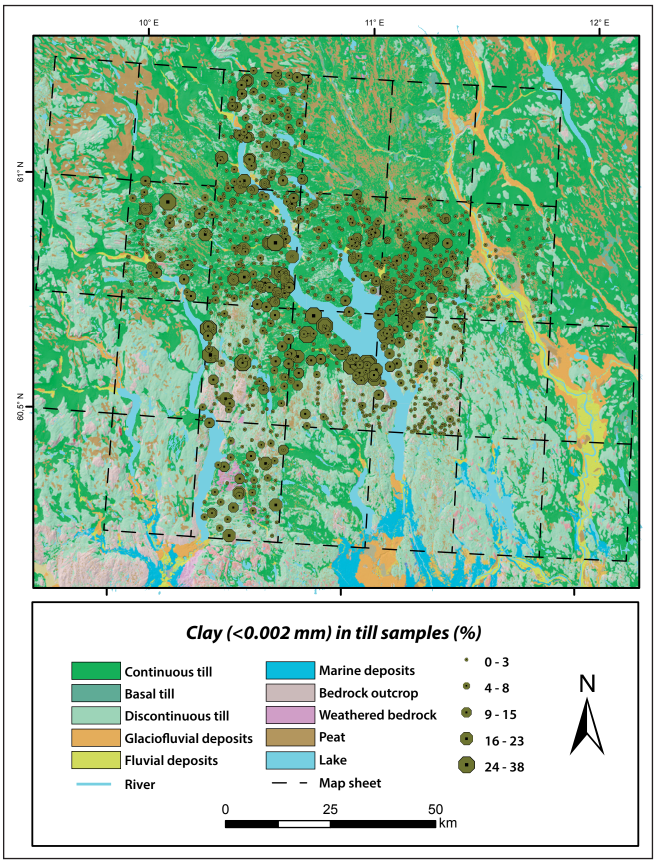

Figure 4. Spatial distribution of clay (<0.002 mm) in surficial till samples.

these clays into the till beds. These clay-rich tills are deposited as stoss-side moraines in the Toten area by a southward-moving glacier.

Some chronological control on the deposition of this clay-rich till in the Toten area is offered by two fragments of a *Mammut primigenius* tooth, which were found in a till trench close to Skreia (Heintz 1955). These fragments are radiocarbon dated to be older than 28 ka (Follestad and Olsson 1979), which indicates that older deposits were reworked by an advancing glacier during the build-up towards the maximum Weichselian glaciation (Follestad 1973).

Rock fragments and petrographic analysis in till

Heyerdal (1811) found two groups of erratic boulders, i.e., one local and one foreign type in the Lake Mjøsa area. Later, Keilhau (1832) described occurrences of erratic boulders from other parts of Norway as a consequence of an ice age (Esmark 1824). Hørbye (1855) carried out systematic work on erratic boulders and showed that boulders have been transported both ways over the Swedish–Norwegian border in the Femunden area. After these early descriptions, the development of a modern petrographic till analysis can be assigned to the works of von Post (1855, 1856). According to Lundqvist (1935), von Post was the first scientist who systematically determined all of the *rock types* in a sample. At the Geological Survey of Norway a simplified version of a petrographic analysis has been used, limiting the characterization to the grain-size fractions between 8 and 4.8 mm.

Late Precambrian sandstone in till clasts

Late Precambrian sandstone clasts (Figure 5) are widely found in till west, north and northeast of Lake Mjøsa. Obviously, till fragments of this lithology broadly follows the distribution of Precambrian sandstone bedrock. In the map sheets Lillehammer (1817 II), Hamar (1916 IV) and Løten (1916 I) Late Precambrian sandstones clearly dominate the grain-size fraction 8–4.8 mm and may reach close to 100% in some of the till samples. The occurrence of Cambro–Silurian rocks in some of the till samples on mapsheet Gjøvik (1816 I) can be explained by interbedded zones of Cambro–Silurian rocks in areas otherwise mapped as Late Precambrian sandstone (Bjørlykke 1979). These details are left out in the simplified version of the bedrock map used in this description.

