The Raudfjellet ophiolite fragment, Central Norwegian Caledonides: principal lithological and structural features

LARS PETTER NILSSON, DAVID ROBERTS & DONALD M.RAMSAY

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

The Raudfjellet complex, Nord-Trøndelag, displays several of the features of a classical ophiolite pseudostratigraphy. At its base is a spectacular ultramafite mylonite. Elements represented include: (1) Ultramafic rocks, mostly dunite with minor harzburgitic and websteritic intrusions as well as sporadic dunite-chromitite cumulates. The dunite is interpreted to represent a single large body of *cumulate* dunite formed between the petrological and seismic Mohos. (2) A mafic unit consisting mostly of mafic cumulates and massive metagabbro, with alternating mafic and ultramafic cumulates near the base. (3) Possible dolerite dykes, in the upper part of the mafic block, with sheeted dykes observed in one small area. No tonalitic differentiates or basaltic lavas have been found at Raudfjellet. An unusual, hydrothermal alteration zone, up to 60 m thick, occurs at the interface between the ultramafic and mafic blocks. This zone consists of talc and listwaenite (magnesite-quartz rock). The ophiolite complex is unconformably overlain by a polymict conglomerate consisting mostly of mafic and ultramafic detritus.
The basal part of the ophiolite complex is a 150 m-thick zone of ultramafic mylonites and ultramylonites with a WNW-ESE-trending mineral/stretching lineation. The olivine + pyroxene paragenesis of the mylonites is interpreted to relate to the original, high-T obduction upon rocks of the Skjøtingen (Seve) Nappe. Although, at present, there are no faunal or isotopic age constraints, based on regional correlations for the eastern Trondheim Region and into the Otta-Vågåmo district south of Dombås, it is argued that the Raudfjellet ophiolite is likely to be of Cambrian to earliest Ordovician age, and its obduction Early Ordovician. Subsequently, the complex and adjacent units were involved in the Siluro-Devonian Scandian orogeny and its ensuing extensional deformation.

Lars Petter Nilsson and David Roberts, Norges geologiske undersøkelse, N-7491 Trondheim, Norway.
Donald Ramsay, 27 Marlee Road, Dundee DD5 3EY, Scotland, UK.

Introduction

Over the past three decades, ophiolite complexes in a variety of dismembered and fragmented forms have been found to constitute an important element in the tectonostratigraphic architecture of the Scandinavian Caledonides. Central Norway, and the Trondheim Region in particular, has featured in the forefront of ophiolite recognition (Gale & Roberts 1972, 1974, Prestvik 1974). These remnants of Early Palaeozoic ocean floor are, by and large, restricted to the Köli Nappes of the Upper Allochthon (Roberts & Gee 1985), which themselves form parts of the exotic Iapetus Ocean and island arc terranes deriving from outboard of the Baltoscandian margin of the palaeoplate Baltica.

In more recent years, other fragmented ophiolitic assemblages have been reported from this same part of Norway (Grenne et al. 1980, Prestvik 1980, Heim et al. 1987, Grenne 1989, Slagstad 1998, Roberts et al. 2002); and also from the Otta-Vågåmo-Østerdal area just south of the Trondheim Region (Sturt et al. 1991). In the northernmost part of the Trondheim Region, a mafic-ultramafic complex of suggested ophiolitic origin has also been reported, from Raudfjellet, close to the Swedish border (Sjöström & Roberts 1992, Roberts 1997) (Fig. 1). In 1999, a collaborative project was set up between NGU and Statskog to investigate the potential mineral resources within an approved extension of the existing Gressåmoen National Park. Dealing specifically with investigations of ophiolitic and related serpentinitic rocks, a major part of the fieldwork involved remapping and studying the talc potential in and around the Raudfjellet complex. This study, which was continued by the first author in 2000, also involved helicopter-supported visits to other ultramafite bodies in this part of Nord-Trøndelag county.

The purpose of this contribution is to present a preliminary account of the geology and structural deformation of the Raudfjellet complex, with a brief discussion of its inferred tectonic setting. The description also serves as a general introduction to a forthcoming companion paper which deals specifically with an unusually well developed, hydrothermally altered zone – and generation of the uncommon rock-type, listwaenite – along the ultramafite-gabbro interface (Nilsson et al., in prep.).

Geological setting

This part of Trøndelag, south of the Grong-Olden Culmination of Mesoproterozoic granitoid rocks, exposes most of the principal members of Caledonide tectonostratigraphy, although not all are continuously exposed. The

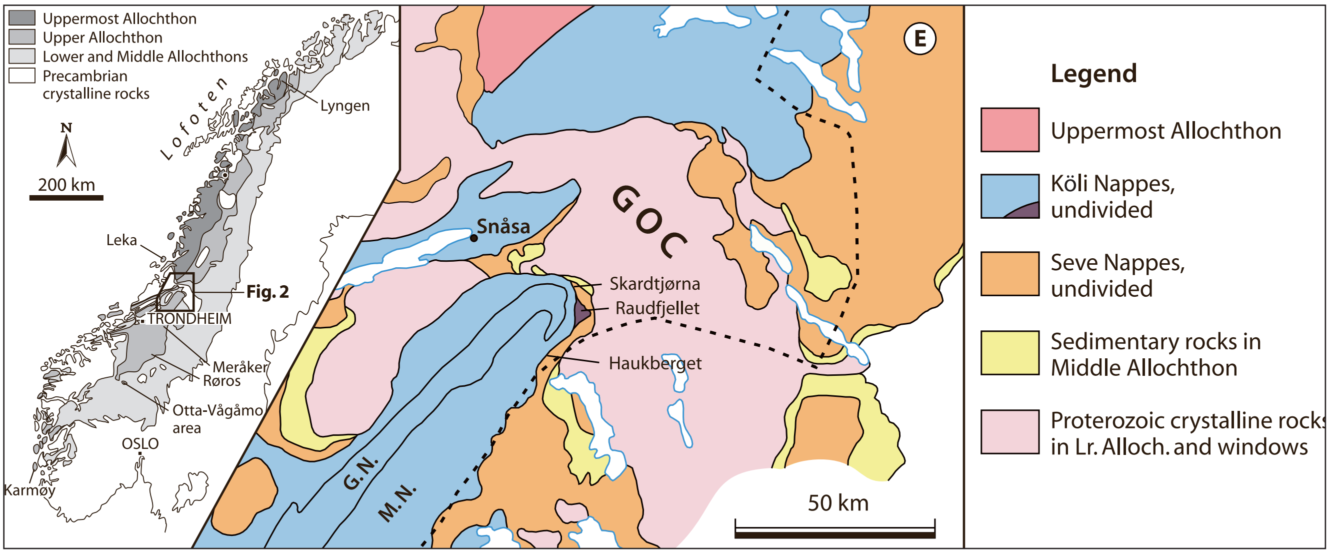

Fig. 1. Simplified tectonostratigraphic map of the region in the vicinity of Raudfjellet. E – eclogite locality ('middle nappe') in the Seve Nappes; GOC – Grong-Olden Culmination; G.N. – Gula Nappe; M.N. – Meråker Nappe.

Precambrian basement rocks and their thin, low-grade sedimentary cover together form the Olden Nappe (Asklund 1938), and these units are tectonically repeated, though more strongly reworked by Caledonian deformation, in the overlying Formofoss Nappe Complex. These Lower Allochthon rocks are succeeded by scattered, lensoid remains of the Offerdal and Leksdal (=Särv) Nappes of the Middle Allochthon (Fig. 1). These 'sandstone nappes' are significant in their separate ways; the Offerdal as a source of most of the commercially exploited flagstone, or 'skifer', of this region, and the Leksdal for its characteristic and locally abundant metadolerite dykes.

Thereafter follow the amphibolite-facies schists, psammites, amphibolites and gneisses of the Skjøtingen (=Seve) Nappe, the basal part of the Upper Allochthon. Northeast of the Grong-Olden Culmination, in Jämtland, Sweden, some thrust sheets within the middle part of the Seve consist of high-pressure, eclogite-facies rocks (Van Roermund & Bakker 1984, Van Roermund 1989) (Fig. 1), pyroxenite layers from which have yielded overlapping Sm-Nd mineral isochron ages of c. 450 Ma (Brueckner et al. 2004, Brueckner & Van Roermund 2004). The Seve Nappe in Nord-Trøndelag lacks eclogites and is succeeded by the generally lower grade, Ordo-Silurian, volcanosedimentary Köli assemblages of the Meråker Nappe (Wolff 1979) (Fig. 1), also known informally as the 'Meråker Belt'.

The mafic-ultramafic complex at Raudfjellet, covering an area of c. 9 km^2, was first registered over a century ago, under the terms greenstone and serpentinite (Törneböhm 1896). Later, Foslie (1959) distinguished between peridotite, pyroxenite and gabbro. Kautsky (1977) considered the complex to be a part of the Seve Nappe, but in a subsequent remapping (by S. Bergman and H. Sjöström) it was interpreted to lie tectonically above the high-grade Seve rocks and form a basal part of the Meråker Nappe (Sjöström & Roberts 1992). At that time, although the Raudfjellet complex had not been interpreted as definitely ophiolitic, this possibility had been discussed by the above authors during the compilation of the 1:50,000 map-sheet 'Gjevsjøen'; and its placement at the base of the lithostratigraphy of the Meråker Nappe indirectly favoured such an interpretation. During the map-compilatory work, an alternative solution, in fact, had been to give the Raudfjellet complex a transitional status – a thrust unit sandwiched between footwall Seve rocks and unconformably overlying Köli metasediments. In a later 1:250,000 map compilation, the ophiolite interpretation was finally adopted (Roberts 1997).

An important observation by Sjöström & Bergman (1989) was the discovery of a polymict conglomerate lying directly above the Raudfjellet complex (Fig. 2). Initially, this was thought, by these authors, to relate to Devonian faulting, but after an assessment of the overall situation the conglomerate was regarded as forming the very basal part of the Ordovician succession of the Meråker Nappe (Sjöström & Roberts 1992). The conglomerate is succeeded by a formation consisting of diverse low-grade, calc-phyllites, graphite schists and volcaniclastic greenschists.

