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Metamorphism of ultramafic rocks in the Central Scandinavian Caledonides

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Lenses and boudins of ultramafic rocks in the Central Scandinavian Caledonides (CSC) represent parts of dismembered ophiolite sequences and fragments of sub-continental upper mantle. The metaperidotites are isofacial with the metamorphic envelope, usually metasediments but in places also metagranitoids.
Metamorphic assemblages in metaperidotites of the CSC, together with additional geological constraints, define a regional metamorphic gradient of prograde metamorphism which passes through the approximate PT-coordinates (in C and kbars): 400/4, 500/6, 600/8, 700/9. The sequence of prograde metamorphic assemblages is (with increasing temperature): antigorite + brucite, antigorite + forsterite, forsterite + talc, forsterite + enstatite + chlorite, and forsterite + enstatite + green spinel. The maximum temperature was not sufficient to replace calcic amphibole by calcic pyroxene. Pargasite overgrowth on earlier tremolite demonstrates the prograde nature of the metamorphism. Most of the ultramafic rocks probably represent progressively metamorphosed serpentinites (mantle- or crustal serpentinites?). The regional distribution of assemblages in the ultramafic rocks of the CSC defines a regular pattern which cross-cuts the nappe boundaries of the area.

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Introduction

Various aspects of ultramafic rocks in the Scandinavian Caledonides have recently been summarized by Qvale & Stigh (1984) who also reviewed the ample literature on the subject. Ultramafic rocks occur very widely in the Scandinavian Caledonides in a number of different rock associations. Several hundred occurrences have been reported and detailed structural, petrological and mineralogical information is available for some of these occurrences (e.g. Calon 1979, Moore 1977, Moore & Hultin 1980, Ohnmacht 1974, Qvale 1978). A voluminous literature exists on some of the garnet peridotite occurrences of the Scandinavian Caledonides (e.g. the Almklovdalen garnet peridotites in the Western Gneiss Region, e.g. Medaris 1984, Carswell 1986).

Ultramafic rocks are found at all levels of the tectonostratigraphy (with the exception of the shallow-level sedimentary foreland nappes of the lower allochthon). Ultramafic rocks are generally subdivided into various categories according to their rock association. Most of the sample material used in this study falls into two major categories: ultramafites in ophiolite associations and solitary, isolated, ultramafic lenses and bodies in continental associations. The first group represents ultramafic fragments from an oceanic upper mantle environment; the second group may represent fragments derived from the upper mantle beneath the continental crust. The mantle source rocks of the ultramafic bodies collected in crustal associations are mineralogically characterized by olivine + Ca-poor pyroxene (Opx) + calcic pyroxene (Cpx) + Al-phase(spinel,garnet) +/-hydrates (amphibole,mica,talc, chlorite, antigorite). Typical rock types include dunites, harzburgites, lherzolites and partially or completely hydrated versions of these. Other ultramafic rock types including e.g. pyroxenites and other olivine-free rocks are not considered in this study. Ultramafic rocks in various associations have so far been collected from about 100 different localities ranging geographically from Bodø to Bergen (a town in SW Norway outside the area of Fig. 1), and tectonostratigraphically from the Western Gneiss Region to the Nordland-Troms nappe complex of the Uppermost Allochthon (Fig. 1).

Many of the ultramafites display relict assemblages and textures which in some cases may be related to a pre-Caledonian history. All collected ultramafites, however, were mineralogically and texturally modified to various extents by Caledonian metamorphism(s). It is the purpose of the project and the present study to use ultramafic (olivine-normative) rocks as sensitive indicators of the PT-regime during the Caledonian orogeny and of the metamorphic (thermal) pattern in the Scandinavian Caledonides.

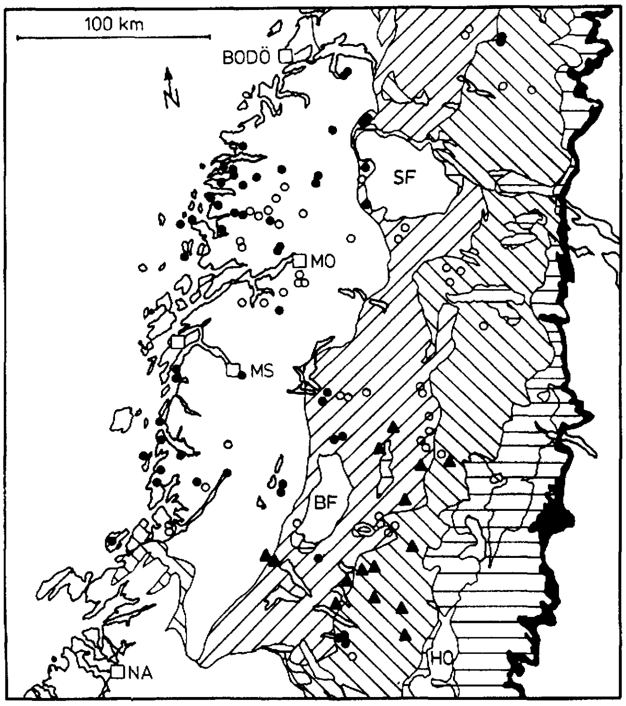

Fig. 1: Sample locality map. Filled circles: samples from visited localities (field relations and petrography known). Open circles: other localities (field relations and petrography unknown). Filled triangles:information taken from the literature. Geology: Dividal group, black: Lower and Middle Allochthon, horizontal ruled; Upper Allochthon (Seve), NW-SE-ruled; Upper Allochthon (Köli), NE-SW-ruled; white Uppermost Allochthon (ultramafites in the west), western gneiss region, basement windows and Baltic Shield (no ultramafic localities included in this study). SF = Saltfjellet, BF = Børgefjelletm HO = Hotagsfjellen, MO = Mo i Rana, MS = Mosjøen, NA = Namsos.

