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REPORT

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Title:
Guidebook to the Field Excursions in the Nordfjord – Stadtlandet – Almklovdalen Area

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Summary:
This report is a guidebook for the field excursions conducted during the Alice Wain Memorial West Norway Eclogite Field Symposium held in Selje from June 21st-28th, 2003. Eskola (1921) drew attention to some of the aesthetically impressive eclogites and garnet peridotites that outcrop in the coastal region of west Norway between Bergen and Trondheim. These occurrences lie within the so-called Western Gneiss Region (WGR), the lowest exposed structural level in the southern Scandinavian Caledonides. The WGR is now recognised as a composite tectono-metamorphic terrane that mostly comprises Proterozoic autochthonous to para-autochthonous basement rocks with minor late Proterozoic cover belonging to the leading edge of the Baltic Plate, along with infolds of the main, outboard-derived Caledonian allochthon. Much of this composite edifice experienced short-lived deep level subduction beneath the Laurentian Plate during the Scandian phase of the Caledonian orogeny. When coupled with the symposium presentations, the field excursions conducted during the symposium week and described herein are designed to give the symposium delegates an opportunity to observe and discuss the geologic history of these high- and ultrahigh-pressure rocks.

Keywords: Eclogite	Gabbro	Ultrahigh-pressure
Peridotite	Western Gneiss Region	Scandian
Subduction	Coesite	Microdiamond

ALICE WAIN MEMORIAL

WEST NORWAY ECLOGITE FIELD SYMPOSIUM

JUNE 21st – 28th, 2003 in SELJE, WEST NORWAY

GUIDEBOOK TO THE FIELD EXCURSIONS

IN THE NORDFJORD – STADLANDET – ALMKLOVDALEN AREA

edited by D. A. (Tony) Carswell

CHAPTER 1:
REVIEW OF THE MINERALOGICAL AND MICROSTRUCTURAL EVOLUTION OF ULTRA-HIGH PRESSURE ECLOGITES IN THE WESTERN GNEISS REGION OF NORWAY

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(a) Historical background to ultra-high pressure metamorphism in the Western Gneiss Region of Norway

Eskola (1921) drew attention to some of the aesthetically impressive eclogites and garnet peridotites that outcrop in the coastal region of west Norway between Bergen and Trondheim. These occurrences lie within the so-called Western Gneiss Region (WGR), the lowest exposed structural level in the southern Scandinavian Caledonides. The WGR is now recognised as a composite tectono-metamorphic terrane that mostly comprises Proterozoic autochthonous to para-autochthonous basement rocks with minor late Proterozoic cover belonging to the leading edge of the Baltic Plate, along with infolds of the main, outboard-derived Caledonian allochthon. Much of this composite edifice experienced short-lived deep level subduction beneath the Laurentian Plate during the Scandian phase of the Caledonian orogeny. Several more recent papers, including those by Andersen et al, (1991); Carswell et al (2002); Cuthbert et al (1983, 2000); Cuthbert & Carswell (1990); Dewey et al (1993); Griffin et al (1985); Krogh & Carswell (1995); Smith (1995), have considered the stabilisation and exhumation of eclogites and other cofacial high pressure (HP) and ultra-high pressure (UHP) rocks in this region, within the context of the tectono-metamorphic development of this segment of the Scandinavian Caledonides.

Smith (1984) provided the first description, as well as confirmation by Raman spectroscopy, of an occurrence of coesite within an eclogite in the WGR. This coesite is preserved (armoured within omphacite in turn enclosed in garnet- see Figure 1-1) within a small, partly retrograded, eclogite pod at Grytting, near Selje, in the SW part of the Stadlandet peninsula. Interestingly, but perhaps just coincidentally, this coesite-bearing eclogite outcrops closely adjacent to the more spectacular-looking coarse-grained orthopyroxene eclogite (Fig. 1-2) described by Eskola (1921). Importantly, thermobarometric evaluation by Lappin & Smith (1978) and Cuthbert et al (2000) of samples of this orthopyroxene eclogite indicates formation under UHP conditions consistent with the stability of coesite in the nearby pod.

Smith's (1988) expansive review article on WGR eclogites, documented confirmed coesite at only one other eclogite locality named Straumen, some 14 km SW of Grytting. In addition, he deduced the likely previous presence of coesite from observations of poly-crystalline or at least multi-crystalline quartz inclusions within garnet or omphacite in samples from five additional eclogite localities, including Årsheimneset, Drage and Liset on Stadlandet. Such poly-crystalline quartz (PCQ) inclusions, sometimes with a distinctive palisade micro-structure – see for example Figure 1-3, are now widely accepted to have pseudomorphed earlier coesite crystals, some of which have a distinctive tabular form.

On this rather limited evidence, Smith (1988) proposed the existence within this coastal region of the WGR of a specific coesite-eclogite province containing rocks that had experienced UHP conditions. However, Smith (1988) did not establish the boundaries for this UHP eclogite province and moreover emphasised that most, if not all, of the intervening "country-rock" gneisses enclosing the various documented eclogite occurrences in this part of the WGR lacked mineralogical evidence that they had witnessed HP (quartz-eclogite stable), let alone UHP (coesite-eclogite stable), conditions. Accordingly, Smith (1988) in fact concluded that, rather than the WGR incorporating a regionally extensive, structurally-coherent, UHPM province or terrane, it in fact comprised a highly imbricated tectonic melange of HP and UHP eclogites enclosed within dominant lower pressure metamorphic rocks. Smith (1995) further expounded his view that the geographically-scattered, coesite-eclogite occurrences represent tectonically dismembered fragments of an early Caledonian (ca. 440 Ma) UHP metamorphic nappe within the WGR and in his elaborate Foreign/In Situ/Foreign (FIF) geodynamic model introduced the notion that the quartz-stable eclogites may in fact have formed during a later Caledonian (ca. 410 Ma) HP (P_{max} ca. 2.0 GPa) event that affected a substantial segment of mixed acid + basic lithology crust.

A further significant step in the recognition of a possible, regionally-extensive, UHP metamorphic terrane within the WGR of Norway, was the reported recovery by Dobrzhinetskaya et al. (1993, 1995) of micro-diamonds from dissolution of samples of garnet-kyanite-biotite-rutile-quartz gneiss and of garnet-pyroxene-amphibole-biotite gneiss from the north coast of the island of Fjørtoft in the Nordøyane, about 80 km to the north of the first coesite-eclogite occurrences documented by Smith (1984,1988). Consequently, in their global overview of the then recognised UHP metamorphic terranes, Coleman & Wang (1995) speculated that the UHP terrane in western Norway might cover an area of roughly 350 x 150 km. Even given more conservative estimates for the size of this UHP terrane, it is clear from the lithostatic pressures required for UHP metamorphism that a substantial mass of initially buoyant continental crust has been inserted (subducted) into the sub-lithospheric mantle, and subsequently exhumed, during the late Silurian to Middle Devonian Scandian plate collision episode.

(b) Most recent discoveries of UHP rocks in the Western Gneiss Region of Norway

Meticulous field and petrographic studies in the outer Nordfjord and Stadlandet areas reported by Wain (1997a) have greatly increased the number of eclogite localities recognised to have experienced UHP metamorphism. Actual relict coesites were identified as micro-inclusions in garnet, omphacite or kyanite in eclogite from five new localities and petrographically-distinctive PCQ pseudomorphs after coesite were recognised in eclogite minerals at a further twelve localities.

Cuthbert et al (2000) reported discoveries in the outer Nordfjord and Stadlandet areas of a further relict coesite-bearing eclogite locality at Flister and of PCQ pseudomorphs after coesite in eclogite pods at Maurstad and Sandvikneset. In addition convincing PCQ inclusions after coesite within garnet were reported from a large eclogite body capping the peaks of Hornet and Bautene to the south of the extensive peridotite outcrops in Almklovdalen and in a smaller eclogite pod in Stigedalen, south of the peridotite outcrops in Bjørkedalen, that together extend the occurrences of UHP eclogites some 40 km east of previously recognised localities (Figure1-4).

The present authors have also recently discovered convincing PCQ inclusions after coesite in garnets within a small flaser-textured eclogite body that outcrops virtually adjacent to the classic HP kyanite eclogite body at Verpeneset on the north shore of Nordfjord. This then is the most southerly UHP eclogite occurrence so far identified within the WGR.

Cuthbert et al (2000) also reported the discovery, confirmed by Terry et al (2000b), of PCQ inclusions after coesite in a pod of kyanite-phengite eclogite at Fjørtoftvika on the island of Fjørtoft, some 85 km north-east of the UHP eclogites localities recognised in the Nordfjord and Stadlandet areas. Importantly this UHP eclogite locality is only about 2 km along strike from the outcrops of the graphite-bearing garnet-kyanite-biotite gneiss from which scarce micro-diamonds were recovered by Dobrzhinetskaya et al (1993, 1995).

Compelling new evidence that the rocks exposed along the north coast of Fjørtoft experienced UHP conditions that extended into the diamond stability field is provided by the recent startling discovery of micro-diamonds in a garnet orthopyroxenite lens within a small outcrop of peridotite at Bardane. These micro-diamonds are interpreted to have formed in response to infiltration by crustal–derived fluids during Caledonian deformation-induced recrystallisation (Van Roermund et al, 2002, Brueckner et al, 2002).

Smith (1988, 1995) reported finding poly- or multi-crystalline quartz thought to have replaced earlier coesite in the large Ulsteinvik-Dimnøy eclogite body on Hareidlandet and in the Hessdalen eclogite body on the opposite side of Vartdalsfjorden, these localities being roughly mid-way between the occurrences of UHP rocks on Stadlandet and Fjørtoft (Fig. 1-4). The UHP status of the Ulsteinvik-Dimnøy eclogite has been confirmed by Carswell et al (2003b) through the discovery of preserved inclusions of coesite within a zircon separate from this eclogite body. Further evidence that rocks in this part of the WGR also experienced UHPM conditions is provided by the reported discovery by Hacker et al (2001) of numerous eclogite localities with relict coesite or PCQ pseudomorphs after coesite on the Sørøyane islands to the west of Hareidlandet.

This steady increase over recent years in the number of recognised occurrences of UHP rocks in the coastal region of the WGR between Nordfjord and the Nordøyene, suggests that the coesite eclogite-bearing UHP metamorphic terrane in the WGR covers an area of at least 5000 km^2 in a coastal strip up to 40 km wide (Fig. 1-4).