Towards the south, the content of Late Precambrian sandstone clasts is still high in areas underlain by Cambro–Silurian rocks (Skjeseth 1963), as is the case in the central and southern parts of map sheet Løten (1916 I) and in eastern parts of map sheet Hamar (1916 IV). In the Dokka (1816 IV) and Gjøvik (1816 I) map sheets Late Precambrian sandstone clasts are strongly represented in till samples, although the sediments

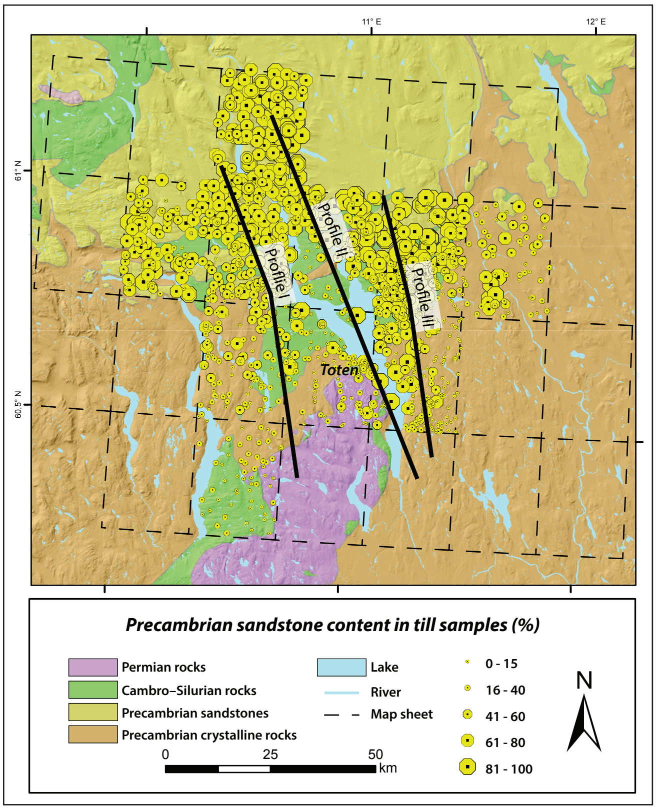

Figure 5. Distribution of Late Precambrian sandstones in tills (grain size 4.8–8 mm). The simplified bedrock map is extracted from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/). The locations of profiles (I, II and III) in Figure 12 are indicated by lines.

are underlain by Cambro–Silurian rocks (Figure 5). Our interpretation is that Weichselian ice flow has dispersed significant amounts of Late Precambrian rocks towards the south.

Precambrian crystalline rocks and Permian rocks underlie till deposits in the southern and eastern parts of the mapped area. In these areas the content of Late Precambrian sandstone drops markedly, but are still represented in a majority of till samples from Tangen (1916 II), Toten (1916 III), Eina (1816 II) and Gran (1815 I) areas (Figure 5).

Cambro–Silurian rocks in till clasts

In central and southern parts of the Løten (1916I) map sheet, and in northern parts of Tangen (1916 II), tills are underlain by the Cambro–Silurian rocks (Figure 6).

Follestad (1973, 1974) performed detailed till stratigraphy studies and found that the concentration of Precambrian sandstone clasts in this area is dependent on sampling depth, such that Cambro–Silurian rock fragments dominates the lower till unit, while the content of Precambrian sandstone increases upwards and even dominates over coarser fractions high up in the sequence. These observations underscore the importance of understanding the till stratigraphy when using glacial drift as a prospecting tool. The Cambro–Silurian clast concentrations in Figure 6 might thus be influenced by sample depth, but on a