Ultramafites in the Central Scandinavian Caledonides

The follwing data presentation and discussion is restricted to the sector of the Scandinavian Caledonides between Namsos and Bodø (reports and communications on the other sectors will follow). A selection of ultramafic rock bodies is given In Fig. 1. The ultramafites occur predominantly in the Upper and Uppermost Allochthons. The size of the usually lensoid bodies ranges from several square kilometres to decimetre size. Many of the smaller bodies are chemically partially or completely modified by exchange metasomatism with the surrounding country rocks (black wall formation). Virtually hundreds of ultramafic bodies larger than 10 m have been found and mapped by the Norwegian Geological Survey (NGU).

The ultramafic rocks are closely associated with metasedimentary rocks of proven or assumed Caledonian age, although some of the occurrences along the northern part of the Helgeland coast are found in gneisses forming the pre-Caledonian cores of the nappes of the Svartisen area (see Figs. 2 and 4). The absence (or scarcity) of ultramafic rocks in the Baltic Shield rocks east of the Caledonian front (Stigh & Rogne 1978), together with the occurrence of the majority of the ultramafites in Early Paleozoic metasediments, suggests that the ultramafic bodies have been emplaced into their present crustal level during the Caledoninan orogeny. Consequently, the ultramafites under consideration represent fragments of Caledonian upper mantle. There are two main associations of ultramafites in the area of Fig. 1: (1) In ophiolite associations the ultramafites occur together with other characteristic rock types of the oceanic lithosphere (e.g. metabasalts with pillow structures). (2) Ultramafites in continental associations occur together with rocks characteristic for continental crust (e.g. metagranitoids, dolomite marbles). The distribution of ultramafic bodies within the two highest tectonic domains of the Scandinavian Caledonides as shown in Fig. 1 appears to be rather erratic and random. Their field relationships and detailed spatial distribution suggest, however, that the ultramafic bodies and lenses are strictly confined to thrust zones, major tectonic boundaries and nappe contacts. The distribution pattern shown in Fig. 1 is, therefore, the consequence of intensive polyphase folding and refolding which postdates nappe transport. Removing the post-nappe transport deformation allows for the recognition of the major thrust zones. Because these thrusts and shearzones are decorated with mantle fragments, they must have transected the MOHO.

The observed dominant association of Caledonian metasediments and mantle fragments may be a consequence of the continuation of crustal thrusts and shear-zones into the upper mantle. Modern analogues of mantle detachments and mantle faults have been described recently by Warner & McGeary (1987). A very schematic profile projection accross the nappe stack of the Svartisen area (locality 6, Fig. 4) illustrates a model for the emplacement of subcontinental mantle into continental crust along mantle faults and detachments (Fig. 2). The chains of ultramafic lenses shown in Fig. 2 may be traced for 100 km or more (e.g. Köli basal thrust in the Saltfjellet area). The emplacement of subcontinental and suboceanic mantle fragments into various levels of continental crust resulted in changes in their chemical, mineralogical and textural characterisitics.

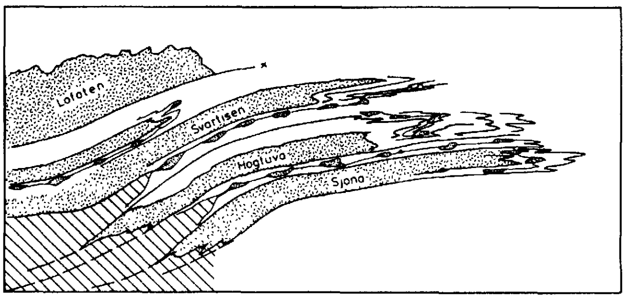

Fig. 2: Schematic cross-section of the Svartisen area showing the three pre-Caledonian cores of the Sjona, Høgtuva and Svartisen nappes, respectively (vertical scale about 70 km, horizontal scale about 200 km). White: Caledonian metasediments. Stippled: lenses and boudins of mantle framents aligned along thrust surfaces which are strongly folded and refolded. Ruled: subcontinental mantle with detachments (continuation of crustal thrusts).

Field and textural relationships

The majority of the ultramafic bodies shown in Fig. 1 are isofacial with their surrounding metamorphic envelope. In some low-grade occurrences the degree of re-equilibration is moderate, however, and many relict phases and assemblages survive. Fig. 3 shows the typical general mesoscale texture of ultramafic lenses and boudins aligned along a tectonic surface (or thrust zone).

Chemical potential gradients between the ultramafic material and the felsic (usually quartz-saturated) envelope resulted in the formation of more or less extensive metasomatic exchange zones, commonly typical zoned monomineralic blackwall sequences. Smaller bodies may be completely modified chemically (e.g. monomineralic actinolite boudins). Most of the ultramafic bodies are veined by late-stage reaction veins with a characteristic mineralogy. The vein assemblage is related to the metamorphic grade of the matrix assemblage (chrysotile + brucite veins in antigorite schists, anthophyllite veins in enstatite + forsterite rocks). Higher grade ultramafites may have been repeatedly fractured and veined during decompression and cooling. This resulted in a network of cross-cutting veins which display individual mineralogical characteristics dictated by the prevailing conditions along the PT-path. Many of the lenses at a number of localities are associated with meta-gabbroic dykes or irregular masses of gabbro. The mafic rocks are isofacial with the ultramafics and the metamorphic envelope. The association of mafic and ultramafic rocks is, however, clearly pre-transport and pre-boudinage as suggested by the evidence shown in Fig. 3 (with the notable exception of the Tollådalen locality, (no. 4, Fig. 4).