(c) The "foreign" versus "in situ" eclogite controversy: the influences of differential retrogression and metastability

The HP and UHP eclogites in the WGR occur as highly variable sized lenticular pods or tabular layers within highly deformed, dominantly quartzo-feldspathic, gneisses. Typically the margins to the eclogite bodies show retrogression to amphibolite-facies mineralogies, co-facial with the mineralogy observed in the surrounding gneisses. Sometimes the amphibolitisation at eclogite margins is a static growth feature apparently triggered by an influx of hydrous fluid. In other instances the strong shear deformation fabric seen in the surrounding gneisses may be observed to have penetrated the margins of the eclogite bodies, resulting in the development of a strongly foliated amphibolite. Not uncommonly, especially towards the margins of the eclogite bodies, omphacites show at least partial replacement by a granulite-facies symplectite of secondary jadeite-depleted clinopyroxene plus sodic plagioclase, as a result of a retrogressive, granulite-facies, decompression stage that preceded the amphibolitisation.

Given the obvious major contrasts in metamorphic grade between the unretrograded eclogites and the encompassing amphibolite-facies gneisses, it has remained uncertain and controversial as to whether or not the "country rock" gneisses enclosing the eclogites, garnet peridotites and other recognised HP and UHP rocks in the WGR experienced comparable HP or UHP conditions. Consequently, there has been a prolonged debate over whether the observed HP and UHP rocks were stabilised "in situ" within the gneisses in an essentially structurally-coherent metamorphic terrane or alternatively represent "exotic" blocks or lenses of HP and UHP rocks within some sort of highly disrupted tectonic melange, as envisaged for example by Smith (1980a).

Krogh (1977) and Griffin et al (1995) established, from consideration of Fe^{2+}/Mg^{2+} partitioning between garnet and omphacite in eclogite samples, the existence of a thermal gradient from around 550^{o}C in the SE to >800^{o}C in the coastal areas to the NW (Fig. 1-5) for the HP-UHP metamorphism across the WGR. From an updated thermobarometric evaluation of phengite-bearing and orthopyroxene-bearing eclogites, Cuthbert et al (2000) established that the regional temperature gradient is matched by a gradient of increasing lithostatic pressures, consistent with the stability of coesite to the north of Nordfjord and of diamond only in the most northwesterly exposed part of the WGR in the Nordøyene. This P-T analysis supports two important conclusions. Firstly, that the rocks in the most northwesterly part of the WGR were subducted to deepest levels during the Caledonian plate collision. Secondly, that the subduction-related P-T gradient across the WGR (Fig. 1-5) has not been greatly disrupted by the widely displayed late-orogenic, exhumation-related, amphibolite-facies, proto-mylonitic fabrics that developed in response to extensional, top-to-west, shear deformation (Andersen et al, 1991).

Terry et al (2000b) have proposed the existence of a major metamorphic discontinuity on the island of Fjørtoft between a higher structural unit/plate that records UHP conditions of ca. 820^{o}C and 3.4-3.9 GPa and a lower unit/plate that only records HP conditions of ca. 780^{o}C and 1.8 GPa. In contrast to the melange model of Smith (1988), Terry et al. (2000b) placed the HP/UHP junction at the lower contact of a regionally extensive and coherent sequence of thrust nappes (Blåho and Saetra nappes) with para-autochthonous Baltica basement (Ulla gneiss and other migmatitic or augen gneisses). No evidence for UHP metamorphism was reported within the lower plate gneisses or their enclosed eclogites. However, pods and layers of garnet peridotite are found within these Baltica basement gneisses, including the important Bardane, UHP, microdiamond-bearing peridotite on Fjørtoft. Also, the documented UHP kyanite eclogite at Fjørtoftvika lies in close proximity to the contact of the upper and lower plates as defined by Terry et al (2000b), and the high strain state of the gneisses makes exact definition of the boundary problematic, as also the assignation of this eclogite to one plate or the other. When these uncertainties are considered along with the overall rarity of evidence for coesite in the WGR (see next section) and the general lack of useful parageneses for geobarometry in the Baltica basement in the northwestern WGR, the HP versus UHP status of the lower plate remains, in our view, a somewhat open question, and it is possible that both units were juxtaposed before, or during, UHP metamorphism. If the lower plate is eventually proven to have experienced UHP metamorphism, then the survival of primary, low P, igneous phases in large masses of partially eclogitised metagabbro (Mørk, 1985) raises the possibility of extreme metastability under UHP conditions here, as it does further south in the WGR (Wain et al., 2001). Indeed, a key issue in understanding the distribution of HP, UHP and lower P metamorphic rocks is the operation of factors controlling the efficiency of metamorphic transformations. As we argue further below, such factors need to be considered carefully before appealing to the tectonic juxtapositioning of non-cofacial rock masses, especially when direct evidence for a major tectonic break is lacking.

Cuthbert & Carswell (1990) and Griffin et al (1985) have previously summarised various lines of evidence and arguments in favour of an essentially "in situ" formation of most crustal protolith eclogites within the WGR during short-lived deep subduction of a slab of continental crust. The two most compelling lines of evidence supporting this interpretation are:

(1) Widespread occurrences of corona-textured metadolerites (eg. Gjelsvik, 1952) and metagabbros (eg. Griffin & Råheim, 1973; Mørk, 1985 a,b; Krabbendam et al, 2000) that display incomplete transformation to eclogite. Crucially, some of these preserve primary igneous contacts with granitoid gneisses (Cuthbert, 1985). It is apparent that the degree of eclogitisation is controlled by the extent of influx of fluids and/or concomitant deformation and hence is crucially dependent on reaction kinetics (Austrheim, 1998). Not only do such rocks demonstrate eclogite formation under conditions of increased P and T from low-pressure (high crustal level) protoliths but they also provide clear evidence of plagioclase metastability under eclogite-facies conditions.

(2) Many eclogites, especially the quartz-stable HP types in the vicinity of Nordfjord, contain garnets of several mm to cm size that display evidence of a prograde growth history under conditions of increasing P and T (Fig. 1-6). Such garnets show a compositional zonation with a marked increase in Mg/Fe ratio from core to rim. Not infrequently they also show a zonation in the entrapped mineral inclusions with the blue-green amphiboles in garnet cores and omphacite inclusions within later growth garnet (Fig.1-7). The growth of such garnet thus apparently commenced under amphibolite-facies conditions and continued under subsequent eclogite-facies conditions.

As indicated earlier, the margins of eclogite and garnet peridotite bodies mostly show retrogression to amphibolite, frequently linked to the development of a deformation fabric. It might be tempting to link this retrogression with tectonic emplacement of the HP-UHP rocks into higher crustal level, lower pressure, gneisses, but then not all eclogite body margins are the focus of such shear deformation and invariably the scale of any observed deformation is inconsistent with the notion that the HP or UHP rocks have been thrust upwards by some 30-90 km, to account for the confining pressure contrasts with the enclosing amphibolite-facies gneisses.

Hence, in the almost ubiquitous absence of obvious petrographic evidence that the "country-rocks" enclosing the HP and UHP rocks also witnessed comparable P-T conditions, the marked contrasts in observed metamorphic grade seem best explained by arguing that the late orogenic deformation associated with the exhumation of this HP-UHP terrane has been partitioned largely into the more ductile quartzo-feldspathic gneisses. This resulted in an essentially pervasive metamorphic reworking of the gneisses and the replacement of any earlier HP-UHP mineralogies by retrograde amphibolite-facies assemblages. By contrast the HP-UHP mineralogies have had much better survival rates in the more structurally-competent mafic and ultramafic rocks. Hence although pervasive tectonism has undoubtedly been responsible for small-scale relative movements between the eclogites and the country-rocks, it is unlikely to provide an adequate explanation for the large-scale relative motions required to produce the striking contrasts in metamorphic grade between the eclogite pods and the encompassingly gneisses observed throughout the WGR. Rather, these contrasts result from the variable efficiency with which the HP or UHP parageneses were overprinted.

Wain (1997a), Krabbendam & Wain (1997) and Wain et al (2000) have provided crucial evidence in support for this differential retrogression interpretation, through their demonstration that small volumes of schists and gneisses in low strain zones immediately adjacent to certain UHP eclogite occurrences on Stadlandet have partly preserved UHP mineralogies, including petrographic evidence of previous coesite stability.

Within the WGR, pelitic paragneisses are relatively scarce but where they do occur, as in outer Nordfjord and on Fjørtoft, they do provide some good petrographic evidence that they experienced HP or UHP conditions, even despite their propensity and susceptibility to retrogression. Indications are that they contained P_{max} assemblages of garnet+phengite+/-kyanite+/-zoisite+/-omphacite+rutile+quartz/coesite. Only in rare instances, such as in the UHP schists along the shore outcrops at Vetrhuset on Nordpollen (Fig. 1-8), has petrographic evidence been preserved for the previous stability of coesite.

By comparison, finding evidence that the voluminous Proterozoic acid-intermediate orthogneisses (Lappin et al, 1979; Harvey, 1983) that outcrop extensively within the WGR also experienced HP or UHP conditions is a much greater challenge. Unequivocal proof that this was the case may, as with comparable rocks the Dabieshan-Sulu UHPM terrane in central China (Ye et al, 2000; Lui et al, 2002), ultimately depend on searching for preserved micro-inclusions of coesite or other HP-UHP mineral phases, within zircon separates.

Given the previously emphasised indications of extreme mineral metastability in metadolerite and metagabbro bodies within the WGR, metastability should also be seriously considered as an additional or alternative explanation for the apparent lack of HP or UHP mineralogies in the orthogneisses. It is feasible that such rocks may have witnessed the HP or UHP conditions but responded in only a limited and incomplete manner.

Some little deformed granitic rocks both on Vagsøy in outer Nordfjord and further north in the Moldefjord region (Carswell & Harvey, 1985) do show limited coronitic development of garnet. Intrusive acid igneous rocks have low inherent H_2O contents bound into small amounts of micas and/or hornblende. During prograde, subduction-related, HP or UHP metamorphism this limited H_2O content is likely to become locked into newly formed phengite and zoisite, minerals that can demonstrably remain stable to UHP conditions. Thus further reactivity may be inhibited in such rocks unless deformation provides channels for fluid ingress. The fact that many of the orthogneisses are observed to retain porphyroclasts of unmixed high-temperature feldspars is a strong pointer to frequent metastability in these rocks under HP and even UHP conditions. More intermediate composition meta-igneous rocks, such as the mangerite at Flatraket (Krabbendam et al, 2000; Wain et al, 2001), show more extensive but still incomplete reactivity, again with residual plagioclase metastability.

