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

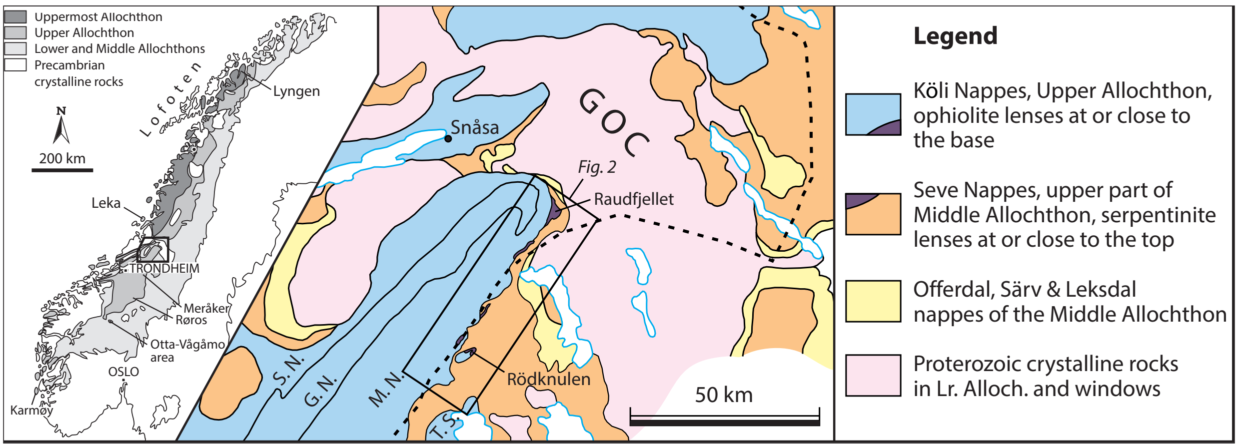

Figure 1. Simplified tectonostratigraphic map of the Raudfjellet region showing the locations of some of the ultramafic-mafic (ophiolitic) lenses discussed in the text. GOC – Grong-Olden Culmination; G.N. – Gula Nappe; M.N. – Meråker Nappe; S.N. – Støren Nappe; T.S. – Tännfors synform. The grey-tone 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

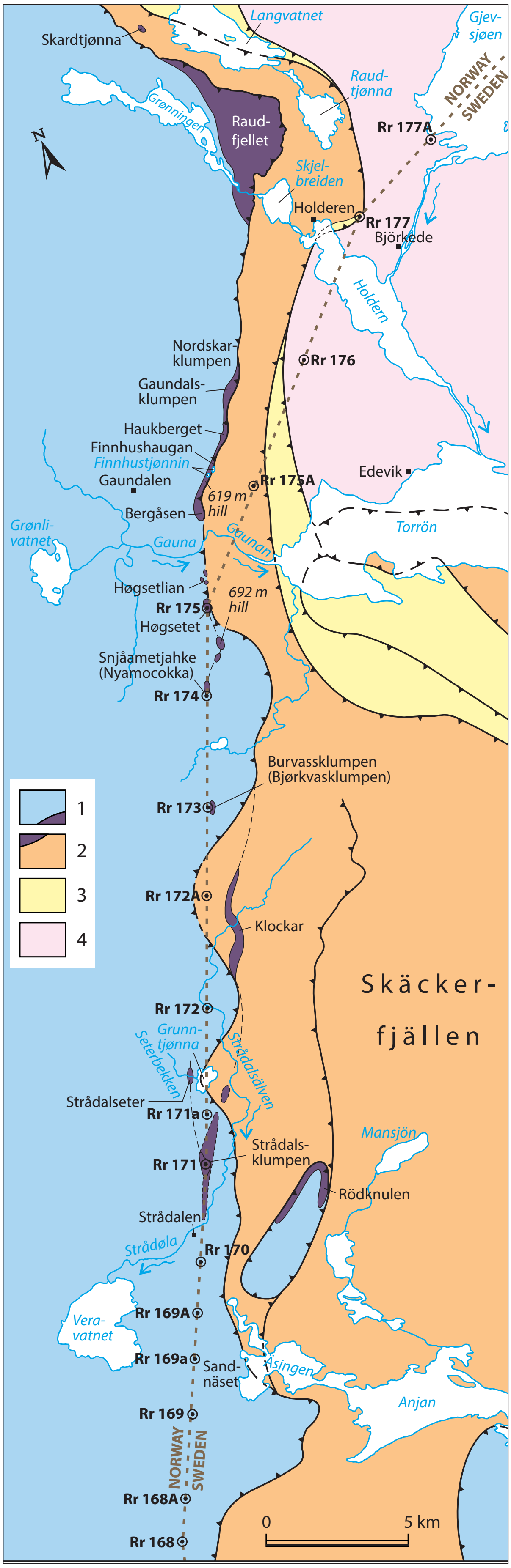

Figure 2. Locations of the ultramafic-mafic bodies and lenses between Skardtjønna and Raudfjellet in the northeast and Rödknulen in the southwest. As well as Foslie's field notebooks from 1934 and 1935, the sources used for the map compilation are (i) for the Norwegian side, Foslie (1959a, b), Wolff (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 – Snjåametjahke (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 *Snjåametjahke* 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