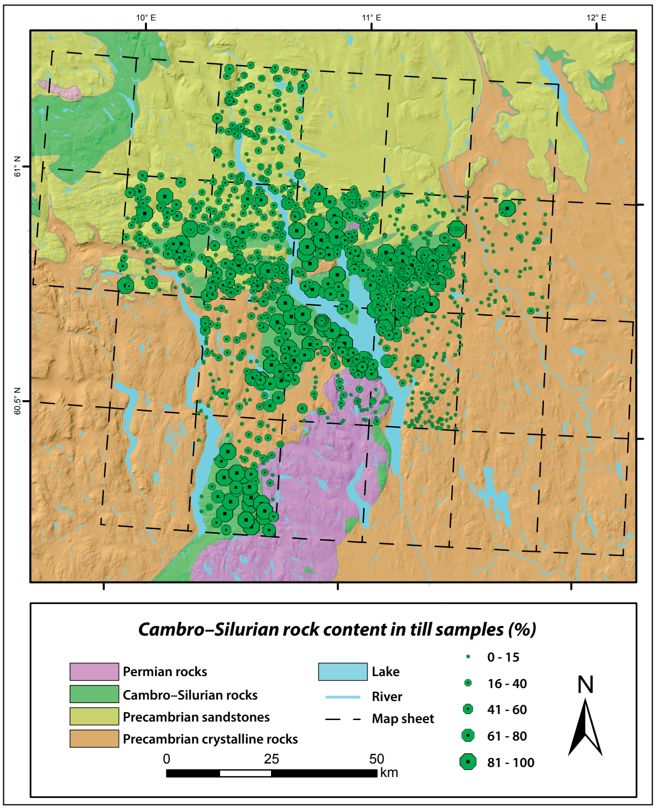

Figure 6. Distribution of the Cambro–Silurian clasts in tills (grain size 4.8–8 mm). The simplified bedrock map is copied from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/).

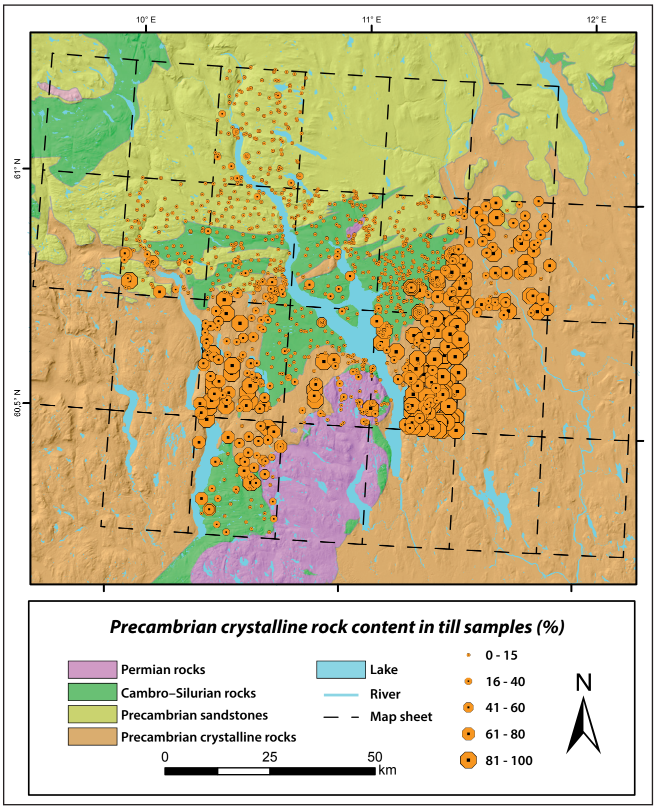

Figure 7. Distribution of the Precambrian crystalline rocks in tills (grain size 4.8–8 mm).

broader scale Cambro–Silurian till-clast content is almost entirely autochthonic and conditioned by underlying Cambro–Silurian bedrock.

Precambrian crystalline rocks in till clasts

As portrayed in Figure 7, Precambrian crystalline clasts clearly dominate till samples underlain by these rocks, which for example is illustrated in the Tangen (1916 II) and Eina (1816 II) areas. In the southeastern areas of the Løten (1916 I) map sheet, outcrops of Precambrian bedrock are clearly reflected in till samples. However, it should be noted that also around Tangen, which is dominated by a discontinuous cover of tills underlain by Precambrian rocks, some areas of continuous till deposits, with a significant content of Late Precambrian rocks, are present. Glacial dispersal to the south is thus also evident where Precambrian crystalline clasts occur for example in Cambro–Silurian terrain (Figure 7).