(d) The HP to UHP transition within the Western Gneiss Region

Wain (1997a) and Wain et al. (2000) observed that coesite or PCQ-bearing, UHP eclogites apparently had a set of petrographic characteristics that were distinct from eclogites lacking any evidence for coesite (interpreted as quartz-stable, HP eclogites). UHP eclogites were reported to generally contain xenoblastic garnets that lack clear prograde compositional zoning and contain only eclogite-facies solid inclusion suites, including coesite or PCQ. HP eclogites commonly contain idioblastic garnet, the larger grains of which enclose monocrystalline quartz inclusions throughout, exhibit strong prograde compositional zoning and have amphibolite-facies inclusion suites in their cores (see for example Figs. 1-6 and 1-7). This latter type is exemplified by the eclogites at Verpeneset, Almenningen and Kroken along the northern side of Nordford (Fig. 1-8), so we name this petrographic group the “VAK-type” eclogites.

A significant number of eclogites have ambiguous petrographic characteristics, such as those lacking prograde zoned garnet with inclusions of early amphiboles in cores but also lacking evidence of coesite stability. UHP eclogites first appear along the north shore of Nordfjord (Fig. 1-8) and persist northwards, being particularly in evidence around the southern part of the Stadlandet peninsula. The region stretching south from Nordfjord to Sognfjord exposes only VAK-type, HP eclogites (Krogh & Carswell, 1995; Cuthbert et al., 2000).

An important observation, arising from the work of Wain (1997a) and Wain et al. (2000), was that HP-type eclogites persist for a distance of about 10 km north of the coesite-in line (southern solid line in Fig. 1-8). Accordingly, they defined a mixed, or transitional, HP-UHP zone whose northern boundary stretched from across the southern end of the Stadlandet peninsula westwards towards Nordpollen (northern solid line on Fig. 1-8). Within this transition zone, Wain et al (2000) described the discretely separate HP and UHP eclogite bodies as occurring up to a minimum of 100 metres from each other.

Thermobarometric evaluation of mineral reaction equilibria, in particular for phengite-bearing eclogite samples (Wain, 1997a; Cuthbert et al., 2000), has for the most part corroborated the barometric distinctions between HP and UHP eclogite samples deduced from petrographic criteria. Even allowing for generous error brackets, significant non-lithostatic apparent pressure gradients have been recorded between adjacent HP and UHP eclogites (Wain et al, 2000; Cuthbert et al., 2000). Wain (1997a), Krabbendam & Wain (1997) and Wain et al. (2000) thus attributed the close juxtapositioning of HP and UHP eclogites within the transition zone to the tectonic interleaving of different structural units. Accordingly it was assumed that the lithotectonic unit containing the UHP eclogites was carried to a higher lithospheric level and emplaced against a different lithotectonic unit containing only HP eclogites.

In our opinion, a number of difficulties arise with this tectonic mixing interpretation of the HP-UHP transition zone in the Outer Nordfjord area. Firstly, no obvious zones of higher strain are observed between outcrops of HP and UHP eclogites within the transition zone, nor is this zone as a whole characterised by higher strains than in the rocks on either side. It is, of course, possible that the pervasive, late, exhumation-related amphibolite-facies deformation and recrystallisation in the WGR (Andersen et al., 1991; Krabbendam & Wain, 1997) has obliterated fabrics associated with such shear zones. Indeed some relative movement between adjacent eclogite bodies must have happened during development of these late fabrics, but such fabrics are not confined to the transition zone, so it cannot be regarded as a distinct displacement horizon during the later stages of exhumation.

Belts of metasediments associated with meta-anorthosite, at least some of which are likely to be allochthonous, lie across the area north of Nordfjord within the predominant orthogneissic basement, (Bryhni, 1989; see Fig. 1-8). UHP eclogites are found in both paragneiss and orthogneiss units, and both types of eclogite can be found in the same lithological unit (Cuthbert et al., 2000). Hence we have found that HP or UHP eclogites cannot be exclusively assigned to particular lithotectonic units within the transition zone.

Our second reservation concerning the tectonic mixing interpretation for the transition zone arises from the difficulty in unambiguously identifying the HP and UHP rocks. Identification of some HP eclogites effectively by default, based upon a *lack* evidence of coesite or PCQ, is unreliable due to the poor preservation potential of both coesite and its delicate PCQ replacement textures. Coesite is, in fact, frustratingly rarely preserved in the WGR compared to other UHP terranes such as the Dabieshan of central China (Carswell & Zhang, 1999) but it is always possible that a single observation of coesite or PCQ in a prograde-zoned “VAK-type” (apparently HP) garnet will render the other petrographic criteria for identification of a HP eclogite invalid. Examples of prograde-zoned garnets with inclusions of coesite are certainly known from other UHP belts, such as in the Kokchetav Massif of Kazakhstan (Parkinson, 2000).

The Årsheimneset UHP eclogite (Fig. 1-8) is known to exhibit prograde-zoned garnets with amphibole-rich inclusion suites -see Figure 1-7 (Carswell et al., 1985), but the same eclogite body also contains good palisade-textured PCQ (Smith, 1988; Cuthbert et al., 2000). Hence here a single body of eclogite clearly shows petrographic characteristics of both of Wain’s (1997a) UHP and HP types, and potentially records development from amphibolite-facies, through HP eclogite-facies to UHP eclogite-facies. Clearly, then, a further weakness of the discriminatory HP and UHP eclogite classification of Wain (1997a) is the assertion that eclogites in the transition zone are each exclusively HP or UHP in character. Clearly if both types are found together in the same body, then it is difficult to envisage how they could have been brought together tectonically.

In the light of these difficulties with the tectonic juxtapositioning interpretation, we have undertaken a detailed examination of a number of eclogite bodies within the transitional HP-UHP zone and in the adjacent HP and UHP zones of the Nordfjord-Stadlandet region. Several of these eclogite bodies will be visited and examined on field excursions during the Alice Wain Memorial West Norway Eclogite Field Symposium at Selje, Stadlandet in 2003.

A key locality is at Vetrhuset on the eastern shore of Nordpollen (Fig. 1-8), close to the northern margin of the transition zone and recognised as an UHP, coesite-bearing eclogite by Wain et al., 2000. Here, a swarm of eclogite pods lies within a belt of semi-pelitic schists. PCQ inclusions in both garnet and omphacite are quite common in these pods, in addition to much rarer, actual preserved, coesite. However, large, subidioblastic garnets are frequently, clearly, compositionally zoned with Fe, Mn and Ca-enriched cores and Mg-enriched rims (Fig. 1-9). The largest of these prograde-zoned grains contain concentrations of hornblende inclusions in their cores. Palisade-textured PCQ inclusions tend to be found in more xenoblastic garnets that may lie only a few millimetres from the zoned garnet grains. The enclosing semi-pelitic, phengite-kyanite-quartz schists contain distinctive, purplish-red garnets up to 5cm in diameter displaying conspicuous prograde compositional zoning. Rarely, PCQ inclusions are found in the narrow, Ca and Mg-enriched garnet rims.

Hence it is now apparent that intimately-associated individual eclogite bodies and their host semi-pelitic schists may display the characteristics of both HP “VAK-type” and UHP garnets. The Vetrhuset eclogites display a range of deformation fabrics: coarser-grained eclogites with a weak linear omphacite-shape fabric tend to contain the prograde zoned “VAK-type” garnets, while more strongly lineated eclogites show PCQ inclusions in omphacite and in later grown or dynamically-recrystallised garnet, especially in garnet-quartz streaks. Hence our observations at this location within the HP-UHP transition zone have revealed evidence for incomplete transformation from lower P metabasic and semi-pelitic rocks to UHP parageneses, leading to partial preservation of certain petrographic characteristics that are typical of HP eclogites. Coesite crystallisation appears to have been associated with a distinct, later stage of garnet growth that either mantles the earlier amphibolite-facies and HP eclogite-facies garnet, or with the recrystallisation of earlier garnet and omphacite during deformation.

The coarse-grained, UHP, coesite-kyanite eclogite at Flatraket harbour (Wain et al., 2000) shows similar characteristics to the coarser-grained eclogites at Vetrhuset, with subidioblastic garnets having darker red cores that contain abundant hornblende inclusions (Fig. 1-10). Rare PCQ inclusions are found within the paler coloured rims of these garnets, so this eclogite clearly demonstrates evolution from amphibolite-facies through HP to UHP eclogite-facies. Parts of this eclogite body have spongy-textured, highly poikiloblastic garnets with only omphacite and kyanite inclusions, showing more complete recrystallisation to the UHP paragenesis, perhaps because the original amphibole inclusions were less well armoured within the garnets and hence more prone to decomposition. Hence the prior textural development of this eclogite seems to have had an important control on the efficiency of UHP recrystallisation in this case. Zircons from this body give TIMS U-Pb age spectra for zircons with peaks at ca. 405 Ma and ca. 400 Ma (Hacker et al., 2001). These ages may correspond to the HP then UHP growth episodes of garnet (Carswell et al., 2003a).

As discussed above, the Årsheimneset eclogite also contains characteristics typical of the HP "VAK-type" eclogites, yet this body outcrops about 5 km into the UHP zone/province (Fig. 1-8) as recognised by Wain et al. (2000). An important observation here (see also Fig. 3-1) is that the central part of this body comprises mainly bimineralic (orthopyroxene-free) eclogite whereas adjacent to the top and bottom contacts with the country-rock gneiss, the main eclogite-facies rock type is an orthopyroxene, phlogopite and magnesite-bearing eclogite that becomes distinctly pegmatitic towards the lower margin, and is spatially associated with veins and lenses of phlogopite and/or phengite-bearing glimmerites. The central, bimineralic eclogite frequently contains conspicuous, up to cm-sized, prograde zoned garnets with cores containing abundant inclusions of dark blue-green amphibole (Fig. 1-7). The coarser-grained orthopyroxene-bearing eclogite (Fig. 1-11) exhibits more irregularly-shaped, large garnets comprising early darker cores with blue-green amphibole inclusions, extensively overgrown by later UHP garnet containing PCQ inclusions after coesite, as well as frequent inclusions of clinopyroxene and phlogopite, indicating that the latter was a stable UHP phase. Hence the Årsheimneset eclogite is another example that shows evolution of a single eclogite body from an early HP (quartz-stable), essentially bimineralic, eclogite, to a more siliceous, orthopyroxene- and phlogopite-bearing, eclogite in which substantial new growth of garnet, orthopyroxene and clinopyroxene took place under UHP conditions and consequently trapped coesite inclusions. Thus, in this case, the UHP mineral growth is thought to have occurred in response to a substantial influx of metasomatising fluid from the enclosing continental crust gneisses. The transformation of the early, essentially bimineralic, HP eclogite into a coarser-grained, even pegmatitic, UHP eclogite can be followed along hydraulic fractures penetrating the former. Once again, field relationships give no support to an interpretation of tectonic mixing of HP and UHP eclogites as proposed by Krabbendam & Wain (1997) and Wain et al (2000).

