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.

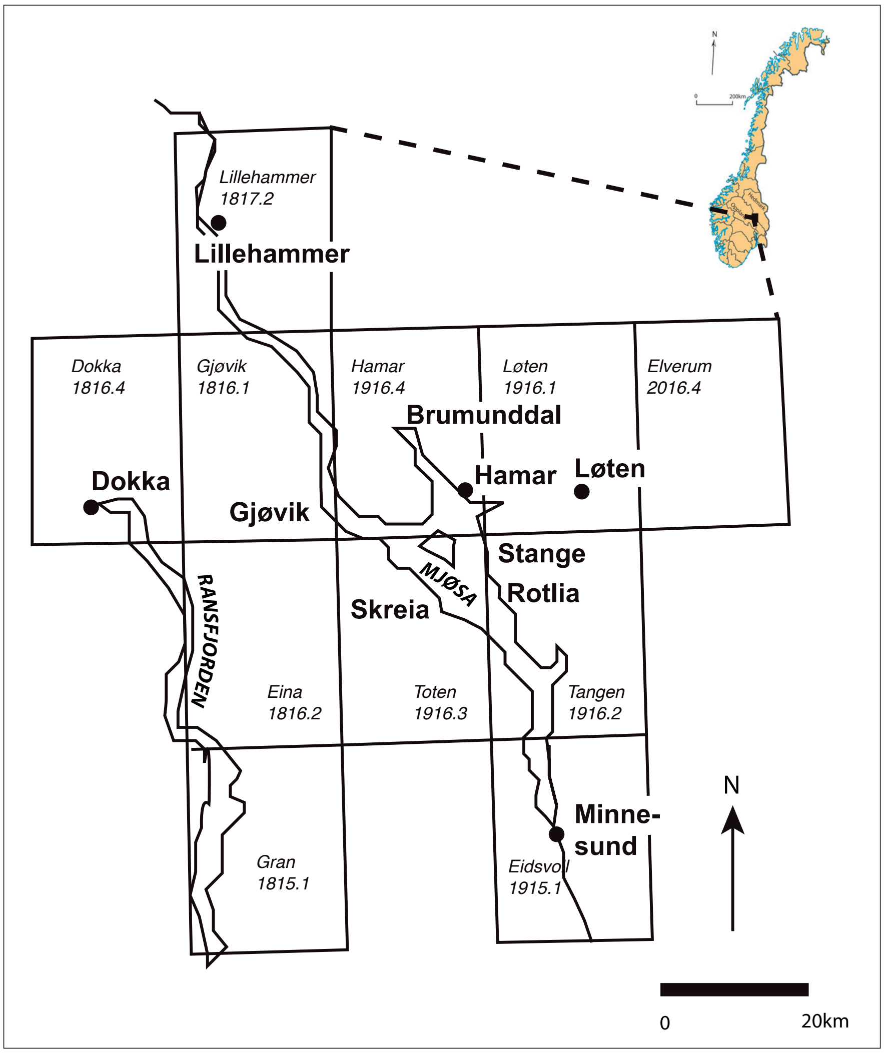

Figure 1. Location of study area. Quaternary maps used in the article, with names, are marked with boxes.

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).

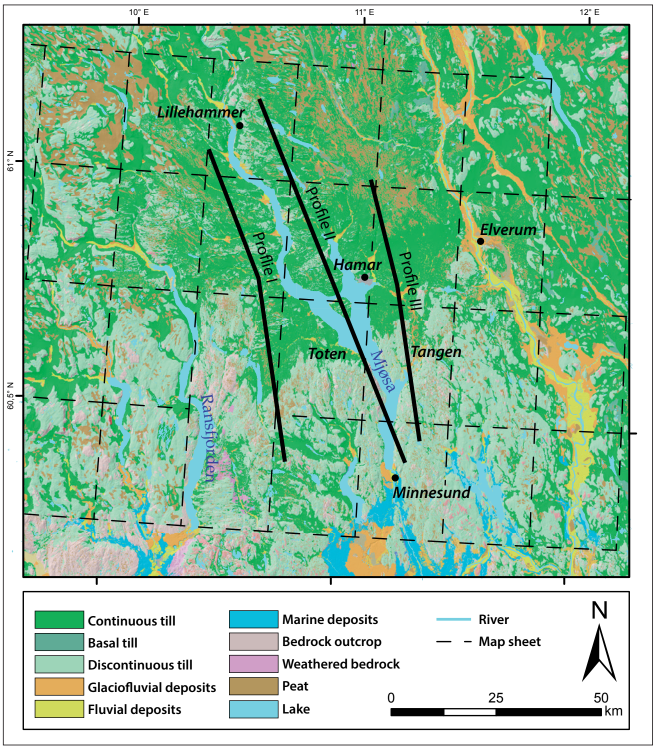

Figure 2. Published Quaternary geological maps at the scale of 1:50,000 extracted from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/). The locations of profiles (I, II and III) in Figure 12 are indicated by lines.

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

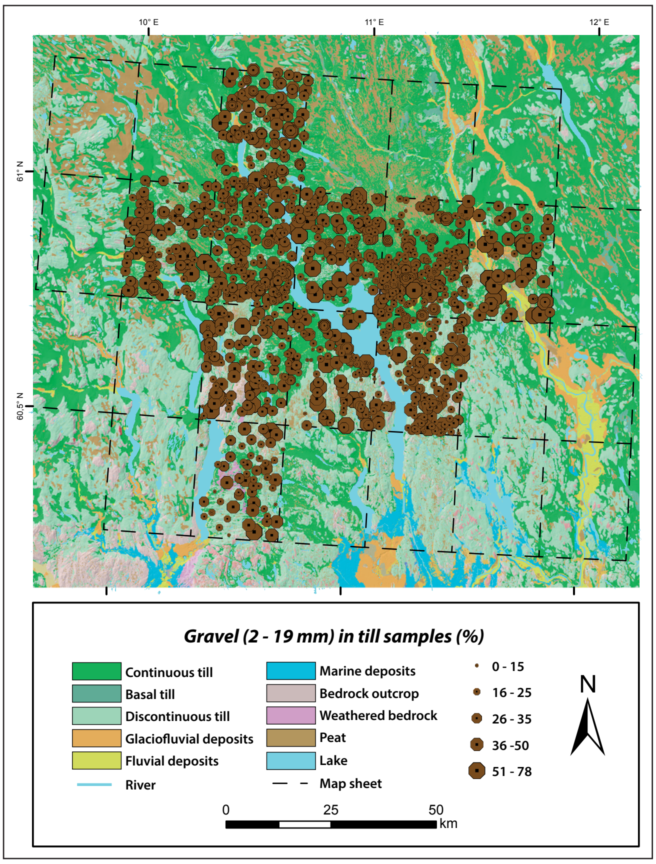

Figure 3. Spatial distribution of gravel (2–19 mm) in surficial till samples.

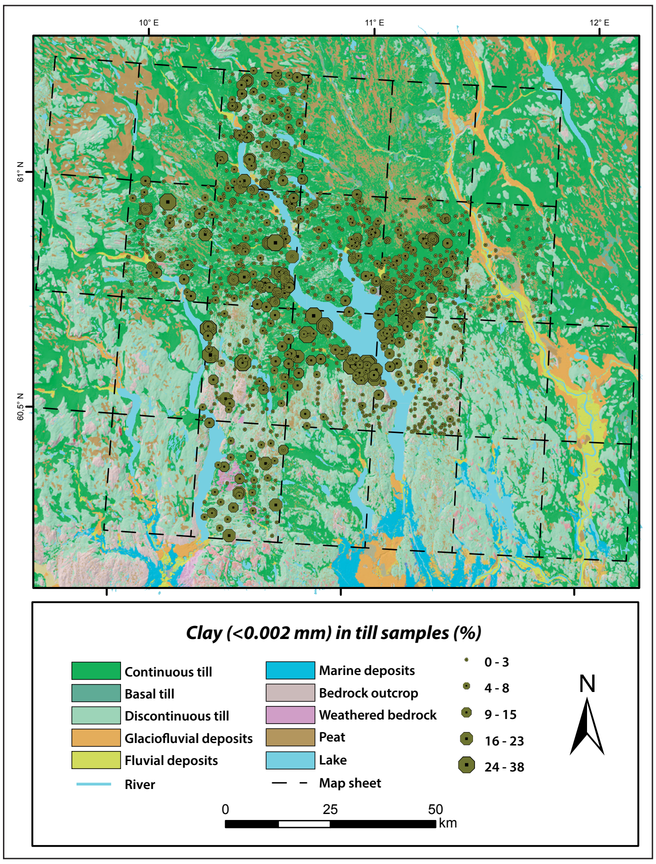

Figure 4. Spatial distribution of clay (<0.002 mm) in surficial till samples.

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

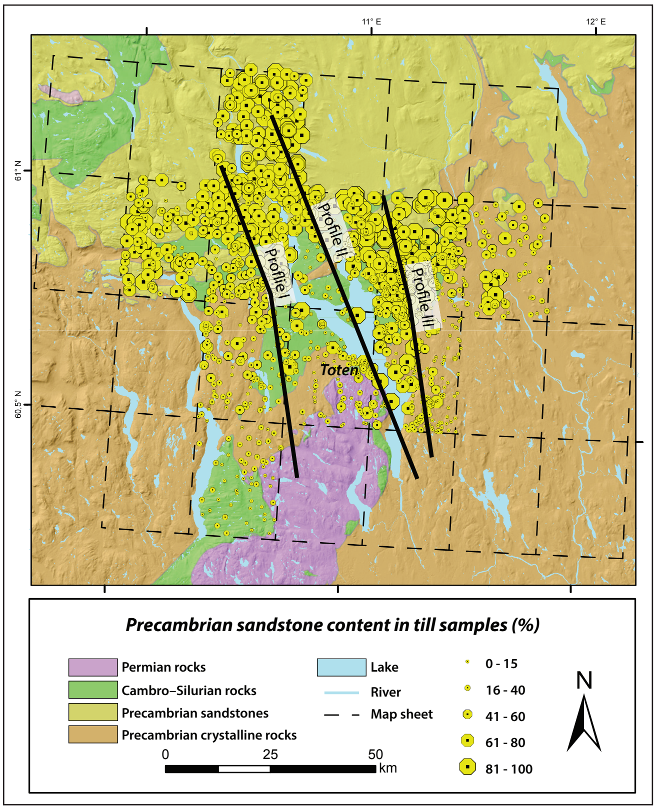

Figure 5. Distribution of Late Precambrian sandstones in tills (grain size 4.8–8 mm). The simplified bedrock map is extracted from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/). The locations of profiles (I, II and III) in Figure 12 are indicated by lines.

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

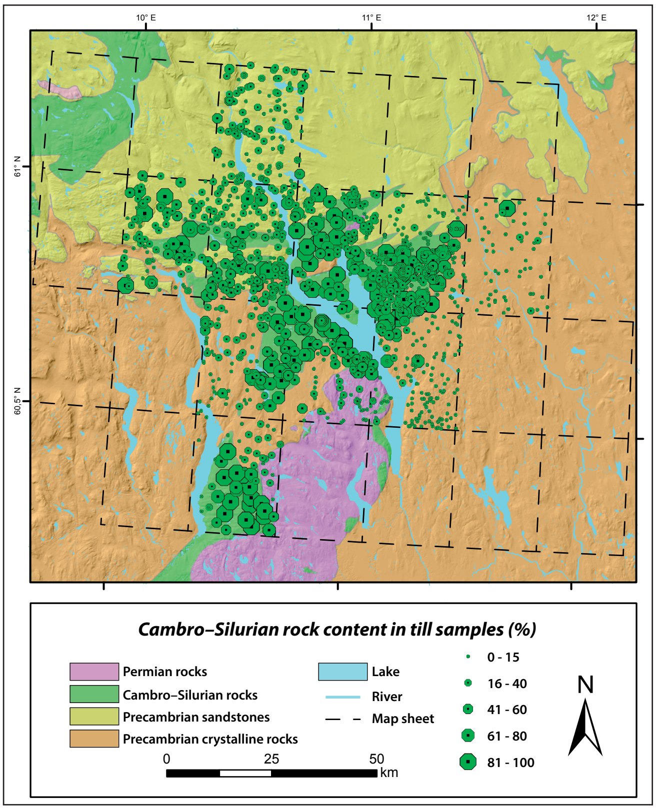

Figure 6. Distribution of the Cambro–Silurian clasts in tills (grain size 4.8–8 mm). The simplified bedrock map is copied from the NGU database (http://www.ngu.no/no/hm/Kart-og-data/).

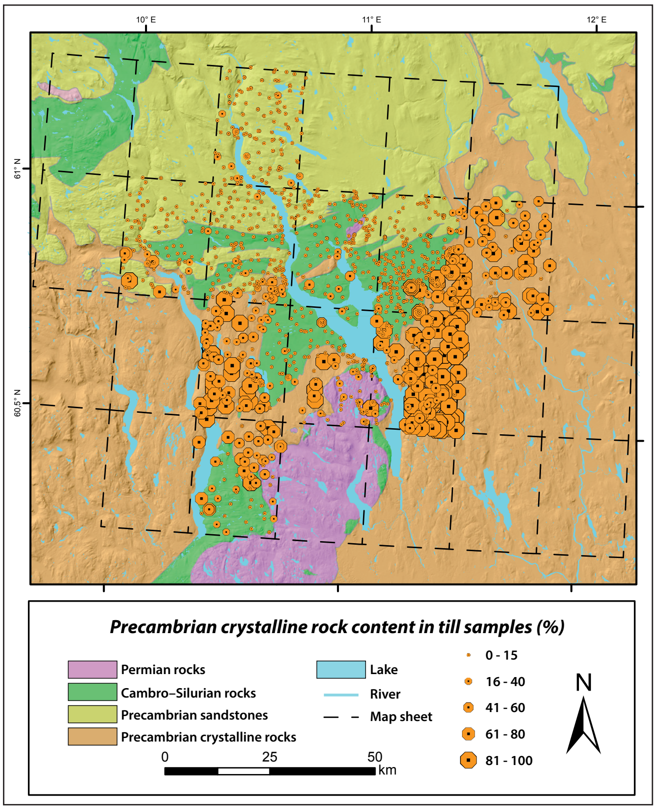

Figure 7. Distribution of the Precambrian crystalline rocks in tills (grain size 4.8–8 mm).

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,

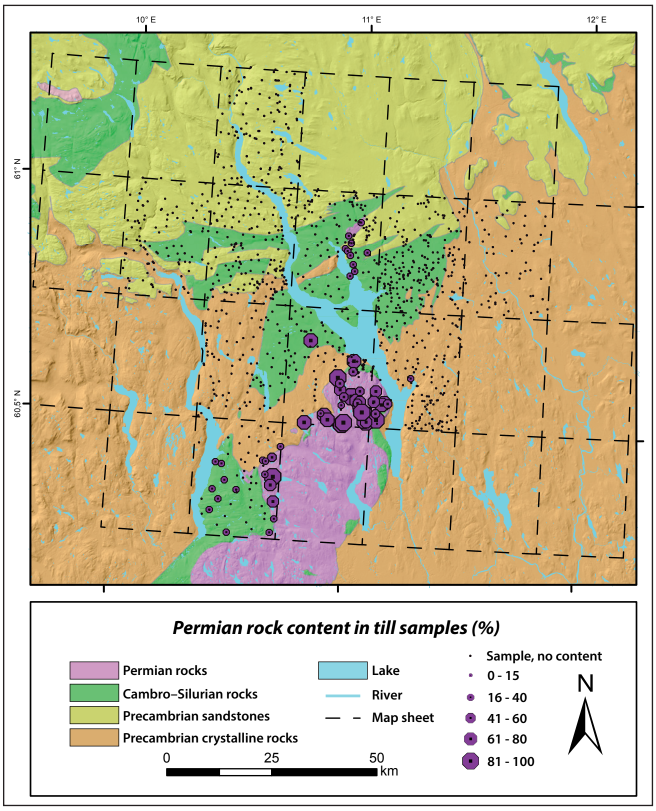

Figure 8. Distribution of the Permian rocks in tills (grain size 4.8–8 mm).

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).

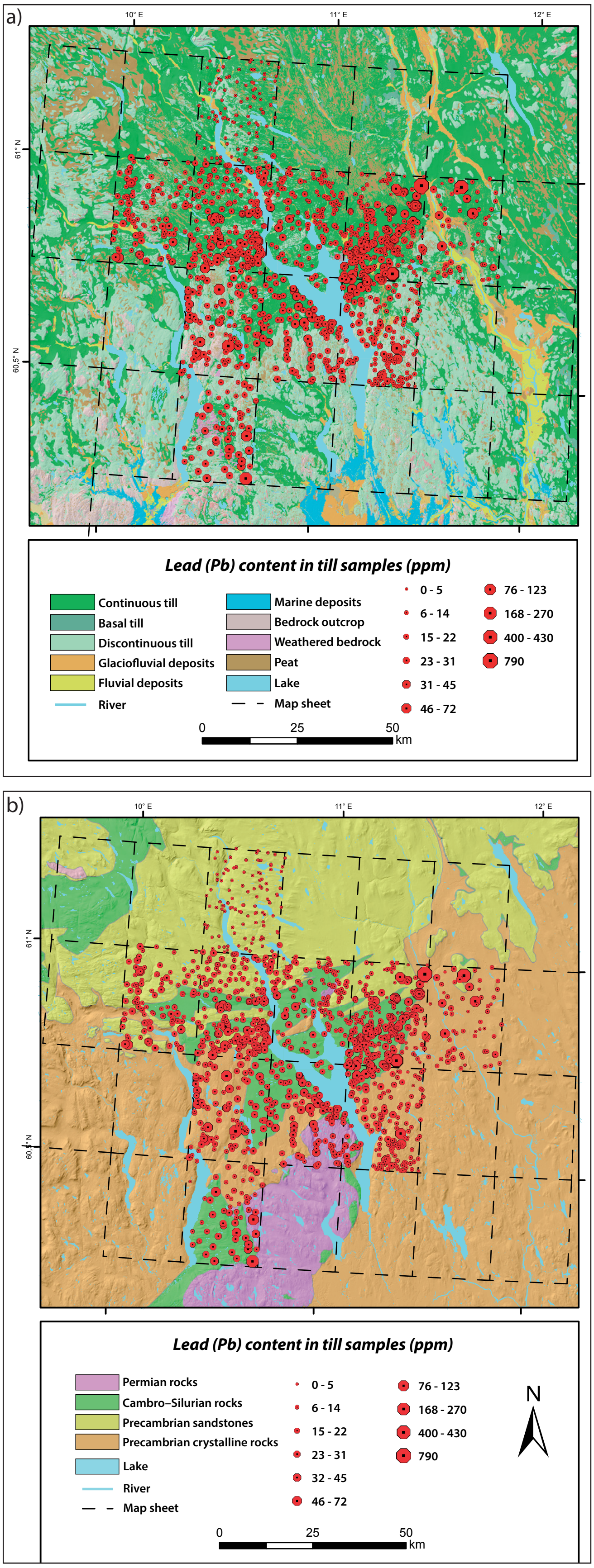

Figure 9. (a) The distribution of lead (Pb) in tills (<0.18 mm) plotted on the Quaternary map.(b) The distribution of lead (Pb) in tills (<0.18 mm) plotted on the bedrock map.

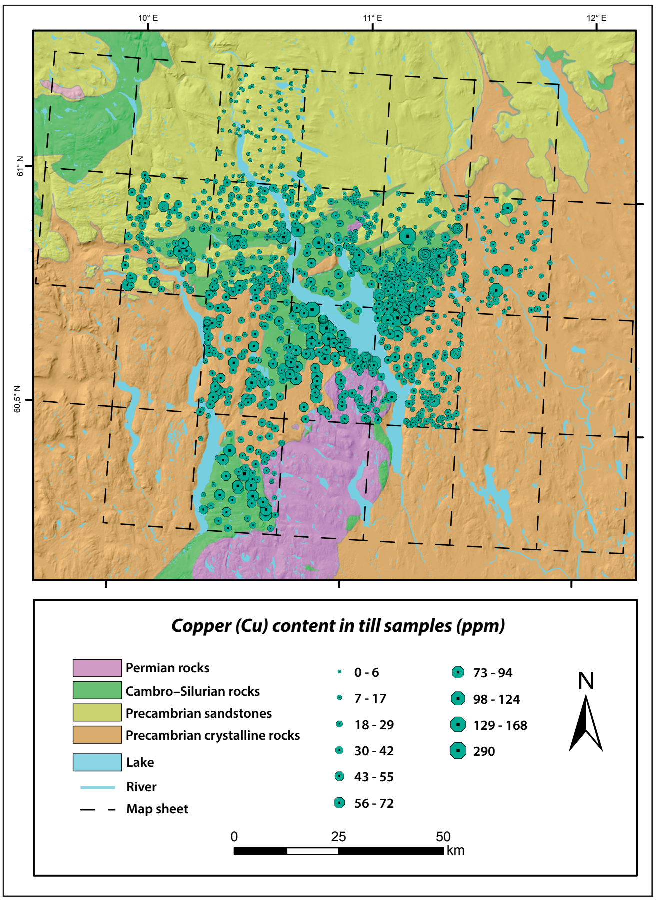

Figure 10. The distribution of copper (Cu) in tills (<0.18 mm).