The Raudfjellet ophiolite fragment is lying with thrust contact, albeit modified by later extensional structures, upon the amphibolite-facies rocks of the Skjøtingen (Seve) Nappe (Fig. 2). In this respect, the Raudfjellet ophiolite is located at a lower tectonostratigraphic level than is the case for the ophiolites occurring in the western parts of the Trondheim Region. There, the ophiolites lie tectonically above epicontinental and immature arc rocks of the Gula Nappe (Gale & Roberts 1974, Sturt & Roberts 1991), an obduction that also invoved mélange development in one particular case (Horne 1979). The timing of ophiolite emplacement is constrained to Mid Arenig at the latest, by the occurrence of abundant fossils in the unconformably

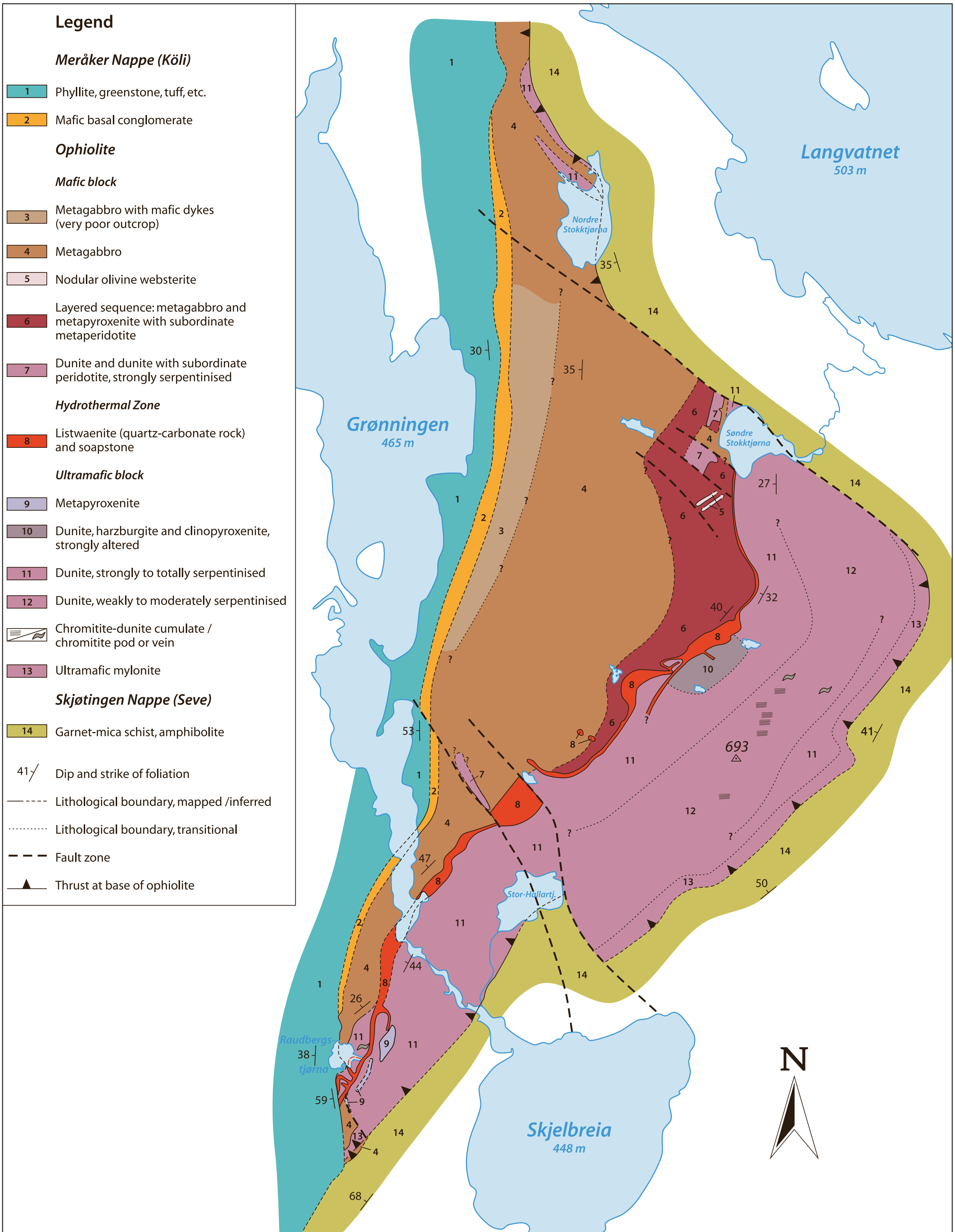

Fig. 2. Geological map of the Raudfjellet ophiolite, modified from Nilsson et al. (2002).

overlying sedimentary succession. In the case of the Raudfjellet ophiolite, in view of the total lack of isotopic dating and absence of fossils in this area, it is impossible, as yet, to say precisely at what time the ophiolite was obducted. It is argued below (p.112), however, that obduction is likely to have occurred in Early Ordovician time.

Raudfjellet ophiolite

Pseudostratigraphy

The Raudfjellet complex comprises a partly dismembered ophiolite fragment, consisting of two main parts or blocks (Fig. 2) — an especially well preserved, ultramafic lower part, overlain by a fairly massive, layered metagabbro (Fig. 3). Dolerite dykes are present in the upper parts of the gabbro, with sheeted dykes observed only in one small area. Basaltic lavas have not been identified. A polymict conglomerate consisting mostly of locally derived, mafic and ultramafic detritus lies unconformably above the ophiolite. A spectacular ultramafite mylonite is present at the very base of the complex in the east, against the subjacent high-grade rocks of the Seve Nappe. Partly because of the presence of a widespread Quaternary cover, but also due to deep erosion prior to deposition of the overlying conglomerate, the higher levels of the ophiolite pseudostratigraphy are either poorly represented or absent.

Ultramafic rocks

The base of the Raudfjellet complex is marked by a thick (c. 150 m) zone of ultramafic mylonites (Fig. 4). At the very base there are lenses of somewhat glassy, dark green ultramylonites (Fig. 5). These tectonites would appear to represent the original, high-T, obduction-related mylonites, as the main mineralogy comprises olivine and pyroxene (conclusions from a detailed study undertaken by B.A.Sturt & D.M.Ramsay in 1999). Variably deformed veins of olivine also cut the mylonitic banding. The ultramafic mylonite rests on a relatively thin amphibolite-facies mylonite, locally a blastomylonite, developed from the high amphibolite-facies paragneisses, psammites and pegmatites of the subjacent Seve Nappe. The mylonites are variably retrogressed to greenschist-facies assemblages, though much of this retrogression was static. However, there is plenty of evidence of greenschist-facies extensional reworking, particularly near the base of the ultramafic mylonite.

The mylonites pass relatively abruptly into massive ultramafites containing scattered, anastomosing, shear zones with a mylonitic fabric. The ultramafic rocks comprise a single, large, dunite body, up to c. 500 m in thickness and covering an area of c. 3 km^2, which, by far, makes up most of the ultramafic block of the Raudfjellet ophiolite (Fig. 2). The big dunite body reaches to the very top of the ultramafic block towards the northwest. At just one place, within a small and

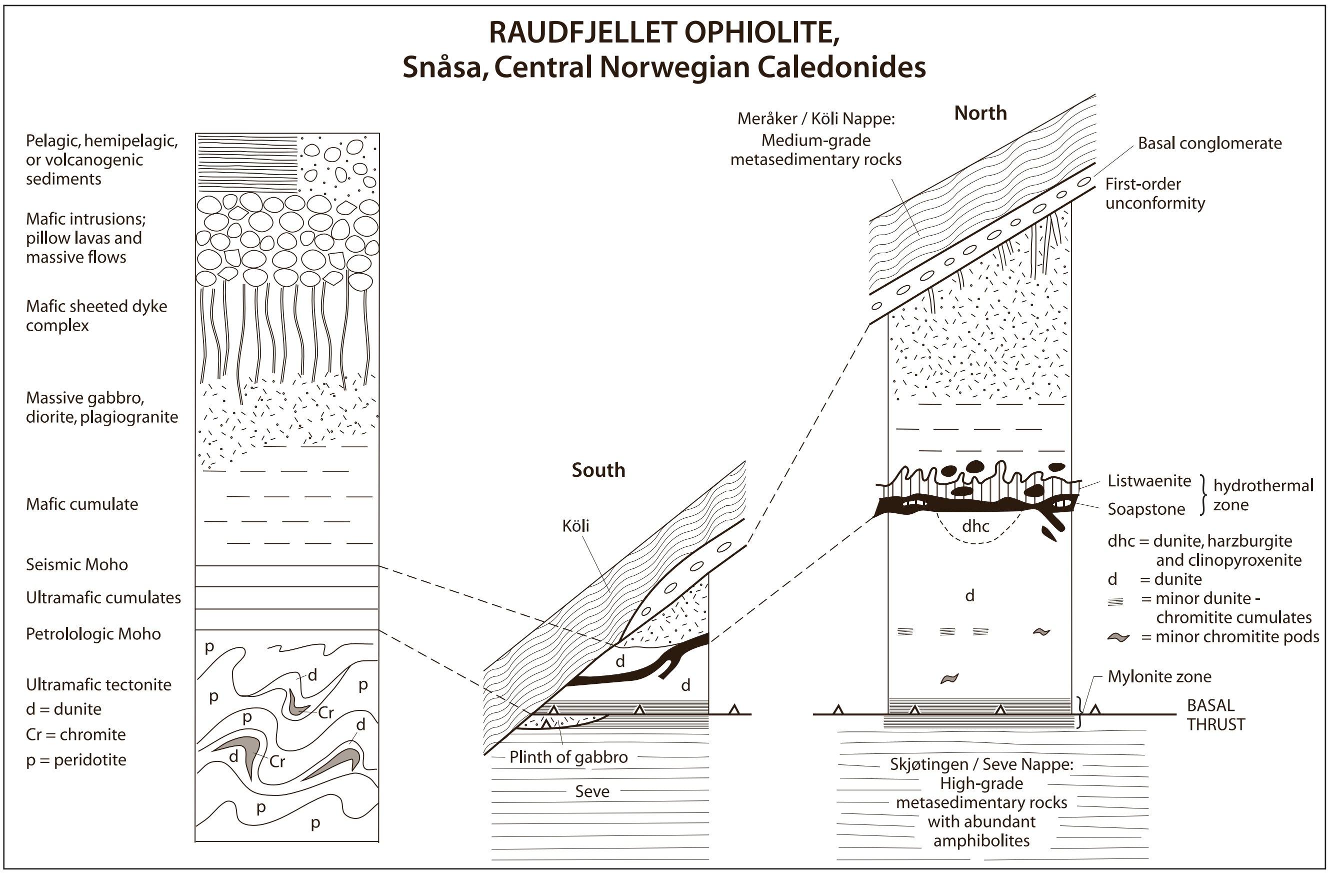

Fig. 3. Left column – a typical, complete ophiolite pseudostratigraphy. Right column – the pseudostratigraphy preserved at Raudfjellet, showing the subjacent Seve high-grade rocks and the overlying conglomerate and other low-grade rocks of Köli affinity.

Fig. 4. Ultramafite mylonite, derived from an otherwise massive dunite/serpentinite. Locality near the southern tip of the ophiolite, looking c. northeast.

Fig. 5. Basal ultramafite mylonite and glassy, dark green ultramylonite. Locality in the extreme eastern part of the ultramafic block outcrop, just above the footwall Seve rocks; looking c. northwest.

well-delineated area measuring 200 x 400 m at the top of the dunite body (Fig. 2), irregular lenses of metaperidotite (metaharzburgite) and metapyroxenite are hosted in the dunite. The lenses strike oblique to subparallel to the upper contact of the dunite body (the contact between the dunite and the hydrothermal zone), and they are tentatively interpreted to represent late harzburgitic and websteristic/clinopyroxenitic intrusions in the dunite.