U-Pb zircon data of Gebauer et al (1985) for an orthopyroxene- and phlogopite-bearing eclogite sample from the Årsheimneset body (labelled SAN-1 from east of “Sandviknaes”) indicate metamorphic zircon growth at ca. 400 Ma, supporting the argument for UHP metamorphism at approximately that time (Carswell et al., 2003a – see below).

The evidence from the Vetrhuset, Flatraket and Årsheimneset eclogite bodies demonstrates that individual eclogites do not necessarily exhibit uniquely “HP” or “UHP” characteristics. This leads us to question the value of using prograde zoning and an apparent absence of PCQ or coesite inclusions in garnet to indicate that the rock has lacked a UHP metamorphic history. These examples demonstrate an evolution from amphibolite-facies parageneses through HP to UHP eclogite during which the efficiency of the metamorphic transformation was limited. Furthermore, they indicate that a number of processes drove the transformation. The clearest manifestation of the transition to UHP parageneses in both eclogites and semi-pelitic schists is the development of new garnet, by overgrowth, recrystallisation and/or neoblast formation. Garnet growth appears to have been the result of a discontinuous series of reactions amongst its matrix phases. The temporally distinct stages of garnet growth were prompted by distinct deformation events and/or triggered by influxes of externally-derived fluids. In the light of these observations it is instructive to also examine some other eclogite bodies that occur within and outside the HP-UHP transition zone.

The spectacularly layered coesite eclogite (Fig. 1-12) at Saltaneset first recognised by Wain (1997a) lies within the UHP zone (see Fig. 1-8), some 5 km north of the northern boundary of the HP-UHP transition zone as defined by Wain (1997a) and Wain et al. (2000). Carswell et al. (2003a) recognised within this eclogite body two generations of garnet growth – aggregates of deeper red, Ca-rich grains characterised by concentrations of tiny rutile needles in their cores, and overgrowths or discrete neoblasts of Ca-poorer and Mg-richer garnet (Fig. 1-13). In conspicuous quartz-garnet layers, the Mg-rich garnet mantles aggregates of the earlier, Ca rich type, or exists as discrete, compositionally-homogeneous grains containing remarkably abundant inclusions of PCQ after coesite (Fig. 1-14), indicating that these layers were originally garnet-coesitite rock. Such layers, or veins, are common in eclogites in the WGR and appear to be metamorphic segregations associated with fracturing and the infiltration of aqueous fluids. In the case of the Saltaneset eclogite the formation of the garnet-coesite layers is clearly associated with growth of the second generation, UHP garnet, so the HP-UHPM transformation was aided by ingress of an aqueous fluid. Carefully extracted UHP garnet, omphacite plus whole rock from a sample of a garnet coesitite vein have yielded a Sm-Nd isochron age of 408.3 +/- 6.7 Ma (Carswell et al, 2003a).

At Flister, a swarm of eclogite pods within semi-pelitic schists and interlayers of meta-anorthosite lies close to the extreme northern edge of Wain's (1997a) transition zone (Fig. 1-8). Wain et al. (2000) described a typical HP eclogite at Flister (N) and a UHP eclogite with PCQ inclusions at Flister (S). Cuthbert et al. (2000) subsequently reported the discovery of relict coesite in an eclogite sample from Flister, but it seems unlikely that this was from either of the eclogite pods sampled by Wain et al. (op. cit.). The coesite-bearing body is a flaser-textured eclogite in which granular streaks of paler garnet are sometimes cored by deeper red porphyroclasts, indicating the break-up, recrystallisation and compositional adjustment of an earlier generation of amphibolite-facies to HP eclogite-facies garnet. Coesite or PCQ has been found only in the late-formed garnet, again indicating a distinct episode of garnet growth or recrystallisation under UHP conditions, in this case clearly aided by deformation. Such flaser-textured eclogites form a distinctive textural type in the Nordfjord-Stadlandet area. Intriguingly, we have recently discovered the comparable flaser-textured eclogite (Fig. 1-15) at Verpeneset, Nordfjord (Fig. 1-8) to also contain PCQ inclusions in neoblastic garnet. Importantly this flaser-textured UHP eclogite is separated by only a narrow screen of gneiss from what is one of the archetypal HP "VAK-type" eclogites with prograde zoned garnets that occupies a spectacularly fresh eclogite roadside outcrop at Verpeneset (Fig. 1-16). This places the southern limit of recognised UHP eclogites further south than that shown in Cuthbert et al. (2000). Wain et al., 2000 did not actually extend their boundary as far west as Verpeneset.

It is clear that the location of both our modified coesite-in line and the northern limit of identified, pre-UHP metamorphism, HP eclogite relics (dashed grey lines in Fig. 1-8) remain only provisional until further detailed petrographic and thermobarometric studies are carried out. Nevertheless, it is evident that tectonic juxtapositioning of HP and UHP eclogites is much too simplistic a view, and we would argue that it played no more than a very minor role during the subduction and early exhumation phases of the Scandian orogenic event. Instead kinetic factors, dictated to a great extent by deformation and fluid activity, controlled the efficiency of transformation of HP and pre-HP parageneses to UHP eclogite-facies parageneses as the descending continental slab passed into the stability conditions of coesite, and beyond the stability of amphibole, leading to apparent intermingling of HP and UHP eclogites (and schists) on all scales from millimetres to kilometres. The increase in modal garnet associated with the HP-UHP transition can be expected to have modified the petrophysical properties of the WGR rocks, such as their density and rheology.

The general east-west trend of the coesite-in line (Fig. 1-8) is apparently discordant to the trend of the eclogite isotherms shown in Figure 1-5. The significance of this is presently unclear, but is likely to be at least partly an artifact of the rather sparse geothermometry upon which the isotherms are based. A more detailed thermobarometric survey will be required to better resolve the regional variation in P and T.

(e) The age of the UHPM metamorphism in the Western Gneiss Region

It was widely assumed that the eclogite-facies metamorphism in the WGR was Precambrian in age (eg. Krogh, 1977) prior to publication by Griffin and Brueckner (1980, 1985) of Caledonian Sm-Nd ages for garnet-omphacite pairs from five eclogite samples. Subsequently it was widely, if not universally, accepted that the HP-UHP metamorphic event occurred at around 425 Ma, this corresponding to the mean Sm-Nd age obtained for these eclogite samples. For example, this age was assumed in the tectonic models for the stabilisation and exhumation for these HP-UHP rocks presented by Andersen et al (1991), Cuthbert & Carswell (1990) and Dewey et al (1993).

The Sm-Nd mineral ages obtained by Griffin & Brueckner (1980, 1985) did not specifically discriminate between the timing of HP and UHP conditions in different parts of the WGR. Based mostly on this dataset, Smith (1985) subsequently speculated that the UHP rocks may have formed at ca. 440 Ma and the HP rocks at ca. 410 Ma, but the limited sample set and large uncertainties in the ages make this difficult to substantiate. Moreover, as documented in the preceding section, our recent petrographic observations on the relative timing of the HP and UHP mineralogies strongly point to the latter having been stabilised later rather than earlier than the HP parageneses. Furthermore, as emphasised in the UHP timing review paper by Carswell et al (2003a), recently published U-Pb ages for zircons (Hacker et al, 2001; Carswell et al, 2003b) and for monazites (Terry et al, 2000a) in specifically identified UHP rocks mostly fall within the rather later 400-410 Ma timeframe.

Compelling evidence that the UHP mineralogies may indeed have formed at close to 400 Ma is provided by the 402+/-2 Ma U-Pb age obtained for metamorphic zircons from the Hareidland eclogite shown to contain micro-inclusions of UHP minerals, including coesite (Carswell et al, 2003b). In addition, Carswell et al (2003a) have reported a statistically-indistinguishable Sm-Nd garnet-omphacite-whole rock isochron age of 408.3+/-6.7 Ma for an eclogite sample from Salta (Fig. 1-8) that contains abundant petrographic evidence of previous coesite stability.
The conclusion that UHP rocks in the WGR formed at close to 400 Ma, much later in the Scandian phase of the Caledonian orogenic cycle than was previously taken to be the case, has profound implications for the dynamic modelling of this continental plate collision belt and certainly signals extremely rapid exhumation of these UHP rocks. Hence, Carswell et al (2003a) have concluded that they were probably exhumed to ca. 35 km depth at a mean rate of ca. 1 cm. per year. They suggested that this rapid initial exhumation could well have been driven by residual bouyancy of the deeply subducted crustal slab that resulted from incomplete eclogitisation. They particularly emphasised the survival of metastable, plagioclase-bearing assemblages in the dominant orthogneisses due to limited reactivity and the probable short duration of the UHP event. Further exhumation to about 8-10 km apparently occurred at a much slower mean rate of ca. 1.3 mm. per year with the final unroofing of the UHP rocks attributable to the late-stage extension collapse of the Caledonian orogen (eg. Andersen et al. 1991).

Acknowledgements

The authors wish to acknowledge the support for recent studies of HP and UHP rocks in the WGR of Norway provided by the Norwegian Research Council, the Norwegian Geological Survey, the British Council, the EU "Access to Research Infrastructures" Programme, the Carnegie Trust for Scottish Universities and the Universities of Sheffield and Paisley.

Addendum

The field localities for the excursions stops listed in Chapters 2-5 are keyed in Figure 1-17 to the geological map of the Nordfjord – Stadtlandet area published by Krabbendam and Wain (1997).

The excursions outlined in Chapters 2-4 are designed to take half a day (4-5 hours), whereas those detailed in Chapters 5 and 6 will take a full day (9-10 hours) including the travelling time to and from Selje.