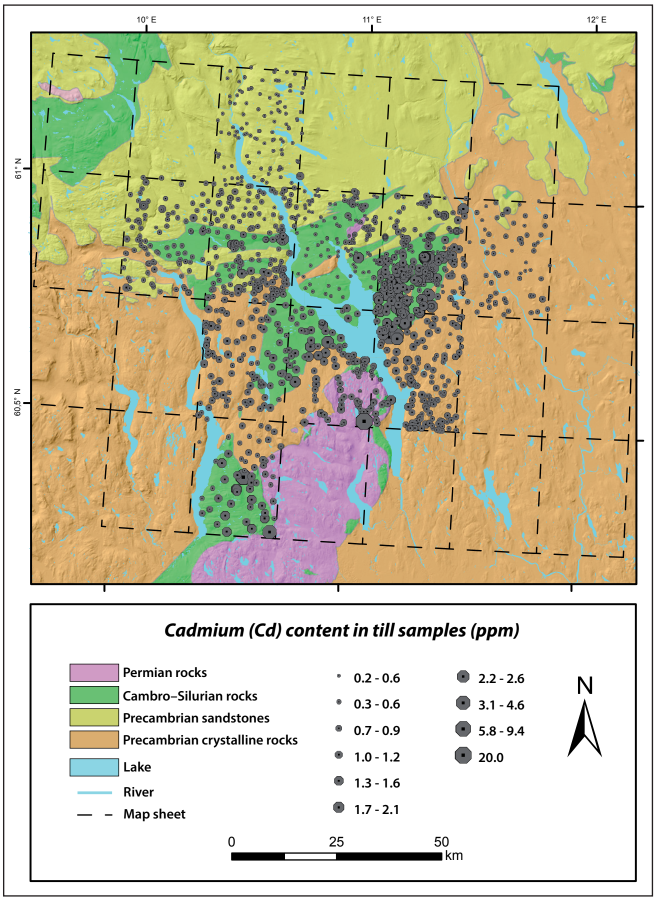

Figure 11. The distribution of cadmium (Cd) in tills (<0.18 mm).

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

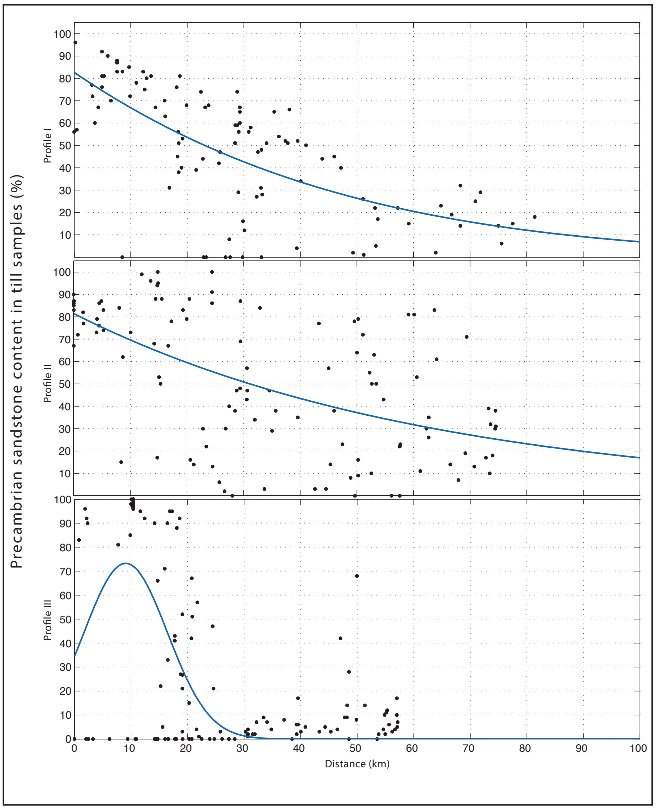

Figure 12. Three profiles running across the western, central and eastern parts of the study area showing the content of Precambrian sandstone clasts in till. For location of profiles (I = Western profile, II = Central profile and III = Eastern profile) see Figures 2 and 5. A first order Gaussian fit 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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References

Aa, A. R. (1979) Dokka, Quaternary geology map 1816 IV, scale 1:50 000. *Norges geologiske undersøkelse*.

Bargel, T. (1981) Elverum 2016 IV. Tabeller og kornfordelingskurver. *NGU report 1879*, 110 pp.

Bargel, T. (1983) Elverum. Quaternary geological map with description 2016 IV, scale 1:50 000, *Norges geologiske undersøkelse*.

Ben, D. and Evans, D. (1998) *Glaciers and glaciation*, Hodder Arnold, London, 734 pp.

Bergersen, O.F. (1964) Løsmateriale og isavsmeltning i nedre Gudbrandsdalen og Gausdal. *Norges geologiske undersøkelse* **228**, 12–83.

Bergersen, O.F. and Garnes, K. (1983) Glacial deposits in the culmination zone of the Scandinavian Ice sheet. *In* Ehlers, J (ed.) *Glacial deposits in north-west Europe*, Balkema, Rotterdam, 23–40.

Bergstrøm, B., Reite, A., Sveian, H. and Olsen, L. (2001) Feltrutiner, kartleggingsprinsipper og standarder for kvartærgeologisk kartlegging/løsmassekartlegging ved NGU. *NGU report 2001.018.*

Bjørlykke, A. (1979) Gjøvik og Dokka Beskrivelse til de berggrunnsgeologiske kart 1816 I og 1816 IV (M 1:50,000) (Med fargetrykte kart). *Norges geologiske undersøkelse skrifter* **25**, 48 pp.

Brøgger, W.C. (1877) Om beskaffenheden av gruset ved Hougesæter på den romerikske slette. *Geologiska Föreningens i Stockholm Förhandlingar*. **3**, 234–241.

Bølviken, B. (1973) Statistisk beskrivelse av geokjemiske data. *Norges geologiske undersøkelse* **285**, 1–10.

Clark, P. U. (1987) Subglacial sediment dispersal and till composition. *Journal of Geology*, **95**, 527–541.

Cuffey, K.M., Conway, H., Gades, A. M., Hallet, B., Lorrain, B., Severinghaus, J.P., Steig, E. J., Vaughn, B. and White J. W. C. (2000). Entrainment at cold glacier beds. *Geology*, **28**, 351–354.

Esmark, J. (1824) Bidrag til vor Jordklodes Historie. *Magazin for Naturvidenskaberne* **3**, 28–49.

Flint, R. (1971) *Glacial and Quaternary Geology*. Wiley, New York, 892 pp

Follestad, B. (1973) Løten, Quaternary geology map with description 1916 I, scale 1:50 000. *Norges geologiske undersøkelse* **296**, 41pp.

Follestad, B. (1974) Tangen, Quaternary geology map with description 1916 II, scale 1:50 000. *Norges geologiske undersøkelse* **313**, 62 pp.

Follestad, B. (1976a) Biri, Quaternary geology map CMN 069070, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. (1976b) Kolbu, Quaternary geology map COP 061062, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. (1976c) Redalen, Quaternary geology map CMN 067068, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. (1976d) Raufoss, Quaternary geology map CMN 063064, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. (1977) Toten, Quaternary geology map with description 1916 III, scale 1:50 000. *Norges geologiske undersøkelse* **335**, 45pp.

Follestad, B. (1978) Brøttum, Quaternary geology map CMN 071072, scale M 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. (1979) Vingrom, Quaternary geology map CKL 071072, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B. and Olsson, I. (1979) The 14C age of the Toten mammoth, eastern Norway. *Boreas*, **8**, 307–312.

Follestad, B. and Rye, N. (1976) Hamar, Quaternary geology map CPQR 065066, scale 1:20 000. *Norges geologiske undersøkelse*.

Follestad, B and Østmo, S.R. (1977) Eidsvoll, Quaternary geology map, scale 1:50 000. *Norges geologiske undersøkelse.*

Fredin, O. (2002) Glacial inception and Quaternary mountain glaciations in Fennoscandia. *Quaternary International,* **95–96**, 99–112.

Goffeng, G. and Follestad, B. (1979) Elverum, Quaternary geology map CUV 067068, scale 1:20 000. *Norges geologiske undersøkelse*.

Haldorsen, S. (1977) The Petrography of Tills – A study from Ringsaker, South-eastern Norway, *Norges geologiske undersøkelse*, **44**, 1–36.

Haldorsen, S. (1982) The genesis of tills from Åstadalen, southeastern Norway. *Norsk geologisk tidsskrift*, **62**, 17–38.

Haldorsen, S. (1981) Grain-size distribution of subglacial till and its relation to glacial crushing and abrasion. *Boreas*, **10**, 91–105.

Haldorsen, S. and Sørensen, R. (1986) Distribution of tills in southeastern Norway. *In* Meer, J.v.D. (ed.) *Tills and Glaciotectonics*, pp. 31–38.

Hallet, B., (1979) A theoretical model of glacial abrasion. *Journal of Glaciology*, **23**, 39–50.

Hallet, B., (1996) Glacial quarrying: a simple theoretical model. *Annals of Glaciology*, **22**, 1–8.

Helle, M., Sønstegaard, E., Coope, G. and Rye, N. (1981) Early Weichselian peat at Brumunddal, southeastern Norway. *Boreas*, **10**, 369–379.

Heyerdahl, H. (1811) Bidrag til en mineralogisk – geognostisk beskrivelse over Ringsagers og Totens Præstegjell I Aggershuus Stift. *Topogarfisk Statistiske Samlinger. Det Kongelige Selskab for Norges Vel*, **1**, 1–60.

Hirvas, H. (1989) Application of glacial geologic studies in prospecting in Finland. *In* R. N. W. Dilabio & W. B. Coker (eds.) *Drift Prospecting*. Geological Survey of Canada, *Bulletin* **435**, 76 pp.

Hørbye, J. C. (1855) Det erratiske Phænomen paa Rigsgrændsen. *Nyt Magazin for Naturvidenskaberne*, **8**, 337–384.

Keilhau, B.N. (1832) Reise i Jemtland og Nordre Trondhjems Amt i Sommeren 1831. *Magazin for Naturvidenskaberne* **11**, 18–160.

Kjærnes, P. A. (1981a) Brandbu, Quaternary geology map CKL 057058, scale 1:20 000. *Norges geologiske undersøkelse*.

Kjærnes, P. A. (1981b) Lunner, Quaternary geology map CMN 053054, scale 1:20 000. *Norges geologiske undersøkelse*.

Kjærnes, P. A. (1982) Grymyr, Quaternary geology map CKL 055056, scale 1:20 000. *Norges geologiske undersøkelse*.

Kjærnes, P. A. (1983) Jevnaker, Quaternary geology map CKL 053054, scale 1:20 000. *Norges geologiske undersøkelse*.

Kjærnes, P. A. (1984a) Gran, Quaternary geology map with description 1815 I, scale 1:50 000. *Norges geologiske undersøkelse Skrifter*, **54**, 26 pp.

Kjærnes, P. A. (1984b) Eina, Quaternary geology map with description 1816 II, scale 1:50,000. *Norges geologiske undersøkelse Skrifter*, **49**, 25 pp.

Kleman, J. (1992) The palimpsest glacial landscape in Northwestern Sweden – Late Weichselian deglaciation and traces of older west-centered ice sheets. *Geografiska Annaler*, **74A**, 305–325.

Kleman, J., Hättestrand, C., Borgström, I. and Stroeven, A., (1997) Fennoscandian paleoglaciology reconstructed using a glacial geological inversion model. *Journal of Glaciology*, **43**, 283–289.

Kleman, J. and Hättestrand, C. (1999) Frozen-bed Fennoscandian and Laurentide ice sheets during the last glacial maximum. *Nature*, **402**, 63–66.

Klassen, R. A. and Thompson, F. J. (1989) Ice flow history and glacial dispersal patterns, Labrador. *In* Dilabio, R. N. W. and Coker, W. B. (eds.) *Drift prospecting*. *Geological Survey of Canada*, **Paper 89–20**, 21–29.

Klassen, R. A. and Thompson, F. J. (1993) Glacial history, drift composition, and mineral exploration, central Labrador. *Geological Survey of Canada*, **Bulletin 435**, 76 pp.

Lundblom, H. (1888) Om den eldre baltiska isströmmen i södra Sverige. *Geologiska Föreningens i Stockholm Förhandlingar*, **10**, 157-189.

Lundqvist, G. (1935) Blockundersökningar. Historik og metodik. *Sveriges geologiske undersøkelse*, **Serie C 433**, 45pp.

Låg, J. (1948) Undersøkelser over opphavsmaterialet for Østlandets morenedekker. Medde. *Norske Skogforsøksvesen*, **35**, 223 pp.

Mangerud, J., Gyllencreutz, R., Lohne, Ø. and Svendsen, J. (2011) Glacial History of Norway. *In* J. Ehlers, P.L. Gibbard and P.D. Hughes, (eds.) *Developments in Quaternary Science*, **15**, 279-298.

Nilsen, O. and Bjørlykke, A. (1991) Silver mineralization in ancient Akersberg mine, Oslo. *Norsk geologisk tidsskrift*, **71**, 121–128.

Olsen, L. (1979) *Kvartærgeologiske undersøkelser i Ø. Gausdal – Lillehammer området, Oppland. Isbevegelser, jordartskartlegging og morenestratigrafi*. MSc thesis, University of Bergen, 480 pp.

Olsen, L. (1983) Isbevegelser i Lillehammer området, SØ-Norge, under siste nedisning. *Norges geologiske undersøkelse*, **378**, 83–91.

Olsen, L. (1985a) Lillehammer. Quaternary geology map with description 1817 II, scale 1:50 000. *Norges geologiske undersøkelse Skrifter*, **60**, 47pp.

Olsen, L. (1985b) Weichselian till stratigraphy in the Lillehammer area, southeast Norway. *Norges geologiske undersøkelse Bulletin*, **401**, 59–81.

Olsen, L. and Follestad, B. (1982) Lillehammer, Quaternary geology map 1817 II, scale 1:50.000. *Norges geologiske undersøkelse*.

Olsen, L. and Grøsfjeld, K. (1999) Middle and Late Weichselian high relative sea levels in Norway: implications for glacial isostacy and ice-retreat rates. *Norges geologiske undersøkelse Bulletin*, **435**, 43–51.

Parent, M., Paradis, S. J. and Doiron, A. (1996) Palimpsest glacial dispersal trains and their significance for drift prospecting. *Journal of Geochemical Exploration*, **56**, 123–140.

Post, von. H. (1855) Om sandåsen vid Köping i Westmanland. *Öfversigt av Kongliga vetenskaps-akademiens förhandlingar*, **1854**, 345pp.

Post, von. H. (1856) Om kross-stensbäddar i Skedvi sockn, *Öfversigt av Kongliga vetenskaps-akademiens förhandlingar*, **1855**, 235 pp.

Reusch, H. (1901) Listerlandet. *Norges geologiske undersøkelse*, **32**, 89–94.

Rye, N. (1976) Høsbjørkampen, Quaternary geology map CQR 067068, scale 1:20 000. *Norges geologiske undersøkelse*.

Rye, N. (1978) Brumunddal, Quaternary geology map COP 067068, scale 1:20 000. *Norges geologiske undersøkelse*.

Rye, N. (1979) Hamar, Quaternary geology map 1916 IV, scale 1:50.000. *Norges geologiske undersøkelse*.

Sahlström, K. E. (1910) Ett drumlinområde i Närke. *Sveriges geologiske undersøkelse*, **Serie C 222**, pp. 12 pp.

Sigmond, E. 1985: Brukerveiledning til Berggrunnskart over Norge, *Norges geologiske undersøkelse*, 32 pp.

Skjeseth, S. (1963) Contributions to the geology of the Mjøsa districts and the classical sparagmite area in the Southern Norway. *Norges geologiske undersøkelse* **220**, 126 pp.

Sollid, J.L. and Sørbel, L. (1994). Distribution of glacial landforms in southern Norway in relation to the thermal regime of the last continental ice sheet. *Geografiska Annaler*, **76A**, 25–35.

Sveian, H. (1979) Gjøvik, Quaternary geology map with description 1816 I, scale 1:50 000 . *Norges geologiske undersøkelse Skrifter*, **345**, 61 pp.

Sveian, H. (1976) Gjøvik, Quaternary geology map CMN 065066, scale 1:20 000. *Norges geologiske undersøkelse*.

Tamm, O. (1915) Några iakttagelser angående Mälarsandstenen. *Geologiska Föreningens i Stockholm Förhandlingar*, **37**, 265-275.

Øyen, P.A.(1900) A glacial deposit near Christiania. *Archiv for Matematik og Naturvidenskap*, **22**, 13pp.

Øyen,P.A.(1904) Undersøgelser af moraenegrus i Asker. *Archiv for Matematik og Naturvidenskap*, **26**, 8pp.

Øyen, P.A.(1907) Undersøgelser av terrassegrus i Asker. *Forhandlinger i Videnskabers Selskabet i Cristiania*. **1**, 15 pp.

RESEARCH ARTICLE

Geophysical expression of the Raudfjellet ophiolite, Nord-Trøndelag, central Norwegian Caledonides

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Based on five profiles derived from helicopter-borne magnetic total-field data, modelling of the Raudfjellet ophiolite has confirmed the general geometry of the mafic-ultramafic complex, though with notable changes along strike from south to north. In the south, the mylonitic thrust zone of the ophiolite, according to modelled profiles 2, 3 and 4, dips regularly at 15-25° northwestwards, reaching a vertical depth of up to 800 m. In the north, modelling shows a more complex 3D picture of the magnetic body, there comprising both the large ultramafic (serpentinitic) block and the highly magnetic ultramafic-mafic cumulates of the overlying gabbroic block. Profile 5 shows an almost flat-lying, 1 500 m-long, prismatic body extending in depth to only 200-250 m. Profile 6, modelled WSW-ENE (i.e. with a 55° angle to profile 5), shows a high-magnetic, 1 000 m-long, nearly rhomb-shaped prismatic body, the footwall of which starts with a 35° dip and ends up with a dip of only 8° towards the southwest. This last body reaches a depth of up to c. 500 m in the southwest, and shows that the ophiolite is wedging out towards the northeast. This appreciable difference both in dip angles and depth ranges is considered to relate to well defined and strong magnetic anomalies where the latter are detected in the poorly exposed mafic block. The distribution of these anomalies is, in turn, inferred to be attributed to NW-SE-trending, strike-slip faults concealed beneath the extensive Quaternary deposits covering the western part of the ophiolite, which have thus resulted in segmentation of the complex.

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Introduction

The mafic-ultramafic complex exposed at and around Raudfjellet in Nord-Trøndelag, close to the Swedish border (Figure 1), was first reported over a century ago by Törnebohm (1896) and then mapped as diorite and serpentinite. A differentiation into peridotite, pyroxenite and gabbro came with the fieldwork and map-compilatory work of Foslie (1959). Later mapping, by S. Bergman and H. Sjöström in 1988, as a contribution to a subsequent compilation of the preliminary 1:50 000 bedrock map-sheet 'Gjevsjøen' (Sjöström and Roberts 1992), provided a more refined picture of the complex on a modern topographic base, and discussions at that time favoured its subsequent interpretation as a dismembered and tectonically fragmented ophiolite (see Roberts 1997a). Subsequently, in a collaborative project between NGU and Statskog aimed at investigating the potential mineral resources within an extension of the Gressåmoen National Park, detailed mapping of the complex by NGU geologists in 1999-2000 led to the compilation of the geological map shown in Figure 2.

In a first description of the Raudfjellet ophiolite, Nilsson et al. (2005) distinguished two separate blocks – mafic and ultramafic – with an intervening, 4.5 km-long, hydrothermal zone comprising soapstone and overlying listvenite. The soapstone, with a talc content of 40-60%, was naturally of potential resource interest, and reconnaissance drilling of eight shallow holes, from 37 to 130 m in length, totalling 579 metres, was therefore carried out already in the winter of 2000. This shallow drilling was based on the first results from the 1999 field season (Nilsson et al. 1999), existing old airborne geophysical data (Håbrekke 1983), and also on the general 3D picture of the ophiolite fragment, dipping gently to the northwest, obtained from a cross-section accompanying the map by Sjöström and Roberts (1992). In the autumn of 2005, two ground-magnetic, NW-SE test profiles were carried out across the ophiolite, including field measurements of magnetic susceptibility. As an interpretation of the acquired data proved to be unexpectedly difficult (see later), Statskog during the winter 2005/2006 raised funding for a new airborne survey. The entire ophiolite and subjacent rocks, altogether 30 km^2, were covered with helicopter-borne, magnetic total-field and spectrometer measurements by NGU in March 2006. The resulting magnetic maps are shown here as Figures 4 and 5. The spectrometer measurements have not yet been compiled on maps. The complete magnetic dataset formed a basis for model calculations of the shape, thickness and extent of the complex at depth, carried out by two of the coauthors (Kero and Johansson 2006). The principal aim of this contribution is to present the main results of the geophysical profiling and resultant model for the mafic-ultramafic complex. Fuller details of the geology and structures are contained in Nilsson et al. (2005).

Geological setting: a summary

Raudfjellet is situated south and west of the Grong-Olden Culmination (GOC), an antiformal structure crossing the main trend of the Caledonides (Figure 1) and exposing Late Palaeoproterozoic to Mesoproterozoic, felsic volcanites and granites (Troëng 1982, Roberts 1997a, b, Roberts et al. 1999). Two main Caledonian nappes constitute the GOC – the Olden Nappe and Formofoss Nappe Complex – each carrying a thin, low-grade, sedimentary cover of Ediacaran-Cambrian and possibly Early Ordovician age (Roberts 1997a). These two nappes form part of the Lower Allochthon of Scandinavian Caledonide tectonostratigraphy (Gee et al. 1985, Roberts and Gee 1985), and are succeeded by diverse nappes of the Middle Allochthon (e.g., Offerdal, Leksdal and Seve nappes). At Raudfjellet, the

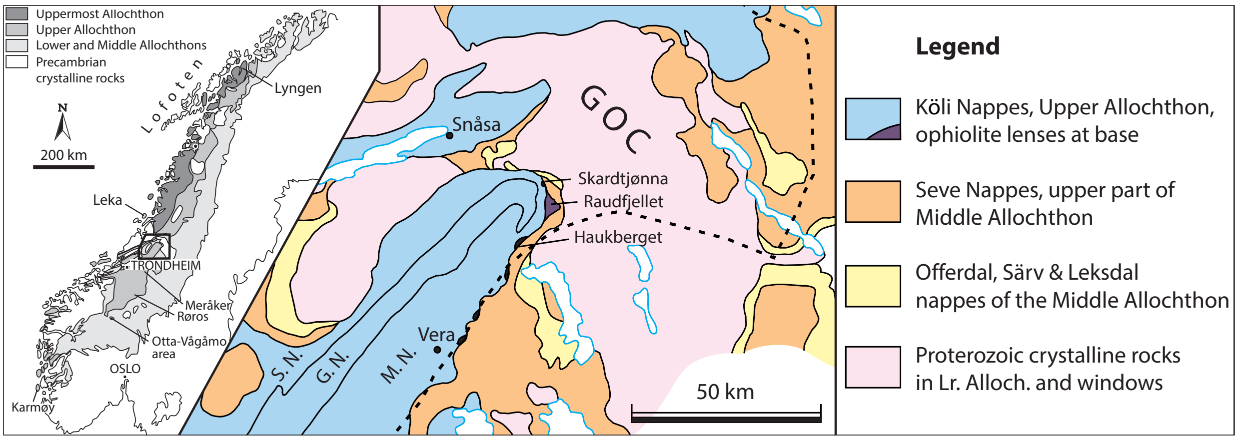

Figure 1. Simplified tectonostratigraphic map of the region in the vicinity of Raudfjellet. GOC – Grong-Olden Culmination; S.N. – Støren Nappe; G.N. – Gula Nappe; M.N. – Meråker Nappe.