The central part of the big dunite body consists of homogeneous, monotonous-looking dunite that is only modestly serpentinised (Fig. 2). Where least altered, it consists of c. 90% olivine and 10% serpentine with accessory disseminated chromite. Towards the northwest, serpentinisation increases, and at the northwestern border of the ultramafic block the dunite is generally completely altered to a dark-grey or, more rarely, sea-green serpentinite.

The dunite at Raudfjellet (Fig. 6a) represents the erosional remnants of a single, very large, high-level dunite body. From field observations and geological mapping, our preliminary interpretation is that this large and lithologically homogeneous body represents the erosional remnants of a single, spatially well-defined, dunitic *cumulate* body situated between the seismic and the petrological Moho. There are no clear signs that the dunite body at Raudfjellet represents a single, large, *discordant* dunite body situated in a host peridotite (harzburgite or lherzolite) of an upper mantle tectonite section of the ophiolite fragment. As far as size is concerned this body, to our knowledge, has few, if any, analogues within the Scandinavian Caledonides. Its pseudostratigraphic location appears to resemble, at least to a certain extent, that of a number of well-known ophiolite complexes, e.g., the very large dunite body making up the core of Mt. Olympus in the Troodos Ophiolite Complex, Cyprus. There, the top of the large dunite body is located close to the border between the host harzburgitic mantle portion of the ophiolite and overlying gabbroic rocks (Moores & Vine 1971, Gass 1980). The pseudostratigraphy at Raudfjellet also shows distinct similarities to that found at the Thetford Mines Ophiolite Complex in Quebec, Canada. There, a widespread and up to 500 m-thick dunitic zone is located between overlying pyroxenitic and peridotitic layered rocks and subjacent mantle peridotite tectonite (e.g., Schroetter et al. 2003).

Contrary to the conditions at Raudfjellet, several of the small, neighbouring fragments of ophiolitic mantle to the southwest of Raudfjellet, e.g., Haukberget (Fig. 1), show typical *discordant* dunite bodies within a mantle peridotite (harzburgite or lherzolite) host. These dunite bodies are more common, both in size (from a few metres, or tens of

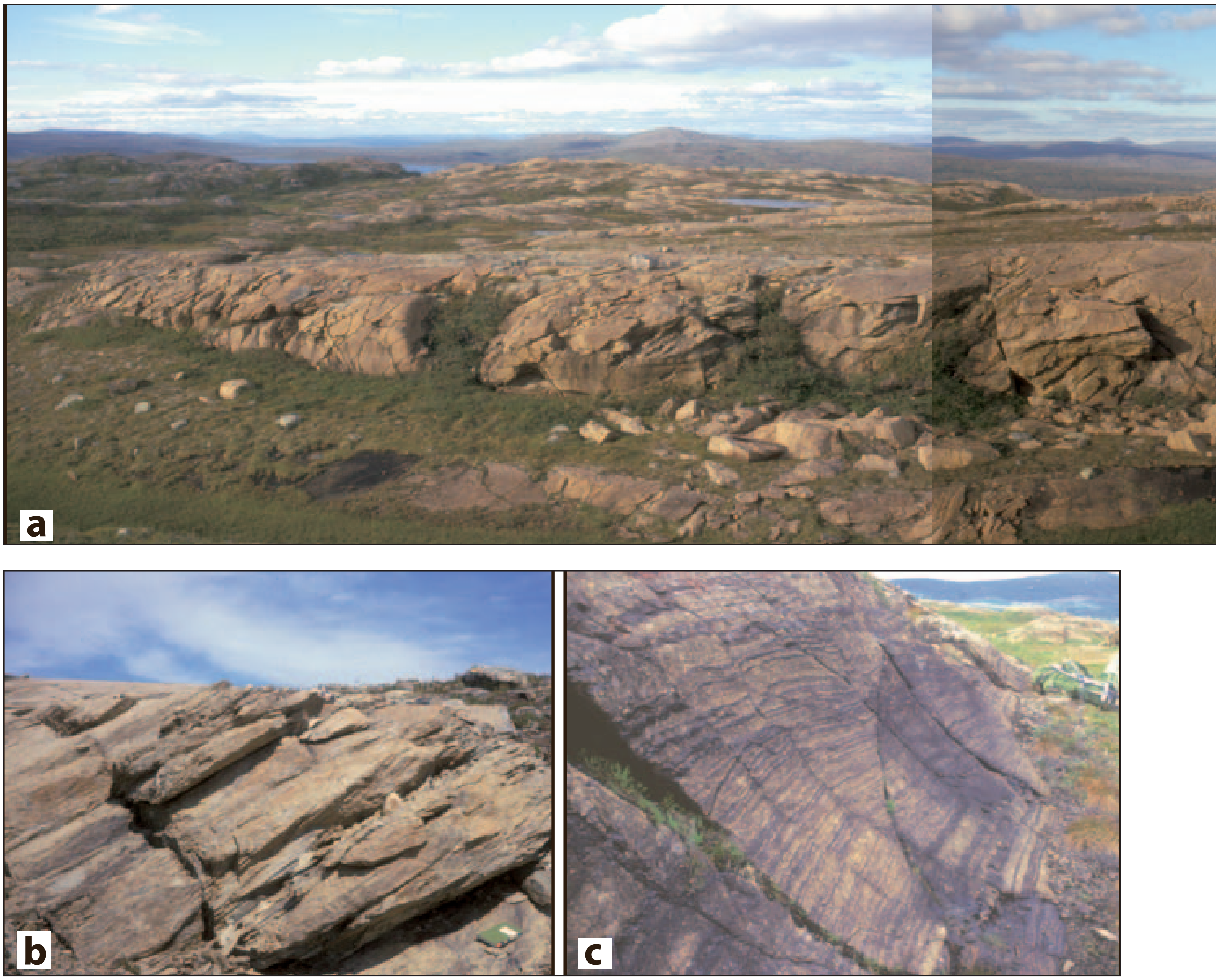

Fig. 6. (a) Panorama from the top of Raudfjellet mountain, looking through more than 90° towards east-southeast (right) to north (left). All the pale yellowish-brown weathered rock is dunite to serpentinite. The hills in the background on the far left are gabbro, situated on the northwest side of the hydrothermal zone running in the terrain depression between the dunite and the gabbro. (b) Foliated dunite, from a locality c. 300 m southeast of søndre Stokktjern; looking c. northeast. (c) One of several local occurrences of dunite-chromitite cumulates within the large dunite body. These are striking mostly at a high angle to the general trend of the dunite body.

metres, up to several hundreds of metres in length) and distribution than the Raudfjellet dunite body. They are irregular in shape, and irregularly distributed within the host peridotite, with roughly equal volumes of the two rock types. The discordant dunite bodies are tentatively interpreted to represent *restites* from partial melting of the mantle peridotite (harzburgite or lherzolite) host.

Within the northernmost part of the Raudfjellet complex there are two, small, serpentinite lenses, arising from tectonic imbrication, and representing metadunites (Fig. 2). Farther north, at Skardtjørna (Fig. 1), there is a single, isolated body (300 x 180 m) of strongly serpentinised dunite at the same tectonostratigraphic level. These bodies, though separated from the main mass of Raudfjellet by a series of strike-slip faults, may represent a northward extension of the Raudfjellet dunite body.

Near the southern apex of the Raudfjellet complex there is a pronounced steep fault, one of several faults that trend NW-SE across the strike of the ophiolite. There has been a significant displacement of the ophiolitic rocks on the southwestern side of this fault relative to the northeastern block (Fig. 2). A profile along the southwestern side of this fault, perpendicular to the thrust front, shows from bottom to top the following sequence: 20 m massive metagabbro, 70 m serpentinite mylonite and finally 70 m of a similar, mostly massive metagabbro. The latter is then terminated at the unconformity. This is the only place along the entire thrust front of the ophiolite where we have observed out-

crops of gabbro in the footwall contact of the ultramafic mylonite (although along much of the mylonite zone there are virtually no outcrops of the footwall rocks). We interpret this as an indication that the ophiolite may have overridden itself in a typical upward-ramping manner along the thrust front. At the same time it is evident that the serpentinite (derived from dunite) has taken up practically all the syn-thrusting strain, leaving a quite massive metagabbro below and a mostly fairly massive metagabbro above the ultramafic mylonite and with knife-sharp contacts between the rocks. In the same area, just to the east of the small tarn Raudbergstjørna, there are two metapyroxenite bodies, one elongated and one with a markedly angular shape, enclosed in the serpentinised dunite. These two bodies are likely to represent late websteritic intrusions in the dunite.

Along the highest ridge of the Raudfjellet mountain which coincides with the middle part of the dunite body, there are several, isolated, minor occurrences of dunite-chromitite cumulates (Fig. 6c). Their strike appears to be quite random, not following the overall pseudostratigraphy of the ultramafic block or the ophiolite as a whole, but as a group they are broadly located to a certain stratigraphic level within the dunite body (Figs. 2 & 3). Each occurrence of these cumulates has a strike length of 5-10 m and the thickness is of the same order. However, some of the occurrences may be followed for several tens of metres along strike. They usually terminate abruptly along strike at both ends against minor internal faults, but die out more gradually towards the top of the sequence. The entire sequence of cumulates in dunite is usually apparently undeformed, or exhibits only a weak ductile deformation (from a semi-molten stage?). The individual cumulate layers are mostly rather uniform in composition. Chromitite layers consist typically of a moderately strong, chromite impregnation in a dunite matrix, whereas the dunite layers are quite uniform. The chromitite layers are not significantly enriched in noble metals (analysed for Pt, Pd and Au).

Stratigraphically below the dunite-chromitite cumulates there are sporadic minor lenses, veins or irregular pods of massive chromitite with no preferred spatial orientation. These lensoid bodies may be followed for some decimetres or metres along their longest axes, whereas their thicknesses can usually be measured in centimetres or decimetres. Three, reconnaissance, noble metal analyses carried out on these pods and veins show that two samples have background levels of noble metals (< 50 ppb Pt+Pd+Au) whereas one has a ppm-level enrichment (> 1 ppm Pt+Pd+Au).

The nature of the boundary between the two blocks

The boundary between the ultramafic and mafic blocks of the Raudfjellet ophiolite is a tectonic contact. This is most clearly seen by the fact that the lowermost parts of the mafic block (mafic and ultramafic cumulates) are slightly discordant to the boundary and thus gradually decreases in thickness from north to south (Fig. 2). In the north, to the west of the tarn søndre Stokktjørna, the thickness of the mafic-ultramafic cumulates is more than a hundred metres, but the thickness decreases to zero already half-way to the southwest along the contact between the two blocks. Along the southern part of this major boundary, only massive to foliated metagabbro, situated stratigraphically above the cumulates, lies in contact with the ultramafic block.