Permian rocks in till clasts

These till rock fragments are almost exclusively found in areas dominated by Permian bedrock (Figure 8), as in the Totenåsen area and in Brumunddal (Hamar 1916 IV). Around Toten, a relatively high proportion of clasts of Permian origin are observed in till samples. Minor, local outcrops of Permian rocks,

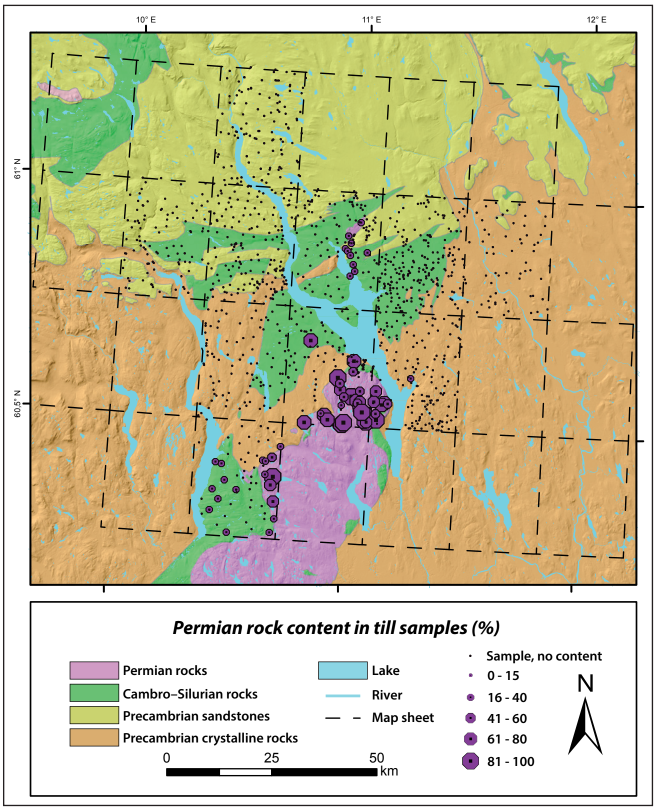

Figure 8. Distribution of the Permian rocks in tills (grain size 4.8–8 mm).

which so far have not been mapped, can explain this. An alternative explanation would be a complex glacial transport, during one or more ice-flow phases, from more remote Permian rock sources.

Content of metal cations (Pb, Cd, Cu, Zn, Co, Ni, V, Ag, Mn. Fe) in tills

Geochemical analyses have been carried out on the till samples and the results are shown in the Electronic Supplement and Figures 9, 10 and 11 for lead (Pb), copper (Cu) and cadmium (Cd), respectively. Geometric deviations and medians are discussed by e.g., Follestad (1974). Chiefly, these analyses show that the content of lead (Pb), copper (Cu) and cadmium (Cd) are higher in till samples taken in areas underlain by Cambro–Silurian rocks than elsewhere in the region. In particular, cadmium (Cd) seems to be associated with Cambro–Silurian rocks in the Løten (1916 I), Tangen (1916 II) and Gran (1815 I) areas (Figure 11). High values are also seen in areas outside these bedrock zones and might show anomalies in bedrock dominated by Precambrian sandstone or caused by interbedded Cambro–Silurian rocks in these areas. However, a complex glacial transport history may also explain these anomalies and should therefore be carefully considered.

A summary of transport length is given in Figures 5 and 12, where profiles are plotted showing content of Precambrian sandstone content in till. Since this bedrock dominates the northern third of the investigated area it provides a useful marker towards the south, following the main ice-transport vector. In all three profiles it is evident that significant amounts of Precambrian sandstone clasts are transported as far as 70 km from the likely source area (Figure 12). Many of the distal samples are from shallow pits in thin till terrain, and show that far transported material is relatively common.