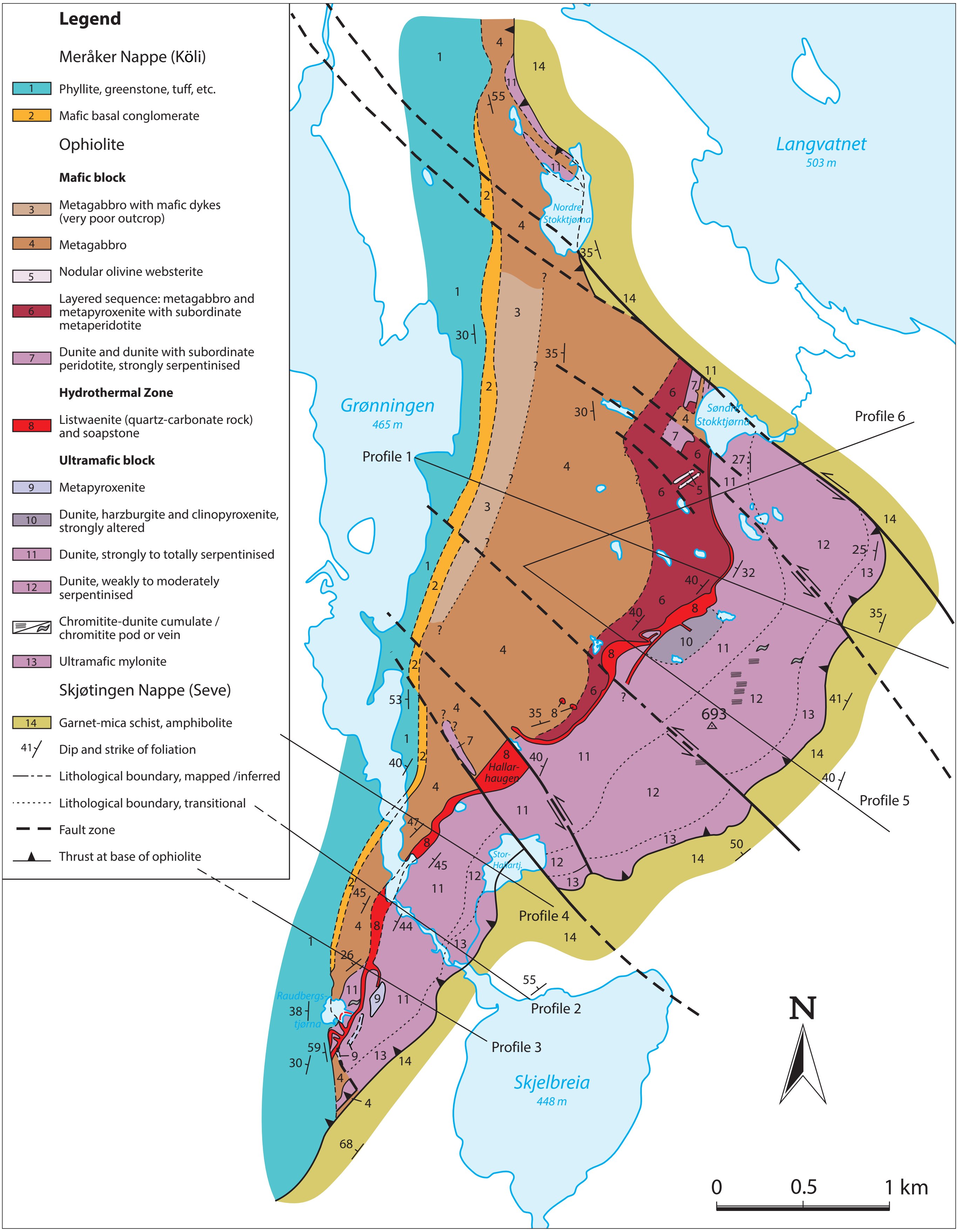

Figure 2. Geological map of the Raudfjellet ophiolite, modified from Nilsson et al. (2005), Sjöström and Roberts (2013) and including interpretations in poorly exposed areas based on the helicopter-borne magnetic map shown in Figure 4. Locations of profiles 2 to 6, extracted for modelling from helicopter-borne magnetic data, as well as the two ground-magnetic profiles 1 and 2, are also shown (profile 2 both ground and air-borne).

substrate to the ophiolite is represented by amphibolite-facies Seve rocks, known as the Skjøtingen Nappe in Mid Norway. The ophiolite itself is considered to form the basal part of one of the Köli nappes (Meråker Nappe), constituting the Upper Allochthon (mainly oceanic and arc terranes); and the ophiolitic rocks are unconformably overlain by a polymict conglomerate (Nilsson et al. 2005). Lenses of comparable ultramafic-mafic rocks, locally with an overlying conglomerate, occur along strike to the southwest (Figure 1), also at the base of the Meråker Nappe (Nilsson and Roberts, this volume). These lenses may link up with the fragmented Handöl ophiolite in the Tännfors area east of Storlien in Sweden (Bergman 1993). Further details of the regional geology are contained in the paper by Nilsson et al. (2005). In addition, a revised colour version of the 1:50 000 bedrock map-sheet 'Gjevsjøen' is now available (Sjöström and Roberts 2013).

Raudfjellet ophiolite

Pseudostratigraphy

The ophiolite fragment at Raudfjellet is partly dismembered consisting of a well preserved ultramafic lower part or block overlain by a hydrothermal zone comprising soapstone and listvenite which, in turn, passes up into a layered metagabbro and metapyroxenite. Above this is a massive, layered metagabbro with, higher up, mafic dykes intruding the gabbro. The assemblage is capped above an unconformity by a polymict conglomerate containing debris derived mostly from the ophiolite. At the very base of the ultramafic block there is a quite spectacular ultramafic mylonite. Details of the pseudostratigraphy have been documented in Nilsson et al. (2005). Here we present just a summary as a background for the geophysical profiling and modelling.

The ultramafic block

The basal mylonites reach up to c. 200 metres in surface width and carry lenses and thin layers of glassy ultramylonite, notably at the very base. The high-temperature, olivine and pyroxene mineralogy suggests that these tectonites are related to the obduction of the ophiolite. In places, the ultramafic mylonite rests on a thin, amphibolite-facies blastomylonite comprising material derived from the rocks of the subjacent Seve Nappe. The mylonites show abundant evidence of a younger, greenschist-facies, extensional reworking.

The ultramafites above the mylonites comprise essentially a single, cumulate dunite body up to c. 800 m in width and with substantial calculated thicknesses (see section on Model calculations where the mylonite zone and dunite body are combined), which is probably the largest such dunite known in the Scandinavian Caledonides. Minor bodies of clinopyroxenite/websterite are hosted by the dunite whereas distinct mantle peridotites (harzburgite or lherzolite) seem to be totally absent at Raudfjellet. Anastomosing, mylonitic shear zones pervade the lower parts of the body. Most of the central part is a homogeneous dunite with only modest serpentinisation, consisting of up to c. 90% olivine and only 10% serpentine by volume with accessory chromite where the dunite is least altered. In places there are minor occurrences of prominently layered, dunite-chromitite cumulates and also lenses of massive chromitite. Higher up in the dunite body, towards the northwest, serpentinisation increases and eventually the alteration is more or less complete. The serpentinised, homogeneous and completely non-stratified dunite (except for the above-mentioned very minor cases where cumulitic chromitite is involved) is interpreted to originate from the zone between overlying typical ultramafic cumulates (e.g. layered dunite-wehrlite) of the lower crust and underlying typical harzburgitic or lherzolitic mantle peridotites, though neither of these rocks is represented at Raudfjellet. In addition, it is conceivable that the Raudfjellet body might have been considerably larger in its original oceanic setting, since we can nowhere observe the contacts between the dunite and its original neighbouring rocks. In an accompanying paper (Nilsson and Roberts, this volume) we describe the difference between Raudfjellet and the next ophiolite fragment to the southwest, the Gaundalsklumpen - Haukberget fragment (Figure 1), where we interpret the ultramafic part of the latter as having derived from the mantle. It should also be emphasised here that there are several examples of ophiolites worldwide showing massive dunite bodies in the same size range and supposedly in the same position in a more general ophiolite stratigraphy as in Raudfjellet. The Thetford Mines Ophiolite, Quebec, Canada has, for example, an up to 500 m-thick dunitic zone confined to the crustal section of the ophiolite, sitting directly on top of the mantle peridotite tectonite (Schroetter et al. 2003).

The hydrothermal zone

The contact between the ultramafic and overlying mafic blocks is disjunctive and tectonic (Nilsson et al. 2005), but is also marked by a spectacular zone of hydrothermal alteration varying in thickness from 5 to 90 m. In general, this zone comprises soapstone at the base and listvenite above, both derivatives of CO_2 metasomatism. The soapstone has a talc content of 40-60% with magnesite as the other major constituent, and with dolomite and serpentine as subordinate minerals. Listvenite is essentially a magnesite-quartz rock that also contains dolomite, talc and chlorite, and traces of chromite.

The mafic block

Above the hydrothermally affected basal layers, mafic-ultramafic cumulates dominate in the high ground on Raudfjellet but are gradually cut out towards the southwest (Figure 2). The ultramafic cumulate layers are subordinate and impersistent, and are represented mostly by metapyroxenite and metaperidotite with sporadic layers of nodular olivine websterite. Within this modally layered unit, syn-magmatic erosional features are seen locally. Above this complex cumulate unit there is a banded metagabbro that gradually gives way upwards into a massive metagabbro, which is the dominant rock type in the mafic block. In the higher parts, which are poorly exposed and heavily forested, the gabbro is transected by sporadic mafic dykes beneath the erosional top surface. Assuming that basaltic volcanites were once present at the top of this fragment of Early Palaeozoic ocean floor, as in the case of several other ophiolites in Mid Norway (e.g., Grenne et al. 1980, Furnes et al. 1988, Grenne 1989, Roberts et al. 2002, Slagstad 2003), in this particular case they have been removed by deep erosion prior to deposition of the unconformably overlying sedimentary succession.

Polymict conglomerate

Following obduction of the ophiolite, most probably in Early Ordovician time (Roberts et al. 2002, Nilsson et al. 2005), uplift, weathering and substantial erosion removed large parts, leaving an irregular surface upon which was deposited a polymict conglomerate. The unconformity at its base cuts down into deeper parts of the ophiolite pseudostratigraphy from north to south (Figure 2). Clasts, up to 35 cm in size, consist of subangular to subrounded ultramafic and mafic rocks with sporadic listvenite. The matrix is mostly dark grey-green, sand-size, ultramafic and mafic material (Nilsson et al. 2005).

Structural deformation

Away from the basal mylonites, a penetrative foliation is a fairly uncommon feature in the ultramafic block but becomes clearer in the metagabbro and layered gabbro/pyroxenite, where it is found to be steeper than the layering and axial planar to top-ESE asymmetrical folds. A fairly strong stretching and mineral lineation plunging c. WNW is prevalent in both blocks, and also in the mylonites. All in all, these structures clearly relate to top-ESE, contractional deformation and thrusting.

A greenschist-facies extensional reworking of the earlier, high-T fabrics is manifested in top-NW, extensional shear-bands in various parts of the ophiolite. Such structures are also common in the basal mylonites, although in this case mostly with a top-SW to WSW sense of shear. Transverse, NW-SE-trending, strike-slip faults are also recognised, notably in the northeast and in the vicinity of Stor-Hallartjern (Figure 2), first described by Sjöström and Bergman (1989). As we shall see later, other strike-slip faults are inferred to be present, judging from an analysis of the airborne magnetic data.

Ground-magnetic profiling

Introduction

In the autumn of 2005, two ground-magnetic test profiles were measured by NGU and Statskog in collaboration. Selection of the locations, directions and lengths of the two profiles was based mainly on the contoured magnetic map from the 1982 helicopter-borne survey (map 1898/02 in Håbrekke 1983). This map shows an irregular and partly very strong, magnetic anomaly covering about half of the ophiolitic rocks at Raudfjellet. Various factors such as visual navigation, insufficient processing of the acquired data, as well as inadequate map compilation have together contributed to a magnetic contouring that did not give a correct (in detail) magnetic picture of the complex but still good enough to obtain a rough impression of what caused the anomaly pattern.

In general, it was considered that the ultramafic block (Figure 2), made up essentially of strongly serpentinised dunite with a high content of secondary magnetite, was the major contributor to the anomaly. The mafic block, essentially composed of massive gabbro, was considered to be mainly non-magnetic (i.e. paramagnetic). Such a simple two-fold model where the main rocks involved show very large contrasts in magnetic susceptibility (on average, about two orders of magnitude), would be ideal in order to obtain an accurate dip angle as well as an indication of the possible depth range of the hydrothermal zone. This is because the hydrothermal zone follows conformably on top of the moderately northwest-dipping, highly magnetic, serpentinite body. At the same time, the hydrothermal zone is situated directly in the footwall of low-magnetic gabbro southwards from Hallarhaugen. The latter would then not mask or hide the hydrothermal zone. This simple model was shown to work in broad terms, but with some unexpected complications and deviations as shown below in the section: Observations along the profiles following the Instrumentation section.

Instrumentation, execution of measurements, data acquisition and monitoring

The ground profiling was conducted by Rolf Lynum (RL) and Lars-Petter Nilsson (LPN) from NGU and Asbjørn Flaat (AF) from Statskog on the 19th and 20th of September, 2005. The magnetic total field was measured with NGU's portable *Scintrex Envi-Mag (serial No. 9310049)* magnetometer, and positioning in UTM-coordinates was determined with a *Garmin eTrex* GPS.

As the first member in the surveying crew, AF laid out profile directions with sticks and compass and measured out 50 m distances with a measuring wire. At every 50 m interval, a waypoint (WP) was registered with the GPS. Between the waypoints, measuring points were paced out for every c. 10 m. As the second member in the crew, RL measured the magnetic total field and logged the UTM-coordinates both of the WPs and the intervening measuring points. As the last in the group, LPN carried the GPS in order to prevent any influence on the magnetic measurements. The magnetic total-field readings (plus a recorded value for magnetic noise) and the GPS positions were recorded in their respective instruments together with the exact time of the readings. In addition, the total-field readings and WP-coordinates were manually logged by LPN for back up. Furthermore, LPN observed and recorded bedrock outcrops along the profiles as well as measuring magnetic susceptibility at selected locations using a hand held *Microkappa (Model KT-5)* from Geofyzika Brno with a quoted detection limit of 1×10^{-5} SI (cf. Table 1). The instrument is based on electromagnetic induction in an air-filled coil with a diameter of 55 mm.

After returning to NGU, the accumulated data from the magnetometer and GPS, well synchronised, were downloaded and tabulated. The measured data were later compared with data for magnetic storms/disturbances recorded at the magnetic base station at Rørvik, Nord-Trøndelag. The readings from the Rørvik base station showed that no magnetic disturbances had occurred during the actual field days.

Helicopter-borne magnetic survey

The helicopter-borne survey in Raudfjellet was carried out in connection with an exploration survey in the neighbouring Skjækerdalen area (Mogaard 2006). The measuring and positioning instrumentation, operating conditions, data acquisition and processing, and finally map production were basically the same in the two assignments. The data below are therefore mostly extracted from the Skjækerdalen report.

The area surveyed at Raudfjellet is a rectangular area measuring 5 × 6 km, with longest side of the rectangle oriented approximately NE-SW (041°). The distance flown and areas covered are approximately 300 line-km and 30 km^2.

Table 1. *Magnetic susceptibility measured using a hand-held Microkappa Model KT-5 on outcrops along the ground-magnetic profile 1. Values are given in SI-units ×10^3, detection limit as quoted by instrument manufacturer Geofyzika Brno is 1×10^{-5} SI-units.*

lithology	**phyllite***	**gabbro****	**pyroxenite-melagabbro†**	**pyroxenite††**	**dunite¶**		**amphibolite‡**	**garnet-micaschist‡**
top-to-bottom	**hanging-wall**							**footwall**
number of outcrops	1	1	3	4	16		1	5
arithmetic mean	0.37	0.30	0.34	56.0	51.2		0.56	1.42
standard deviation	0.16	0.06	0.09	20.7	11.6		0.20	1.74
median	0.37	0.29	0.36	54.5	50.4		0.58	0.62
maximum value	0.65	0.40	0.49	89.7	92.0		0.75	6.77
minimum value	0.19	0.22	0.16	16.5	30.2		0.36	0.03
number of values (n)	12	13	26	17	46		3	20
individual measured values								
	0.36	0.24	0.40	78.4	44.7	60.8	0.36	0.21
	0.19	0.22	0.38	54.5	60.7	52.0	0.75	0.06
	0.21	0.27	0.45	66.4	40.5	63.5	0.58	0.32
	0.42	0.33	0.38	53.7	41.3	50.4		0.12
	0.23	0.29	0.48	34.7	42.6	54.4		0.03
	0.61	0.35	0.35	89.7	50.4	72.8		0.03
	0.53	0.40	0.35	63.9	42.9	60.3		1.61
	0.28	0.35	0.41	47.0	51.2	71.3		4.06
	0.37	0.32	0.43	86.6	48.0	41.5		2.36
	0.24	0.22	0.40	78.2	45.4	49.5		2.70
	0.39	0.40	0.42	64.7	63.6	51.5		1.11
	0.65	0.29	0.40	23.0	52.9	50.7		2.25
		0.28	0.49	47.8	38.2	52.0		3.46
			0.38	54.9	35.2	59.0		6.77
			0.16	50.3	48.7	42.4		0.41
			0.18	16.5	39.9	46.1		0.64
			0.27	41.2	50.2	54.1		0.55
			0.26		30.2	92.0		0.52
			0.32		64.6	43.2		0.62
			0.19		53.1	40.6		0.61
			0.21		48.4	54.7		
			0.23		72.4	53.2		
			0.32		32.6	42.9		
			0.27					
			0.36					
			0.26					

*The listed lithologies represent a sequence from hanging-wall at: * Meråker Nappe, Furuhattangen; ** massive, isotropic; † paramagnetic/layered; †† ferromagnetic/layered; ¶ partly or totally serpentinized; until ‡ Seve, which is the footwall.*

Survey topographic and magnetic conditions

The topography is fairly moderately undulating in the survey area with 226 m between the highest and lowest points in the terrain. The terrain is partly vegetated with open forest and intervening areas of exposed bedrock. We are not aware of any reported discrepancies from the 30 ± 10 m nominal ground clearance for the 'bird' (the magnetometer) during the survey.

Diurnal changes in the Earth's magnetic field affect magnetic data. At the magnetic base station (in Verdal), no magnetic storms or other abrupt variations in the Earth's magnetic field that could have affected the magnetic data were recorded during the survey period.

Data acquisition

The survey aircraft was an *Aérospatiale Écureil AS 350 B-2*. The flying speed was approximately 100 km per hour (28 metres per second). Flight lines were flown in alternating directions at headings of 13° and 311° with a nominal flight line spacing of 100 m. A 5-frequency EM system and the magnetometer were enclosed in a 6-m long 'bird' suspended by cable 30 m below the helicopter (the EM-data were also collected, but not processed in the Raudfjellet assignment). The nominal flying height was 60 m above ground level (AGL).

NGU personnel responsible for data acquisition were John Olav Mogaard and Janus Koziel. The pilot from HELITRANS AS was Jens Fjelnset.

Magnetic measurements

A *Scintrex CS-2 cesium* vapour magnetometer was used. The magnetometer resolution is 0.01 nT. The sampling rate was 10 measurements per second (approximately 3 m spacing).

A *Scintrex ENVI*-mag proton precession magnetometer was located at the base in Verdal, and was used for base station measurements. The base station magnetometer was synchronised with the Scintrex magnetometer in the helicopter to ensure proper removal of diurnal magnetic changes from the helicopter magnetic measurements. The magnetic total field at the base station was digitally recorded during flights every third second.

Navigation, altimetry and data logging

The navigation system used is an *Ashtech G12*, 12 channel receiver. Position accuracy using this system is better than ± 5 m. The navigation console is a *PNAV 200*1 manufactured by the Picodas Group Ltd, Canada. Profile line data are entered into the console and are displayed on a left/right-display on the console. The pilot can see his position with respect to these predefined lines and make adjustments accordingly.

The helicopter is equipped with a *King KRA-430* radar altimeter measuring height above ground level. The altimeter data are recorded digitally and altitude is displayed in front of the pilot. The altimeter is accurate to 5 percent of the true flying height.

Processing and map preparation

The data were processed at the Geological Survey of Norway in Trondheim using Geosoft processing software (Geosoft Oasis Montaj 6.2, 2005). Obvious inaccuracies in navigation were manually removed from the data. The datum used was WGS84 and the projection was UTM zone 33.

Total field magnetic data: The data were inspected flight-by-flight and any cultural anomalies were identified and manually removed. A base station correction was applied to each flight using corrections based on diurnal measurements from the base station magnetometer at the base in Verdal. Finally, a time lag of 0.6 sec (6 points) was applied to the base-mag corrected (levelled) magnetic data.

A total magnetic field map in scale 1:20 000 was produced using a grid cell size of 25 × 25 metres.

Model calculation

A model calculation based on the helicopter-borne magnetic measurements was performed in 2006 by Kero and Johansson (op. cit.). From the gridded total magnetic intensity dataset, five profiles were extracted for modelling by means of the modelling software Potent (Geophysical Software Solutions 2005). The locations of the profiles are shown in Figures 2, 4 and 5.

Magnetic properties

The Earth's magnetic (inducing) field in the area has a total intensity of 50 000 nT, a declination 0°, and an inclination of 73°.