A further consequence of the tectonic boundary is that pure ultramafic cumulates, e.g., dunite-wehrlite cumulates with chromite and sulphide horizons, are nowhere represented in the Raudfjellet pseudostratigraphy. The absence of such cumulates and Cr-mineralisation is a characteristic feature of almost all the ophiolite remnants along the south-

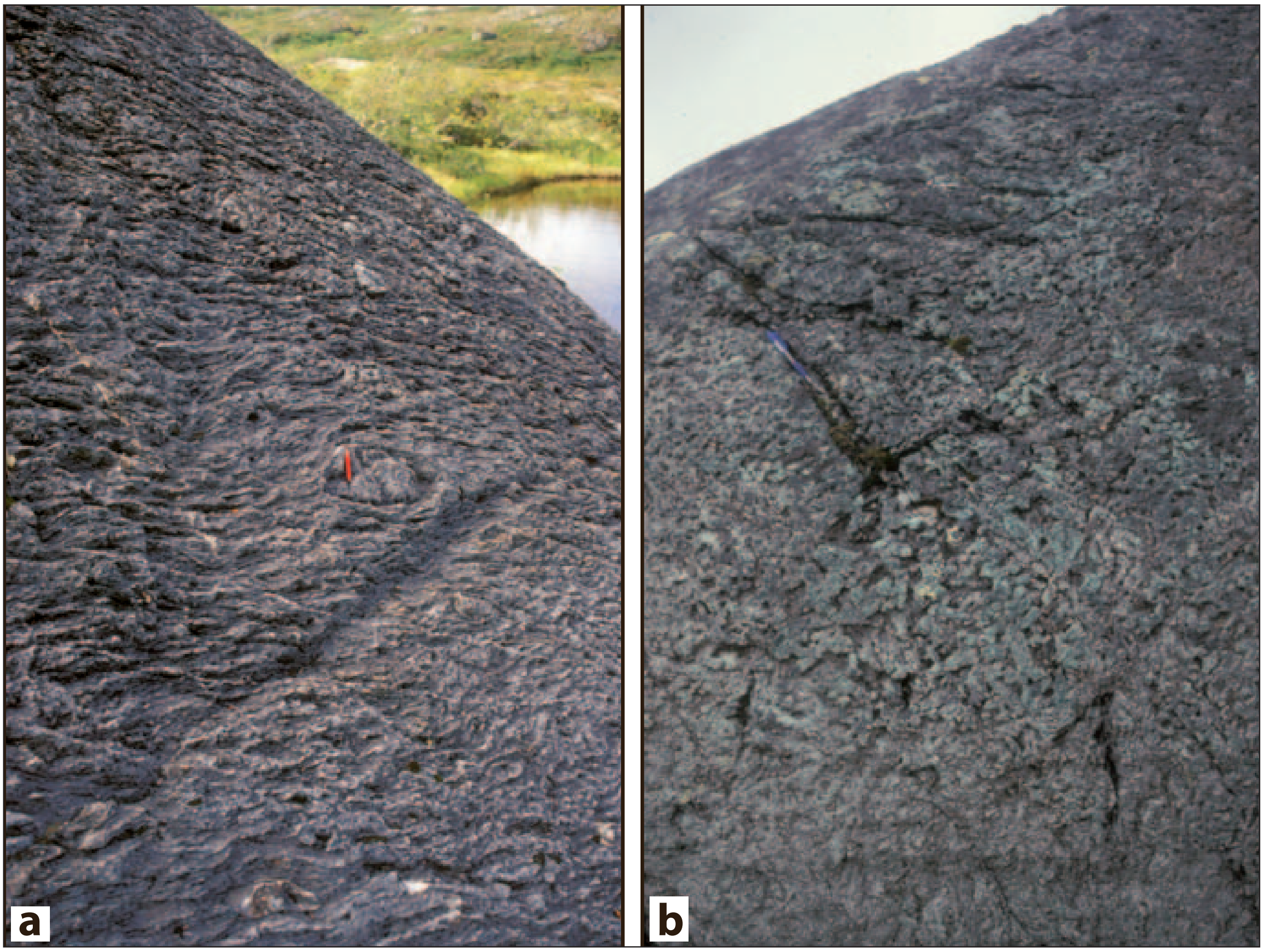

Fig. 7. (a) Soapstone from the hydrothermal zone. The chemically resistant, very soft talc stands out in ridges between the much harder carbonates, mainly magnesite. (b) Hydrothermally altered gabbro (HAG) from the hanging-wall contact of the hydrothermal zone. The rock has undergone strong Mg-metasomatism, and the main minerals are bright green or emerald-green actinolite (smaragdite) and a dark green common hornblende. The smaragdite crystals are particularly well weathered out on the outcrop shown.

eastern margin of the Trondheim Nappe Complex as well as for the Vågåmo Ophiolite south of Dombås (Nilsson et al. 1997).

The hydrothermal zone

The border between the mafic and ultramafic blocks is otherwise marked by a spectacular and unusually wide zone of hydrothermal alteration (Figs. 2, 7 & 8). This zone, with its various, potentially economic mineral deposits, will be the theme of a separate paper (now in preparation), and therefore only a brief summary is included here. The hydrothermal zone extends along nearly the whole length of the contact between the two blocks. In the far south, however, the zone deviates from the contact and trends obliquely southwards into the ultramafic block where it develops as a zone of net-veined soapstone.

The hydrothermal zone generally consists of soapstone at the base and a magnesite-quartz rock termed listwaenite (less commonly reported as listvenite; also known as virginite) at the top (Fig. 3). The thickness of the zone varies markedly, from less than 5 m to about 90 m. The footwall boundary of the hydrothermal zone is very well defined through a 0.5–2 m-wide transitional zone consisting of random, sheaf-like, pale talc porphyroblasts set in a very fine-grained, sea-green, serpentine matrix at the base of the soapstone unit. The hangingwall contact of the hydrothermal zone is also usually well defined, where the listwaenite borders upwards against a strongly hydrothermally altered metagabbro or metapyroxenite. Normally this border is quite sharp and regular, but in some places thin stringers of listwaenite penetrate several metres into the hydrothermally altered gabbro. The altered metagabbro is actually also part of the hydrothermal zone in that it is clearly affected by hydrothermal alteration; however, it has not suffered any CO_2 metasomatism, with formation of carbonate minerals, as have the listwaenite and the soapstone.

Within the hydrothermal zone, the soapstone has a talc content of approximately 40–60 %. It is a pale grey soap-

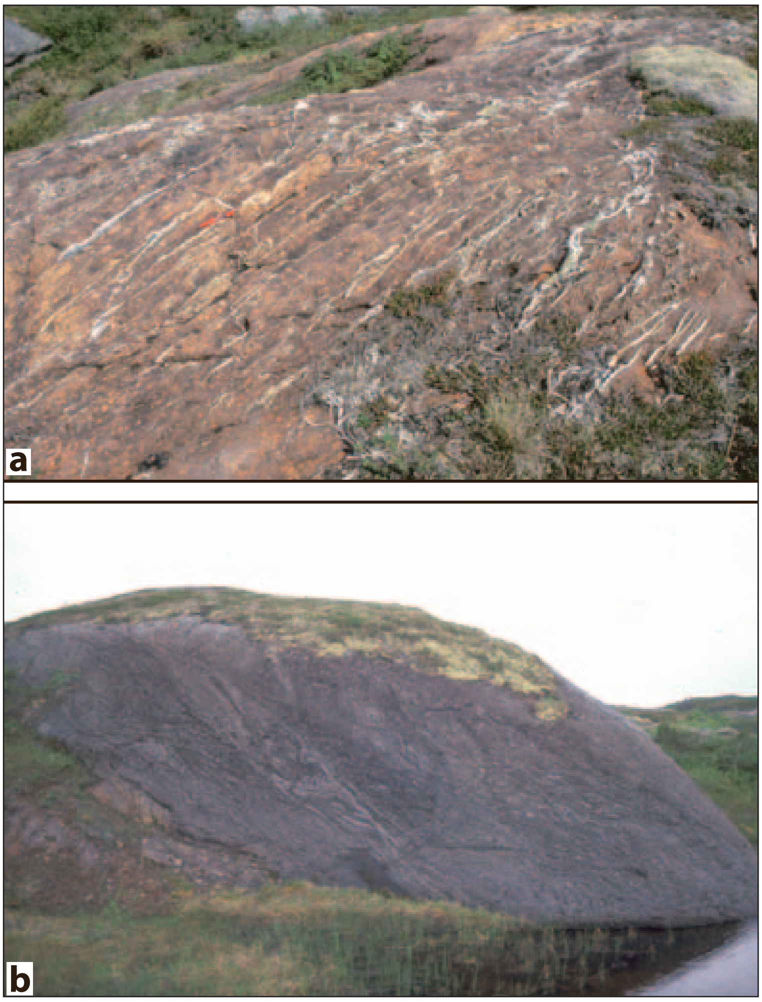

Fig. 8. (a) The main rock of the hydrothermal zone is listwaenite (listvenite), a quartz-bearing carbonate rock that forms when soapstone is reacting with excess CO_2 during falling temperature. The outcrop shows reddish-brown weathering carbonates, mainly magnesite, with ribbons of quartz weathered out on the surface. (b) Banded soapstone, shown in detail in Fig. 7a. When cut, this soapstone has a very attractive appearance, due to the prominent structures in the rock.

stone type that, in addition to talc, contains magnesite as the major mineral. Dolomite and serpentine occur locally as subordinate mineral constituents. The chlorite content is generally very low, and tremolite occurs only sporadically. Chromite and secondary magnetite occur in fine-grained dissemination, mostly in trace amounts, and with a strikingly uneven distribution.

The major mineral in the listwaenite is magnesite. Quartz occurs in varying amounts. Other minerals are dolomite and subordinate amounts of talc and chlorite, while chromite and magnetite occur as dissemination in trace amounts. The contents of talc and chlorite increase with the quartz content. The ratio between magnesite and dolomite varies locally, but is on average approximately 3:1, independent of the content of quartz, talc and chlorite. This means that both carbonate-rich and carbonate-poor listwaenite, on average, show the same magnesite:dolomite ratio. The magnesite has been investigated by microprobe and typically it carries some iron in addition to magnesium in the mineral structure. Analyses show on average 5–6 weight % FeO, but the individual analyses vary substantially. Furthermore, bulk analyses of the listwaenite show large variations in magnesium content, from about 20 to 40 weight-% MgO. The reason for this is both local variations in the magnesite: dolomite ratio as well as large variations in the silica content.

The hydrothermally altered gabbro (HAG) above the listwaenites passes transitionally upwards into the normal, unaffected metagabbro. The true thickness of the HAG varies considerably, from a few metres up to 40–50 m. Due to the modest dip (20-30°) observed in certain places, the actual outcrop of the HAG can be up to 150-200 m wide. In the northern part of the hydrothermal zone where the listwaenite borders mafic-ultramafic cumulates to the northwest, the hydrothermal fluids have had a strong preference for selectively altering the pyroxenite and minor peridotite layers, leaving the interlayered gabbroic cumulates seemingly unaffected by the H_2O-rich volatiles. The pyroxenites are here altered to a monomineralic amphibole rock whereas the peridotites are altered to a dense, dark grey to black serpentinite.