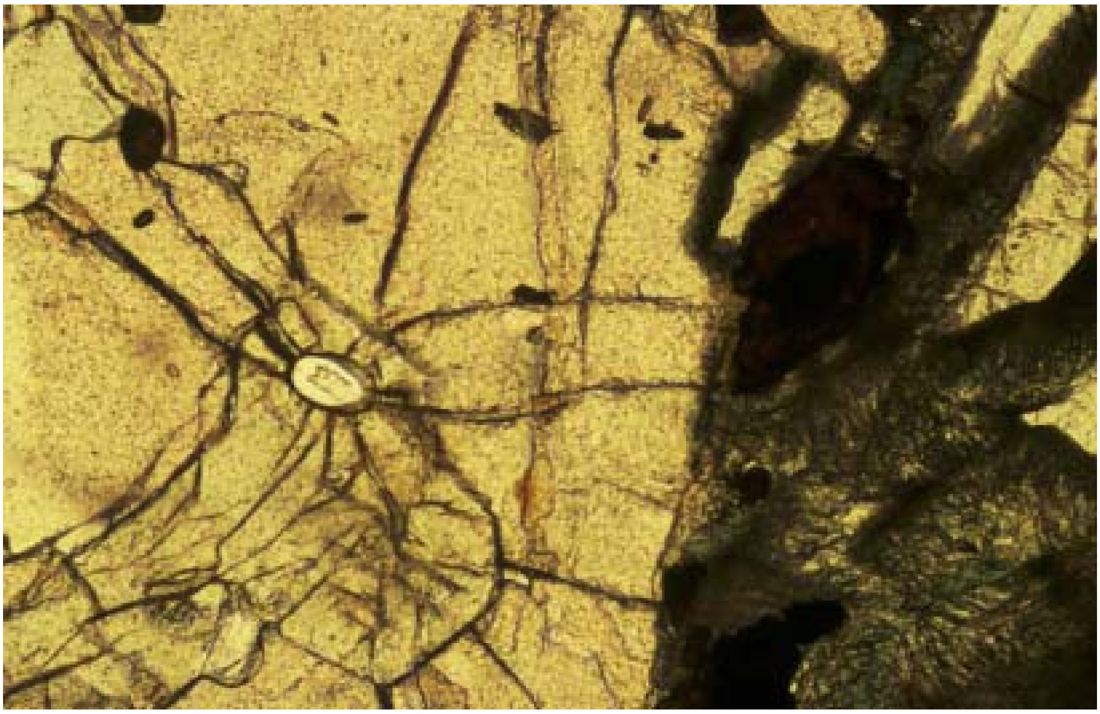


Figure 1-1: Relict micro-inclusion of coesite in a sample of the UHP eclogite discovered by Smith (1984) at Grytting near Selje. Note the irregular-shaped higher relief coesite relict surrounded by a lower relief corona of poly-crystalline replacement quartz. This inclusion is enclosed within an omphacite grain that is in turn enclosed and armoured within garnet. The right-hand side of the image comprises mostly secondary symplectite after omphacite. Plane polarised light photomicrograph with field of view ca. 2mm across.

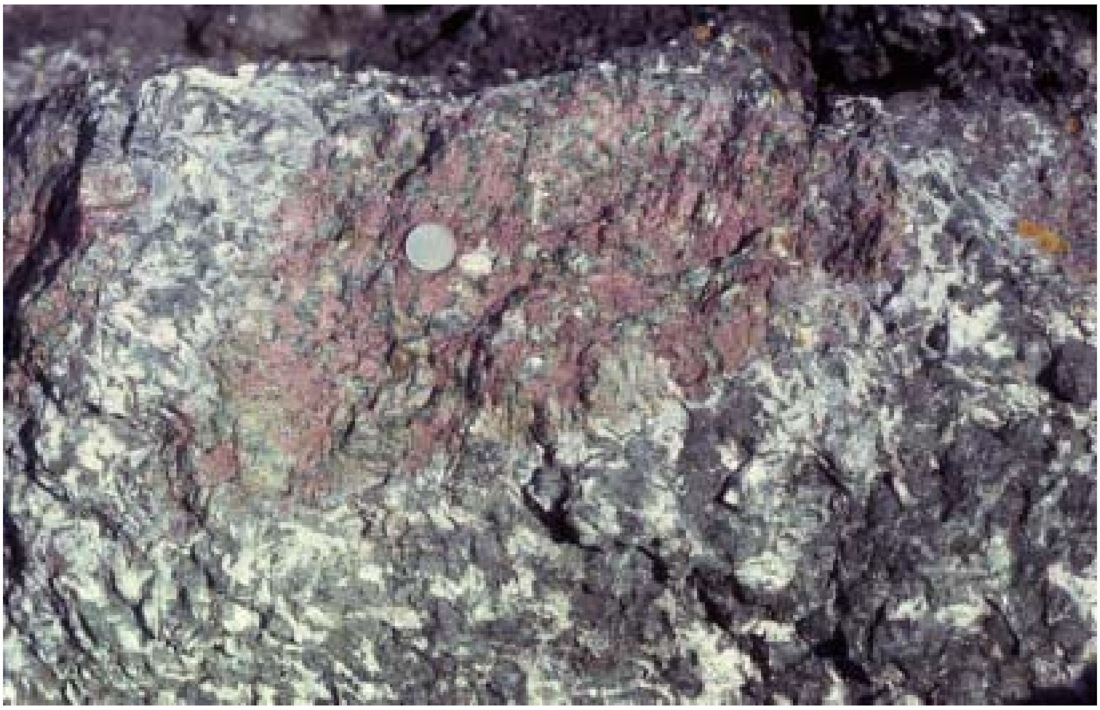


Figure 1-2: Coarse-grained relict of orthopyroxene eclogite surrounded by retrograde replacement amphibolite within the spectacular eclogite pod on the foershore at Grytting near Selje, highlighted by Eskola (1921).

Figure 1-3: A ca. 800 microns in length poly-crystalline quartz inclusion after coesite, with a distinctive palisade texture, enclosed in a large UHP garnet crystal within a coarse-grained garnet-quartz vein (interpreted to have been originally a garnet-coesite vein) in layered eclogite sample A306 from Saltaneset.

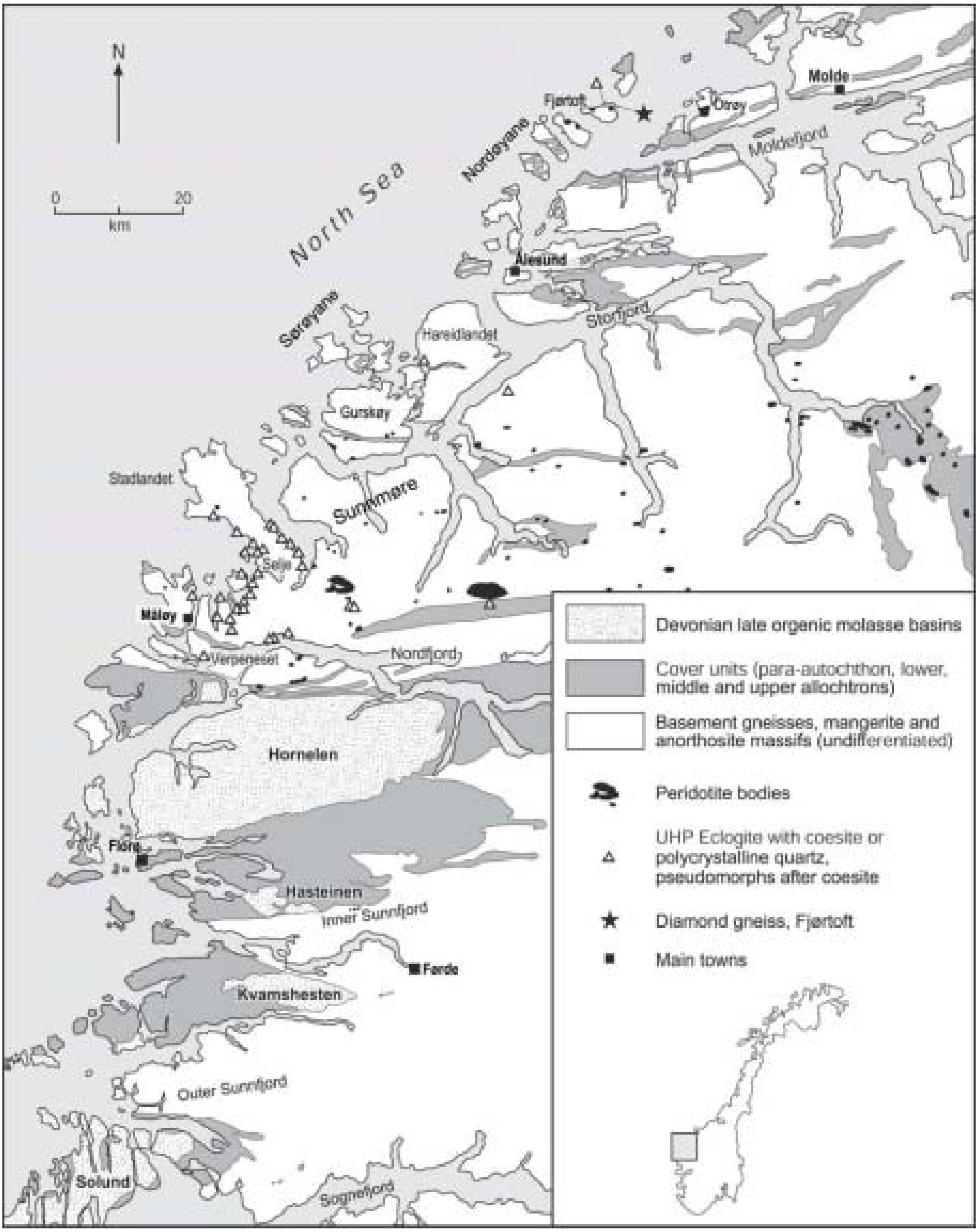


Figure 1-4: A generalised geological map for the Western Gneiss Region between the Sognfjord and Moldefjord areas showing the respective distributions of documented occurrences of UHP (coesite-bearing) eclogites, UHP diamond gneiss and peridotite bodies.