Based on susceptibility measurements, the indicated magnetic bodies have an assumed susceptibility of approximately 0.05 SI units. However, initial modelling results showed that magnetic bodies with the above, assumed susceptibility cannot explain the measured anomalies. Therefore, it became clear that the investigated magnetic bodies must also be characterised by a certain degree of remanent magnetisation. In order to achieve a good fit between the measured and the calculated anomalies, a remanent magnetisation of 1.5 A/m has been assumed for profiles 2-5 and 2.0 A/m for profile 6. The direction of the remanent magnetisation is assumed to be in alignment with the present direction of the Earth's magnetic (inducing) field.

The assumed properties are very realistic if compared to known properties of similar magnetic rocks but it must be emphasised that, in the case of Raudfjellet, only the magnetic susceptibility value used for modelling is based on actual measurements within the investigated area.

Observations along the ground-magnetic profiles (Figure 3)

Profile 1

Profile 1, 3 370 m long, measured in the direction 109° and with 10 m spacing between each measuring point, extends from

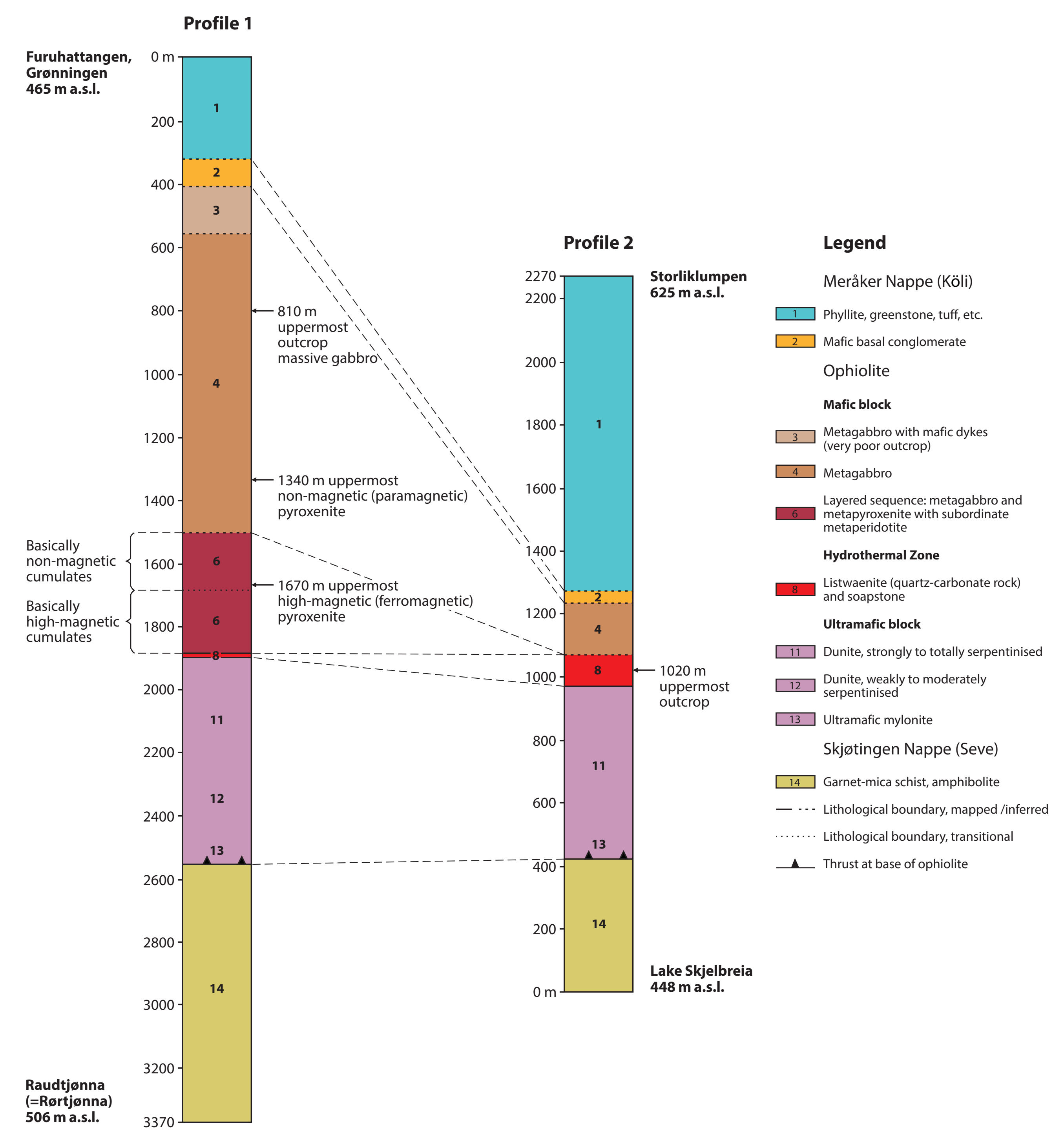

Figure 3. Geology drawn as columns along two ground-magnetic profiles, 1 and 2, across the Raudfjellet ophiolite. Locations of the profiles are shown in Figure 2. Profile 1 was measured from NW to SE; profile 2 from SE to NW. Bedrock observations are indicated as well as a geological correlation between the two profiles.

the point Furuhattangen at the shore of lake Grønningen in the northwest to the tarn Raudtjønna in the southeast across the northern and supposedly thickest part of the ophiolite fragment (Figure 2). The profile starts in non-outcropping Köli metasedimentary rocks and after about 500 m passes into massive gabbro that continues for about 1 500 m along the profile. The first outcrop encountered is massive gabbro at 810 m from the start of the profile. From c. 1 500 m, the gabbro gradually changes character from massive to layered gabbro including also subordinate leucogabbro/anorthosite and accompanied by an increasing number of ultramafic layers stratigraphically downwards (see stratigraphic column in Figure 3). The first ultramafic layers encountered along the profile at 1 340 m are non-magnetic (i.e. paramagnetic) pyroxenite in massive gabbro, but later also high-magnetic (i.e., ferromagnetic) pyroxenite and peridotite layers were encountered from 1 670 m. The number of ultramafic layers is increasing downwards towards the contact with the hydrothermal zone at 1 890 to 1 900 m. As a whole, we may regard the 180 metres between 1 500 and 1 680 m as basically non-magnetic cumulates and the 220 m between 1 680 and 1 900 m as high-magnetic cumulates of the mafic block. The latter will then contribute to masking the here thin and non-magnetic hydrothermal zone situated just below these cumulates. At the southeastern side of the hydrothermal zone, the large, monotonous serpentinite/metadunite body (the main constituent of the ultramafic block) is passed (over a distance of c. 650 metres) before we enter the poorly exposed, low-magnetic, Skjøtingen (Seve), footwall mica schists with minor amphibolites at c. 2 550 m and continue on the last c. 820 m-long portion of the profile down to the shore of Raudtjønna.

An unexpected phenomenon was encountered along this profile. Some of the ultramafic pyroxenitic and peridotitic layers in the mafic block were shown to be strongly magnetic with measured total field values along the profile up to 54 083 nT with a corresponding magnetic susceptibility of 61 × 10^{-3} SI. These values are almost equal to even the highest total field values obtained when profiling over the large serpentinite body (max. 54 405 nT and corresponding 56 × 10^{-3} SI). The profile section with high-magnetic cumulates occurring between 1 680 and 1 890 m were inserted as a separate high-magnetic body in the interpretation of the profile (Figure 6). In this way, the non-magnetic hydrothermal zone came to be intercalated between the two high-magnetic blocks.

Anomalous negative spikes with values down to -7 000 nT are regarded as noise and have been removed from the profile (Figure 6). The results from the airborne measurements showed no sign of local magnetic minima in the area.

Profile 2

Profile 2, 2 270 m long, measured in the direction 300°, and also with 10 m between each measuring point, started in the southeast at the shore of lake Skjelbreia well into the Skjøtingen (Seve) nappe footwall of the ophiolite (Figure 2). The profile then passed through the high-magnetic serpentinite body between 420 and 970 m, crossed soapstone and listvenite of the hydrothermal zone between 970 and c. 1 070 m, then the massive gabbro which has here thinned very much between c. 1 070 and c. 1 220 m; and finally traversed low-grade Köli phyllites, etc., over the last kilometre up to the crest of the hill Storliklumpen at 620 m. asl. (Figure 6). The last outcrop observed was of listvenite at the shore of lake Grønningen at 1 020 m, i.e. only half-way along the profile. Along the last 1 250 m of profile 2 no outcrops were observed, thereby making interpretation of this particular magnetic profile more difficult. Very little noise was recorded along this profile as compared with profile 1. A single c. 1 000 nT sudden drop in total field occurred in the border zone between serpentinite and soapstone/listvenite near the outlet of lake Grønningen. On the other hand, the high values measured above the serpentinite body did not fall off as soon as expected when entering into the non-magnetic hangingwall rocks to the serpentinite (first the hydrothermal zone, then massive gabbro of the ophiolite and finally the overlying Köli phyllites). In fact, the measured total field values did not diminish much at all, remaining remarkably high and stable, and falling only from c. 52 200 nT at 1 200 m to c. 51 900 nT at 2 270 m at the end point Storliklumpen. This hill is situated at c. 1 000 metres into the phyllites and associated rocks lying above the ophiolite and is, in addition, 155 m higher than lake Grønningen with the last outcrops consisting of serpentinite and listvenite. The measured total field values thus necessitated a very gently northwest-dipping surface of the large serpentinite body for a best possible curve fit when modelling the profile (Figure 6). This unexpectedly low angle of dip (c. <5-10°) did not fit at all with dips measured on the surface near the outlet of lake Grønningen and in the surrounding terrain (c. 25-45° dip angles), nor with the information obtained from the nearest drillholes (Dh 2 and 7, Nilsson 2000).

Due to the problems of properly explaining these quite unexpected measuring results and the very shallowly dipping body modelled from the readings, Statskog decided not to continue further ground profiling. Instead they decided to carry out a new airborne survey to obtain a better overview of the whole area in a wider context.

Modelling results from the helicopter-borne magnetic survey

Total magnetic field and magnetic vertical derivative maps

The total magnetic field map in Figure 4 shows a great number of interesting magnetic anomalies, both larger structures and smaller features, clear linear structures and some quite irregular ones. Foremost, a number of very large and strong positive anomalies, as well as complementary negative ones, occur within and along both the ultramafic and the mafic block of the ophiolite. Since the map, however, was financed and compiled in connection with the ongoing exploration for talc/soapstone and magnesite, focus was placed on the magnetic trace and signature of the hydrothermal zone and its immediate and concordant substrate, i.e. the large sepentinite body of the ultramafic block. Many of the other, new and interesting anomalies have therefore so far been left out and not followed up in the field. This applies, for example, to the many small and very strong 'point anomalies' within the lower, cumulitic part of the mafic block where thin and impersistent, high-magnetic, pyroxenite layers (ferropyroxenites) alternate with gabbroic cumulates. The large, NW-SE-trending, negative anomaly in the midst of the massive gabbro unit (i.e., where the mafic block is expected to be at its thickest) on the east side of

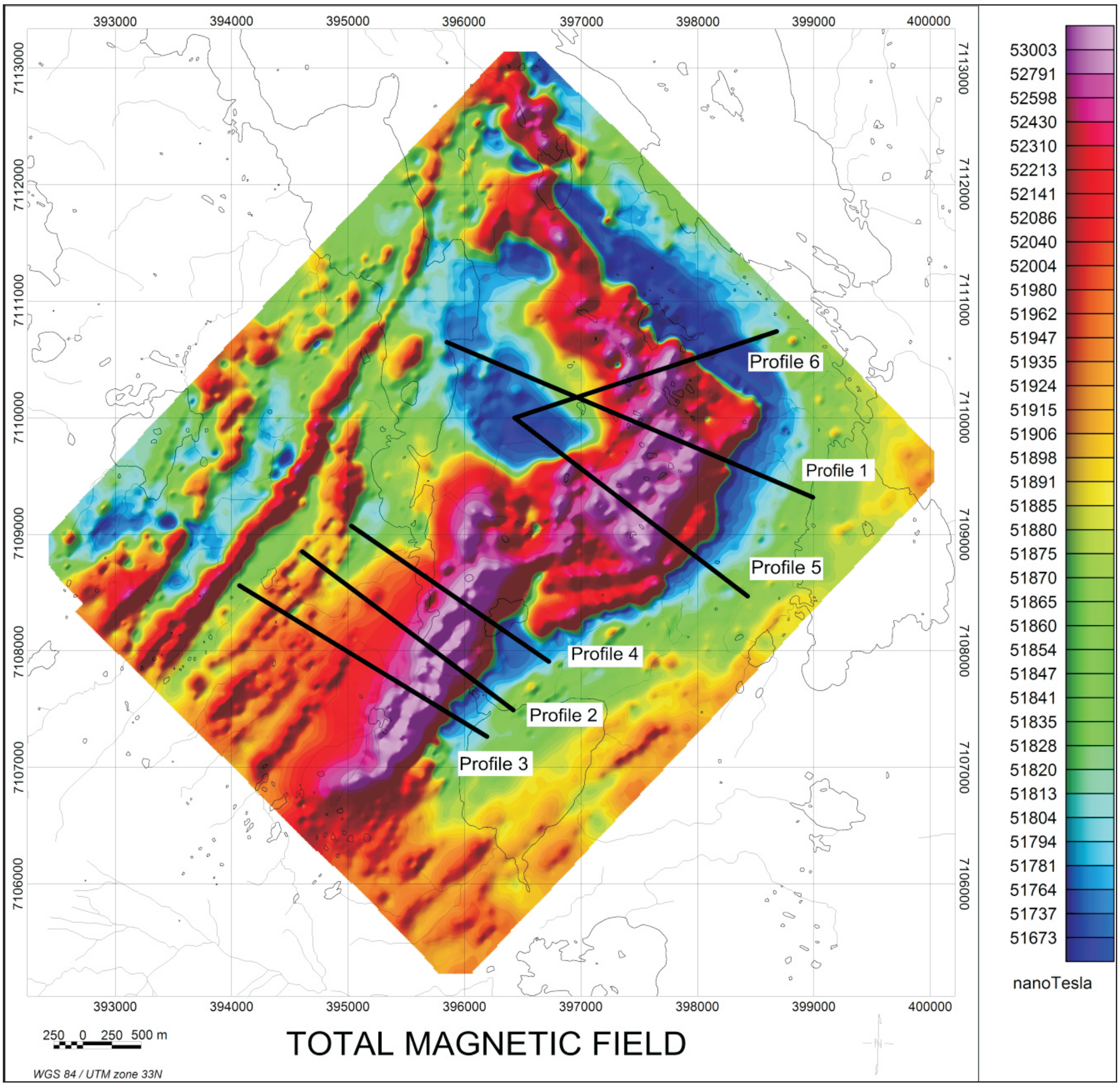

Figure 4. The total magnetic field measured from the helicopter. The intensity of the total magnetic field is given in nanoTesla. The locations of the five profiles (2 to 6) extracted for the modelling are shown together with profile 1.

lake Grønningen is located in an unexposed area devoid of any outcrops, and it is therefore still unknown to us what it really represents. Whatever the causes, the individual anomalies in the new aeromagnetic map may serve as a very good basis for any future detailed field study of the ophiolite fragment. The same applies to the magnetic vertical derivative map in Figure 5. This map especially enhances internal structures in the metadunitic ultramafic block (Figure 2). The anomaly pattern seems to have been caused mainly by the strong tectonic fragmentation of the body, and in addition possibly by substantial variations in the degree of serpentinisation of the precursor dunite. Based on the new aeromagnetic maps, the first author (LPN) suggested modelling the geology along four new profiles plus the old profile 2 discussed above. The modelling work was carried out by two of the present coauthors (Kero and Johansson 2006).

Modelling results from the southwestern area (Figure 7, profiles 2-4)

The modelling of the southwestern part of the survey area (profiles 2-4, Figure 7) shows a sheet-like magnetic body with a convex upper surface and flat, inclined base dipping at c. 40° to the northwest. The sheet has a maximum thickness of approximately 200 m and a length of 2 km, and it reaches a depth of at least 1 200-1 500 metres below the ground surface. The depth extent is actually a minimum value since the model can be extended farther down without causing any significant change in the calculated anomaly at the surface. The base of the sheet appears to correspond with the down-dip extension of the thrust fault exposed and mapped on the topographic surface. The modelling shows that the northeastern edge of the sheet dips to the northeast.

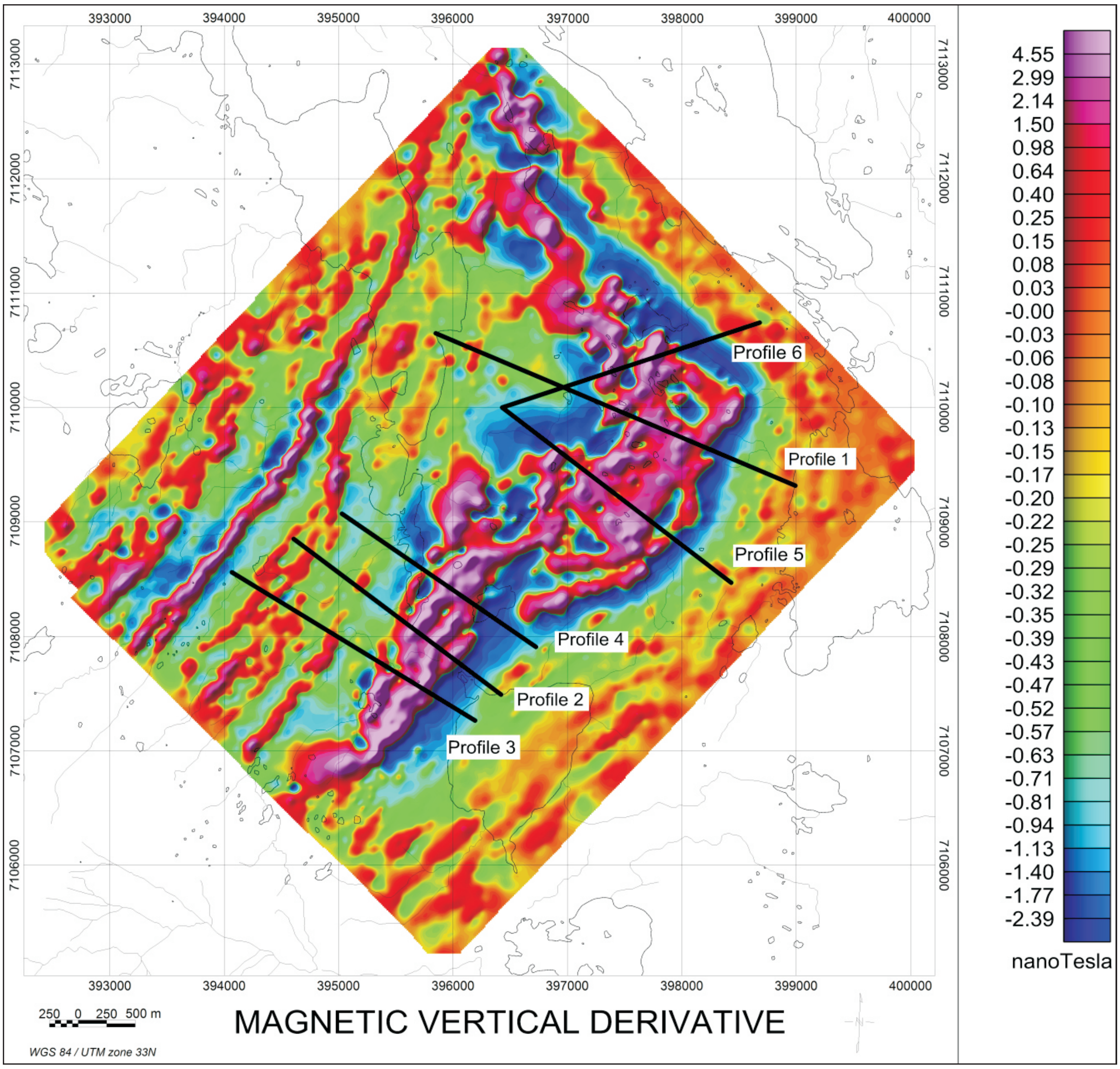

Figure 5. The magnetic vertical derivative with values given in nanoTesla. The locations of the five profiles (2 to 6) extracted for the modelling are shown together with profile 1. The anomaly pattern is enhancing the internal structures in the ultramafic (metadunitic) block.

The main anomaly displays a number of 'internal peaks', a feature which suggests that the simple sheet model could possibly be replaced by a series of thin sheets with varying susceptibility and/or remanent magnetisation. However, the modelling shows that the magnetic pattern could just as well be explained by the magnetic body having an irregular form near the surface, or even by topographic effects. A more detailed analysis of the internal structure of the magnetic body would require the acquisition of far more detailed magnetic data. Measurements of magnetic susceptibility along the ground-magnetic profile 1 varied, for example, between 0.03 and 0.09 SI units (46 individual field measurements distributed at 16 locations along the profile, and the values varied very irregularly along the profile); see Table 1.

It should be added that chemical analyses of metadunite samples verify substantial local variations in the content of serpentine, i.e. the content of serpentine vs. olivine (cf. Nilsson 2000, fig. 20 and table 7). When olivine is transformed to serpentine, the latter is accompanied by significant amounts (several wt.%) of very fine-grained, disseminated, secondary magnetite. This is the mineral contributing to the magnetic body/bodies causing the positive magnetic anomaly/anomalies here in question. The nature of the apparent remanent magnetisation is not yet clear.