Another significant feature of the Caledonian ultramafics is the nearly universal presence of carbonate phases in various textures and assemblages in rocks of all metamorphic grades. Less than 10% of the collected material did not contain any carbonate phase. This is also the case for all localities outside the geographical range of Fig. 1. Carbonates (commonly magnesite) are modally very abundant at many localities. An interesting observation is that the interface between carbonate- rich and carbonate-poor portions of a given ultramafic lens is geometrically unrelated to the structural features of the envelope. It is also unrelated to the contact surface of the ultramafic body. This suggests that the carbonate formation was also a pre-transport and pre-boudinage process.

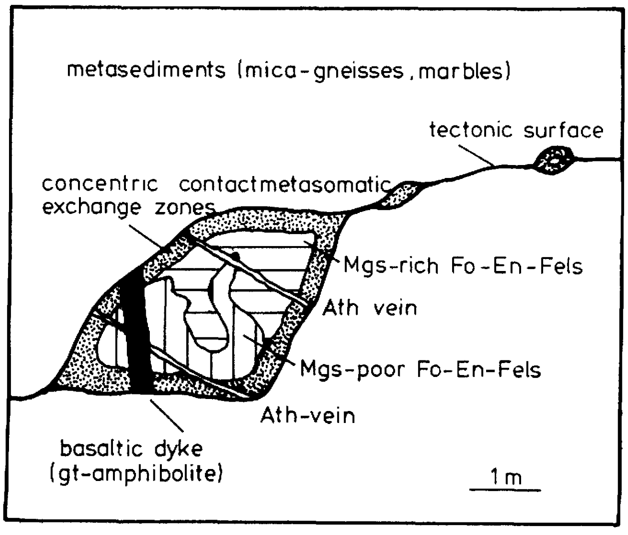

Fig. 3: Textural relationships of a small metaperidotite boudin.

Ultramafic assemblages from selected localities

In the following section some selected localities or groups of localities will be discussed in some detail. The selected localities are shown in Fig. 4 together with two major tectonic boundaries. These boundaries separate (a) the Nordland nappes of the Uppermost Allochthon in the west from the Köli complex in

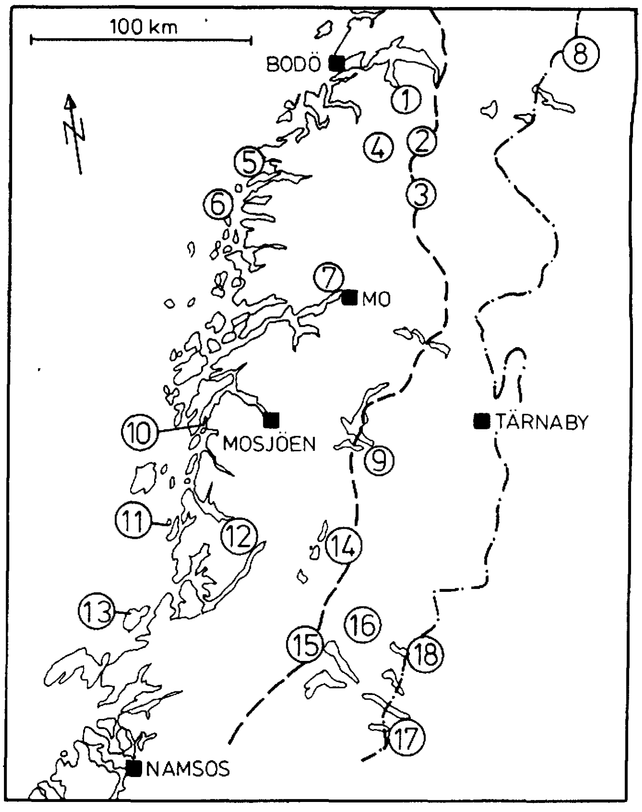

Fig. 4: Location of ultramafic rocks discussed in the text. Dashed line: boundary between Uppermost Allochton (in the west) and Köli complex, dash-pointed line: Seve/Köli boundary. (1) Misvær, (2) Hessihompan (Saltdal), (3) Bjøllådalen, (4) Beiardalen, (5) Ørnes, (6) coastal area west of Svartisen (Meløy-Rødøy), (7) Altermark, (8) Råvejaure, (9) Hattfjelldal, (10) Vefsenfjorden, (11) Vegafjorden, (12) Velfjorden, (13) Leka, (14) Bjørgefjell, (15) Steinfjellet, (16) Joma, (17) Murusjøen, (18) Ruotats.

the central part of the area, and (b) the latter from the Seve complex in the east (compare also with Fig. 1). The pressure-temperature estimates and characterization of the metamorphic grade given in this section are partly based on Fig. 6. The derivation of this figure will be presented in a later section.

(1) Misvær:

This is a group of relatively large ultramafic bodies with a heterogeneous chemistry but dominated by lherzolitic bulk compositions. The ultramafic lenses are situated near the base of the Beiarn Nappe, and are associated with metasediments (paragneisses, marbles, quartzites) and occur in close proximity to granitic intrusions. The rocks show complex polyphase assemblages and tectures.

The earliest phase is represented by a ghost fabric of fine-grained magnetite defining an old foliation. The foliation was subsquently overgrown by coarse forsterite and enstatite (peak assemblage). The stable calcic and aluminous phases at this stage were tremolite and chlorite, respectively. The forsterite + enstatite assemblage is of prograde metamorphic origin (probably from crustal contact metamorphism of either crustal or mantle serpentinite). The peak assemblage (En + Fo + Tr + Chl: note, all abbreviations of mineral names after Kretz (1983); Spl is used for prograde green spinel) was subsequently modified by two distinct hydration episodes which produced (a) forsterite + talc and (b) later antigorite. The latest stage assemblage Atg + Fo + Tr is isofacial with the assemblages in the underlying Fauske marbles. Post-peak, but still early, anthophyllite veins were considerably modified by later talc formation. A generation with antigorite veins transects earlier vein systems. Magnesite occurs in the association En + Fo + Tlc + Mgs.