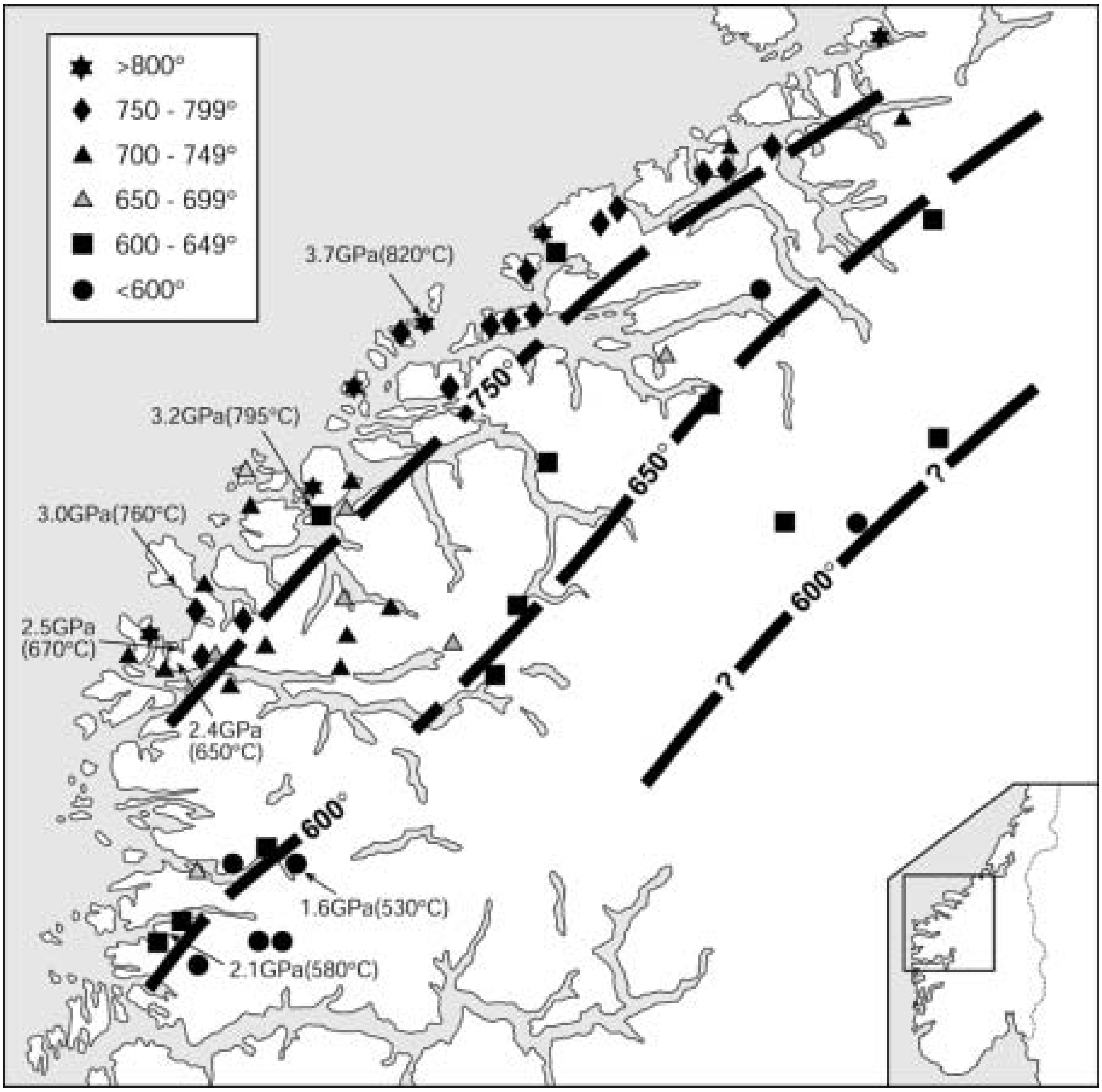


Figure 1-5: Regional temperature gradient across the Western Gneiss Region of Norway based on Fe^{2+}/Mg^{2+} partitioning between garnet and omphacite in eclogites (after Griffin et al, 1985) plus indications of the concomitant pressure gradient based on P-T estimates for eclogite samples from various localities indicated by Cuthbert et al (2000), Carswell et al (2003a) and Terry et al (2000b).

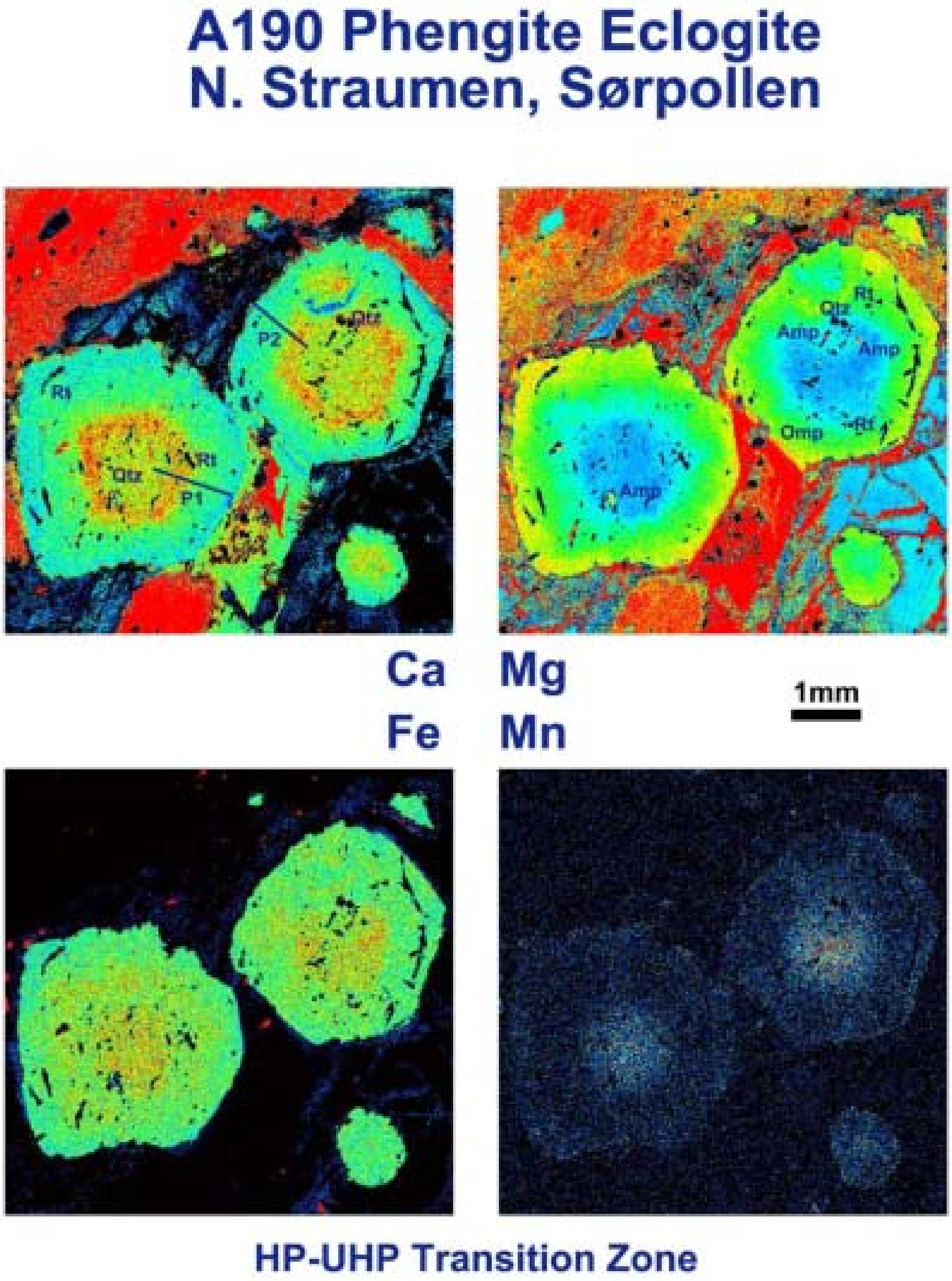


Figure 1-6: Composition maps of Ca, Mg, Fe and Mn distributions within prograde growth zoned garnets, with micro-inclusions of quartz, amphibole, zoisite and rutile in core regions, in a phengite-bearing eclogite sample A190 collected from just to the north of Straumen on Sørpollen within the HP-UHP Transition Zone of Wain et al (2000).

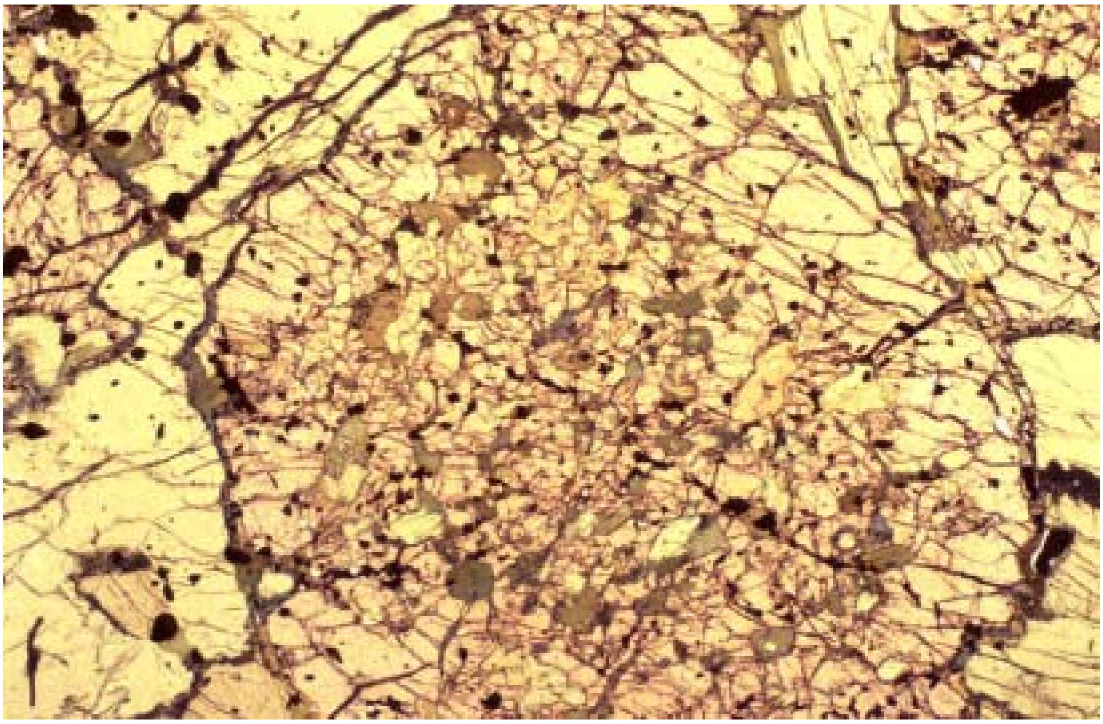


Figure 1-7: Plane polarised photomicrograph, with field of view ca. 9 mm across, of a prograde zoned garnet with blue-green amphibole inclusions in the core passing into a marginal zone with omphacite inclusions. Bimineralic eclogite sample A605 from the central part of the orthopyroxene-bearing eclogite body at Årsheimneset on Stadlandet – see also Figure 3-1.