Modelling results from the northeastern area (Figure 7, profiles 5- 6)

The anomalous pattern in the northeastern part of the area (profiles 5 and 6) is more complex than in the southwest (Figure 7). The apparent geometry differs quite significantly between the two profiles. A reasonable fit with the measured data requires a more pronounced contribution from remanent magnetisation

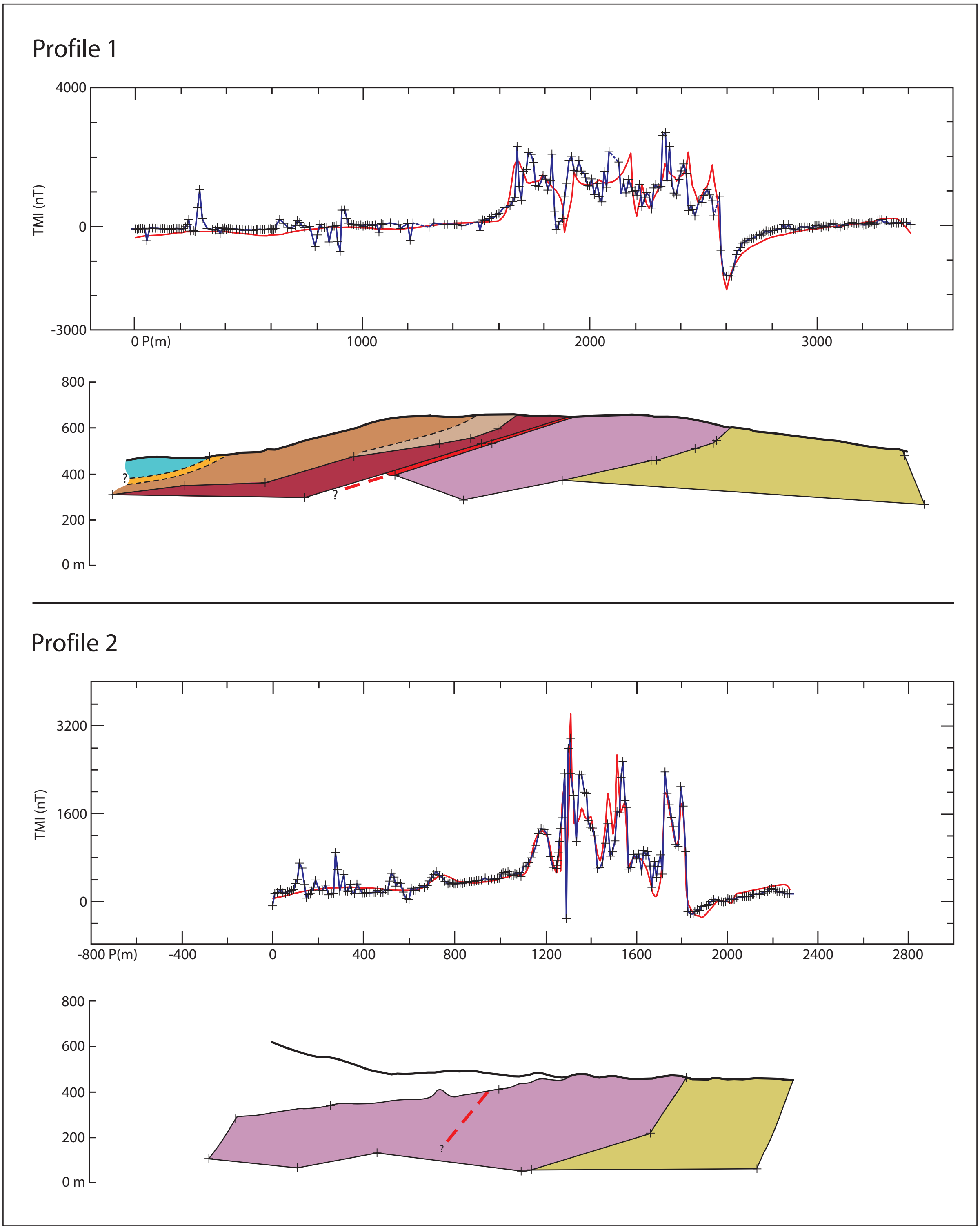

Figure 6. Modelling of profiles 1 and 2 based on ground-magnetic measurements. The blue line represents the measured magnetic field, the red line the theoretical response from the model. Colouring of the bodies is in accordance with that shown on the geological map in Figure 2 and the columns in Figure 3. A number of local, deviant readings lower than -1 000 nT caused by instrument disturbances have been deleted from the graph of profile 1.

as compared to the profiling in the southwestern part of the investigated area. Again, internal variations have been neglected when modelling the magnetic body.

Profile 5 (Figure 7) displays a sheet-like, almost lenticular, approximately horizontal magnetic body with a length/thickness ratio of c. 3:1. The thickness of the sheet is 200-300 m and its upper, outermost contacts dip outwards, i.e., towards NW in the northwest and towards SE in the southeast.

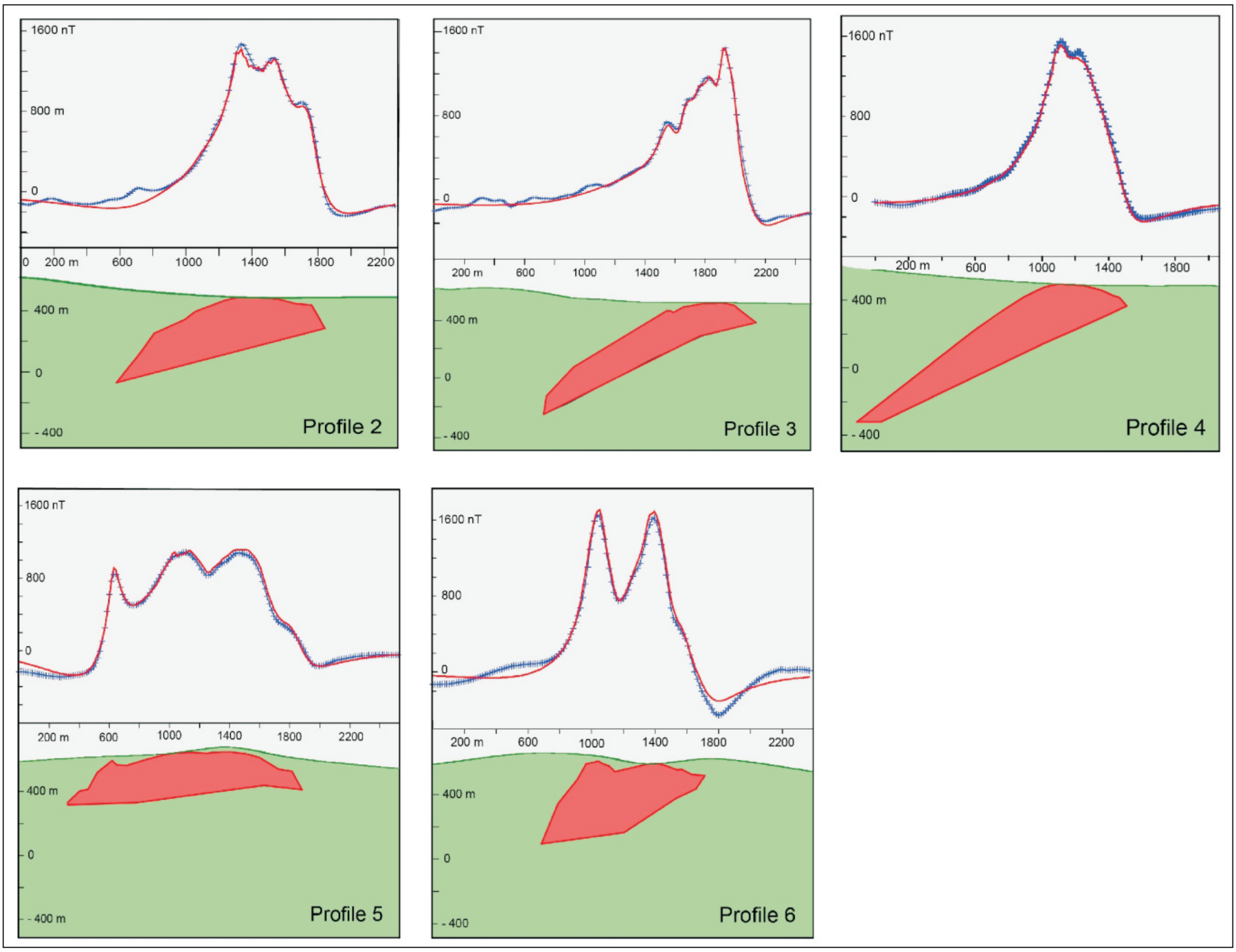

Figure 7. Modelling of the helicopter-borne data from Raudfjellet. The blue line represents the measured magnetic field, the red line the theoretical response from the model. Profile locations are shown in Figures 2, 4 and 5. For magnetic properties of the Earth's magnetic field and the assumed properties of the anomalous magnetic body, see text.

Profile 6 (Figure 7) also shows the body to have a sheet-like form although it is shorter, thicker and more stunted than in Profile 5. The overall dip is c. 45° to the southwest, but again there is a tendency to show outward dips (SW and NE, respectively) close to the surface. The vertical cross-section is rhombic in shape (edge length approximately 600 m), suggesting that the magnetic body can be interpreted to have a sheet-like form with very limited depth extension. Although the interpreted depth extension is comparatively poorly resolved, it is nevertheless obvious that the depth extent of the body is far more limited than in the southwestern area. An alternative interpretation would be that the thickness of the sheet decreases dramatically with depth.

Discussion

The helicopter-borne, magnetic total-field data presented here have indicated that the relatively simple picture of the subsurface form of the c. 9 km^2 Raudfjellet ophiolite reported earlier (Nilsson et al. 2005) requires some modification. The magnetic anomaly pattern strongly indicates that NW-SE-trending, steep to vertical, strike-slip faulting has segmented the ophiolite in a way not readily recognised during the earlier surface bedrock mapping, especially in the largely unexposed and forested areas of the mafic block in the west (cf. Figures 2 and 4). The ophiolitic complex and its neighbouring Seve and Köli metasupracrustal rocks show markedly different magnetic properties. The ophiolitic rocks as a whole contain either abundant magnetite (the only ferromagnetic mineral present in significant amounts) or only paramagnetic and diamagnetic minerals.

Based on five profiles derived from helicopter-borne magnetic total-field data (Figure 4), modelling of the Raudfjellet ophiolite has confirmed the general geometry of the mafic-ultramafic complex, though with notable changes along strike from south to north (Figure 7). The modelled profiles 2, 3 and

4 show a large ultramafic body of variably serpentinised dunite dipping regularly at 30-40° (hanging-wall side of the body) towards northwest for at least 1 200 to 1 500 m in the southern half of the ophiolite, thus corresponding to a vertical depth of 600-800 m. The footwall of this high-magnetic modelled body, which represents the mylonitic thrust zone of the ophiolite, dips regularly at 15-25° northwestwards.

In the northern half, however, i.e., to the north of the distinct Hallarhaugen fault-bound segment, the regular pattern seen in the south is markedly disrupted. Modelling here shows a more complex 3D picture of the magnetic body which includes both the large ultramafic (serpentinitic) block and the highly magnetic, ultramafic-mafic cumulates (ferropyroxenites) of the overlying mainly gabbroic block. Profile 5 shows an almost flat-lying, 1 500 m-long, prismatic body with a depth range in the order of only 200-250 metres. The hanging-wall side of this prism is dipping at c. 45° towards the northwest. Profile 6, modelled WSW-ENE (i.e. with a 55° angle to profile 5), shows a high-magnetic, 1000 m-long, nearly rhomb-shaped prismatic body, the footwall of which starts with a 35° dip and ends up with a dip of only 8° towards the southwest. The depth range of this last body is up to 500 m in the southwest, and further shows that the ophiolite is wedging out towards the northeast. The hanging-wall side of this rhomb-shaped body is dipping at c. 60° towards the southwest. This abrupt change in the depth extension of the modelled magnetic body occurring around Hallarhaugen may be explained by the prominent strike-slip faulting of the ophiolite, which has resulted in extensive block faulting and segmentation of the complex.

The observed rapid changes between thin, highly magnetic, ferropyroxenite layers and low-magnetic gabbro layers in the lower, cumulitic parts of the mafic block (Figures 3 and 6) proved to be difficult to deal with in the final modelling. This was due to both the limited amount of geophysical field data available for the modelling and the scarcity of geological information within the poorly exposed, lower, layered portion of the mafic block. The relatively thin and impersistent ferropyroxenite layers, each one in itself a quite insignificant tabular body compared to the size of the serpentinised dunite block, were therefore ultimately included in the one, single, highly magnetic body that constitutes the basis for the model calculations.

To resolve the various components of the 'ultramafic block' and the layered sequence of metagabbro-metapyroxenite would require far more detailed geophysical data and would furthermore, to be reliable, have to be confirmed by drilling. Should further investigations be made at some future date, the present geological information and geophysical modelling results will nevertheless provide a good basis for the planning of the work.

Acknowledgements
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References

Bergman, S. (1993) Geology and geochemistry of mafic-ultramafic rocks (Köli) in the Handöl area, central Scandinavian Caledonides. *Norsk Geologisk Tidsskrift*, **73**, 21-42.

Foslie, S. (1959) Geologisk kart JÆVSJØEN (Rektangel 51C), M 1:100 000. *Norges geologiske undersøkelse*.

Furnes, H., Pedersen, R.B. and Stillman, C.J. (1988) The Leka ophiolite complex, central Norwegian Caledonides: field characteristics and geotectonic significance. *Journal of the Geological Society of London*, **145**, 401-412.

Gee, D.G., Kumpulainen, R., Roberts, D., Stephens, M.B., Thon, A. and Zachrisson, E. (1985) Scandinavian Caledonides, Tectonostratigraphic Map, 1:2 million. *In* Gee, D.G. and Sturt, B.A. (eds.) *The Caledonide Orogen – Scandinavia and related areas*. John Wiley & Sons, Chichester.

Geophysical Software Solutions (2005) Potent reference Manual. *Geophysical Software Solutions Pty. Ltd., Canberra*, 108 pp.

Geosoft (2005) OASIS Montaj v 6.2 Mapping and processing system. The core software platform for working with large volume spatial data. Quick start tutorials. *Geosoft Incorporated, Toronto*, 258 pp.

Grenne, T. (1989) Magmatic evolution of the Løkken SSZ Ophiolite, Norwegian Caledonides: relationships between anomalous lavas and high-level intrusions. *Geological Journal*, **24**, 251-274.

Grenne, T., Grammeltvedt, G and Vokes, F.M. (1980) Cyprus-type sulphide deposits in the western Trondheim district, central Norwegian Caledonides. *In* Panayioutou, A. (ed.) *Ophiolites.* Proceedings of the International Ophiolite Symposium, Cyprus, 1979. *Geological Survey of Cyprus, Nicosia*, pp. 727-743.

Håbrekke, H. (1983) Geofysiske målinger fra helikopter over et område nord for svenskegrensen i Lierne og Snåsa kommuner, Nord-Trøndelag fylke. *Norges geologiske undersøkelse Rapport* 1898, 12 pp + 8 maps.

Kero, L. and Johansson, R. (2006) Raudfjellet; modellberäkning. *Sveriges Geologiska Undersökning Rapport 08-733/2006*, 12 pp.

Mogaard, J.O. (2006) Data Acquisition and Processing – Helicopter Geophysical Survey, Skjaekerdalen, 2006 Nord-Troendelag county, Norway. *Norges geologiske undersøkelse Report* 2006.041, 11 pp.

Nilsson, L.P. (2000) Oppfølgingsarbeider på magnesitt, talk og kleberstein i Raudfjellet, Snåsa. *Norges geologiske undersøkelse Rapport* 2000.57, 133 pp + 1 map at 1:10 000 scale.

Nilsson, L.P., Sturt, B.A. and Ramsay, D.M. (1999) Ofiolittundersøkelser i Snåsa og Lierne: en rekognosering for å påvise mulig interessante forekomster av malm, industrimineraler og naturstein. *Norges geologiske undersøkelse Rapport* 1999.114, 92 pp + 1 map at scale 1:10 000.

Nilsson, L.P., Roberts, D. and Ramsay, D.M. (2005) The Raudfjellet ophiolite fragment, Central Norwegian Caledonides: principal lithological and structural features. *Norges geologiske undersøkelse Bulletin*, **445**, 101-117.

Nilsson, L.P. and Roberts, D. (2014) A trail of ophiolitic debris and its detritus along the Trøndelag-Jämtland border: correlations and palaeogeographical implications. *Norges geologiske undersøkelse Bulletin*, **453**, 29 - 41.

Roberts, D. (1997a) Geologisk kart over Norge. Berggrunnsgeologisk kart GRONG, M 1:250 000. *Norges geologiske undersøkelse*.

Roberts, D. (1997b) Geochemistry of Palaeoproterozoic porphyritic felsic volcanites from the Olden and Tømmerås windows, Central Norway. *Geologiska Föreningens i Stockholm Förhandlingar*, **119**, 141-148.

Roberts, D. and Gee, D.G. (1985) An introduction to the structure of the Scandinavian Caledonides. *In* Gee, D.G. and Sturt, B.A. (eds.) *The Caledonide Orogen – Scandinavia and related areas.* John Wiley & Sons, Chichester, pp. 55-68.

Roberts, D., Nissen, A.L. and Walker, N. (1999) U-Pb zircon age and geochemistry of the Blåfjellhatten granite, Grong-Olden Culmination, Central Norway. *Norsk Geologisk Tidsskrift,* **79**, 161-168.

Roberts, D., Walker, N., Slagstad, T., Solli, A. and Krill, A. (2002) U-Pb zircon ages from the Bymarka ophiolite, near Trondheim, Central Norwegian Caledonides, and regional implications. *Norsk Geologisk Tidsskrift*, **82**, 19-30.

Schrotter, J.-M., Pagé, P., Bédard, J.H., Tremblay, A. and Bécu, V. (2003) Forearc extension and sea-floor spreading in the Thetford Mines Ophiolite Complex. *In*: Dilek, Y. & Robinson, P.T. (eds) *Ophiolites in Earth History*. Geological Society, London, Special Publications, 218, 231-251.

Sjöström, H. and Bergman, S. (1989) Asymmetric extension and Devonian(?) normal faulting: examples from the Caledonides of eastern Trøndelag and western Jämtland. (Extended abstract) *Geologiska Föreningens i Stockholm Förhandlingar*, **111**, 407-410.

Sjöström, H. and Roberts, D. (1992) Gjevsjøen, berggrunnskart 1823-2, 1:50 000, foreløpig utgave. *Norges geologiske undersøkelse*.

Sjöström, H. and Roberts, D. (2013) Gjevsjøen, berggrunnskart 1823-2, 1:50 000, revidert foreløpig utgave; digitalt fargeplott. *Norges geologiske undersøkelse*.

Slagstad, T. (2003) Geochemistry of trondhjemites and mafic rocks in the Bymarka ophiolite, Trondheim, Norway: petrogenesis and tectonic implications. *Norwegian Journal of Geology*, **83**, 167-185.

Törnebohm, A.E. (1896) Grunddragen af det centrala Skandinaviens bergbyggnad. *Kongliga Svenska Vetenskaps-Akademiens Handlingar*, **28** (5), 212 pp.

Troëng, B. (1982) Uranium-rich granites in the Olden window, Sweden. *Mineralogical Magazine*, **46**, 217-226.

RESEARCH ARTICLE

A trail of ophiolitic debris and its detritus along the Trøndelag-Jämtland border: correlations and palaeogeographical implications

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Based partly on personal field observations, but also largely on extracts from field notebooks written by the late Steinar Foslie in the 1930s, descriptions are given of the several, small, elongate lenses of partially serpentinised mafic-ultramafic rocks situated at or close to the base of the Köli nappes over a 80 km stretch of the border region of Norway (Trøndelag) and Sweden (Jämtland). These semi-continuous lenses are considered to represent highly fragmented lower sections of an ophiolite, akin to those exposed at Raudfjellet and Handöl, and also farther south in the Feragen-Raudhammeren area near Røros. In some cases, serpentinite-clast conglomerates lie unconformably upon the lensoid ophiolite bodies. It is suggested, on regional-geological evidence, that the disjointed Raudfjellet-Handöl- Feragen ophiolite fragments may possibly be of latest Mid Cambrian to Early Tremadocian age, as in the case of the larger bodies of ophiolite in the western Trondheim Region and on Leka, but the magmatic origins of these two groups of ophiolite are quite dissimilar. Whereas the 'western' ophiolites are suprasubduction-zone complexes with primitive arc involvement, and inferred by some workers to have been emplaced on the outboard side of a microcontinent' that rifted and drifted away from Baltica, those in the 'eastern' Trøndelag-Jämtland border area have no arc component and are considered to have formed part of the ocean floor of an extending seaway (Baltoscandic Sea) that developed during Cambrian time between the microcontinent and the Baltoscandian passive margin of Baltica.

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Introduction

The Raudfjellet mafic-ultramafic complex, situated close to the Swedish border in Nord-Trøndelag, was first recognised as such by Törnebohm (1896), appearing on his map compilation of the Trondheim Region as a body of serpentinite and diorite. Subsequent fieldwork by Foslie (1959) distinguished peridotite, pyroxenite and gabbro, and later remapping by Bergman and Sjöström in 1988 (incorporated in Sjöström and Roberts 1992) led to a further differentiation, and eventual recognition of the complex as a fragmented ophiolite (Nilsson et al. 2005).

Törnebohm (1896) also recognised a series of small, variably serpentinised, ultramafic bodies along strike to the southwest of Raudfjellet (Figures 1 and 2), indicated as serpentinite on his 1: 800 000 map, occurring at what appeared to be roughly the same tectonostratigraphic level. On account of their relative resistance to erosion, these small lensoid bodies inevitably stood out as pinnacles in the topography, and at least two of them are the sites of cairns marking the boundary between Norway (Nord-Trøndelag) and Sweden (Jämtland). In his classical monograph, Törnebohm (1896) provided rough sketches of profiles through three of these small bodies, though with a minimum of description. A good deal more information was reported by Steinar Foslie in his field notebooks (for his maps, printed in 1959) but this was never published.

The main purpose of this contribution is to provide short descriptions of each of these 'serpentinite' bodies, as well as noting the principal features of other mafic-ultramafic complexes as far south as the Feragen-Raudhammeren area, near Røros, and to discuss briefly their occurrence in terms of the regional geology of this part of the Mid-Norwegian and Mid-Swedish Caledonides. Also considered, in the discussion section, are the palaeogeographical implications of the regional distribution of these, and other, fragmented ophiolite assemblages in this part of the Caledonides. Much of the description of the small lensoid bodies has been retrieved from a careful examination of Foslie's many notebooks, but also aided by helicopter trips in 1999 to two of the small isolated occurrences and their overlying conglomerate.