(2) Hessihompan and (3) Bjøllådalen:

Three large lenses (each some hundred metres in length) are aligned along a major tectonic zone, the basal thrust zone of the Köli Nappe Complex. Around the Saltfjellet gneiss window, the Caledonian nappe stack is tectonically strongly reduced. The rocks are geologically very similar to the lenses at locality 3, Bjøllådalen (Semskefjellet).

The peak assemblage Fo + Tlc + Tr + Chl is characteristic for middle amphibolite facies conditions. A reasonable estimate for conditions of metamorphism in the Köli rocks along the western rim of the Saltfjellet gneiss complex is about 580 - 640°C at 6 to 8 kbars. The absence of migmatites and the typical assemblage in the metapelites (staurolite + quartz + kyanite + biotite + muscovite + garnet) restricts the maximum temperature to values below that of talc + forsterite of ca. 680°C. It must be noted that the above PT conditions are in situ conditions post-dating the formation of the nappe stack. All rocks of the area have been subjected to theses conditions, including the gneisses of the Saltfjellet window and its parautochthonous cover (alum shale).

(4) Beiardalen (Tollådalen):

There are two types of ultramafic bodies in Tollådalen, metapyroxenites and metaserpentinites. Both types are closely associated with a gabbro intrusion. The gabbros postdate the formation of the nappe stack and intruded metasediments (marble xenoliths in the gabbro contain: spinel + clinohumite and grossular + vesuvianite assemblages). Contact metamorphism in the ultramafites produced En + Fo + Tr + Chl + green-brown spinel as the maximum temperature assemblage (700 - 750°C). Field relationships suggest that there is no genetic relationship between the forsterite-enstatite felses and the gabbro stock. It is rather suggested that the high-grade ultramafics represent partially dehydrated serpentinites of lherzolitic bulk chemistry (this is in contrast to the mentioned metapyroxenites which are clearly genetically related to the gabbros). The ultramafites show very abundant metasomatic reaction veins (predominatly Ath veins) of up to 20 cm thickness. The matrix assemblage En + Fo was partially replaced by Ath, Tlc and Mgs during cooling. In some portions of the bodies volume alteration of forsterite to calcic amphibole can be detected. The process may be described by the schematic reaction: 5 Fo + 11 $SiO_{2(aq)}$ + 4 $CaCl_2^{\circ}$ + 4 H_2O --> 2 Tr + 4 HCL° (where $SiO_{2\ (aq)}$ denotes the aqueous silica complex ($CaCl_2^{\circ}$ stands for the aqueous calcium chloride complex). The operation of this general reaction which replaces forsterite by tremolite can be demonstrated in many ultramafic lenses. This in turn shows that it may be difficult to distinguish primary harzburgitic from lherzolitic rock compositions because much of the calcium found in the ultamafites may be of crustal origin.

(5) The Ørnes (Meløy) body:

This body is a typical representative of the highest grade ultramafites in the area of Fig. 1. The assemblage En + Fo + pargasite + green spinel + chlorite indicates a maximum temperature of 750°C at pressures near 10 kbar (base of the stable continental lower crust, Fig. 2). The prograde character of the assemblage is indicated by zoned calcic amphiboles with tremolite cores and paragasite rims. In some samples forsterite is extensively replaced by magnesite and enstatite. Abundant anthophyllite veins postdate the carbonatization of the ultramafites.

(6) Coastal area west of Svartisen:

A large number of localities of ultramafites are found in this area including Hestmona, Rødøy, Grønøy, Holandsfjorden, Melfjorden, Værnes and many others. All these occurrences are relatively similar. The maximum PT assemblage is En + Fo + Tr (or pargasite) + Chl +/- Spl. A later overprint resulted in the formation of magnesite and late talc. Most samples are free from late antigorite. Very coarse grained enstatite + magnesite rocks are characteristic for the area. The assemblage formed at the expense of forsterite according to the reaction: Fo + $CO_2 \rightarrow$ Mgs + En. The reaction replaces earlier formed prograde (from serpentinite) forsterite at the metamorphic peak conditions or slightly lower conditions. The only preserved mantle phase seems to be chromite and at Grønøy calcic pyroxene. The latter, however, may also represent a relic from a serpentinite precursor stage. In several samples three spinel phases are present: green prograde hercynitic spinel, magnetite and probably mantle (?) chromite. Metamorphic conditions for the peak assemblage are in the range of 680 - 750°C at 9-10 kbars.

(7) Altermark:

The ultramafic bodies at Altermark are fully hydrated (or carbonated) metaharzburgites. The textures suggest that two reactions modified the chemistry of the ultramafites: Fo + CO_2 + H_2O →Atg + Mgs and Atg + $SiO_{2(aq)}$ + H_2O →Tlc. The talc + antigorite assemblage resulted from SiO_2 metasomatism of antigorite schist. The regional metamorphic assemblage was most probably Atg + Fo. This indicates, together with the assemblages in metapelites (Grt + Chl + Bt), marls (Pl + Zo + margarite) and dolomitc marbles (Dol + Cal + Qtz + Tr), metamorphic conditions of about 480 - 520C at 4 - 6 kbars (upper greenschist facies to the beginning of amphibolite facies). The metamorphic grade in large portions of the Mo i Rana area is relatively low (lower than for example in the Köli complex to the east of Mo).