The mafic block

<u>The mafic-ultramafic cumulates</u>

The stratigraphically lowermost exposed parts of the mafic block (some distance away from the hydrothermal zone) are represented by the mafic-ultramafic cumulates, which have a gentle to moderate (20–40°) dip to the northwest. The ultramafic cumulate layers are clearly subordinate to the gabbroic ones in terms of volume. The ultramafic members are represented by metapyroxenite and, in a few places, also metaperidotite, and they are not persistent along strike, appearing and disappearing suddenly both along and normal to the layering. Both the pyroxenite layers and the peridotite layers occur irregularly without any kind of clear and systematic, spatial distribution in the cumulate sequence. The boundary between the gabbro and the ultramafites generally follows a strikingly irregular path, indicating a close relationship in both time and space between the two (Fig. 9). At one place, in a fault-bounded segment to the southwest of søndre Stokktjørna (unit 5 in Fig. 2), the ultramafic cumulates are developed as a nodular olivine websterite with knolls or nodules of fine-grained, dark-green, slightly serpentinised dunite set in a pyroxene or amphibole matrix. This rock-type has a prominent reddish-brown weathering crust. The nodular pyroxenite is interlayered with a common, greenish-grey weathering, massive, amphibole-altered clinopyroxenite or websterite (Fig. 10). In certain places, syn-magmatic ero-

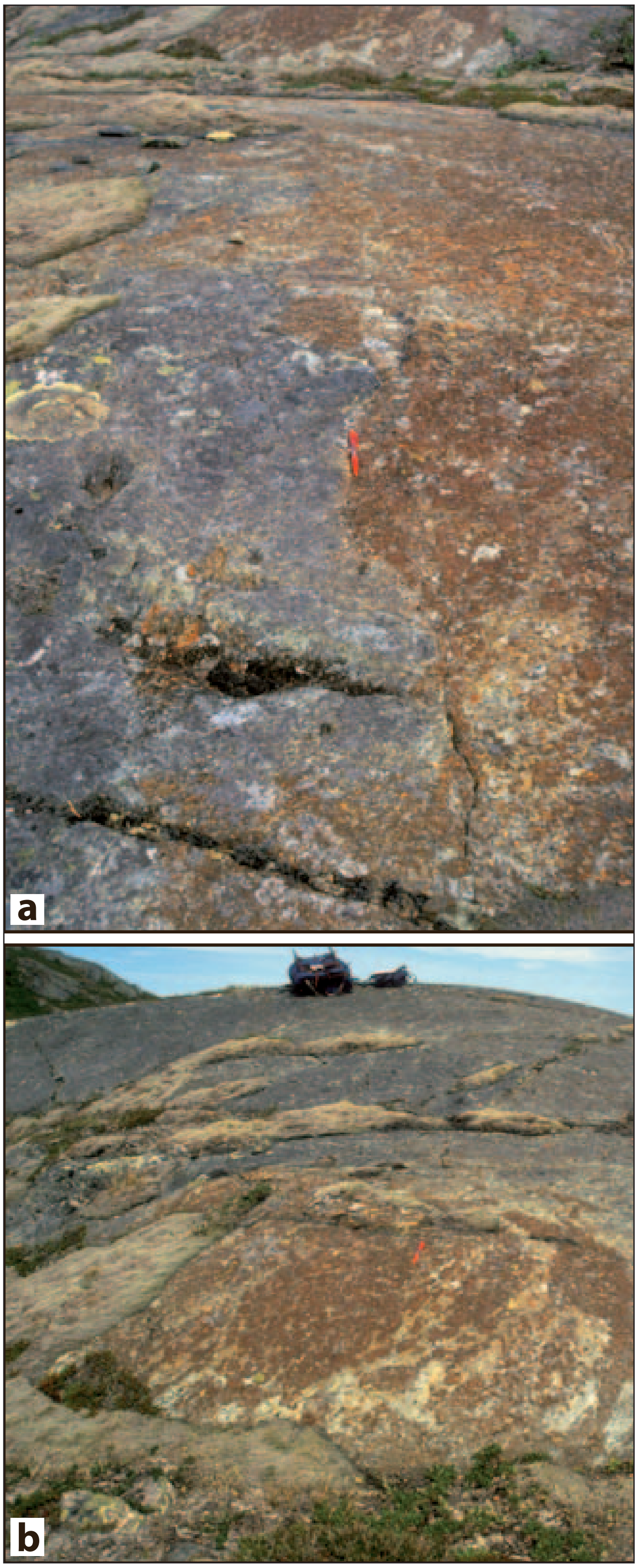

Fig. 9. (a) The highly irregular boundary between metagabbro (dark grey) and metapyroxenite (reddish brown) in the mafic-ultramafic cumulates in the lowermost portion of the mafic block indicates an intimate relationship between the two. (b) Patch of olivine metapyroxenite in metagabbro, developed as a nodular rock.

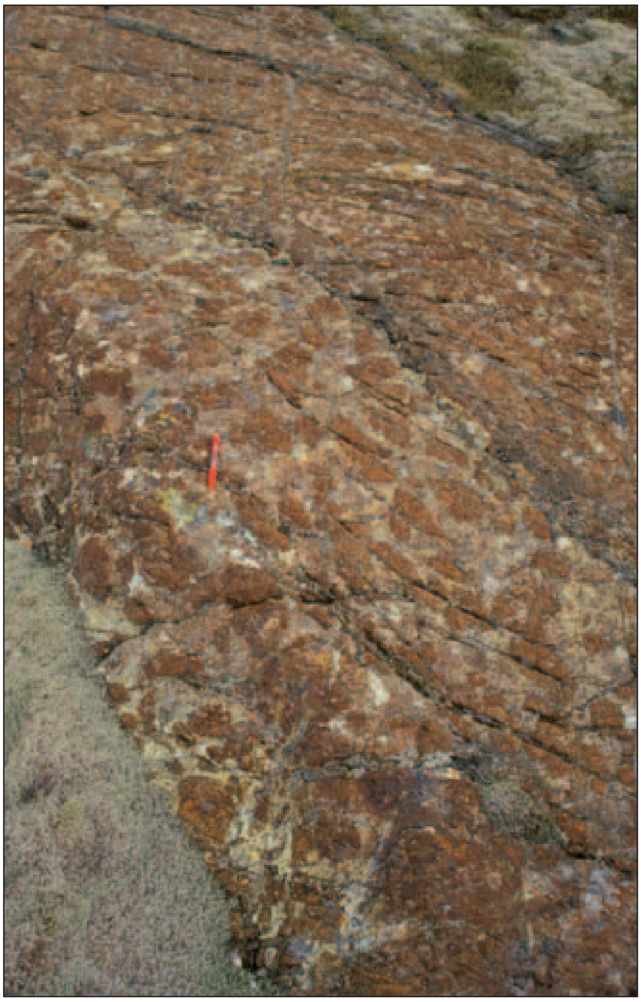

Fig. 10. Nodular olivine metawebsterite. Fragments or nodules of slightly serpentinised olivine are set in a matrix dominated by alteration products of pyroxene.

sional features are observed, where existing, early-formed, pyroxenite layers were tilted and transected at angles of up to c. 45° by new, lithologically similar, pyroxenite cumulate layers.

The lowermost part of the gabbro is generally a layered metagabbro consisting of alternating mafic and more leucocratic layers, with layer thickness in the order of dm to m, and with either sharp or partly diffuse boundaries between the two. There is a rhythmic layering present where the layers vary somewhat in modal composition and thickness (Fig. 11).

The massive gabbro and mafic dykes

Up sequence, the modal layering becomes less distinct and gradually changes character via a finely 'laminated' metagabbro with cm-thick layers to a massive metagabbro that constitutes the dominant rock type in the mafic block (Fig. 2). Close to the erosional top surface, scattered mafic dykes make an appearance and in one place possible dykes-in-dykes were reported by D.M.Ramsay and the late

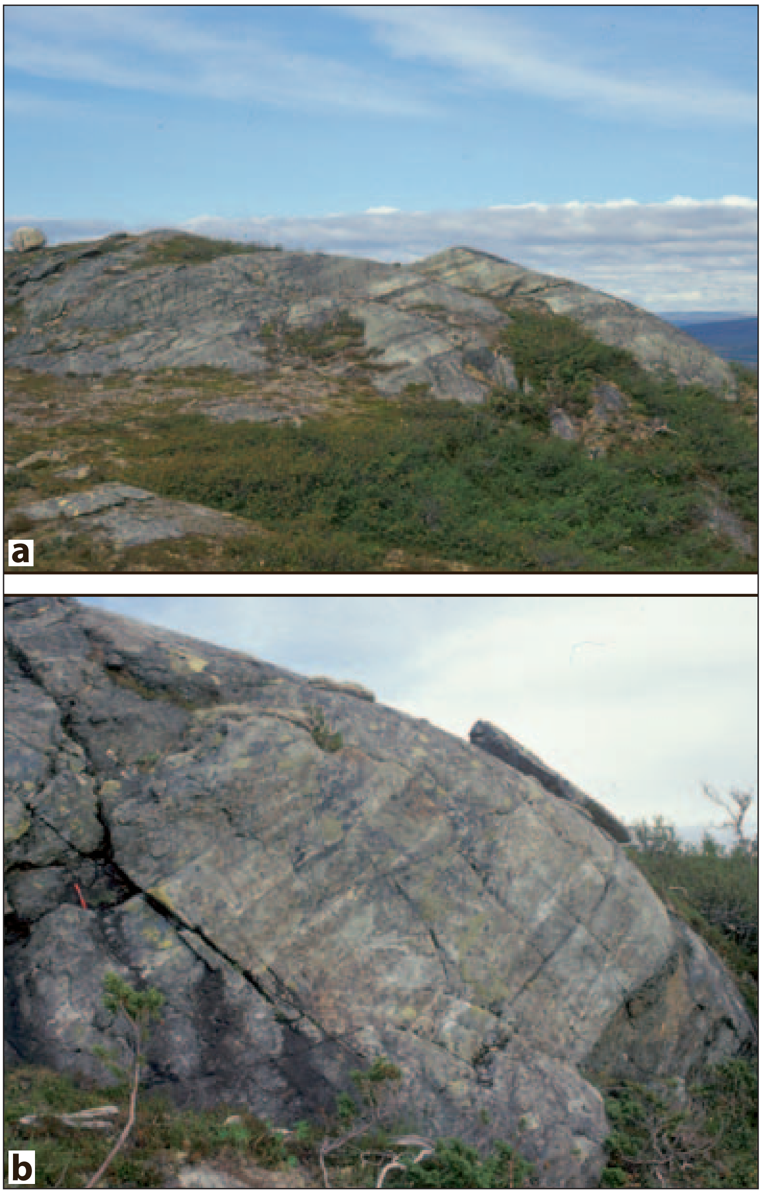

Fig. 11. (a) Layered metagabbro dipping at circa 20º towards the northwest. (b) Detail of the layered metagabbro with a dark brown metapyroxenite layer in the footwall.

B.A.Sturt. This particular area, however, is almost completely covered by superficial deposits. Consequently, very little information is available from the uppermost parts of the ophiolite fragment, in stark contrast to the remainder of the Raudfjellet complex.