The general geology of this border region and the Raudfjellet area in particular is described in a companion paper in this volume (Nilsson et al. 2014), as well as in an earlier contribution (Nilsson et al. 2005). We therefore refer the reader to these publications for details of the geology. Maps of this border area of Jämtland and Nord-Trøndelag include those of Wolff (1977), Strömberg et al. (1984), Roberts (1997), Sjöström and Roberts (2013) and Bergman et al. (2012).

Descriptions of the serpentinite bodies

We describe the occurrences from north to south, beginning with a small serpentinite – or what Törnebohm preferred to call 'serpentinised olivine rock' – occurring at Skardtjønna just 2-3 km to the north of Raudfjellet. All the occurrences of these 'serpentinite' bodies are shown in Figure 2.

Skardtjønna

The isolated Skardtjønna lens was remapped in 2003 in connection with prospecting for soapstone in the area just to the north of Raudfjellet (Nilsson 2003). The 180 × 300 m lens consists essentially of serpentinised dunite. Unlike the remainder of the ultramafic lenses described below it is not situated at or above the Seve/Köli contact but is located c. 350 m to the east of, i.e. below, the mapped boundary (Figure 2), within amphibolites of the upper Seve Nappe (Sjöström and Roberts 2013). However, small talcified serpentinite bodies are not uncommon in Seve schists and amphibolites in this part

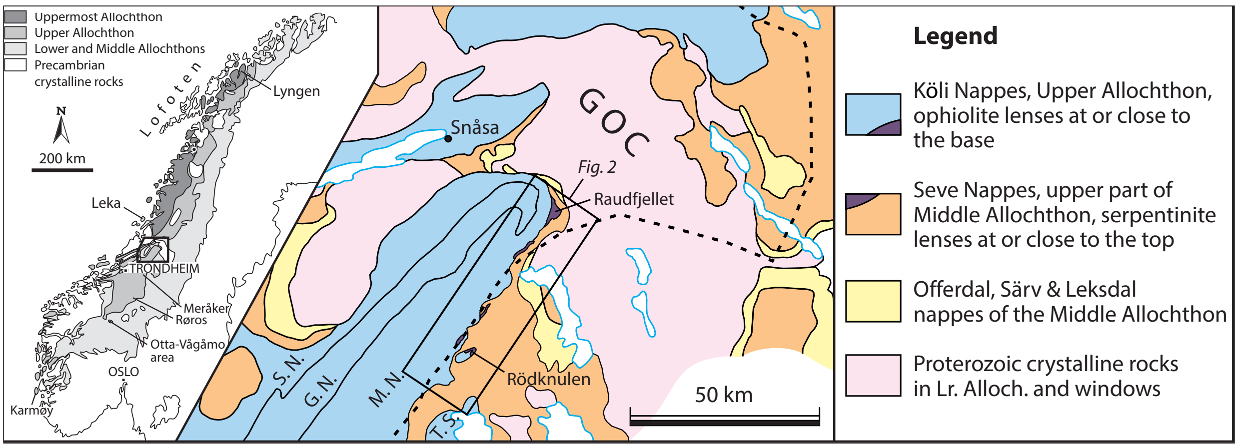

Figure 1. Simplified tectonostratigraphic map of the Raudfjellet region showing the locations of some of the ultramafic-mafic (ophiolitic) lenses discussed in the text. GOC – Grong-Olden Culmination; G.N. – Gula Nappe; M.N. – Meråker Nappe; S.N. – Støren Nappe; T.S. – Tännfors synform. The grey-tone map to the left shows the location of the main map, northeast of Trondheim, and the approximate position of the Otta-Vågåmo area southwest of Røros. The elongate rectangle shows the area depicted in Figure 2.

of Trøndelag, including areas to the northeast of the Grong-Olden Culmination (Fig. 1) (Reinsbakken and Fossen 1988). In addition to the Skardtjønna lens, soapstone occurs in amphibolite-hosted, very small and strongly deformed, elongated serpentinite lenses in shear zones situated in the same area, but closer to the Seve/Köli contact.

Raudfjellet

The 9 km² Raudfjellet ophiolite fragment, by far the largest of the northern group of ophiolite fragments here described, is treated in an accompanying contribution (Nilsson et al., this volume) as well as in an earlier review paper (Nilsson et al. 2005) to which we refer. The Raudfjellet ophiolite has been the target for talc/soapstone and magnesite exploration during the last one and a half decades, and a number of exploration reports, notes and other material have emerged from this work. The Raudfjellet body principally consists of two rigid blocks, one ultramafic (variably serpentinised dunite) at the base which is discordantly overlain by a mainly gabbroic block. A thin polymict conglomerate occurs unconformably upon the mafic block. Clasts are mainly of ultramafic, mafic and magnesite-quartz (listvenite) rocks, and the matrix is composed entirely of mafic and ultramafic material (cf. figure 12 in Nilsson et al. 2005). The homogeneous, serpentinised and completely non-stratified dunite is considered to originate from the zone between overlying ultramafic cumulates (e.g., dunite-wehrlite cumulates) of the lower crust and underlying typical harzburgitic or lherzolitic mantle peridotites, though neither of these rocks is represented at Raudfjellet. The dunitic block is up to 200-300 m thick according to model calculations based on aeromagnetic measurements (Nilsson et al., this volume) and at most 1 km wide across the highest ridge of Raudfjellet and 4.5 km in length.

Although we are far from knowing its exact position in a more general ophiolite stratigraphy, the Raudfjellet metadunite

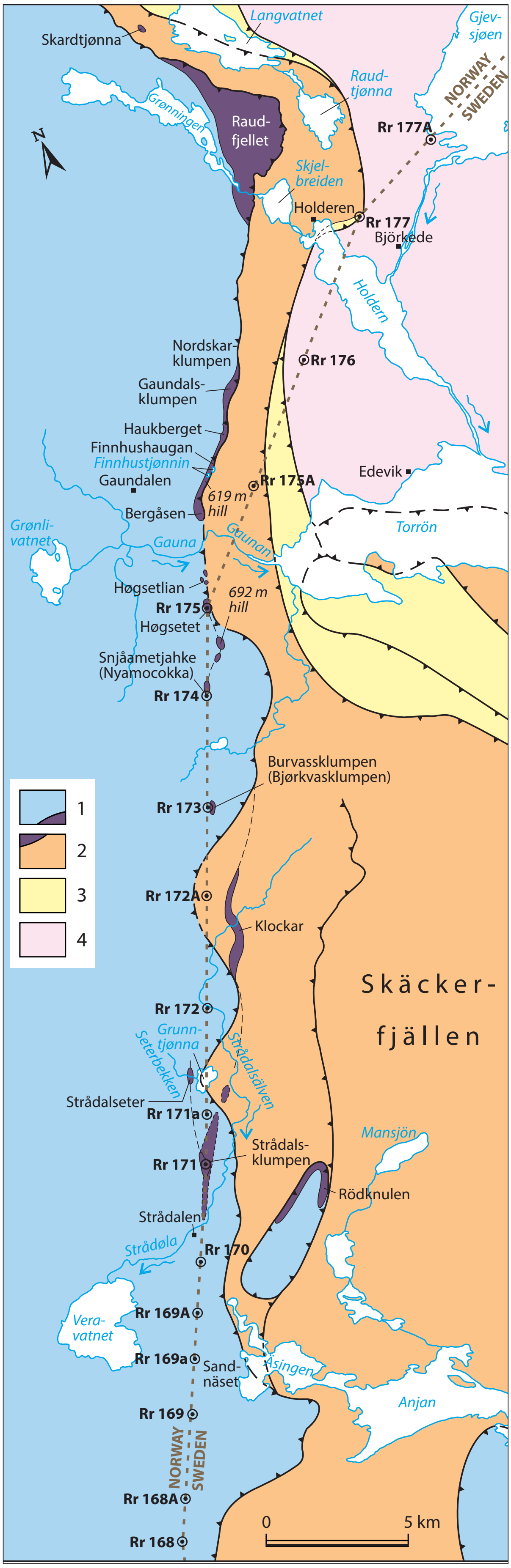

Figure 2. Locations of the ultramafic-mafic bodies and lenses between Skardtjønna and Raudfjellet in the northeast and Rödknulen in the southwest. As well as Foslie's field notebooks from 1934 and 1935, the sources used for the map compilation are (i) for the Norwegian side, Foslie (1959a, b), Wolff (1977) and Sjöström & Roberts (2013), and (ii) for the Swedish side, Törnebohm (1896), Stigh (1979), Strömberg et al. (1984) and Bergman et al. (2012). The border between Norway and Sweden and the numbered border posts (Rr = Riksrös) mentioned in the text are indicated. The colour scheme is the same as in Figure 1. The legend numbers are:- 1. Köli nappes of the Upper Allochthon with ophiolite lenses at or close to the base; 2. Upper Seve nappe with serpentinite lenses at or close to the top, Middle Allochthon; 3. Offerdal, Särv and Leksdal nappes of the Middle Allochthon; 4. Proterozoic crystalline rocks, Lower Allochthon. Thrust contacts are shown with small triangles on the hanging-wall side.

body may perhaps be compared to the 'large dunite bodies' that occur in the mantle portion of the Leka Ophiolite Complex, and then mainly within a distance of 500 m from the overlying ultramafic cumulate sequence (Albrektsen et al. 1991, p. 212). The largest dunite body on Leka is only c. 100 m wide and 550 m in length, i.e., only a fraction of the Raudfjellet body. In addition, it is conceivable that the Raudfjellet body could have been even bigger in its original oceanic setting, since the contacts between the dunite and its original neighbouring rocks are nowhere to be seen, contrary to the case on Leka. Ultramafic (mainly metapyroxenitic) and mafic (metagabbroic; from leucogabbro to melagabbro) cumulates in the lower parts of the mafic (gabbroic) block are gradually wedging out towards the southwest and disappearing about half way from north to south through the body. The exploration target is a 4.5 km-long hydrothermal zone between the two blocks where soapstone is developed at the base and magnesite-bearing listvenite in the upper parts. Following its thrust emplacement, quite likely in Early Ordovician time, and deposition of the overlying polymict conglomerate, the ophiolite was later affected by inferred late-Scandian extensional deformation, and disrupted by steep, NW-SE-trending, sinistral strike-slip faults (Sjöström and Bergman 1989).

Gaundalsklumpen - Haukberget

The mostly very well exposed, narrow, ultramafic-mafic lens at Gaundalsklumpen-Haukberget (Figure 2) ranges from 100 to 400 m in outcrop width and may be followed more or less continuously with a moderate NW dip, from the southern slopes of Nordskardklumpen for 6 to 7 km towards the southwest across Finnhushaugan to Bergåsen where three 1:50 000-scale map-sheets meet in a common corner (Sjöström and Roberts 2013). During a short reconnaissance trip to the area by helicopter in 1999, it was noticed that the long and narrow lens of Foslie (1959a) had an attached 150 x 1 000 m gabbroic part on its northwestern side. Both the mafic and the ultramafic rocks were in turn overlain by a >3 km-long conglomerate consisting of mafic-ultramafic ophiolitic detritus (cf. Sjöström and Roberts 2013). Contrary to the ultramafic part of Raudfjellet which consists almost entirely of metadunite, the ultramafic part of the Gaundalsklumpen-Haukberget lens appears to be a serpentinised mantle peridotite (harzburgite or lherzolite?), weathering greenish-grey, with discordant dunite bodies, roughly 50/50 of each by volume. Good outcrops show large (2-4 cm) black amphibole prisms set in a greenish matrix of altered olivine plus possibly also altered orthopyroxene.

Cobbles and boulders of gabbro, leucogabbro, red-brown carbonate rock as well as pyroxenite were recorded within the conglomerate on the western side of Gaundalsklumpen. In parts of the conglomerate with smaller pebble and gravel-size clasts and with an intercalated bed of green sandstone, we measured bedding at 177°/47°W and a schistosity at 205°/62°W. On the northwestern side of Haukberget, the ultramafite is overlain by 2 m of gabbro plus pyroxenite detritus and conglomerate beds followed above by 17 m of gabbro-clast conglomerate with scattered pyroxenite cobbles and partly with pyroxenite in the groundmass. At a closely neighbouring locality the ultramafite is first overlain by 20 cm of ultramafic 'sandstone' followed by gabbro conglomerate with interbedded ultramafic detritus (observations recorded by D.M. Ramsay).

In his field diary from 02.08.1934, Steinar Foslie noted from the eastern footwall of the ultramafite body at Haukberget: "a 150 m-wide garnet-mica schist and feldspar porphyroblast schist, then typical amphibolite…", i.e. typical Seve garnetiferous schists and amphibolite. On 01.08.1935, Foslie further observed and described in expressive terms a 5-6 m-wide and very well developed pseudo-conglomerate of variably talcified serpentinite, located within the uppermost (northwestern) part of the serpentinite body up to just northwest of the top of Haukberget.

Finnhushaugan - Bergåsen

At Finnhushaugan, c. 1.5 km to the southwest of the 807 m summit (trigonometric point) of Haukberget (Figure 2), Foslie (field diary 11.08.1935) has mapped two outcrops of ultramafites, one on the northeastern side of the two tarns Finnhustjønnin and the other on the 619 m knoll on the southwestern side. He noted that the northeastern serpentinite is up to 100 m wide in outcrop, and that especially on its hanging-wall side it is strongly talcified with a peculiar 'fragment-like' structure. On the 619 m knoll he recorded a slightly harder serpentinite, 75 m in width, which is exposed in the steep southwestern cliff of the 619 m hill. Directly to the southwest, the terrain is unexposed over a distance of 1.5 km farther to the southwest as far as to the 75 m high and forested Bergåsen knoll. There, Foslie observed that a serpentinite occupied the whole of the NE-SW-trending highest ridge at Bergåsen, as well as the upper parts of the steep sides towards the southwest, south, southeast and east, and drew a c. 150 m-wide and 400 m-long, NE-SW oriented serpentinite lens on his 'Jævsjø' map. The most important conclusion he made, however, was that he regarded the serpentinite body to be continuous, under the morainic cover, from Haukberget to the 619 m knoll at Finnhustjønnin and probably also farther to Bergåsen, i.e., in accordance with the 6 km-long and up to 300 m-wide ophiolite fragment shown on the recent bedrock map 'Gjevsjøen' (Sjöström and Roberts 2013). Foslie further observed that the 619 m serpentinite outcrop, the Bergåsen lens and the big ultramafic lens at Høgsetet to the south side of the river Gauna were all situated along a curved line, weakly convex to the west.

Høgsetet – Snjååmetjahke (Nyamocokka) – Burvassklumpen (Bjørkvasklumpen)

Høgsetet (in translation, 'High Seat' or throne) is a historically well known, prominent hilltop along the Norwegian/Swedish border (Figure 2), visible from far away in the landscape. It is also border post No.175 where the frontier makes one of its many sharp bends. The ultramafite at Høgsetet was mapped already by Kjerulf (1871). Foslie visited Høgsetet on 25.08. and 28.08.1935 and the text that follows is mostly a translated and in part edited extract from his field notebook.

Høgsetet is a small, moderately west-dipping ultramafite lens measuring some 170 x 250 m and with its central point just to the north of the 702 m top cairn. A well exposed 60 m-long prong runs from the main body to the south onto the Swedish side of the border. The Høgsetet ultramafic lens is underlain by coarse-grained amphibolites towards the north and east. On the eastern side, strike and dip was measured at 210/45°NW. Foslie regarded the ultramafite to have " a westerly dip through the whole lens, but with very well rounded terminations towards both the north and the south". The rock from the eastern margin of the body across the hilltop is described as a peridotite, but with a peculiar greenish hue ("garnierite?") in the serpentinised zone 75 m to the west of the cairn. It must be added here that it puzzled Foslie that the ultramafite at Høgsetet was not a typical ultramafite with a real root zone at depth; that would have been a more common and understandable situation for an intrusive body based on current thinking. Rather, he considered that the Høgsetet ultramafic body had no root zone at all, but was instead a fairly shallow lens floored by an amphibolite towards the east and north.

In the hillside Høgsetlian to the north of Høgsetet there are several small knolls of serpentinite associated with amphibolite, and three of the bigger ones are marked on Foslie's map, one of them in close association with amphibolite. Two kilometres to the southsouthwest of Høgsetet, Foslie observed an outcrop of " fairly massive hornblende gabbro, partly totally massive pyroxenitic". Foslie correlated this outcrop with similar, but bigger outcrops on Nyamocokka 1.5 km farther to the south-southwest along strike. What we today would consider as the main ophiolite level, however, continues due south from Høgsetet. On the 692 m hill (top point located 1330 m south to south-southwest of the Høgsetet cairn on topographic map-sheet 'Vera') Foslie described a NNE-SSW oriented, 75 m-wide and 280 m-long, well exposed peridotite lens, mostly with yellowish weathering. On the hanging-wall side he reported 15 m of a coarse pyroxenitic rock as well as some massive gabbro "here and there along the ridge". Towards the footwall the lens is more serpentinitic, and here he discovered a small and irregular chromitite lens. The occurrence of chromitite and yellowish weathering of the bulk mass is indicative of metadunite (see Feragen description. p. 36).

To the southwest of the last-mentioned lens he located another lens close to a small tarn, consisting of somewhat talcified serpentinite 40 m wide in outcrop and oriented NNE-SSW. It is difficult to be quite sure which one of the tiny tarns here Foslie refers to, but it seems fairly reasonable that this particular lens links up with the moderately westward-dipping serpentinite lens and serpentinite conglomerate beds in the *Nyamocokka* area (border post No. 174), or *Snjååametjahke* as it is spelt on modern maps (Figure 2). In his field diary for 25.08.35, Foslie doesn't mention either the serpentinite lens or the serpentinite conglomerate during his mapping at Nyamocokka, but Törnebohm (1896, p. 77-78) actually shows a profile through the lens and overlying conglomerate. Stigh (1979, p.152-154) also described this occurrence and mentioned an outcrop to the north of border cairn 174 where the serpentinite conglomerate is in contact with "a solitary, primitive ultramafite. The sequence dips westwards and the serpentinite conglomerate underlies the primitive ultramafite…". Foslie (1959a, b), however, indicated on his 'Jævsjø' and 'Bjørkvasklumpen' maps that the strata from Høgsetet extend exactly along the frontier towards the south-southwest, passing first Nyamocokka and then just to the east of Bjørkvasklumpen (Burvassklumpen) (border post No. 173; Figure 2) before they make a slight bend onto the Norwegian side of the border and eventually link up with a small talcified peridotite outcrop in a stream near Strådalsetra, and finally with the big ultramafic body at Strådalsklumpen located 20 km to the south-southwest of Høgsetet along the frontier.

At Bjørkvasklumpen (border post No. 173), or Burvassklumpen on new maps, Foslie (16.08.35) did not register any serpentinite lens, but Törnebohm did. Törnebohm (1896, p. 77) shows a moderately west-dipping serpentinite lens, cropping out just to the east of the border cairn. The ultramafic lens is overlain by a conglomerate with hornblende schist matrix that crops out at the border post. Törnebohm further remarked that this conglomerate looks somewhat "serpentine-like". Otherwise, Foslie's observations and map are well in accordance with Törnebohm's profile when it comes to the distribution of the main rocks, garbenschists and hornblende schists in the summit area of the mountain.

Klockar

On the regional bedrock map of Sweden (Strömberg et al. 1984, Karis and Strömberg 1998) the various ultramafic bodies are located along the Seve-Köli nappe boundary. There is also a southward link from the 692 m lens just south of Høgsetet to a 4 km-long ultramafic lens at *Klockar* (Figure 2) in the Strådalsälven valley, located some 10 km to the south-southwest of the 692 m lens, but only 1 km from the national frontier. The shape and size of the Klockar lens is based on several outcrops in the valley, but we have not been able to acquire any further information on the actual extent of this ultramafic lens. It does seem reasonable, however, to suspect the existence of two or perhaps three, tectonically repeated, parallel levels of fragmented ophiolite in this area. The lowermost level is exposed in the Strådøla/Strådalsälven valley extending just into Sweden, and includes the large Klockar lens which is situated at the actual Seve-Köli contact on the Jämtland map, but slightly down into the upper Seve Nappe on the more recent 1:1 million-scale bedrock map of Sweden (Bergman et al. 2012), shown here in Figure 2. The next level is at some distance up into the Köli nappe succession, practically following the national frontier (through Høgsetet – the 692 m lens – the small lens northeast of Nyamocokka - Nyamocokka – Bjørkvasklumpen – Strådalsetra - Strådalsklumpen). A possible third and uppermost structural level, essentially gabbroic-pyroxenitic, is located on the hanging-wall side of the second level and exposed in the Høgsetet-Nyamocokka area as mentioned above, and possibly also farther to the southwest.

Strådalsklumpen (Knulen or Strådalsklumpröset)

Karis and Strömberg (1998) correlated the Klockar lens with a 5.5 km-long, NE-SW-trending lens passing over Strådalsklumpen (border post No. 171; Figure 2), whereas Foslie (field diary for 17. and 18. 08. 35 and the 'Bjørkvasklumpen' map) interprets the same lens to be a more modest one, just 1 km long and trending N-S to NNE-SSW. Whatever the case, there are several outcrops of ultramafic and gabbroic rocks in the actual area, such that the difference in map interpretation might possibly be explained by the existence of two or more, tectonically repeated, slices of dismembered ophiolite as suggested above for the Klockar section. When traced out using the 1:1 million map of Bergman et al. (2012) as background, the 5.5 km-long lens shown on the Jämtland map (Strömberg et al. 1984), but with discontinuous exposure, appears to cut directly across the Seve-Köli contact at a c. 60° angle. As this is hardly tenable, if not impossible, it is more likely that this interpreted, long, narrow lens represents two or more, minor, ultramafic lenses occurring at different levels in the tectonostratigraphy – the lowermost one in the Seve unit close to the Strådalsälven river, and the upper one concurrent with the lens mapped by Foslie (Figure 2).

Foslie mapped a c. 210 x 870 m peridotite lens (numbers refer to size of actual outcrop) with the border cairn No. 171 close to the centre of the lens. He stippled a line extending 2.7 km towards the north-northeast where the peridotite lens appears to link up with the above-mentioned 15 m-wide exposure of a slightly talcified peridotite in the Seterbekken brook just to the west of Strådalseter. He doesn't mention any possible peridotite level in Sweden farther to the northeast. Foslie was therefore probably not aware of the ultramafite outcrops upstream in the Strådalsälven valley, even though this is the horizon that Törnebohm (1896) marked as the single serpentinite horizon extending all the way from Strådalen to Raudfjellet in the northeast on his 1:800 000-scale overview map accompanying his classical monograph.