(8) Råvejaure (Tsækokk, Vaimok)

The geology of the area has been described recently by Kullerud (1987). The ultramafic rock samples from this locality were made available by Kullerud. The ultramafic lenses are associated with eclogites and belong tectonically to the Seve complex. Kullerud's (1987) estimate for the metamorphic conditions during eclogite formation is 680° C and 14 kbar. The typical assemblage in the ultramafic rocks is Fo + En + green spinel and pargasite (no Chl!). It belongs to the highest grade rocks found in the entire area of Fig. 1. The temperature estimate on the basis of the above assemblage is about 750°C and, therefore, higher than Kullerud's estimate based on conventional eclogite geothermometry. The reason for this discrepancy is not yet clear.

(9) Hattfjelldal (Røssvatnet)

A large number of ultramafic bodies occur in the lower units of the Köli complex in the Hattfjelldal area. These are predominantly fully hydrated metaharzburgites. Atg + Fo and Atg + brucite are typical assemblages. Carbonate-rich varieties are relatively rare. Late chrysotile is particularly abundant in sheared (or fractured) rocks. The maximum metamorphic temperature of the antigorite-brucite-forsterite schists was around 400°C (middle greenschist facies, biotite or chloritoid zone in metapelites). Ultramafic lenses of the uppermost allochthon collected by W. Dallmann some hundred metres above the major thrust separating the Köli complex from the Helgeland Nappe Complex have an identical mineralogy and hence a metamorphic grade like the ultramafites in the Köli complex. The assemblage Atg + Tlc + Mgs requires temperatures below 450 - 480°C. Blackwall formations around the ultramafic lenses (Chl + Tr + Tlc) and wall rock assemblages (Ep + Qtz + Ms + Pl) are consistent with the temperature estimate above. The in situ greenschist facies metamorphism postdates nappe transport and affects both the Helgeland and the Köli nappe complexes. An older metamorphism of unknown age affected the rocks of the Helgeland Nappe in the Hattfjelldal area (lower to middle amphibolite facies).

(10) Vefsenfjorden:

This includes Rødøy and other localities south of the Sju Søstre mountains. The ultramafic bodies in this area most likely represent parts of the same dismembered ophiolite sequence which may be found at localities 11, 12, and 13 of Fig. 4, stretching from Rødøy to Leka. The typical assemblage is Atg + Fo and the calcic phase, if present is calcic pyroxene. Its chemical composition suggests, however, that the pyroxene does not coexist with Atg + Fo (earlier phase). Chromite seems to be a very early phase and chlorite was the stable Al phase during the main metamorphic episode.

The Rødøy body contains, in layers and patches, metamorphic and partly hydrated equivalents of dunites, harzburgites and lherzolites. Carbonated versions contain the typical assemblages Atg + Tlc + Mgs + Tr or Atg + Mgs + Fo. A temperature estimate of 450 to 500°C seems to be realistic for the area.

(11) Vegafjorden

This includes some localities west and north of Brønnøysund. The ultramafites are characterized by the stable assemblage Fo + Atg + Tr + Chl +/- Mgs. Critical assemblages in matapelites indicate conditions near equilibrium of the discontinuous AFM-reactions (a) Grt + Chl →St + Bt and (b) St + Chl. Together, the assemblages are consistent with metamorphic conditions near 500-550°C. and 5 - 6 kbars.

(12) Velfjorden

The localities at Heggefjord and Sausvatnet east of Brønnøysund belong to this group. The ultramafic bodies are of high metamorphic grade with typical peak assemblages En + Fo + Tr + Chl/Spl +/- Mgs. The textures of these rocks suggest a complex metamorphic evolution. It is apparent that the precursor rocks of the high-grade ultramafites were hydrated versions of lherzolites (and/ or harzburgites), most probably antigorite schists. Common for the rocks of this area are the extremely elongated olivine (forsterite) crystals which are commonly found in contact-metamorphic terrains (pseudo-spinifex textures, e.g. Evans 1977). The unusual texture may be diagnostic for rapid crystal growth in regimes with a very high heating rate and with much dehydration water present. The peak assemblage mentioned above was subsequently modified by partial re-hydration (talc and later antigorite again). The observations suggest that regional metamorphism of the area did not exceed the conditions of the greenschist/amphibolite facies transition zone similar to the locality groups 10 and 11.

(13) Leka:

Ample literature is available on the ophiolites of Leka (e.g. Prestvik 1972a, Prestvik 1980 Furnes et al. 1988). The Caledonian metamorphic overprint of the ultramafic members (both mantle rocks and ultramafic cummulates) of the ophiolite complex is only poorly known. Early relict phases (mantle phases) include olivine, clino- and orthopyroxene, and chromite. All typical mantle rock types are represented, dunites, harzburgites, and lherzolites with a typical ophiolitic short-range compositional layering. The Caledonian metamorphism seems to be below the stabilty field for forsterite in the presence of excess water. The textural relations are somewhat unclear. Atg + Fo represents a possible relatively early Caledonian assemblage, the main assemblage, however, seems to be Brc + Atg suggesting conditions below about 400°C which would be broadly consistent with the reported chloritoid in metapelitic schists of the area (Prestvik 1972b).

(14) Børgefjell

The swarm of small ultramafic lenses west of the Børgefjell gneiss complex contains Fo + Tlc + Tr + Chl, a typical mid-amphibolite facies assemblage (550 650°C). Carbonate phases are absent, and the total rock chemistry is lherzolitic. This represents also the potential equilibrium assemblage for the Helgeland basal thrust ultramafics in the Hattfjelldal area prior to late shearing and re-equilibration.

(15) Steinfjellet:

All information about the localities are taken from Lutro (1979). Lutro describes Atg + Fo + Mgs in ultramafics at the base of the Helgeland Nappe Complex and Atg + Fo in ultramafics of the Köli complex. There is, altogether, not much evidence in this particular area for a distinct metamorphic break across the boundary of the Upper and the Uppermost Allochthons. However, there is clear evidence for a decreasing metamorphic grade within the Köli complex towards the east.