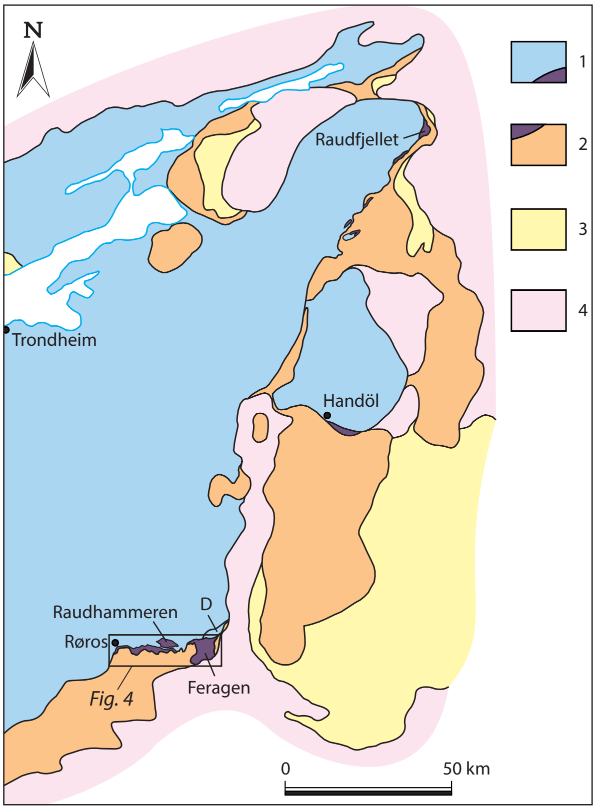

Figure 3. Tectonostratigraphic map of the eastern Trondheim Region, Tännfors synform and other allochthons in Jämtland. The colour scheme is the same as in Figure 1. The numbers in the legend refer to: 1. Köli nappes of the Upper Allochthon, with ophiolite lenses at or close to the base. 2. Seve nappes, 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

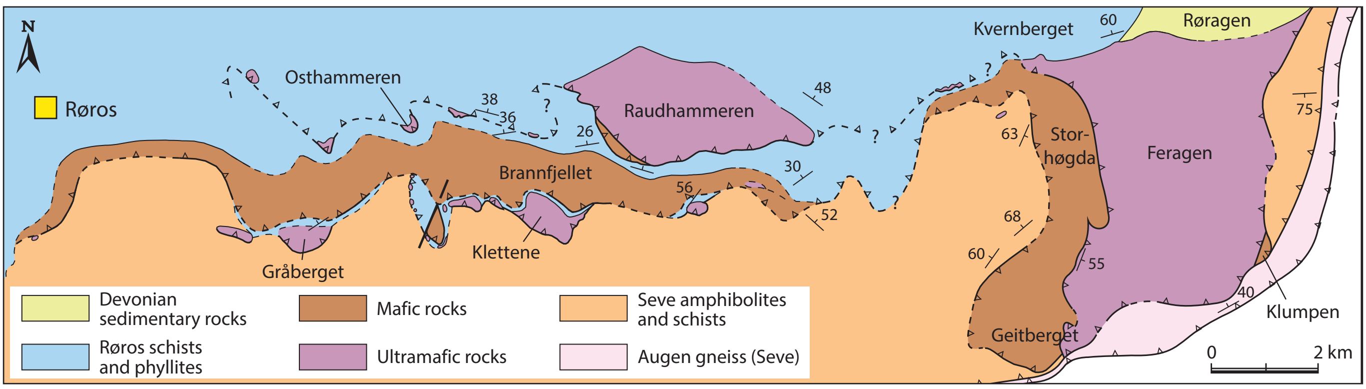

Figure 4. Simplified map of the Feragen-Raudhammeren-Røros district. Thrust contacts are shown as slightly thicker lines with small triangles on the hanging-wall side. The strike/dip symbols indicate foliation. The map is based on a manuscript map by B.A. Sturt, D.M. Ramsay and L.P. Nilsson, 1996-99, 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).

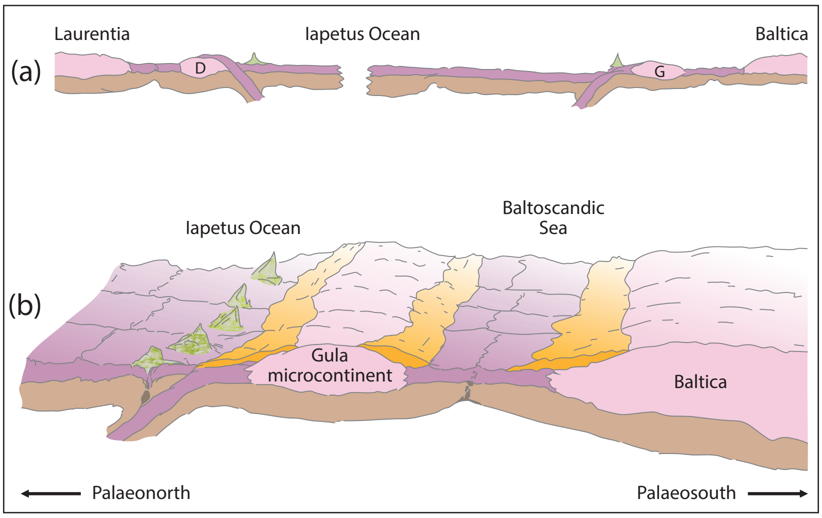

Figure 5. (a) The inferred Baltica-Iapetus-Laurentia palaeogeographical situation in latest Mid Cambrian-Early Tremadocian time, showing the Dashwoods (D) and Gula (G) microcontinents. Obduction of ophiolite on D occurred earlier (Late Furongian) than that on G (Late Tremadocian-earliest Arenig). (b) 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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