Foslie described the main peridotite type as yellowish weathering with a coarse weathering crust. In the northernmost parts of the lens he also observed a more reddish-yellow weathering coloration in the rock without suggesting any reason for this colour change. He did, however, note that the peridotite is more strongly serpentinised towards its margins, with tremolite present in the very outer contact zone. To the southwest of the border cairn, a shallow-dipping garnet-mica schist (Seve mica schist) constitutes the footwall rock to the ultramafite, whereas an equally shallowly dipping 'quartzitic' rock (dip 15° towards NW) forms the hanging-wall to the lens. Towards the south, the peridotite terminates in what Foslie described as a "tight arc-like form". Where the Strådøla river makes a sharp bend towards the west (close to the actual frontier), Foslie encountered outcrops of gabbro on the south side of the river.

Rödknulen (Röknölen)

To the southeast of Strådalsklumpen, the next ultramafic body is a several km long lens that is folded at nearly 180°. It occurs along the inner periphery of a WSW-ENE-trending, 5 km-long klippe of Köli rocks surrounded by Seve schists. The ultramafic rocks crop out at several places along a ridge named Rödknulen (Figure 2). It should be noted that the Rödknulen lens, as shown on the Jämtland map (Strömberg et al. 1984), is not situated exactly along the Seve-Köli contact, but at a short distance up into the Köli succession. Karis and Strömberg (1998, p. 321) commented on this stratigraphic position within the Köli for at least some of the ultramafic bodies. They also recognised that "one of the most interesting characteristics concerning the Köli succession along the national frontier is that the ultramafic bodies seem to form a nearly continuous layer that probably corresponds to a specific stratigraphic level of Lower Ordovician age in the eugeoclinal succession". They were therefore clearly aware of this fact, but did not discuss it further. Kulling (1972, p. 242), in a monograph on the Scandinavian Caledonides, pointed out that although Törnebohm "gave several examples of the stratigraphy of the conglomerate- and serpentine-bearing bedrock" in these areas, "a stratigraphical sequence could not however be worked out. The serpentinite and serpentinite conglomerate occur together with amphibolite, garben schist, garnet-mica schist, greenstone conglomerate and polymict conglomerate, with pebbles of greenstone, quartzite, schist, etc.". Contrary to this statement, Foslie demonstrated that he had mapped as meticulously as possible and thereby was able to establish a detailed stratigraphy on the Norwegian side of the frontier over large areas along strike, as evident from his map-sheets 'Jævsjøen' and 'Bjørkvassklumpen'. Foslie died in 1951 before he had had time to compile his field notes into map-sheet descriptions. As far as the present authors are aware, this is the first attempt to extract extensively from Foslie's precisely recorded field observations in these areas since Chr. Oftedahl and Trygve Strand reviewed his manuscript maps before printing in the late 1950s.

Handöl

Moving south, the next ultramafic-mafic body encountered at the base of the Köli occurs some 60 km south of Strådalsklumpen in the Handöl area of Jämtland, east of Storlien (Figure 3). There, in an extensive, saucer-shaped outlier of Köli nappe rocks termed the Tännfors synform (Beckholmen 1980) (Figures 1 and 3), the 'Rödberget ultramafic-mafic Complex' consists of tectonic lenses of a variety of ultramafic rocks, metagabbros, mafic dykes

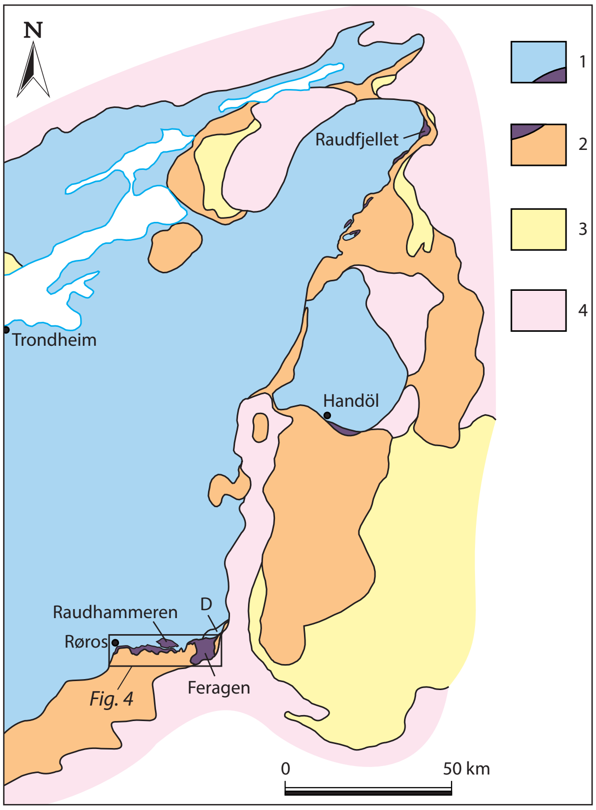

Figure 3. Tectonostratigraphic map of the eastern Trondheim Region, Tännfors synform and other allochthons in Jämtland. The colour scheme is the same as in Figure 1. The numbers in the legend refer to: 1. Köli nappes of the Upper Allochthon, with ophiolite lenses at or close to the base. 2. Seve nappes, Middle Allochthon, with serpentinite lenses close to the top. 3. Offerdal, Särv and Leksdal nappes of the Middle Allochthon. 4. Proterozoic crystalline rocks (granites and felsic volcanites) in the Lower Allochthon and tectonic windows. D – Devonian at Røragen near Feragen (see Fig. 4).

and some plagiogranites superposed tectonically upon garnet-mica schists, amphibolites and paragneisses of the upper Seve Nappe (Bergman 1993). This assemblage of igneous rocks has been interpreted as a dismembered ophiolite, and named the *Handöl ophiolite* (Gee and Sjöström 1984, Bergman 1993). The fragmented ultramafic-mafic complex is overlain, apparently conformably, by a heterogeneous succession of greenschist-facies, calcareous psammitic and pelitic rocks, some marble and conglomerate horizons, and quite numerous intrusive and extrusive rock units, termed the Bunnran Formation (Bergman 1993). The entire succession is cut by scattered metadolerite dykes.

The ultramafic components of the Rödberget Complex include foliated serpentinised dunite and, at an upper level, a 50 m-thick talc schist with a 10 m-thick mélange consisting of diverse ultramafic and mafic rock fragments in a mainly ultramafic, foliated matrix. A cumulate section (c. 400 m thick) includes metapyroxenite, metagabbro, leucogabbro and meta-anorthosite. Plagiogranite occurs sporadically within the layered cumulates and as cross-cutting dykes and concordant lenses. Full details are contained in Bergman (1993). The ophiolite and its overlying magmatosedimentary succession has been interpreted as having originated in an Andaman Sea-type oceanic basin (Bergman 1993). In terms of regional tectonostratigraphy, the ophiolite and Köli nappe rocks of the Tännfors synform were initially included in the 'Virisen terrane' by Stephens and Gee (1985) and a correlation suggested with the ultramafic and adjacent rocks of the Feragen area, near Røros (Figures 3 & 4) (see below). Subsequently, the rocks of the Tännfors synform were considered to represent a separate Köli terrane (Stephens and Gee 1989).

Feragen – Raudhammeren – Gråberget area

Ultramafic and mafic rocks comparable to those described above occur extensively to the east-southeast of the historic mining town of Røros, and are shown in simplified form in Figure 4. The largest body, at Feragen, was considered to be part of an ophiolite by Moore and Hultin (1980), and later studies have lent support to this interpretation. In this area the ophiolite is clearly duplicated by thrusting from the NNW; see also Nilsson et al. (1997). The southernmost part of the southern main row of ophiolite slices (Figure 4) consists of mantle peridotites

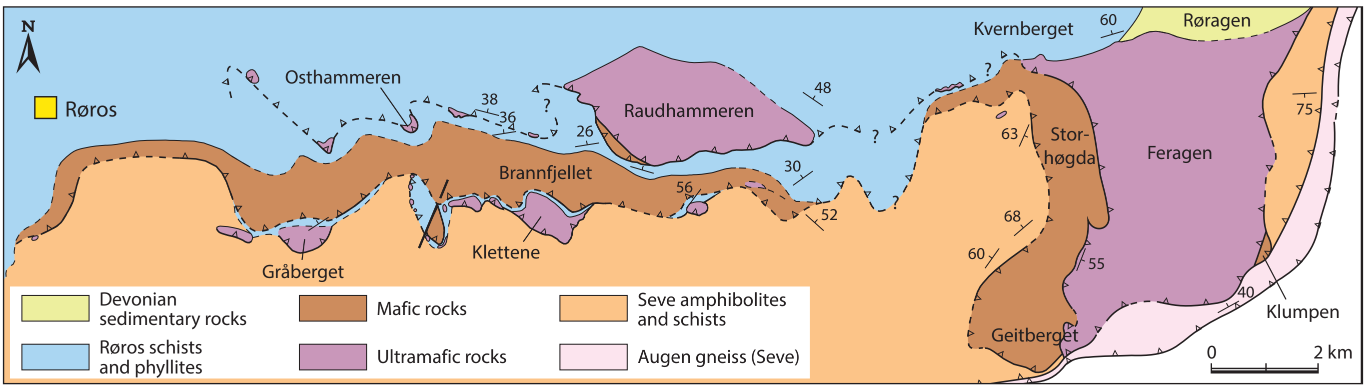

Figure 4. Simplified map of the Feragen-Raudhammeren-Røros district. Thrust contacts are shown as slightly thicker lines with small triangles on the hanging-wall side. The strike/dip symbols indicate foliation. The map is based on a manuscript map by B.A. Sturt, D.M. Ramsay and L.P. Nilsson, 1996-99, modified from Rui (1981a, b). Some data from Håbrekke (1980) and Cotkin (1983) are also used in the compilation.

of various size thrust upon Seve garnet-mica schists. These isolated peridotite bodies of very variable size are, to the north, separated from a c. 28 km-long and E-W-trending, continuous mafic body on Brannfjellet (Figure 4) by thin slivers of the well known Røros schists and phyllites which belong to the Köli succession. These low-grade metasedimentary rocks are considered to be equivalent to the Sel Group from the area near Otta, south of Dombås (Sturt et al. 1995). Directly to the north of the Brannfjellet mafic body, the Røros phyllites are overlying the ophiolite fragment across a sedimentary contact. Farther to the north, there is a second, discontinuous main row of ophiolite fragments, which here consist entirely of mantle peridotites, and are thrust-emplaced above the phyllites. These mantle peridotites are, in turn, overlain along a primary contact by the same phyllites as those occurring below the thrust plane.

Petrographically, the mantle tectonite bodies consist of peridotite (cpx-bearing harzburgite to cpx-poor lherzolite) with an equal amount of various types of dunite (everything now moderately to strongly, or even totally serpentinised). Dunites occur as fairly regularly developed layers in alternation with peridotite. This modal layering resembles the rhythmic layering observed in the lower ultramafic parts of ophiolite complexes, but is far less persistent and contains fewer repetitions. In these cases, the dunite exhibits a cumulitic texture and associated chromitite deposits are persistent semi-continuously along strike for up to several hundred metres, i.e., reminiscent of stratiform chromitite deposits. Other dunite types may include discordant or tabular bodies, branching dunite veins and possibly also some that could be characterised as "large dunite bodies" (cf. Albrektsen et al. 1988, from Leka). Furthermore, it should be emphasised that within the northwestern quarter of the 16 km^2 Feragen body the amount of dunite clearly exceeds that of mantle peridotite, leaving the impression that the peridotite is floating as rafts in a dunite host (Nilsson 1980, Cotkin 1983). In addition, especially at Raudhammeren (Fig. 4), there are also good examples of partly or totally dunitised peridotites, resembling those described from Leka (Maaløe 2005).

Feragen, Raudhammeren and the other ultramafic bodies in the Røros district, also those extending farther to the southwest, have accounted for more than 90% of Norway's total production of chromium ore. We know that the chromium ore is exclusively hosted by the dunites, but as yet nobody has investigated which types of dunite are actually hosting the chromium ore and which ones are not. The many and strongly dismembered, mantle tectonite fragments seem to have originated from different depth sections of the sub-oceanic upper mantle. The chromite composition, platinum-group element (PGE) contents and PGE distribution pattern recorded from a number of the chromitite pods and veins are indicative of such a depth difference (Nilsson 1990a, b, Nilsson et al. 1997).

The large 28 km-long Brannfjellet mafic fragment comprises the following rock types (cf. Figure 4): massive gabbros (main rock type), flaser gabbro (in Storhøgda, bordering the Feragen body to the west), gabbros with dykes and possibly also dykes in dykes (e.g., in the Brannfjellet area to the southwest of Raudhammeren where both massive and porphyritic varieties of metadolerite are present), metabasaltic lavas (e.g., in the Geitberget area to the southwest of the Feragen body), a single outcrop of actinolite-chlorite-carbonate rocks (in the northwest) and, finally, mafic tectonite plinths (e.g., in the southeastern corner of the Feragen body where the ophiolite has overridden itself and left behind this heavily recrystallised and tectonised fragment of a mafic rock at the very thrust front of the Feragen body). Here, we leave open the possibility that the actinolite-chlorite-carbonate rock (located and mapped by B.A. Sturt & D.M. Ramsay nearly twenty years ago) might perhaps represent an ultramafic lava. Regarding the tectonic slicing up of the original ophiolite, Sturt & Ramsay had clearly demonstrated that the Feragen body was overlain unconformably by the Røros (Köli) phyllites at Kvernberget to the north. In the extreme south, however, the same Feragen ultramafite displays top-WSW extensional shear-bands overprinting the mylonites at the thrust front. This reactivated tectonic contact can be traced northeastwards, linking with the Røragen Detachment (Norton 1987, Gee et al. 1994) beneath the Devonian Røragen basin (Figure 4).

Discussion

A common thread to all the above occurrences is the presence of a variety of ultramafic and mafic rocks in various, partial to advanced stages of serpentinisation, and in some cases with an overlying polymict conglomerate composed of clast and matrix material derived largely from the subjacent ultramafic-mafic complex. In three of the larger occurrences, the complexes have been interpreted and described as fragmented or dismembered ophiolites. Another significant similarity is that all the larger or smaller tectonic-lensoid occurrences occur at or very close to the base of the easternmost Köli nappe in this part of the central Scandinavian Caledonides, directly above higher-grade rock units ascribed to the Seve nappes. This suggests that we are dealing with relics of some form of oceanic basin floored by mafic to ultramafic protoliths, with the now separate occurrences having been thoroughly tectonised, stretched out and retrogressed during one or more phases of the Caledonian orogeny, including late-Scandian extension. In view of the situation at Handöl, part of the ocean basin may have been in fairly close proximity to a regional promontory or recess along a continental margin which functioned, from time to time, as a sourceland for some of the components of the overlying magmatosedimentary Bunnran Formation.

The tectonostratigraphic situation in the Feragen-Raudhammeren area (Figure 4) is comparable to that farther to the northeast, i.e., with the ultramafic-mafic bodies at or close to the base of the Köli, and with rocks of upper Seve Nappe affinity directly below. To the southwest, over a strike distance of 100 km, between Røros and Folldal, several isolated, mainly ultramafite bodies have been recorded at or close to the base of the Köli, some with overlying serpentinite conglomerate (Nilsen and Wolff 1989, Nilsson et al. 1997). Farther southwest along strike, and particularly south of Dombås, we encounter the Vågåmo ophiolite and its unconformably overlying, fossiliferous, Otta serpentinite conglomerate (Sturt et al. 1991, 1995, Harper et al. 1996, 2008) (Figure 1, left inset) and associated low-grade Köli rocks of the Sel Group (Bøe et al. 1993). This association, except for the fossils, has much in common with what we have described earlier, at Raudfjellet, Handöl and Feragen, and the Vågåmo ophiolite has, in fact, been suggested to extend northeastwards to Feragen, albeit as fragmented, solitary, ultramafic-mafic bodies (Nilsson et al. 1997). This interpretation has, however, been questioned by Andersen et al. (2012), as will be explained below.

At this point, it is relevant to mention the principal tectonostratigraphic subdivisions of the Caledonide orogen, wherein the Köli nappes are representative of the exotic, oceanic terranes of the Upper Allochthon (Roberts and Gee 1985). These thrust sheets lie directly upon the Middle Allochthon, comprising the Seve Nappe Complex (reassigned from Upper to Middle by Andréasson and Gee 2008) and other subjacent 'sandstone nappes' which once formed the continental rise of the Baltoscandian margin of Baltica. Below this, and commonly beneath tectonic slices of basement orthogneisses, are the platformal and shelf associations of the Lower Allochthon (Roberts and Gee 1985, Stephens and Gee 1989). In their contribution, Andersen et al. (2012) described a mélange unit situated between the Lower and Middle Allochthons in the Bergen area of western Norway, earlier reported by Færseth et al. (1977), Qvale (1978) and Qvale and Stigh (1985). They maintained that this unit could be followed northeastwards to the Otta-Vågå area at the very same tectonostratigraphic level, and thence even farther into the Røros district. However, there is definitely no mélange at the top of the Lower Allochthon in the tract between Otta and Røros. Solitary mafic-ultramafic bodies do occur in this district, as noted above, but only in the Köli metasedimentary rocks of the Upper Allochthon, and there are few, if any, indications of mélange development. Thus, the suggestions made by Andersen et al. (2012) for major, regional-scale correlations are misleading and must be rejected.

This is not to imply that we repudiate the observations and interpretations of Færseth et al. (1977), Qvale (1978), Andersen et al. (2012) and others from the Bergen Arcs district of West Norway. Their data and inferences from that particular area appear to be secure and acceptable, including the proposal by Andersen et al. (2012) that the Baltoscandian margin was hyperextended in latest Neoproterozoic-earliest Phanerozoic, pre-Caledonian time with the likely development of a ribbon microcontinent and small ocean basin. This concurs with earlier suggestions by, e.g., Roberts (1980), Emmett (1996), Ihlen et al. (1997), Grenne et al. (1999), Roberts et al. (2002), Rice (2005) and Hollocher et al. (2012) that at least one elongate microcontinent and adjacent seaway existed offshore of the Baltoscandian margin at this time. This elongate, narrow oceanic tract between the Baltoscandian margin and the outboard-drifting microcontinent is here named the Baltoscandic Sea (Figure 5b) – a seaway which is inferred to have widened (palaeo)westwards into the Tornquist Sea and the similarly cool-water oceanic tracts outboard of the microcontinents Ganderia and Avalonia (e.g., Cocks and Torsvik 2005).

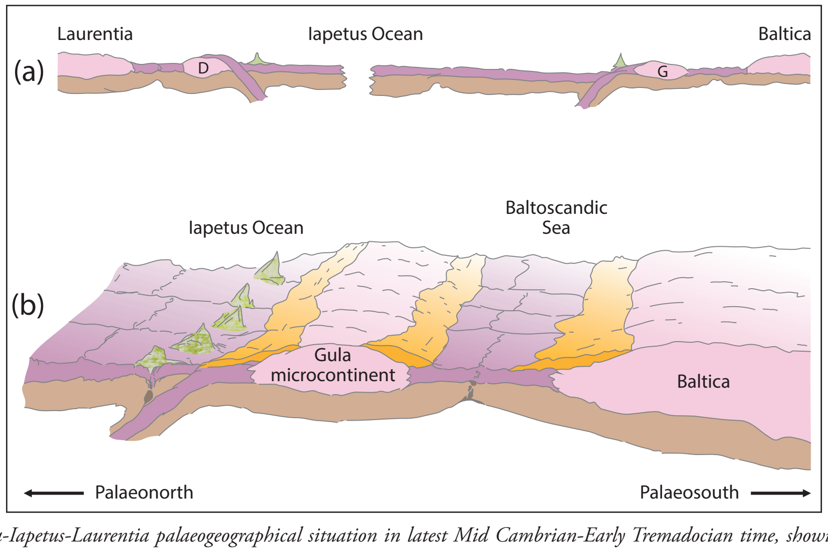

Figure 5. (a) The inferred Baltica-Iapetus-Laurentia palaeogeographical situation in latest Mid Cambrian-Early Tremadocian time, showing the Dashwoods (D) and Gula (G) microcontinents. Obduction of ophiolite on D occurred earlier (Late Furongian) than that on G (Late Tremadocian-earliest Arenig). (b) Enlargement of the Baltican side of sketch (a), also for latest Mid Cambrian-Early Tremadocian time, showing the hyperextended, cool-water Baltoscandic Sea which is inferred to have developed as a ribbon (Gula) microcontinent rifted away from Baltica and drifted rapidly northwards towards low palaeolatitudes in Early to Mid Ordovician time (to the left in the figure). See text for further explanation. Colour scheme: violet – ocean floor; brown – lithospheric mantle; green – primitive volcanic arc; yellow – sedimentary deposits; pink – continental crust.

The cartoon shown in Figure 5a depicts what we think could have been the situation close to the margins of Baltica and Laurentia during the Mid Cambrian-Tremadocian time interval. Offshore subequatorial Laurentia, a microcontinent (named Dashwoods) had drifted away from the mainland creating a narrow (Humber) seaway in its wake (Waldron and van Staal 2001). This is not unlike the interpreted situation for Baltica, with the extensionally generated, cool-water, Baltoscandic Sea and Gula ribbon microcontinent (Figure 5b). One difference is that initial oceanic contraction and ophiolite obduction upon the Dashwoods block occurred c. 10 mill. yrs. earlier (Late Furongian) than in the case of the western Trondheim Region ophiolites (see below).

As closure of the Iapetus Ocean progressed and accelerated, involving a rapid anticlockwise rotation of Baltica (Cocks and Torsvik 2005, Torsvik and Cocks 2014), the Gula microcontinent with its cargo of fragmented ophiolite and primitive arc rocks drifted fairly quickly northwards into warmer, subequatorial waters, soon accumulating sedimentary successions with diverse genera of Laurentian fossils. A mature island arc developed in Mid Ordovician time, concurrent with renewed seaward subduction close to Laurentia, as described in Grenne and Roberts (1998) and depicted in Hollocher et al. (2012). Seaward subduction also occurred at this time immediately offshore Baltica, generating the Mid to Late Ordovician, ultrahigh-pressure rocks in what is now the middle Seve Nappe (Brueckner and Van Roermund 2004, Brueckner et al. 2004, Root and Corfu 2012, Majka et al. 2014; see below).