(16) Joma:

The ultramafites of the Joma area represent low metamorphic conditions. Atg + Tlc is of little diagnostic value but in any case indicates temperatures below ca. 550°C. Abundant very low-grade graphite schists associated with the ultramafites suggest much lower temperatures, however. A temperature near 400°C seems to be a more realistic estimate. It is interesting to note that the large-scale chain of lenses of ultramafic bodies within the Köli complex (lower Köli (?)) displays a metamorphic overprint ranging from about 400°C in the south to 600-650°C in the Saltfjellet area, and similar (or higher) conditions have been reported from the Narvik area further north (Crowley & Spear 1987).

(17) Murusjøen

Along the Norwegian/Swedish border near Gäddede (Murusjøen area), a large number of ultramafic bodies belonging to the Seve complex (western belt) exhibit relatively high-grade metamorphic assemblages: En + Fo + Tr + Chl. The assemblages indicate typical middle to upper amphibolite facies conditions 650 - 700°C at 6 - 8 kbars). Metapelites of the area contain staurolite + garnet + kyanite + biotite. Interesting silica-deficient wall-rocks developed along some of the ultramafic country rock contacts. In particular, corundum - kyanite-staurolite - zoisite - margarite - biotite assemblages are quite unusual, indicating pressures greater than ca. 7 kbars and deserve further investigation.

(18) Ruotats

The metamorphic characteristics of many of the ultramafic bodies within the Köli/Seve nappe complexes in the southeastern area of Fig. 1 (triangles) have been summarized in an excellent thesis by Calon (1979). He reports that all the Köli ultramafites are of Fo + Atg + Di + Chl + Mgs grade, corresponding to about 450°C with early high-grade relics preserved locally (Ol + Opx + Cpx + Spl). Metapelites are of a consistent chlorite/biotite grade. Ultramafites from the Seve complex show a very wide range of metamorphic conditions. All the bodies are isofacial, however, with their matrix rocks (metasediments, meta-mafic rocks). The ultramafites of the eastern and western Seve belts contain Fo + Atg + Tlc + Tr + Chl in accordance with the Ky + St assemblage of the metapelites in the envelope (around 550°C). Ultramafic rocks of the central belt are of higher grade, Fo + En + Tr + Chl + Mgs, which is consistent with the Sil + Kfs assemblage in gneisses (ca. 700°C). At Ruotats proper aluminous ultramafites contain the assemblage garnet + olivine and are associated with eclogites. The situation seems to be similar to the Seve units further north (see locality 8). In general, very little is known about the obviously complex polymetamorphic and polyphase history of the Seve complex. It is quite possible that the metamorphic grade displayed by the Köli units represents the effects of the latest post-deformational regional metamorphism.

Regional distribution of some Al-bearing minerals and of the Fo + Ath assemblage

Fig. 5 shows the distribution pattern of chromite, Al-spinel, garnet and the assemblage anthopyllite + forsterite in the ultramafites of Fig. 1. Chromite is considered to be an early (mantle) phase. It is always associated with younger magnetite and usually also with chromium-bearing chlorite. Texturally chromite is a relict phase and its occurrence is unrelated to the pattern of Caledonian regional metamorphism. Prograde spinel formed from the decomposition of Mg-chlorite under upper amphibolite facies conditions or in the contact aureoles of the Velfjorden localities (locality 12, Fig. 4). The green prograde spinel is a hercynite - spinel (sensu stricto) solid solution. Magnetite + chlorite replace hercynitic spinel along the cooling and decompression path. Garnet + forsterite has been described from one locality in the central Seve complex (Du Rietz 1935) (No. 18, Fig. 4). The relict Grt + Ol assemblage has been almost completely replaced by pargasite + spinel (Calon 1979).

The assemblage anthopyllite + forsterite occurs relatively widespread in the ultramafic bodies of the area under consideration. The textures suggest that the assemblage is retrograde: it was found exclusively in rocks with a relict assemblage enstatite + forsterite. This may indicate that the regional metamorphic gradients (dP/dT) were large (high -pressure, medium-temperature type, see Fig. 6 and discussion below).

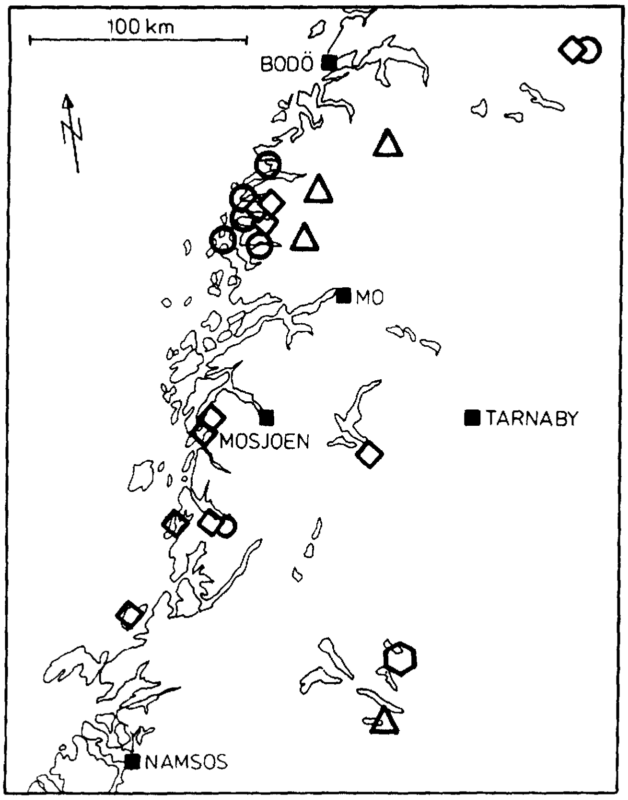

Fig. 5: Distribution of primary pre-Caledonian chromite (diamonds), green Caledonian spinel (circles), garnet (hexagon), and anthophyllite + forsterite (triangles) in metaperidotites.