Discussion

In Norway, the lithological composition of clasts in tills and other glaciogenic deposits (stone counts) was early adopted by Brøgger (1877), Reusch (1901) and Øyen (1900, 1904, 1907) to describe distance and mode of glacial transport in east Norway. Already Låg (1948) used this method (stone count) in his studies of tills around Mjøsa. Bergersen (1964) extended this with careful analysis of clast roundness, in combination with stone counts in till studies in Gudbrandsdalen valley. This together with later studies of long-axis orientation of gravel in tills have provided new information on till transportation and till formation in east Norway (Bergersen and Garnes 1983, Olsen 1979, 1983, 1985a, b).

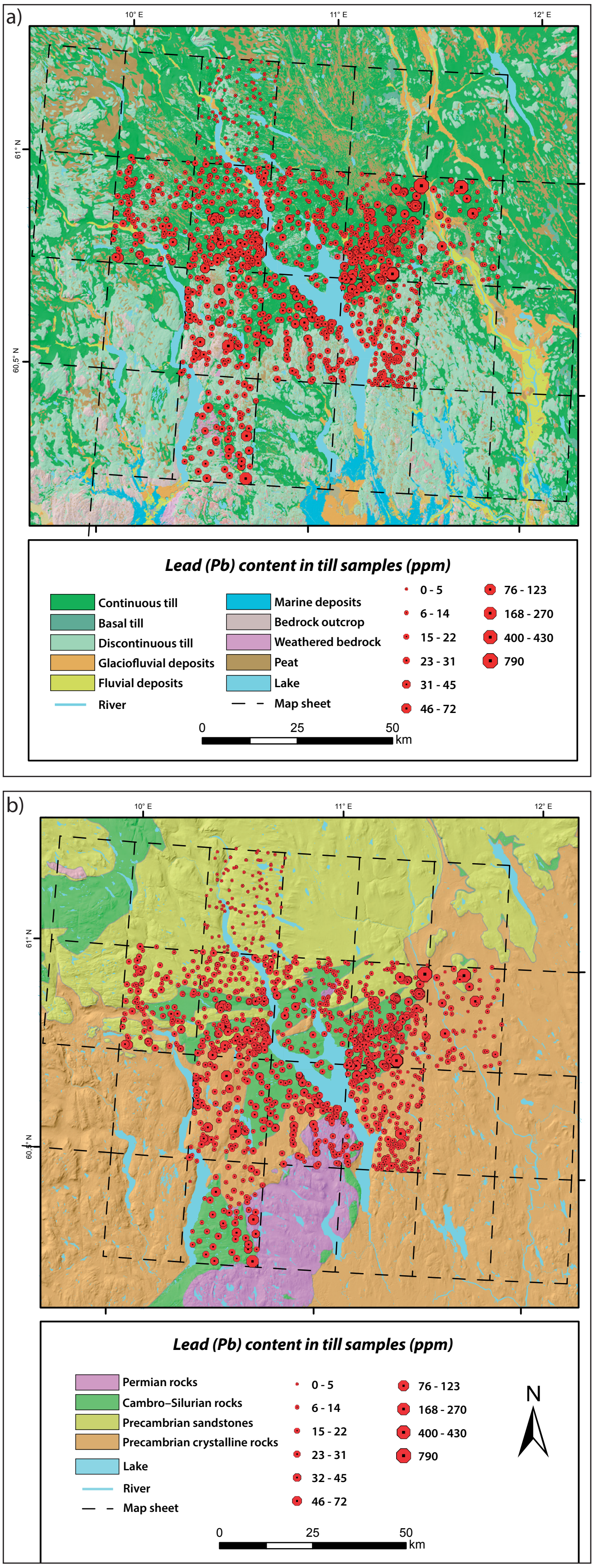

Figure 9. (a) The distribution of lead (Pb) in tills (<0.18 mm) plotted on the Quaternary map.(b) The distribution of lead (Pb) in tills (<0.18 mm) plotted on the bedrock map.