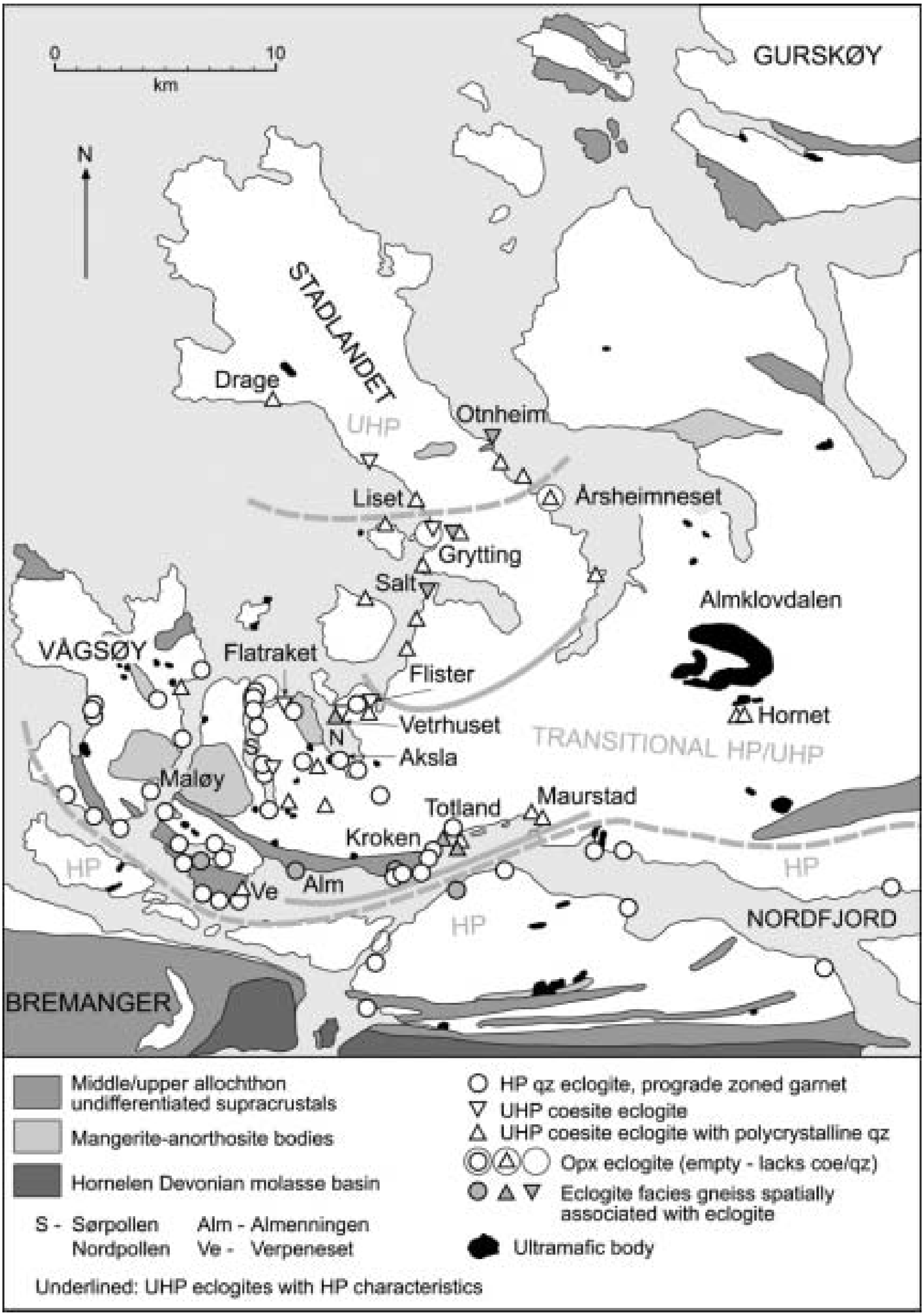


Figure 1-8: Map for the Outer Nordfjord and Stadlandet area of the Western Gneiss Region showing the relative distributions of documented occurrences of UHP (coesite-stable) and HP (quartz-stable) eclogites relative to the HP-UHP Transition Zone boundaries (solid lines) indicated by Wain et al (2000) and the modified boundaries (broken lines) proposed in this review.

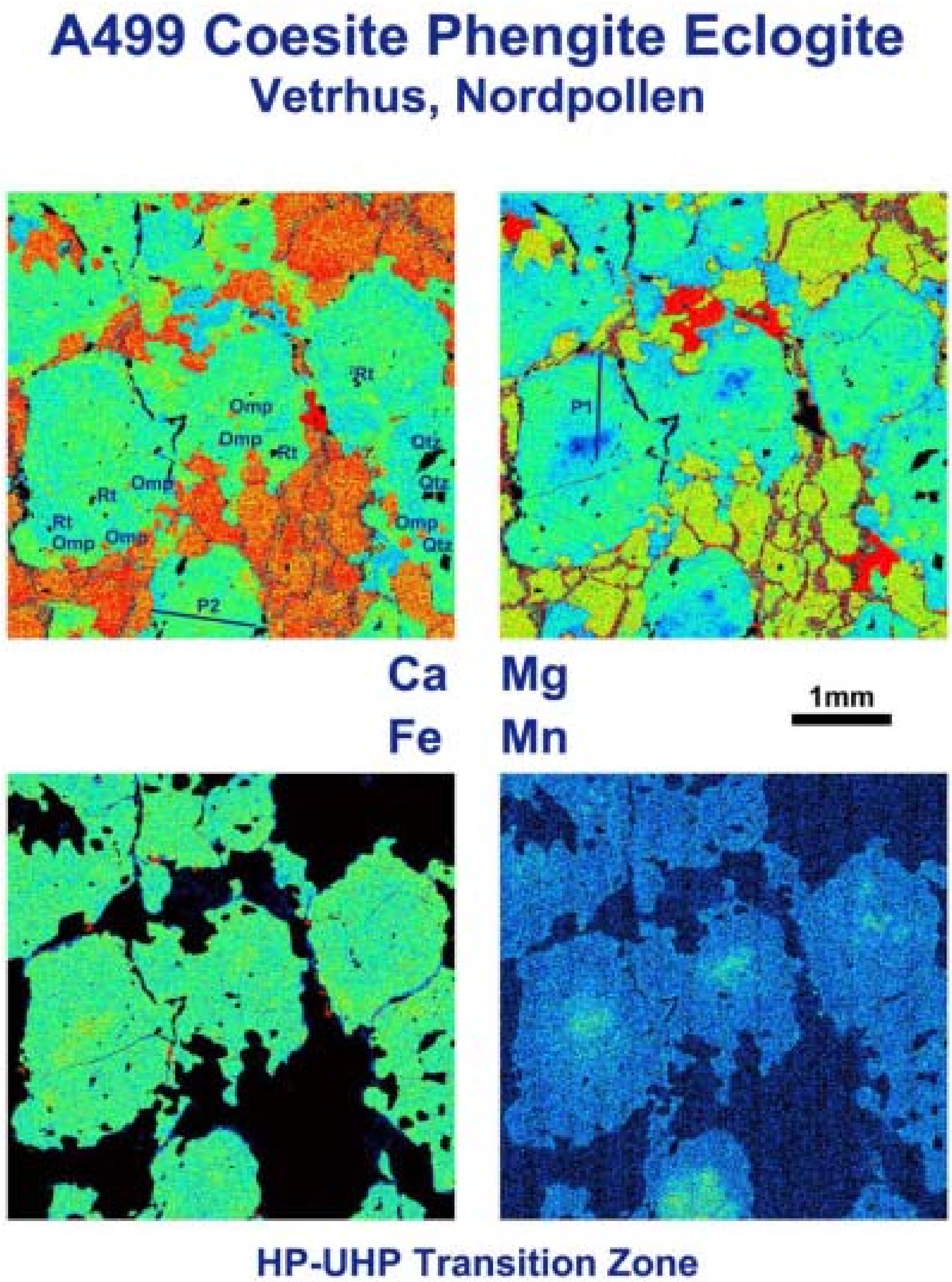


Figure 1-9: Composition maps of Ca. Mg, Fe and Mn distributions within prograde growth zoned garnets in a phengite-bearing UHP eclogite sample A499 -containing some convincing poly-crystalline quartz pseudomorphs after coesite- from Vetrhuset on Nordpollen.

Figure 1-10: Polished slab of sample A394 from the kyanite- and phengite-bearing UHP eclogite body at Flatraket harbour. Note that the large garnets have darker coloured, prograde zoned, cores with bluish-green amphibole inclusions. The garnet cores are overgrown by paler coloured UHP garnet that encloses some poly-crystalline quartz pseudomorphs after coesite.

Figure 1-11: Polished cut slab of orthopyroxene-bearing eclogite sample A601 collected from towards the lower margin of the Årsheimneset eclogite body in the SE part of the Stadlandet peninsula. Note that two generations of garnet growth are apparent. Large early garnet porphyroblasts are prograde zoned with dark amphibole inclusions in cores. The later UHP garnet is granular and paler coloured and has been observed to contain poly-crystalline quartz inclusions after coesite.

Figure 1-12: Polished slab of layered UHP eclogite sample A306 from Saltaneset containing what is interpreted to originally have been a coarse-grained garnet-bearing coesitite vein.