Phase relationships in the CMASH system

The phase relationships in ultramafic rocks can be discussed in the system CMASH (C=CaO, M=MgO, A=Al_2O_3, S=SiO_2, H=H_2O). A large volume of experimental data, both calorimetric studies of individual mineral phases and phase equilibruim studies, is available for phases and phase assemblages in this system. These data tightly constrain the thermodynamic properties of mineral phases and reaction equilibria in this system.

Fig. 6 shows the calculated phase relationships for CMASH rocks. Within the area shown in Fig. 1 the stable prograde Caledonian assemblages found in ultramafic rocks can be placed into different pressure temperature fields of the calculated phase diagram (Fig. 6). The critical assemblages are (in order of increasing grade): brucite + antigorite, forsterite + antigorite, talc + forsterite, forsterite + enstatite + chlorite, and forsterite + enstatite + spinel.

The assemblages are separated by the equilibria numbered in Fig. 6 and listed in Table 1. The CaO component, if present, is stored in either diopside (at low and very high metamorphic grades) or tremolite (at intermediate grades).

The scarcity of appropriate bulk compositions (metalherzolites) in the lower amphibolite facies areas of Fig. 1 and the insufficient sampling density precluded further subdivision of the antigorite + forsterite field by means of reaction 2 (Table 1, Fig. 6). None of the collected rocks from the high-grade coastal area west of Svartisen (diamonds in Fig. 6) contained diopside as a product of reaction 6. However, calcic amphibole in these rocks (in aluminous ones) is of pargasitic composition. In many samples pargasite overgrows earlier tremolite. This demonstrates very convincingly

Table 1: Reactions and equilibria in the CMASH system. (same numbers as in Fig. 6).

1)	ATG + 20 BRC = 34 FO + 51 H2O
2)	ATG + 8 DI = 18 FO + 4 TR + 27 H2O
3)	ATG + 18 FO + 4 TLC + 27 H2O
4)	9 TLC + 4 FO 5 ATH + 4 H2O
5)	ATH + FO = 9 EN + H2O
6)	TR + FO = 5 EN + 2 DI + H2O
6A)	AMPHIBOLE + OLIVINE => OPX + H2O
7)	TLC + FO = 5 EN + H2O
8)	CHL = FO + 2 EN + SP + 4 H2O
8A)	CHLORITE => OLIVINE + OPX + Fe-Mg SPINEL + H2O
9)	ATG + 14 TLC = 90 EN + 55 H2O
10)	ATG = 14 FO + 20 EN + 31 H2O

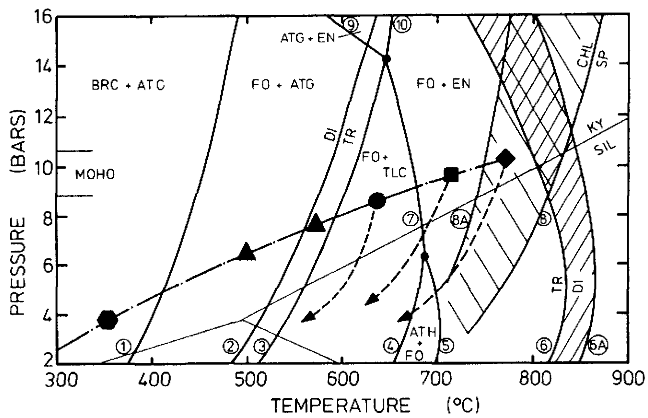

Fig. 6: Calculated phase-relationships for metaperidotites using thermodynamic data for the solids of Berman et al. (1985), for H20 of Kerrick & Jacobs (1981), and the PTX code of Perkins et al. (1986). The equilibria (1) through (10) are for the pure CMASH system and are listed in Table 1. Curve 6A represents an approximate limit for pargasitic amphibole in metaperidotite, curve 8A represents the first appearance of hercynitic spinel in natural metaperidotites. The positional range of the subcontinental MOHO and the aluminosilicate phase-diagram are given for comparison. The heavy point-dashed line represents the general metamorphic gradient in the Central Scandinavian Caledonides. Filled geometrical symbols along the metamorphic gradient are the same as in Fig. 7. Dashed curves indicate the decompression (cooling) path of the three higher grade assemblages. Note that late-stage anthophyllite can only form from the highest grade assemblages.

the prograde metamorphic character of these ultramafic bodies. On the other hand, pargasite + forsterite will be replaced by Cpx and Opx at significantly higher temperatures than indicated by equilibrium 6 (Fig. 6). An approximate upper limit for pargasite + forsterite is also shown in Fig. 6 (equilibrium 6A).

The upper temperature limit for chlorite in natural ultramafic rocks is at a lower temperature than in the pure MASH system (equlilibrium 8A and 8 in Fig. 6, respectively, and Table 1) because additional components (Fe mainly, but also Cr, Ni) are strongly partitioned into the spinel phase. Green hercynitic prograde spinel commonly occurs together with Mg-chlorite, which suggests conditions of the ruled divariant field of Fig. 6 limited by the curves 8 and 8A respectively (occurrences shown in Figs. 5 & 7).

The observed assemblages may be placed on a tentative regional metamorphic gradient (dash-pointed line, Fig. 6). The shape and location of the metamorphic gradient is given by the regional presence of coarse kyanite in various rock types. The aluminosilicate equilibria are also shown in Fig. 6. Sillimanite usually appears as a late retrograde phase, which may be related to the cooling and decompression path as indicated in Fig. 6 (dashed path). The high-grade termination of the PT-array of Fig. 6 (coastal area west of Svartisen, Fig. 4) may have been relatively close to the kyanite-sillimanite equilibrium. The general metamorphic gradient for the area of Fig. 1 is further supported by the occurrence of kyanite + zoisite in various rock types at scattered localities which have been metamorphosed at about 650°C indicating pressures > 8 kbars (Bucher-Nurminen et al. 1983).