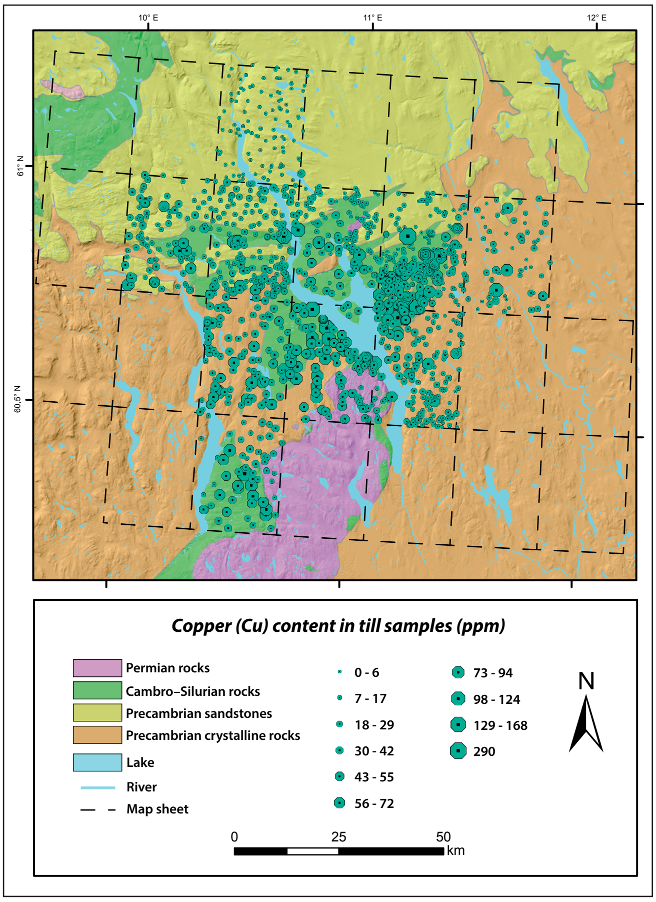

Figure 10. The distribution of copper (Cu) in tills (<0.18 mm).

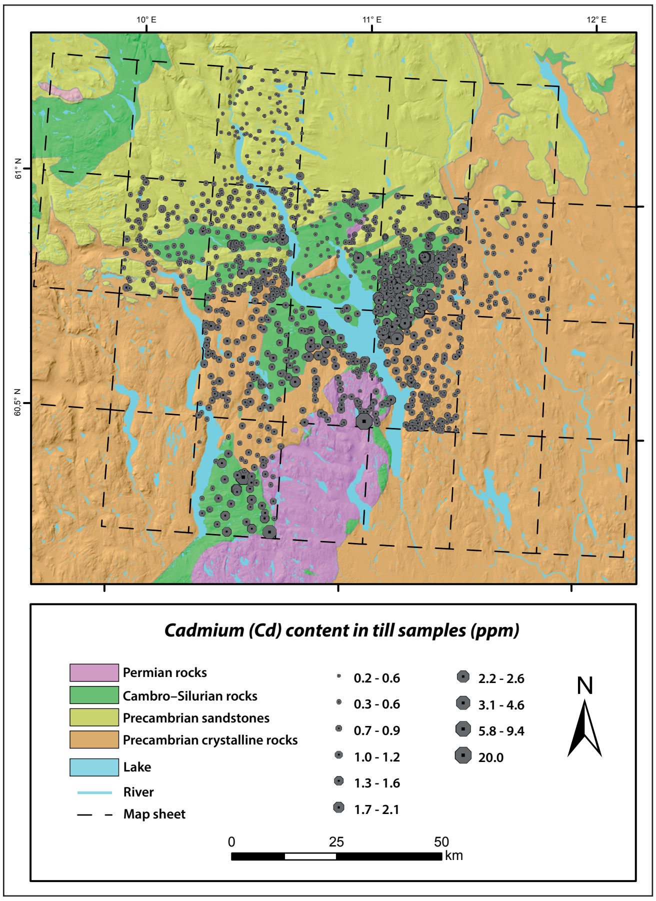

Figure 11. The distribution of cadmium (Cd) in tills (<0.18 mm).