Polymict conglomerate

The polymict conglomerate that lies unconformably upon the ophiolite is generally only poorly exposed. The best examples, which also show that the conglomerate lies above a first-order, angular unconformity, are found to the southwest of Grønningselva along Holdesbekken (Fig. 12). There, clasts are subangular to subrounded and consist mostly of ultramafic and mafic rocks with sporadic pebbles of listwaenite. Clast size varies from less than a centimetre up to 30–35 cm. A crude clast lineation plunges at a moderate angle to WNW, roughly normal to the general strike. The matrix of the clast-supported conglomerate consists mostly of ultramafic and mafic sand-size material, in part serpentinised.

In general, the unconformity appears to cut down into pseudostratigraphically deeper parts of the ophiolite in moving from north to south. In northern parts of the area, only one sizeable exposure of this conglomerate has been found. There, clasts of gabbro predominate over ultramafite, hornblende schist and rare carbonate-quartz rock, and the matrix is composed of sand- to gravel-size, schistose, mafic/ultramafic material. A pebble lineation is also discernible, again plunging moderately towards WNW.

During helicopter reconnaissance work, a comparable conglomerate was found along the northwestern side of an ophiolite fragment on Haukberget (Fig. 1), some 6 km southwest of Holdesbekken. In this area, the conglomerate varies from an ultramafic gravel or sand to polymict clast-supported conglomerate, to a gabbro conglomerate with only scattered pebbles or cobbles of pyroxenite and a red-brown carbonate rock.

Structural deformation

The presence of upper mantle, harzburgitic peridotites and dunite bodies in direct contact with continental-rise metasedimentary rocks (Seve Nappe) of the Baltoscandian margin is itself a major indication of tectonic juxtaposition. As described above, the base of the ultramafic block in the east is represented by an impressive ultramafite mylonite reaching up to 150 m in thickness; and the very basal part is ultramylonitic (Figs. 5 & 13a). Blastomylonitic textures in the subjacent Seve rocks of the footwall also attest to the tectonic nature of the contact. The boundary between the two main, ultramafic and mafic blocks of the Raudfjellet complex is also tectonic, as witnessed by the marked angular discordance between the cumulate layering and the actual contact. However, the disjunctive nature of this inter-block boundary is far less dramatic than is the case for the major thrust along the sole of the ophiolite.

A penetrative foliation is not an obvious feature of these mafic and ultramafic rocks away from the mylonite zone, but can be seen in places in the metagabbro and especially in the layered units where pyroxenite bands are present. In these cases the schistosity is slightly steeper than the cumulate layering and rare, top-ESE, tight, asymmetric folds may be seen (Fig. 13b). In dunite just above the mylonite zone, there are well developed, thin, top-E, anastomosing shear zones with a protomylonitic fabric. Locally, high-strain zones

Fig. 12. Polymict conglomerate exposed in the bed and bank of the stream Holdesbekken. Clasts consist of gabbro, ultramafic rock and listwaenite. The matrix is composed entirely of mafic and ultramafic material derived from the ophiolite. The bedrock beneath the foot of the late Brian Sturt is gabbro.

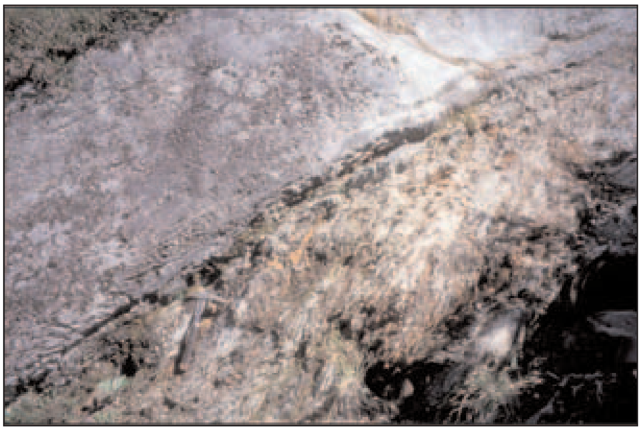

Fig. 14. Tectonic contact between metagabbro (above) and strongly schistose listwaenite; looking north-northeast. Overall, the moderately steep schistosity shallows off upwards, concave toward bottom-right, indicating that the contact is a thrust. A widely spaced cleavage and shear bands in the listwaenite (just perceptible near the base of the photo) also supports the top-to-the-southeast thrusting. Locality close to the eastern shore of Grønningen, where the listwaenite crosses the lake (see Fig. 2).

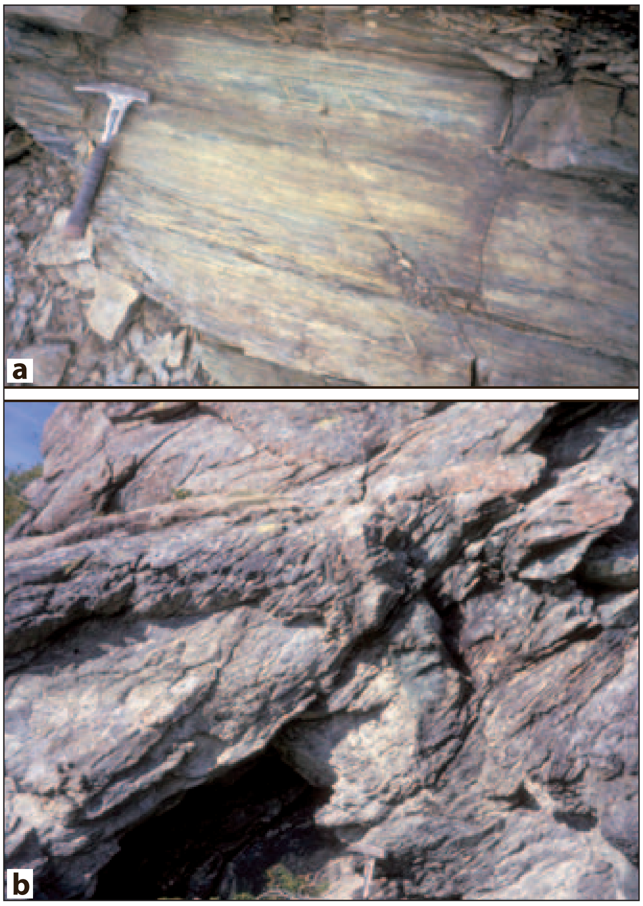

Fig. 13 (a) Ultramafite mylonite with slivers of green-grey ultramylonite. Base of the ultramafic block, c. 500 m southeast of søndre Stokktjern; looking south.
(b) Asymmetric fold in banded gabbro with pyroxenite layer (dark green), showing a crude axial planar schistosity. Locality in the easternmost part of the mafic block, c. 1 km south of søndre Stokktjern; looking north-northeast.

Fig. 15. Extensional shear bands in serpentinised ultramafite mylonite. Locality in the basal, northeasternmost part of the ultramafic block; looking c. northwest.

within the metagabbro are strongly schistose, and show tight to isoclinal folds with sheared-out middle limbs; these structures show a general easterly vergence. An associated feature throughout both blocks is a fairly strong stretching and/or mineral lineation plunging at moderate to low angles to between WNW and W. This lineation is also well developed in the mylonites at the base of the ultramafite in the east, where there are also indications of the presence of sheath folds. The footwall Seve rocks just below the contact also show a prominent lineation parallelling that in the mylonites. Axes of rare isoclinal folds also trend c. E-W, indicating that strain was sufficiently high to cause rotation into the thrust transport direction. Taking the Raudfjellet complex as a whole there is, thus, quite good evidence that the earliest internal structures and the pervasive mylonitisation relate to top-ESE, contractional deformation and thrusting.

Evidence of greenschist-facies extensional reworking of the earlier, higher-temperature, contractional fabrics can be seen in different parts of the complex. In rare cases, notably within the listwaenite, a low-angle spaced cleavage deforms the main foliation. On closer inspection, this takes the form of top-NW to -NNW, extensional shear bands, but there are also signs of top-SE movements affecting the foliation in the highest parts of the listwaenite as a consequence of southeastward thrusting of the hangingwall gabbro (Fig. 14). Extensional shear bands are also quite common within the basal mylonites (Fig. 15), here mostly with a top-SW sense of shear; these shear bands clearly deform the mylonitic foliation and transect top-E, syn-mylonitisation folds.

During our field studies we have seen some evidence favouring the notion that the Raudfjellet complex has been dissected and displaced along NW-SE-trending, strike-slip faults (cf. Sjöström & Bergman 1989). Fault-generated lateral displacements of different parts of the ophiolite are especially conspicuous to the west of the tarn Søndre Stokktjørna (Fig. 2), but also between Stor Hallartjørna and Grønningen. Along the northeastern margin of the complex the basal thrust surface has also been displaced quite markedly in a left-lateral sense. To the northwest of Stor Hallartjørna an elongated serpentinised dunite body is very clearly displaced sinistrally along a NW-SE-trending fault across the border between the two blocks, and has come to rest as an 'exotic' body well within the mafic block (Fig. 2). Also, near the southern apex of the Raudfjellet complex there is a clear sinistral displacement along a minor strike-slip fault.

Discussion

The Raudfjellet complex displays several features of a classical ophiolite pseudostratigraphy (Coleman 1977, Moores 1982). As with many of the ophiolites recognised in the Norwegian Caledonides, it is dismembered and fragmented (Furnes et al. 1985, Sturt & Roberts 1991). At Raudfjellet, the ultramafic block is tentatively interpreted to represent a single, large dunite body of cumulate origin located between the petrological and seismic Moho. This is an interpretation purely based on our field observations and map compilation (Fig. 2). Macroscopic modal layering, on any scale, is lacking within this dunite body with the exception of a few localities showing dunite-chromitite cumulates developed very locally and only on the metre scale (cf. Fig. 6c). It should be emphasised here that purely ultramafic cumulates with a well developed macroscopic modal layering, e.g., dunite-wehrlite cumulates, as have been described from the Leka Ophiolite Complex (Prestvik 1980; Furnes et al. 1988), have not been found in either of the two tectonic blocks at Raudfjellet. Both mafic-ultramafic cumulates and massive gabbro are present in the mafic block, but high-level tonalitic differentiates have not been found. Possible sheeted mafic dykes cutting gabbro have so far been recorded in only one locality. The higher levels of a typical ophiolite, i.e., pillowed and massive basalts, and pelagic and volcanogenic sediments (units which are extensively developed in the ophiolites of the western Trondheim Region), are not represented at Raudfjellet.

It is worth pointing out here that our conception of what constitutes a typical ophiolite assemblage has been changing over the last two decades, notably through the extensive exploration of the seabed using submersibles and remotely operated vehicles. Several cases have been reported of transtensional core complexes exposing serpentinised and, in part, mylonitised mantle peridotites, overlain directly at the dome flanks by either restricted outcrops of sheeted dykes, basaltic lavas or even sedimentary rocks (Blackman et al. 1998, Karson 1998, Kelley et al. 2001, 2005), Thus, in the Caledonides, apparently dismembered ophiolites may not necessarily have been dismembered during obduction and later processes but may be true representations of specific parts of the ocean floor of Iapetus.