The age of the fragmented and disjointed ophiolite extending from Raudfjellet to Feragen/Raudhammeren is, as yet, unknown. Felsic rocks amenable to U-Pb dating are unfortunately rare or lacking, and even the plagiogranite near Handöl proved to be devoid of zircons (S. Bergman, pers. comm.). A lack of fossils in the unconformably overlying successions also precludes any suggestion of a minimum age constraint. However, accepting the earlier suggestion of a possible link between the Feragen-Raudhammeren complex and the Vågåmo ophiolite, then an upper age constraint would be provided by the Late Arenig to Llanvirn faunas in the matrix of the Otta conglomerate (Bruton and Harper 1981, Harper et al. 2008), at the base of the Sel Group overlying the ophiolite. This would, in turn, suggest that the Raudfjellet-Handöl-Feragen ocean-floor rocks could well be of latest Mid Cambrian to Early Tremadocian age, as with most of the fragmented ophiolites in the western Trondheim Region and on Leka (Dunning and Pedersen 1988, Roberts et al. 2002, Slagstad et al. 2014). Nonetheless, we should await future developments on the geochronology front and, for the moment, regard the above as just a reasonable speculation.

In terms of palaeogeographical setting, a possible equivalence in age between the ophiolitic rocks along the Trøndelag-Jämtland border and those in the western Trondheim Region does not imply that they have the same magmatic ancestry. On the contrary, the Løkken, Støren, Bymarka, Vassfjellet and associated ophiolite fragments are suprasubduction-zone complexes with a significant primitive volcanic-arc involvement (Grenne 1989, Roberts et al. 2002, Slagstad 2003, Hollocher et al. 2012, Slagstad et al. 2014), and have been interpreted to have developed close to, and been obducted onto, the outboard side of the 'Gula microcontinent' (cf. Roberts et al. 2002, figure 8, Hollocher et al. 2012, figure 21) (Figure 5b). The Raudfjellet-Feragen tract of ophiolitic rocks, on the other hand, represents products from the (hyper)extending Baltoscandic Sea floor, between the microcontinent and the Baltoscandian passive margin of Baltica (Figure 5b), without any subduction component or trace of arc magmatism at this point in time. The volcanic arc component appeared just a little later, concurrent with palaeo-northward subduction as the seaway contracted, during accumulation of the Middle Ordovician successions in the several Köli nappes in this part of the Caledonides.

Following from the above, it is interesting that the abundant amphibolites in the subjacent upper Seve nappes have fairly consistent geochemical signatures indicative of MORB settings, also with hardly any trace of volcanic arc involvement (Solyom et al. 1979, Stephens et al. 1985, D.Roberts, unpubl. data). In these cases, the protolith basalts to the upper Seve amphibolites, interlayered with schists and psammites with sporadic lenses of serpentinised ultramafites, were also most likely extruded on the floor of the Baltoscandic Sea, and probably in the palaeo-southern part of the seaway. As a result of the seaward subduction, the upper Seve amphibolites were metamorphosed at amphibolite-facies conditions, which contrasts with the subjacent ultrahigh-pressure rocks of the middle Seve Nappe with their Mid to Late Ordovician eclogites (Brueckner and van Roermund 2004, Brueckner et al. 2004, Root and Corfu 2012) and even microdiamonds (Majka et al. 2014). The Raudfjellet-Handöl-Feragen tract of ocean-floor rocks above the Seve, on the other hand, were metamorphosed at comparatively shallow depths at only greenschist- to lower amphibolite-facies conditions (Bergman 2007).

Conclusions

The border area between Norway and Sweden in the counties of Nord-Trøndelag and Jämtland, south of the Grong-Olden Culmination, has long been known to expose large or smaller bodies of ultramafic-mafic rock complexes (e.g. Kjerulf 1871, Törnebohm 1896). Some, such as those at Raudfjellet and near Handöl, have subsequently been investigated quite thoroughly and described as fragmented ophiolites (Bergman 1993, Nilsson et al. 2005, 2014). A few others are indicated on old map-sheets, without ever having been described. In this contribution we provide initial descriptions of several of the smaller ultramafic-mafic lensoid bodies, based partly on personal field observations, but also by extracting relevant data from the comprehensive field notebooks from the 1930s by the late Steinar Foslie.

Most of these lensoid bodies consist of partially or wholly serpentinised ultramafic rocks, largely mantle peridotite, with gabbro above. Several are overlain unconformably by conglomerate dominated by boulders, cobbles and pebbles of the subjacent ultramafic and mafic rocks. The lensoid bodies occur either at the very base of the low-grade Köli nappe (structurally directly above high-grade amphibolites and schists of the Seve Nappe) or as tectonic imbricates just above, within the Köli. This structural situation is the same as for the Raudfjellet and Handöl ophiolites, and the smaller detached lenses which we have described in this contribution are considered to represent the lower sections of a once continuous ophiolite. Farther south, the same situation obtains in the Feragen-Raudhammeren area near Røros. There, mantle peridotites with dunite and chromitite deposits prevail, especially at Feragen, with Seve rocks in the footwall, but there is also a gabbro-dominated imbricate slice above, within low-grade Köli rocks, locally with mafic dykes cutting the gabbros, and also in places with metabasalts.

Although isotopic dating is lacking, we speculate that the Raudfjellet-to-Feragen ophiolite may be of Mid Cambrian to Early Tremadocian age, as with the larger bodies of ophiolite in the western Trondheim Region and on Leka. However, the magmatic origins of these two groups of ophiolites are quite different. The 'western' ophiolite fragments are suprasubduction-zone complexes with involvement of primitive volcanic arcs (Grenne 1989, Roberts et al. 2002, Slagstad et al. 2014), inferred by some workers to have been emplaced on the outboard side of a microcontinent named 'Gula' in Early Arenig time (Roberts et al. 2002, Hollocher et al. 2012). On the contrary, the 'eastern' lensoid fragments discussed above are considered to have formed part of the ocean floor (and subjacent mantle) of a (hyper)extending seaway (the Baltoscandic Sea) that developed between the microcontinent and the Baltoscandian passive margin of Baltica in Mid to Late Cambrian time. Protolith basalts to the Seve amphibolites are also suggested to have been generated on the floor of this seaway. Subsequent seaward subduction, in Mid Ordovician time, led to slicing up of the seafloor and adjacent continental margin successions, with some units (e.g., middle Seve) subducted down to depths commensurate with metamorphism at eclogite-facies conditions.

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References

Albrektsen, B.A., Furnes, H. and Pedersen, R.B. (1991) Formation of dunites in mantle tectonites, Leka Ophiolite Complex, Norway. *Journal of Geodynamics*, **13**, 205 – 220.

Andersen, T.B., Corfu, F., Labrousse, L. and Osmundsen, P.T. (2012) Evidence for hyperextension along the pre-Caledonian margin of Baltica. *Journal of the Geological Society, London*, 169, 601-612.

Andréasson, P.G. and Gee, D.G. (2008) The Baltica-Iapetus boundary in the Scandinavian Caledonides and a revision of the Middle and Upper Allochthons. (Abstract) *33rd International Geological Congress, Oslo, Norway, Session EUR-06*.

Beckholmen, M. (1980) Geology of the Nordhallen-Duved-greningen area in Jämtland, central Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar*, **100**, 335-347.

Bergman, S. (1993) Geology and geochemistry of mafic-ultramafic rocks (Köli) in the Handöl area, central Scandinavian Caledonides. *Norsk Geologisk Tidsskrift,* **73**, 21-42.

Bergman, S. (2007) P-T paths in the Handöl area, central Scandinavia: record of Caledonian accretion of outboard rocks to the Balto-scandian margin. *Journal of Metamorphic Geology*, **5**, 265-281.

Bergman, S., Stephens, M.B., Andersson, J., Kathol, B. and Bergman, T. (2012) Bedrock map of Sweden, scale 1:1 million. *Sveriges geologiska undersökning K 423*.

Brueckner, H.K. and van Roermund, H.L.M. (2004) Dunk tectonics: a multiple subduction/eduction model for the evolution of the Scandinavian Caledonides. *Tectonics*, **23**, TC2004, doi:10.1029/2003TC001502.

Brueckner, H.K., van Roermund, H.L.M. and Pearson, M. (2004) An Archean(?) to Paleozoic evolution for a garnet peridotite lens with sub-Baltic Shield affinity within the Seve Nappe Complex of Jämtland, Sweden, central Scandinavian Caledonides. *Journal of Petrology*, **45**, 415-437.

Bruton, D.L. and Harper, D.A.T. (1981) Brachiopods and trilobites of the Early Ordovician serpentine Otta Conglomerate, south central Norway. *Norsk Geologisk Tidsskrift*, **61**, 151-181.

Bøe, R., Sturt, B.A. and Ramsay, D.M. (1993) The conglomerates of the Sel Group, Otta- Vågå area, Central Norway: an example of a terrane-linking succession. *Norges geologiske undersøkelse*, **425**, 1-24.

Cocks, L.R.M and Torsvik, T.H. 2005: Baltica from the late Precambian to Mid Palaeozoic times: the gain and loss of a terrane's identity. *Earth-Science Reviews*, **72**, 39-66.

Cotkin, S.J. (1983) *The petrogenesis and structural geology of the Feragen peridotite and associated rocks, Sør-Trøndelag, East-central Norway*. Unpubl. M.Sc. thesis, University of Wisconsin, Madison. 180 pp + map.

Dunning, G.R. and Pedersen, R.B. (1988) U-Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: implications for the development of Iapetus. *Contributions to Mineralogy and Petrology*, **98**, 13-23.

Emmett, T. F. (1996) The provenance of pre-Scandian continental flakes within the Caledonide orogen of south-central Norway. *In:* Brewer, T.S. (ed.) *Precambrian crustal evolution in the North Atlantic Region*. Geological Society, London, Special Publication, 112, 359-366.

Foslie, S. (1959a) Geologisk kart JÆVSJØEN (Rektangel 51C), M 1:100 000. *Norges geologiske undersøkelse*.

Foslie, S. (1959): Geologisk kart BJØRKVASKLUMPEN (Rektangel 51A), M 1:100 000. *Norges geologiske undersøkelse*.

Færseth, R.B., Thon, A., Larsen, S.G., Sivertsen, A. and Elvestad, L. (1977) Geology of the Lower Palaeozoic rocks in the Samnanger-Osterøy area, major Bergen Arc, western Norway. *Norges geologiske undersøkelse*, **334**, 19-58.

Gee, D.G. and Sjöström, H. (1984) Early Caledonian obduction of the Handöl ophiolite. (Abstract) *Meddelanden från Stockholms Universitets Geologiska Institutionen*, **255**, 72.

Gee, D.G., Lobkowicz, M. and Singh, S. (1994) Late Caledonian extension in the Scandinavian Caledonides – the Røragen Detachment revisited. *Tectonophysics*, **231**, 139-155.

Gee, D.G., Janák, M., Majka, J., Robinson, P. and van Roermund, H.(201): Subduction along and within the Baltoscandian margin during closing of the Iapetus Ocean and Baltica-Laurentia collision. *Lithosphere*, **5**, 169-178.

Grenne, T. (1989) Magmatic evolution of the Løkken SSZ Ophiolite, Norwegian Caledonides: relationships between anomalous lavas and high-level intrusions. *Geological Journal*, **24**, 251-274.

Grenne, T., Ihlen, P. and Vokes, F.M. (1999) Scandinavian Caledonide metallogeny in a plate tectonic perspective. *Mineralium Deposita,* **34**, 422-471.

Harper, D.A.T., Mac Niocaill, C. and Williams, S.H. (1996) The palaeogeography of early Ordovician Iapetus terranes: an integration of faunal and palaeomagnetic constraints. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **121**, 297-312.

Harper, D.A.T., Bruton, D.L. and Rasmussen, C.M.Ø. (2008) The Otta brachiopod and trilobite fauna: palaeogeography of Early Palaeozoic terranes and biotas across Baltoscandia. *Fossils and Strata*, **54**, 31-40.

Hollocher, K., Robinson, P., Walsh, E. and Roberts, D. (2012) Geochemistry of amphibolites-facies volcanic and gabbros of the Støren Nappe in extensions west and southwest of Trondheim, Western Gneiss Region, Norway: a key to correlations and paleotectonic settings. *American Journal of Science*, **312**, 357-416.

Håbrekke, H. (1980) Magnetiske, elektromagnetiske- og radiometriske målinger fra helikopter over Feragen, Røros. *Norges geologiske undersøkelse Rapport*, **1750/33C**, 11 pp + 11 map enclosures.

Ihlen, P.M., Grenne, T. and Vokes, F.M. (1997) The metallogenic evolution of the Scandinavian Caledonides. Transactions of the Institute of Mining & Metallurgy, Section B, 106, 194-203.

Karis, L. and Strömberg, A.G.B. (1998) Beskrivning til berggrundkartan over Jämtlands län, Del 2: Fjälldelen. *Sveriges geologiska undersökning*, Ca 53:2, 363 pp.

Kjerulf, T. (1871) Om Trondhjem Stifts geologi. Nyt Magazin for Naturvidenskabene, **18**, 79 pp.

Kulling, O. (1972) The Swedish Caledonides. *In*: Strand, T. & Kulling, O. *Scandinavian Caledonides*. Wiley-Interscience, 151-302.

Majka, J., Rosén, Å., Janák, M., Froitzheim, N., Klonowska, I., Manecki, M., Sasinkova, V. and Yoshida, K. (2014) Microdiamond discovered in the Seve Nappe (Scandinavian Caledonides) and its exhumation by the 'vacuum cleaner' mechanism. *Geology*, **42**, 1107-1110.

Moore, A.C. and Hultin, I. (1980) Petrology, mineralogy and origin of the Feragen ultramafic body, Sør-Trøndelag, Norway. *Norsk Geologisk Tidsskrift*, **60**, 235-254.

Maaløe, S, (2005) The dunite bodies, websterite and orthopyroenite dikes of the Leka ophiolite complex, Norway. *Mineralogy and Petrology*, **85**, 163-204.

Nilsen, O. and Wolff, F.C. (1989) Geologisk kart over Norge, berggrunnskart RØROS & SVEG – 1:250 000. *Norges geologiske undersøkelse.*

Nilsson, L.P. (1980) Undersøkelse av ultramafiske bergarter og krommalm på strekningen Røros-Feragen, Sør-Trøndelag. *Norges geologiske undersøkelse Rapport*, **1650/33A**, 100 pp + 3 map enclosures.

Nilsson, L.P. (1990a) Platinum-group mineral inclusions in chromitite from the Osthammeren ultramafic tectonite body, south central Norway, *Mineralogy and Petrology*, **42**, 249-263.

Nilsson, L.P. (1990b) Platinum-group mineral inclusions in chromitite from the Osthammeren ultramafic tectonite body; south central Norway. *In*: Boyd, R. et al., *NTNF project no. MB10.20346 Geochemistry of platinum metals in ophiolites in Norway, Final report*, Norges geologiske undersøkelse Report, 90.065, 44 +220 pages, 32-92.

Nilsson, L.P. (2003) Befaring av nyoppdaget klebersteinsforekomst ved Langvasselva i Snåsa. *Norges geologiske undersøkelse Rapport,* 2003.083, 12 pages.

Nilsson, L.P., Sturt, B.A. and Ramsay, D.M. (1997) Ophiolitic ultramafites in the Folldal-Røros tract, and their Cr-(PGE) mineralisation. (extended abstract) *Norges geologiske undersøkelse Bulletin*, **433**, 10-11.

Nilsson, L.P., Roberts, D. and Ramsay, D.M. (2005) The Raudfjellet ophiolite fragment, Central Norwegian Caledonides: principal lithological and structural features. *Norges geologiske undersøkelse Bulletin*, **445**, 101-117.

Nilsson, L.P., Kero, L., Johansson, R. and Roberts, D. (2014) Geophysical expression of the Raudfjellet ophiolite, Nord-Trøndelag, central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin*, **453**, 13-27.

Norton, M.G. (1987) The Nordfjord-Sogn Detachment, W. Norway. *Norsk Geologisk Tidsskrift*, **67**, 93-106.

Qvale, H. (1978) *Geologisk undersøkelse av et kaledonsk serpentinittfelt ved Baldersheim, Hordaland*. Unpubl. Cand. real. thesis, Univ. of Oslo, 252 pp.

Qvale, H. and Stigh, J. (1985) Ultramafic rocks in the Scandinavian Caledonides. *In* Gee, D.G. and Sturt, B.A. (eds.) *The*

Caledonide orogen – Scandinavia and related areas. John Wiley & Sons, Chichester, 693-715.

Reinsbakken, A. and Fossen, H. (1988) MURUSJØEN berggrunnskart 1923 I, 1: 50 000, foreløpig utgave. *Norges geologiske undersøkelse.*

Rice, A.H.N. (2005) Quantifying the exhumation of UHP-rocks in the Western Gneiss Region, S.W. Norway: a branch-line – balanced cross-section model. *Austrian Journal of Earth Sciences*, **98**, 2-21.

Roberts, D. (1980) Petrochemistry and palaeogeographic setting of Ordovician volcanic rocks of Smøla, Central Norway. *Norges geologiske undersøkelse*, **359**, 43-60.

Roberts, D. (1997) Geologisk kart over Norge. Berggrunnsgeologisk kart GRONG, M 1:25 0000. *Norges geologiske undersøkelse.*

Roberts, D. and Gee, D.G. (1985) An introduction to the structure of the Scandinavian Caledonides. *In*: Gee, D.G. and Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas*. John Wiley & Sons, Chichester, 55-68.

Roberts, D., Walker, N., Slagstad, T., Solli, A. and Krill, A. (2002) U-Pb zircon ages from the Bymarka ophiolite, near Trondheim, Central Norwegian Caledonides, and regional implications. *Norsk Geologisk Tidsskrift*, **82**, 19-30

Root, D. and Corfu, F. (2012) U-Pb geochronology of two discrete Ordovician high-pressure metamorphic events in the Seve Nappe Complex, Scandinavian Caledonides. *Contributions to Mineralogy and Petrology*, **163**, 769-788.

Rui, I. (1981a) RØROS, berggrunnsgeologisk kart 1720 II – M 1:50 000. *Norges geologiske undersøkelse*.

Rui, I. (1981b) BREKKEN, berggrunnsgeologisk kart 1720 III – M 1:50 000. *Norges geologiske undersøkelse*.

Sjöström, H. and Bergman, S. (1989) Asymmetric extension and Devonian(?) normal faulting: examples from the Caledonides of eastern Trøndelag and western Jämtland. (Extended abstract) *Geologiska Föreningens i Stockholm Förhandlingar*, **111**, 407-410.

Sjöström, H. and Roberts, D. (1992) Gjevsjøen, berggrunnskart 1823-2, 1:50 000, foreløpig utgave, *Norges geologiske undersøkelse*.

Sjöström, H. and Roberts, D. (2013) Gjevsjøen, berggrunnskart 1823-2, 1:50 000, revidert utgave; digitalt fargeplott. *Norges geologiske undersøkelse.*

Slagstad, T. (2003) Geochemistry of trondhjemites and mafic rocks in the Bymarka ophiolite fragment, Trondheim, Norway: petrogenesis and tectonic implications. *Norwegian Journal of Geology*, **83**, 167-185.

Slagstad, T., Pin, C., Roberts, D., Kirkland, C.L., Grenne, T., Dunning, G., Sauer, S. and Andersen, T. (2014) Tectonomagmatic evolution of the Early Ordovician suprasubduction-zone ophiolites of the Trondheim Region, Mid-Norwegian Caledonides. *Geological Society, London, Special Publication*, **390**, 541-561.

Solyom, Z., Andreasson, P.G. and Johansson, I. (1979) Geochemistry of amphibolites from Mt. Sylarna, Central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar*, **101**, 17-27.

Stephens, M.B., Furnes, H., Robins, B. and Sturt, B.A. (1985) Igneous activity within the Scandinavian Caledonides. *In:* Gee, D.G. and Sturt, B.A. (eds.) *The Caledonide orogen – Scandinavia and related areas*. John Wiley & Sons, Chichester, 623-656.

Stephens, M.B. and Gee, D.G. (1989) Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America Special Paper*, **230**, 17-30.

Stigh, J. (1979) *Ultramafites and detrital serpentinites in the central and southern parts of the Caledonian allochthon in Scandinavia*. Ph.D. thesis, Dept. of Geology, Chalmers Inst. of Technology, Göteborg, Publ. A27, 222 pp.

Strömberg, A.G.B., Karis, L., Zachrisson, E., Sjöstrand, T. and Skoglund, R. (1984) Karta over berggrunden i Jämtlands län utom förutvarande Fjällsjö k:n, M 1:200 000. *Sveriges geologiska undersökning*.

Sturt, B. A., Ramsay, D.M. and Neuman, R.B. (1991) The Otta conglomerate, the Vågåmo ophiolite – further indications of Early Ordovician orogenesis in the Scandinavian Caledonides. *Norsk Geologisk Tidsskrift*, **71**, 107-115.

Sturt, B.A., Bøe, R., Ramsay, D.M. and Bjerkgård, T. (1995) Stratigraphy of the Otta-Vågå tract and regional stratigraphic implications. (extended abstract) *Norges geologiske undersøkelse Bulletin*, **427**, 25-28.

Torsvik, T.H. and Cocks, L.R.M. (2014) New global palaeogeographical reconstructions for the Early Palaeozoic and their generation. *Geological Society, London, Memoirs*, **38**, 2-24.

Törnebohm, T.E. (1896) Grunddragen af det central Skandinaviens bergbyggnad. *Kongliga Svenska Vetenskaps-Akademiens Handlingar*, **28** (5), 212 pp.

Waldron, J.W.F. and van Staal, C.R. (2001) Taconian orogeny and the accretion of the Dashwoods block: a peri-Laurentian microcontinent in the Iapetus Ocean. *Geology*, **29**, 811-814.

Wolff, F.C. (1977) Geologisk kart over Norge, berggrunnskart ØSTERSUND 1:250 000, *Norges geologiske undersøkelse*.