The present study shows widespread glacial transport of till clasts to the south over the area. These results are quite similar to the results obtained by Låg (1948) and Øyen (1900). Øyen even found that up to 10% of the rock fragments in the Ås moraine close to Oslo, were Late Precambrian sandstones, probably derived from the Mjøsa area. He pointed out that the transport distance must have been around 140 km for these clasts. These studies clearly demonstrate that a long transport distance for significant amounts of glacigenic material might occur.

Flint (1971) argued that factors influencing till composition are: (1) the properties of the ice sheet, (2) the geomorphology of the area and ice flow of the glacier, and (3) the different rock-type properties and resistances against glacial erosion. Theoretical studies reinforce these ideas showing the complexity of till formation and a vast range of subglacial erosion rates (e.g., Hallet 1979, 1996, Haldorsen 1981). Moreover, a till area is seldom dominated by only one ice-flow direction, but several glacial configurations with starkly different ice flows both in direction and magnitude may have influenced a till stratigraphy. Some of these glacial stages, if the basal glacier ice is below the pressure melting point, may have passed with very little influence on the sediment sequence (Kleman 1992, Kleman and Hättestrand 1999, Cuffey et al. 2000).

Already Follestad (1973, 1974) and Olsen (1979, 1985a, b) emphasized the importance of understanding glacier dynamics and basal ice conditions to explain glacial transport. Till transport in the basal ice of a glacier will in most cases reflect the underlying bedrock and be characterized by a silty and fine, sandy matrix. If the transport has taken place higher up in the glacier (englacially or supraglacially), the matrix will be characterized by a lower content of the finer grain sizes and often a much higher content of long-transported material (Benn and Evans, 1998). These early studies of Follestad (1973, 1974) and Olsen (1979, 1985a) do not discuss the effects of changing ice-sheet configuration and cold-bedded ice, even though basal thermal boundaries must have migrated over the area during ice-sheet expansion and retreat. A discussion on this complication is given by Parent et al. (1996), and should be considered in particular in central areas of Fennoscandia and North America, where frozen bed conditions might have prevailed during the much of the Quaternary.

The geomorphology of the area and the observed movement of the glacier strongly suggest ice flow towards the south during deglaciation in the area. The direction of ice movements relative to terrain obstacles decide where plucking of unconsolidated material will be in the ice, i.e., at the base, or higher up in the