The age of the Raudfjellet ophiolite is not known. A loose upper constraint is provided by the unconformably overlying conglomerate with ophiolitic detritus. This is characteristic of many conglomerates suprajacent to obducted and otherwise deformed ophiolites in the Köli Nappes of central Norway. In those cases, geochronology and biostratigraphical control denote that the highest levels of the ophiolites cannot be younger than Mid Arenig (Vogt 1945, Ryan et al. 1980). Isotopic dating of oceanic trondhjemites and rhyodacites indicates that the age of the ophiolites ranges from Cambrian to Early Ordovician (see review in Roberts et al. 2002) In other parts of Norway, however (e.g., Karmøy, Lyngen), dismembered and fragmented ophiolites extend up into the Middle Ordovician (Pedersen & Furnes 1991, Oliver & Krogh 1995); and at Stavfjord in western Norway there is one ophiolite complex of Late Ordovician age (Dunning & Pedersen 1988, Furnes et al. 1990).

There is, thus, firm evidence indicating that ophiolites deriving from diverse parts of the Iapetus Ocean range in age from Cambrian to Late Ordovician. In the case of the Raudfjellet ophiolite, however, we would argue that a Cambrian to Early Ordovician age would seem the more likely. The overlying, low-grade Köli rocks, including the basal conglomerate, extend southwards into the Meråker Nappe (Wolff 1979), or 'Meråker Belt', containing a volcanosedimentary succession that was first deformed during the Siluro-Devonian, Scandian orogeny.

Although the topic of regional correlations is outside the scope of this present contribution, we note here, in brief, some comparable situations involving ultramafic/mafic complexes, namely in the Handöl area in Jämtland, Sweden, and in the Otta-Vågåmo district, south of the Trondheim Region. At Handöl, ultramafic rocks, gabbros and mafic dykes of unknown age occur in several lensoid bodies at the base of the Köli, in thrust contact with amphibolite-facies Seve Nappe rocks (Bergman 1993). Above the ultramafic/mafic complex is a composite sedimentary/meta-igneous formation containing an impersistent polymict conglomerate with clasts of psammite, marble, quartzite and granite. Mafic dykes are common in both the magmatic complex and the overlying Köli formation, and have a similar chemistry, thus linking the two units in space and time. Bergman (1993) interpreted the ultramafic/mafic complex as a dismembered ophiolite that formed in a marginal basin in proximity to a continental source; and thrust emplacement of this ophiolite-based Köli Nappe was inferred to have occurred in Early to Mid Silurian time.

The ultramafic/mafic complex in the Otta-Vågåmo area has also been interpreted as an ophiolite – the Vågåmo Ophiolite (Sturt et al. 1995). Although the age of the complex is unknown, it has been shown to have been thrust upon folded rocks of the subjacent Heidal Group in earliest Ordovician times, and unconformably overlain and overstepped by Middle Ordovician and younger rocks of the Sel Group (Sturt et al. 1991, Bøe et al. 1993, Sturt & Ramsay 1999). It has been proposed (Nilsson et al. 1997, Sturt et al. 1997) that some 30 separate remnants of the Vågåmo Ophiolite, occupying a similar tectonostratigraphic position, together with a continuation of the overlying Sel Group, can be traced northeastwards into the SE Trondheim Region. Thus, the tectonostratigraphy of the Otta-Vågåmo area has correlatives north of Røros and farther north into the 'Meråker Belt'. While details of these proposed correlations do not concern us here, what is of interest is that the Vågåmo Ophiolite was obducted, and initally deformed and metamorphosed, in Early Ordovician time.

At the present time, although we have no absolute proof of the age of obduction of the Raudfjellet ophiolite, and its coeval, initial, internal deformation and metamorphism, it has been argued above that it is likely to have been Early Ordovician. The unconformably overlying conglomerate cuts down, from north to south, through an already deformed, metamorphosed and internally disrupted magmatic complex. Thus, in many ways, it has a similar history to that of the Vågåmo Ophiolite and, indeed, to several of the dismembered ophiolite fragments of the western Trondheim Region. A difference, however, is that the Raudfjellet ophiolite, together with the Vågåmo Ophiolite and its northerly extensions, lies tectonically above Seve Nappe rocks of the Baltoscandian continental rise, whereas the western Trondheim Region ophiolites, with a relict blueschist-facies assemblage in one area (Eide & Lardeaux 2002), were emplaced upon Köli epicontinental and volcanic arc rocks (Gula Nappe) of an inferred microcontinent (Grenne et al. 1999, Roberts et al. 2002). A tectonic mélange is also recorded, beneath the Støren ophiolite (Horne 1979). Moreover, the post-obduction basinal succession in the western Trondheim Region contains a rich and diverse fauna, a high proportion of which is of Laurentian affinity (Bruton & Bockelie 1980, Neuman & Bruton 1989). On the other hand, temporally equivalent rocks of the 'Meråker Belt' in the NE Trondheim Region are largely devoid of fossils; and the suggested, correlative Sel Group contains a fauna of mixed Baltican-Laurentian affinities (Bruton & Harper 1981). In one area in eastern Trøndelag (Nordaunevoll, Gauldalen), black graphitic shales intercalated with Fundsjø Group pillowed metabasalts (basal part of the Meråker Nappe), contain the Baltican, Tremadoc graptolite *Rhabdinopora flabelliforme* (Vogt 1889, Størmer 1941). These phyllitic shales have a distinctive, U- and V-rich geochemical signature which is traceable in black shales of Late Cambrian-Early Ordovician age all along the Baltoscandian margin at structural levels extending up from the autochthon into the lower Köli Nappes (Gee 1981, Andersson et al. 1985).

The precise age of all the contractional structures – east-verging folds, foliation, prominent lineation – within the Raudfjellet complex is still unclear. We have argued in favour of an Early Ordovician age of obduction and, if correct, the top-ESE fold vergence, associated foliation, penetrative lineation and strong mylonitisation fabrics would have been linked to this early tectonic emplacement. In this same region of central Norway and Sweden, however, Ordo-Silurian successions in the Köli Nappes are, in some cases, deformed into major recumbent folds, and in many instances are also floored by thick mylonites, with comparable, prominent, E to SE stretching lineations. Yet, these particular folds, mylonites and lineations were generated during the Siluro-Devonian, Scandian orogeny. The pebble lineation in the conglomerate overlying the Raudfjellet complex is, to all intent and purposes, subparallel to the linear fabric in the ophiolite. Whilst the ophiolite must also have participated in Scandian orogenesis, separating the earlier obduction fabrics from broadly coplanar and colinear structures of Scandian age may not be easy. So there remains a problem for future research, to try to determine the precise age, or ages, of all these structures and foliate fabrics. It is quite conceivable, for example, that, as appears to be the case here at Raudfjellet, parallel or subparallel lineations in juxtaposed thrust sheets may have formed during different Caledonian, tectonothermal events.

The extensional structures, including shear bands and spaced cleavage, would appear to be less problematic in terms of their age of generation. There is a good deal of evidence now, from central Norway as a whole, and with increasing support from isotopic dating, that much of the ductile to semiductile, extensional deformation recorded in this region is a late-Scandian phenomenon, and occurred during Devonian time (Braathen et al. 2000, Nordgulen et al. 2002, Kendrick et al. 2004, Eide et al. 2005).

A major detachment recognised in the Røros district – the Røragen detachment (Norton 1987) – has been extrapolated northwards and was believed by Sjöström & Bergman (1989) to occur beneath the conglomerate now known to lie unconformably above the Raudfjellet complex. Clearly, the northward continuation of this particular detachment, as indicated by both Norton (1987) and Sjöström & Bergman (1989), and shown on the map compilation by Sjöström & Roberts (1992), is incorrect, but this does not deny the importance of Devonian extensional deformation in the Trondheim Region as a whole.

Conclusions

The Raudfjell complex displays many of the features recognised as constituting the pseudostratigraphy of a typical ophiolite, although as with most of the ophiolitic relics in the Scandinavian Caledonides it is dismembered and fragmented. At its base is a spectacular ultramafite mylonite. Elements represented include:-

(1) Ultramafic rocks, mostly dunite with subordinate harzburgitic peridotite and various pyroxenites, but with sporadic occurrences of dunite-chromitite cumulates. The main portion of the ultramafic block, based on field observations, is interpreted to represent a single, large dunite body of cumulate origin, originating from between the petrological and seismic Mohos.

(2) A mafic unit consisting of mafic cumulates and massive metagabbro. In the lower parts, a sequence of alternating mafic and ultramafic cumulates is present, and syn-magmatic erosional features have been recorded within the pyroxenites.

(3) Dolerite dykes are believed to occur in the upper part of the mafic unit, with possible sheeted dykes observed in only one small locality.

Basaltic lavas, which are common in many fragmented ophiolites in Norway, have not been identified at Raudfjellet; and no tonalitic differentiates have yet been found. An unusual feature, however, is the presence of a hydrothermal alteration zone, up to c. 60 m thick, at the tectonic interface between the ultramafic and mafic blocks. This zone consists of talc and listwaenite (magnesite-quartz rock). The Raudfjellet ophiolite complex is unconformably overlain by a polymict conglomerate consisting mostly of locally derived, mafic and ultramafic detritus.

The basal part of the ophiolite is a 150 m-thick zone of ultramafic mylonites with a WNW-ESE-trending mineral/stretching lineation. Lenses of glassy ultramylonites at the base consist of olivine and pyroxene, and are interpreted to relate to the original, high-T obduction upon rocks of the Skjøtingen (Seve) Nappe. As fossils are absent in the overlying sedimentary succession and as we have no isotopic dating, the age of the ophiolite complex and the time of its obduction are not known. However, based on the regional correlations that have been proposed for the eastern Trondheim Region and southwestwards into the Otta-Vågåmo district, it is argued that the Raudfjellet ophiolite is likely to be of Cambrian to earliest Ordovician age, and its obduction Early Ordovician. Subsequently, during Siluro-Devonian time, the complex and adjacent units were involved in the Scandian orogeny, including late-Scandian extensional deformation.

Acknowledgements

We are most grateful to Statskog, and in particular to Asbjørn Flaat, for all their logistic help in our collaborative project, including field accommodation and quick access to Raudfjellet by boat on Grønningen lake. Fylkesgeolog Ole Sivert Hembre, Ingvar Lindahl, then Statskog's geologist, and Asbjørn Flaat are also thanked for their leading roles in establishing and running the Raudfjell project with its focus on the potential economic resources within the hydrothermal zone. Thanks also go to the reviewers, Harald Furnes, Tore Prestvik and Øystein Nordgulen, for their critical comments and helpful suggestions which led to improvements in the final manuscript. Irene Lundquist helped with the final drafting and composition of several of the figures.

Last, but by no means least, we would like to express our thanks and deep gratitude to the late Professor Brian Sturt, formerly Director of Research at NGU and pictured in Figure 12, for his initiatives, enthusiasm and companionship during the earlier stages of this project fieldwork. This publication is dedicated to his memory.