In addition, available pressure-temperature estimates from conventional thermobarometry from the Köli complex north of the area shown in Fig. 1 (Crowley & Spear 1987) are very similar to the PT-array shown in Fig. 6. Furthermore, PT-arrays from a thermobarometric profile through the Caledonian nappe stack in western Ofoten (Steltenpohl & Bartley 1987, Hodges & Royden 1984, Royden & Hodges 1984) are nearly identical to the one proposed in Fig. 6. Although the range of metamorphic conditions covered by these recent studies is considerably smaller, it is evident that all Caledonian metamorphic rocks of the entire area between the Grong-Olden culmination and Ofotfjorden define a consistent Caledonian PT-array irrespective of the tectonostratigraphic position of the rocks.

It is also interesting to note that no prograde anthophyllite + forsterite assemblage have been observed in the ultramafic rocks (see above). Anthophyllite occurs in late hydrothermal veins and as a phase replacing earlier high-pressure type metamorphic gradient and a decompression path as shown in Fig. 6. The size of the stability field for anthophyllite + forsterite is very sensitive to the bulk Fe/Mg ratio of the rock.Increasing Fe/Mg in the bulk rock significantly enlarges the Ath + Ol field (Trommsdorff 1983). The effect amplifies the argument made above. In many enstatite + forsterite rocks the high-grade assemblage is directly replaced by talc + forsterite by reaction 7 (Table 1, Fig. 6).

Regional distribution of metamorphic assemblages in the CMASH system

The regional distribution of critical assemblages in the CMASH system is shown in Fig. 7. The distribution pattern is remarkably (and surprisingly) regular, particularly in the northern part of Fig. 7. The sample density is not yet sufficient for a reliable mapping of reaction isograds. However, some general features are evident (compare also with comments made in the chapter 'Ultramafic assemblages from some selected localities'): The highest grade Caledonian metamorphic core area is the coastal area west of Svartisen. A systematic decrease in metamorphic grade can be observed toward the southeast. The isograds cut the nappe boundaries of the Uppermost Allochthon nappe complexes at high angles. The metamorphic temperature range is about 200°C. The rocks of the Mo i Rana area define a thermal low area which may possibly be correlated with the thermal low along the southern Helgeland coast. The coastal area southwest of Mosjøen (Helgeland coast) is a clear metamorphic low area, with some superimposed

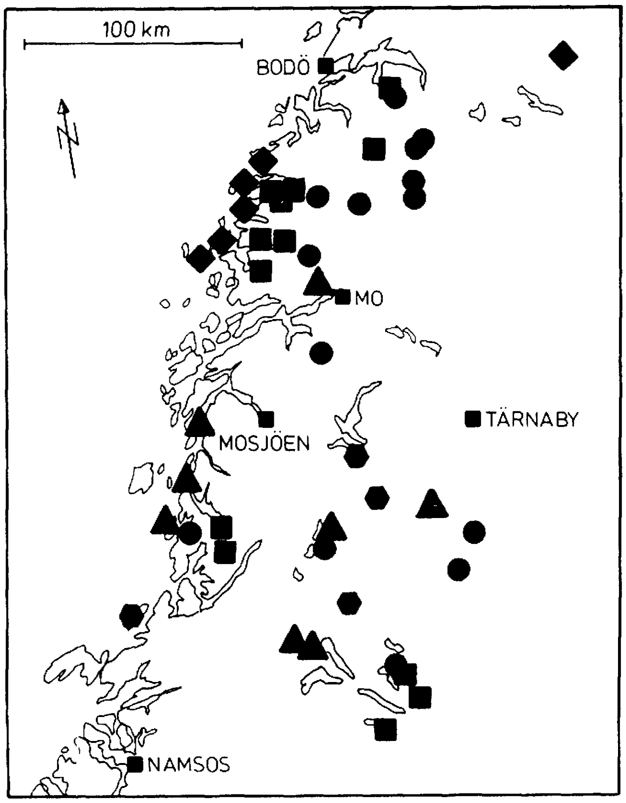

Fig. 7: Regional distribution of critical assemblages in the CMASH system in metaperidotites due to the Caledonian metamorphism. Hexagons: BRC + ATG, Triangles: ATG + FO + DI/TR, Circles: FO + TLC, Squares: FO + EN + TR + CHL, Diamonds:. FO + EN + TR + SP.

complications caused by late contact aureoles around Caledonian intrusions. The general picture in the southeast area of Fig. 7 is somewhat heterogeneous at present. A part of the problem comes from the difficulty in separating pre-Caledonian, early-Caledonian (high-pressure) and main Caledonian (Barrovian) events in the ultramafics of the Seve Nappe Complex (Calon 1979, Claesson 1987, Williams & Claesson 1987, Kullerud, 1978). With improved age information, much of the ambiguities could be resolved.

Additional aspects

Additional aspects of Caledonian metamorphism of ultramafics not discussed in this short progress report include: the presence of carbonate phases in many of the observed assemblages, the phase relationships of carbonate-bearing ultramafics, processes of carbonate formation in ultramafics, the processes of early serpentinization and carbonatization, the tectonic setting and position during the serpentinization process, the source of the aqueous fluid (and carbon dioxide), the distribution of distinct ultramafics in the pre-Caledonian mantle, the possible presence of partially serpentinized ultramafites in the upper mantle, the emplacement of the ultramafic rocks in continental crustal material, and many others.

Acknowledgements

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Norwegian ILP Contribution No. 63.

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