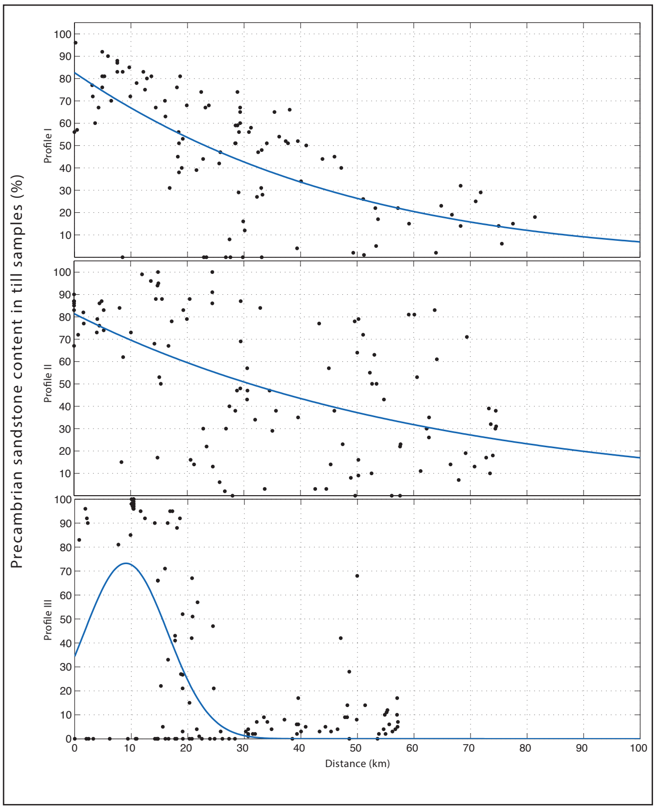

Figure 12. Three profiles running across the western, central and eastern parts of the study area showing the content of Precambrian sandstone clasts in till. For location of profiles (I = Western profile, II = Central profile and III = Eastern profile) see Figures 2 and 5. A first order Gaussian fit was applied to the data (blue line) to visualize the general decrease in concentrations with ice-flow distance.

ice along valley sides, or dropped or slid from higher ground onto the ice in nunatak areas. This may, as mentioned above, be significant for the transport length of the till material and should be carefully considered, e.g., during prospecting campaigns. The distinct stoss-side moraines along the Totenåsen mountain southwest of Mjøsa, shows that the ice sheet at least during maximum glacial configuration, might have moved almost independently of the terrain. However, during the final deglaciation, topography to a higher degree governed ice flow, which is indicated by slightly diverging ice-flow indicators in the area.

Different rock types have different resistance to glacial erosion (abrasion and plucking) and this has played an important role in erosion and transport of the Cambro–Silurian rocks. This is widely observed in the black slates of Hedemarken, where a clear overrepresentation of Late Precambrian rocks occurs. Similar conditions are also described by Haldorsen (1977) in the Ringsaker area, where erodible rocks are widely dispersed along the ice-flow trajectory.

The general trends in the distribution of geochemical elements of the till fraction <0.18 mm generally follows the results found for distribution of rock types in the till gravel fraction. Both indicate a dominant transport direction towards the southeast and south from their likely bedrock sources. It is known that the distribution of chemical elements follows and varies with grain size (Haldorsen 1977, 1982, Ottesen 1985). However, we have limited our geochemical analyses to the bulk of fines (<0.18 mm), as the majority of the till samples are from relatively shallow pits (<1 m deep), and mainly from silty-sandy tills, with little variation in grain-size distributions. Therefore, we suggest that a potential difference in terminal grades (grain-size bias) is a subordinate factor for explaining anomalies in our data.

The Cd–Cu–Pb anomalies in several Cambro–Silurian areas are interesting because they cover sizeable areas, and some of the absolute concentrations are quite high. Small Pb deposits are known to occur in other parts of this rock sequence (e.g., Nilsen and Bjørlykke 1991) and might thus explain high concentrations of heavy elements. Since these anomalies occur over relatively large areas it is tempting to suggest that element dispersion has happened through glacial transport.

In general our results indicate that the till composition low in a till stratigraphy closely reflects the underlying bedrock. However, higher up in the till sequence significant deviations may occur and long-transported clasts and elements are common. It is thus imperative to understand the Quaternary history and till stratigraphy in an area for successful mineral exploration. It is also recommended that sampling is made in the lowermost part of the till sequence where till matrix composition often closely resembles that of the underlying bedrock. These results are in line with several other studies in North America and Fennoscandia (e.g., Clark 1987, Hirvas 1989, Klassen and Thompson, 1993).

Conclusion

This study clearly shows that till composition in general, and basal till in particular, reflects the underlying bedrock. However, far transported clasts and matrix components in till is widespread and must always be considered. Glacial transport vectors of till include both direction and transport length, and these might have varied distinctly during the last glaciation (Weichselian) and throughout several Quaternary glaciations.

Metallic anion composition in till is akin to the pattern of till fragments, and closely resembles that of the underlying bedrock. However, also in this case there are indications of significant transport and dispersal. Affinity of certain elements to certain grain-size fractions (in till) should also be considered when prospecting for minerals. It is thus clear that a close understanding of till stratigraphy and glacial history of an area is essential for successful mineral exploration.

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