References

Asklund, B. 1938: Hauptzüge der Tektonik und Stratigraphie der mittleren Kaledoniden in Schweden. *Sveriges geologiska undersökning C417*, 1–99.

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

Blackman, D.K., Cann, J.R., Janssen, B. & Smith, D.K. 1998: Origin of extensional core complexes:evidence from the Mid-Atlantic Ridge at Atlantis Fracture Zone. *Journal of Geophysical Research 103 (B9),* 21,315–21,333.

Braathen, A., Nordgulen, Ø., Osmundsen, P.T., Andersen, T.B., Solli, A. & Roberts, D. 2000: Devonian, orogen-parallel, opposed extension in the Central Norwegian Caledonides. *Geology 28,* 615–618.

Brueckner, H.K., Van Roermund, H.L.M. & Pearson, N.J. 2004: An Archean(?) to Paleoproterozoic 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.

Brueckner, H.K. & Van Roermund, H.L.M. 2004: Dunk tectonics: a multiple subduction/eduction modell for the evolution of the Scandinavian Caledonides. *Tectonics 23, No. 2, TC2004*, 1–20.

Bruton, D.L. & Bockelie, J.F. 1980: Geology and paleontology of the Hølonda area, western Norway – a fragment of North America. *In* Wones, D.R. (ed.) *The Caledonides in the USA*. Virginia Polytechnic Geological Sciences Memoir 2, 41–55.

Bruton, D.L. & Harper, D.A.T. 1981: Brachiopods and trilobites of the early Ordovician serpentine Otta Conglomerate, south central Norway. *Norsk Geologisk Tidsskrift 61*, 153–181.

Bøe, R., Sturt, B.A. & 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 Bulletin 425*, 1–24.

Coleman, R.G. 1977: *Ophiolites*. Springer-Verlag, Berlin, 229 pp.

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

Eide, E.A. & Lardeaux, J.M. 2002: A relict blueschist in meta-ophiolite from the central Norwegian Caledonides – discovery and consequences. *Lithos 60*, 1–19.

Eide, E.A., Haabesland, N.E., Osmundsen, P.T., Andersen, T.B., Roberts, D. & Kendrick, M.A. 2005: Modern techniques and Old Red problems – determining the age of continental sedimentary deposits with $^{40}Ar/^{39}Ar$ provenance analysis in west-central Norway. *Norwegian Journal of Geology 85*, 133–149.

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

Furnes, H., Ryan, P.D., Grenne, T., Roberts, D., Sturt, B.A. & Prestvik, T. 1985: Geological and geochemical classification of the ophiolite fragments in the Scandinavian Caledonides. *In* Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide Orogen – Scandinavia and related areas.* John Wiley & Sons, Chichester, 657–670.

Furnes, H., Pedersen, R.B. & Stillman, C.J. 1988: The Leka Ophiolite Complex, central Norwegian Caledonides: field characteristics and geotectonic significance. *Journal of the Geological Society, London 145*, 401–412.

Furnes, H., Skjerlie, K.P., Pedersen, R.B., Andersen, T.B., Stillman, C.J., Suthren, R.J., Tysseland, M. & Garmann, L.B. 1990: The Solund-Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: geology and tectonic environment. *Geological Magazine 127*, 209–224.

Gale, G.H. & Roberts, D. 1972: Palaeogeographical implications of greenstone geochemistry in the southern Norwegian Caledonides. *Nature 238*, 60–61.

Gale, G.H. & Roberts, D. 1974: Trace element geochemistry of Norwegian Lower Palaeozoic basic volcanics and its tectonic implications. *Earth & Planetary Science Letters 22*, 380–390.

Gass; I. 1980: The Troodos massif: its role in the unravelling of the ophiolite problem and its significance in the understanding of constructive plate margin processes. *In*: Panayiotou, A. (ed.) *Ophiolites*. Proceedings of ther International Ophiolite Symposium, Cyprus 1979, 23–35.

Gee, D.G. 1981: The Dictyonema-bearing phyllites at Nordaunevoll, eastern Trøndelag, Norway. *Norsk Geologisk Tidsskrift 61*, 93–95.

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. & 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, 727–743.

Grenne,T., Ihlen, P.M. & Vokes, F.M. 1999: Scandinavian Caledonide metallogeny in a plate tectonic perspective. *Mineralium Deposita 34,* 422–471.

Heim, M., Grenne, T. & Prestvik, T. 1987: The Resfjell ophiolite fragment, central Norwegian Caledonides. *Norges geologiske undersøkelse 409*, 49–72.

Horne, G.S. 1979: Mélange in the Trondheim Nappe suggests a new tectonic model for the central Norwegian Caledonides. *Nature 281*, 267–270.

Karson, J.A. 1998: Internal structure of oceanic lithosphere: a perspective from tectonic windows. *In* Buck, W.R., Delayny, P.T., Karson, J.A. & Lagabrielle, Y. (eds.) Faulting and magmatism at Mid-ocean Ridges. *American Geophysical Union 106*, 177–218.

Kautsky, F. 1977: Berggrundsbeskrivning over Jäfsjön-Langvatnet-Heggsjöfjellområdet. *Norges geologiske undersøkelse, Kartarkivet, original 179/85.055D*, 55 pp.

Kelley, D.S., Karson, J.A., 9 coauthors and the AT3-60 shipboard party. 2001: An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30°N. *Nature 412*, 145–149.

Kelley, D.S., Karson, J.A., Früh-Green, G.L. & 23 other coauthors 2005: A serpentinite-hosted ecosystem: the Lost City hydrothermal field. *Science 307*, 1428–1434.

Kendrick, M.A., Eide, E.A., Roberts, D. & Osmundsen, P.T. 2004: The Middle to Late Devonian Høybakken detachment, central Norway: $^{40}Ar/^{39}Ar$ evidence for prolonged late-/post-Scandian extension and uplift. *Geological Magazine 141*, 329–344.

Moores, E.M. 1982: Origin and emplacement of ophiolites. *Reviews of Geophysics and Space Physics 20*, 735–760.

Moores, E.M. & Vine, F.J. 1971: The Troodos Massif, Cyprus, and other ophiolites as oceanic crust: evaluation and implications. *Royal Society, London, Philosophical Transactions, A268*, 433–466.

Neuman, R.B. & Bruton, D.L. 1989: Brachiopods and trilobites from the Ordovician Lower Hovin Group (Arenig/Llanvirn), Hølonda area, Trondheim region, Norway: new and revised taxa and paleogeographic interpretation. *Norges geologiske undersøkelse Bulletin 414*, 49–89.

Nilsson, L.P., Sturt, B.A. & 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., Lindahl, I., Hembre, O.S. & Flaat, A. 2002: The mineral resources in Raudfjellet, Snåsa municipality, North Trøndelag county, Norway. *Prospect presentation*, 8 pp + 2 figures.

Nordgulen, Ø., Braathen, A., Corfu, F., Osmundsen, P.T. & Husmo, T. 2002: Polyphase kinematics and geochronology of the late-Caledonian Kollstraumen detachment, north-central Norway. *Norwegian Journal of Geology 82*, 299–316.

Norton, M.G. 1987: The Nordland-Sogn Detachment, W. Norway. *Norsk Geologisk Tidsskrift 67*, 93–106.

Oliver, G.H.J. & Krogh, T.E. 1995: U-Pb zircon age of 469 ± 5 Ma for a metatonalite from the Kjosen Unit of the Lyngen Complex, northern Norway. *Norges geologiske undersøkelse Bulletin 428,* 27–32.

Pedersen, R.B. & Fumes, H. 1991: Geology, magmatic affinity and geotectonic environment of some Caledonian ophiolites in Norway. *Journal of Geodynamics 13*, 183–203.

Prestvik, T. 1974: Supracrustal rocks on Leka, Nord-Trøndelag. *Norges geologiske undersøkelse 311*, 65–87.

Prestvik, T. 1980: The Caledonian ophiolite complex of Leka, north-central Norway. *In* Panayioutou, A. (ed.) *Ophiolites*. Proceedings of the International Ophiolite Symposium, Cyprus, 1979. Geological Survey of Cyprus, Nicosia, 555–566.

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

Roberts, D. & Gee, D.G. 1985: An introduction to the structure of the Scandinavian Caledonides. *In* Gee, D.G. & 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. & 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.

Ryan, P.D., Williams, D.M. & Skevington, D. 1980: A revised interpretation of the Ordovician stratigraphy of Sør-Trøndelag, and its implications for the evolution of the Scandinavian Caledonides. *In* Wones, D.R. (ed.) *The Caledonides in the USA*. Virginia Polytechnic, Geological Sciences, Memoir 2, 99–105.

Schroetter, J.-M., Page, P., Bédard, J.H., Tremblay, A. & 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. & Bergman, S. 1989: Asymmetric extension and Devonian(?) normal faulting; examples from the Caledonides of eastern Trøndelag and western Jämtland. (Extended abstract) *Geologiska Föreningen i Stockholm Förhandlingar 111,* 407–410.

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

Slagstad, T. 1998: *High-K_2O plagiogranite and greenstones in ophiolitic rocks of Bymarka, Trondheim.* Diploma thesis, Norwegian University of Science and Technology, Trondheim, 98 pp.

Sturt, B.A. & Roberts, D. 1991: Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. *In* Peters, T. et al. (eds.) *Ophiolite genesis and evolution of the ocean lithosphere.* Ministry of Petroleum & Minerals, Sultanate of Oman, 745–769.

Sturt, B.A. & Ramsay, D.M. 1999: Early Ordovician terrane-linkages between oceanic and continental terranes in the central Scandinavian Caledonides. *Terra Nova 11*, 79–85.

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

Sturt, B.A., Ramsay, D.M. & Bjerkgård, T. 1997: Revisions of the tectonostratigraphy of the Otta-Røros tract. (Extended abstract) *Norges geologiske undersøkelse Bulletin 433*, 8–9.

Størmer, L. 1941: Dictyonema shales outside the Oslo Region. *Norsk Geologisk Tidsskrift 20*, 161–169.

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

Van Roermund, H.L.M. 1989: High-pressure ultramafic rocks from the allochthonous nappes of the Swedish Caledonides. *In* Gayer, R.A. (ed.) *The Caledonide geology of Scandinavia*. Graham & Trotman, London, 205–219.

Van Roermund, H.L.M. & Bekker, E. 1984: Structure and metamorphism of the Tängen-Inviken area, Seve Nappes, central Scandinavian Caledonides. *Geologiska Föreningen i Stockholm Förhandlingar 105*, 301–319.

Vogt, J.H.L.1889: Funn av Dictyonema ved Holtsjøen, Holtålen. (Lecture, 16 November 1888). *Forhandlinger i Videnskabs-Selskabet i Christiania (for 1888)*. p.12.

Vogt, Th. 1945: The geology of part of the Hølonda-Horg district, a type area in the Trondheim region. *Norsk Geologisk Tidsskrift 25*, 449–528.

Wolff, F.C. 1979: Beskrivelsene til de berggrunnsgeologiske kartbladene Trondheim og Östersund 1:250 000. *Norges geologiske undersøkelse 353*, 77 pp.