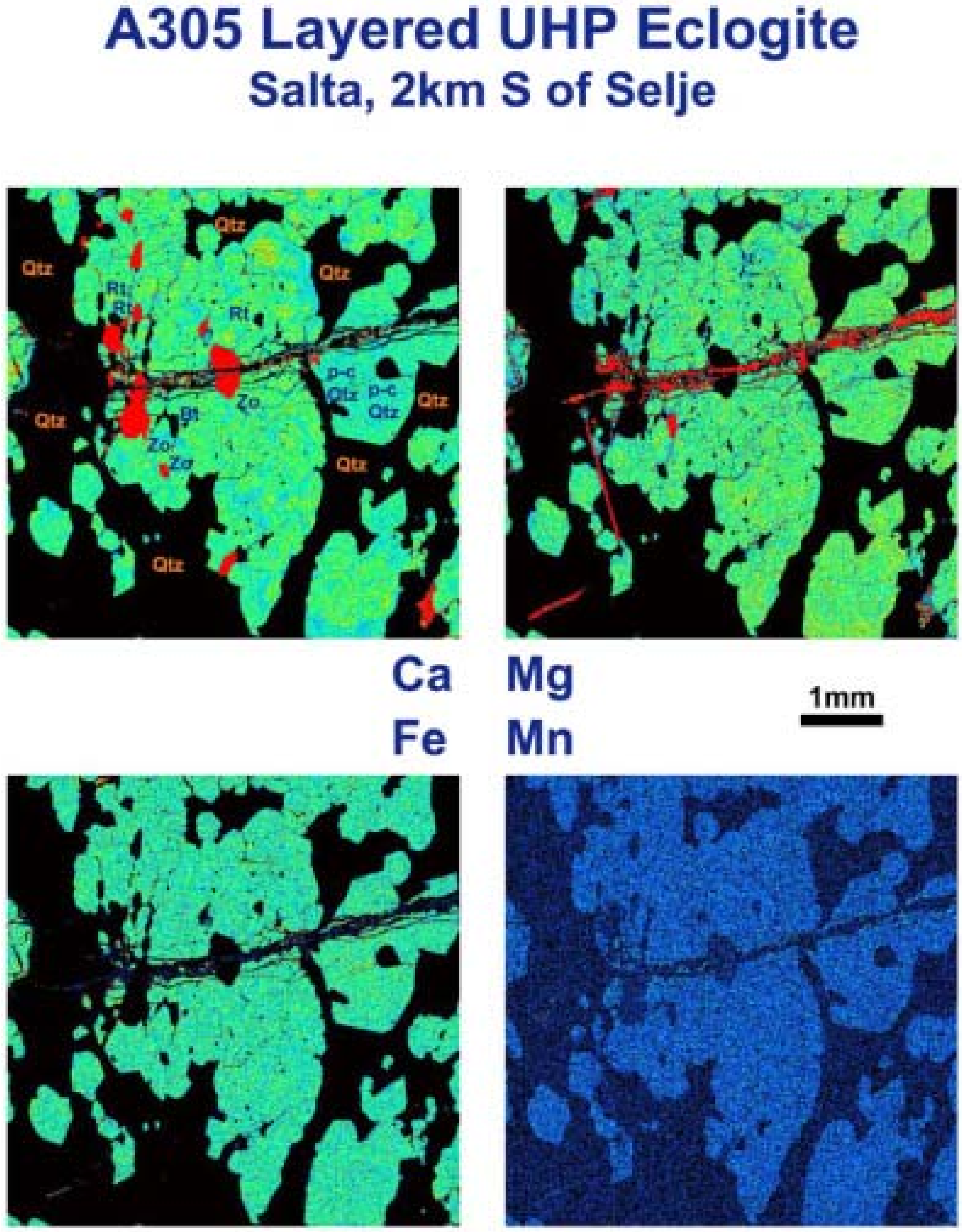


Figure 1-13: Electron microprobe X-ray elemental maps of the distributions of Ca, Mg, Fe and Mn within garnet grains at the margin of a garnet plus quartz (previously coesite) layer with UHP eclogite sample A305 from Saltaneset.

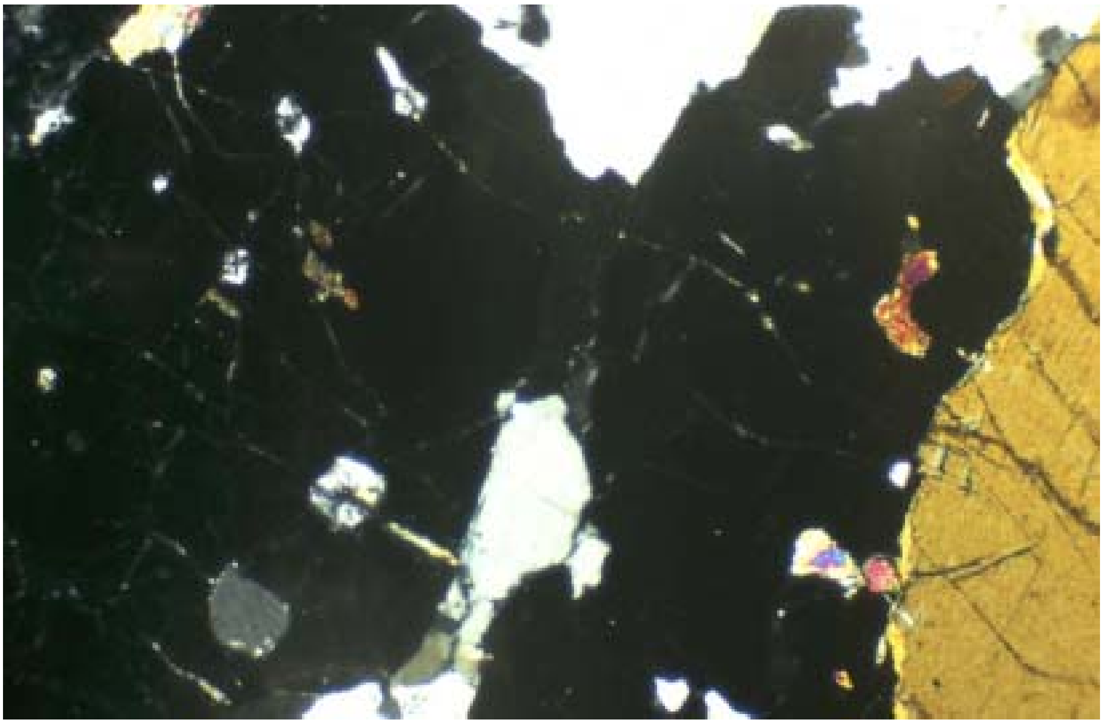


Figure 1-14: Inclusions of poly-crystalline quartz after coesite in a large garnet within the coarse-grained garnet coesitite vein in layered UHP eclogite sample A306 From Saltaneset – see also Figure 1-12. Cross polarised light photomicrograph with field of view ca. 4.5 mm across.

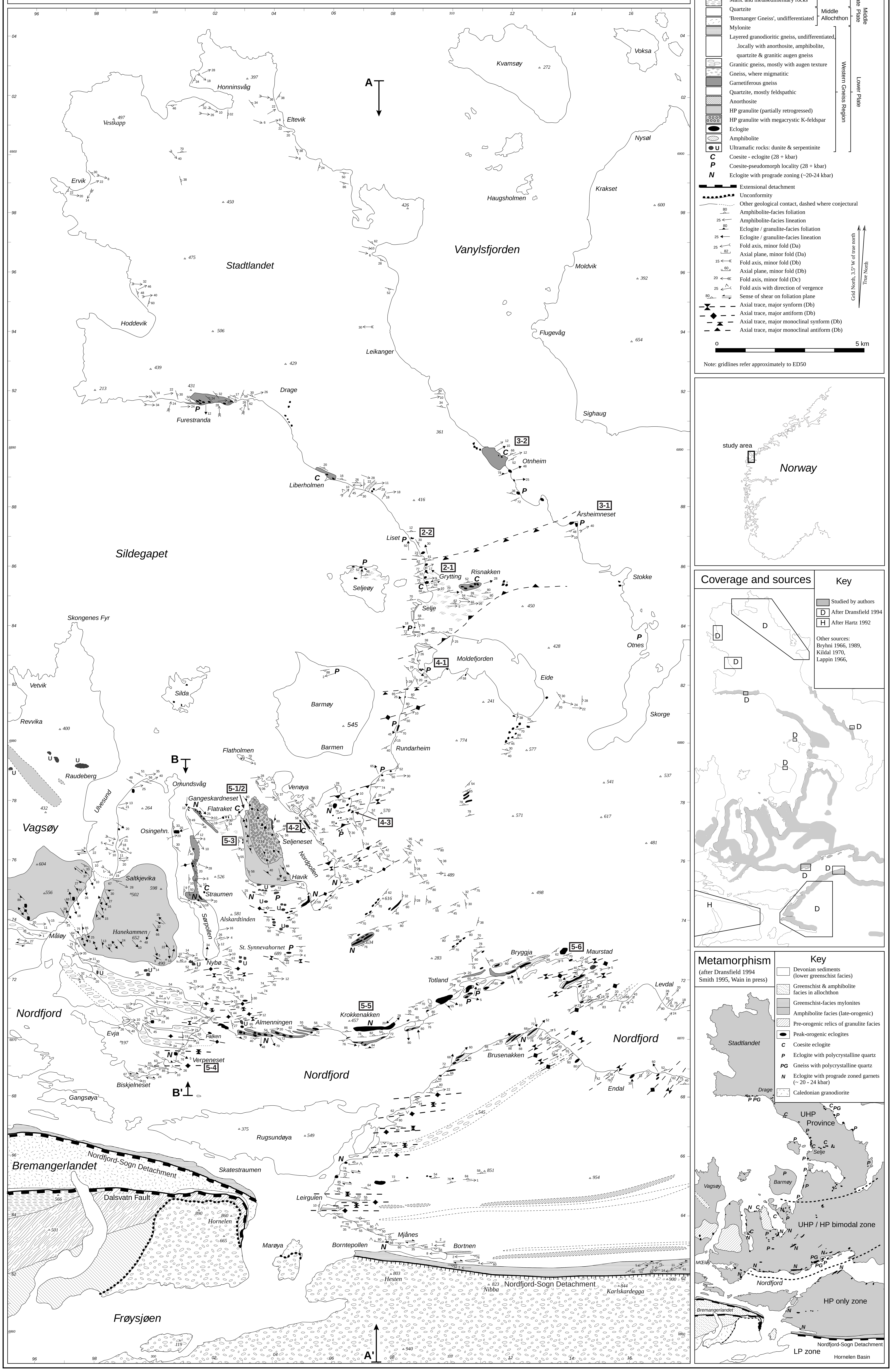
Figure 1-15: Flaser-textured, essentially bimineralic, UHP eclogite at Verpeneset on the northern coast of Nordfjord. The UHP status of this eclogite is indicated by the presence of poly-crystalline quartz inclusions in garnets. This small, darker, more Fe-rich, eclogite lens occurs closely adjacent to the southern margin of the spectacular paler kyanite eclogite body at Verpeneset.

Figure 1-16: Field photograph of the kyanite+phengite+zoisite+quartz HP eclogite body at Verpeneset, Nordfjord. Note that the larger garnets display prograde colour zonation with the darker, higher Fe, cores also containing amphibole inclusions in contrast to only omphacite inclusions in the paler, more Mg-rich, garnet margins.

Figure 1-17 (see page 51): Geological map of the Nordfjord-Stadlandet area of west Norway by Krabbendam & Wain (1997) with the localities for the excursion stops listed in Chapters 2-5 added.

Geological map Nordfjord - Stadtlandet area, West Norway

Maarten Krabbendam & Alice Wain (1997), with additional data from Bryhni 1966, Dransfield 1993, Hartz 1992, Kild•al 1970, Lappin 1966



CHAPTER 2:
EXCURSION TO THE UHP ECLOGITES AT GRYTTING AND LISET

Tony Carswell, Simon Cuthbert and Maarten Krabbendam

14.00: Leave the Selje Hotel on foot and proceed northwards via the beach and the foreshore outcrops to the Grytting locality, roughly 400 meters north of Selje church – see Figure 2-1.

14.15-15.45: STOP 2.1: GRYTTING UHP ECLOGITES
The justifiably famous eclogite bodies at Grytting are now designated as a national treasure and accordingly **sample collecting within the marked area at this locality is strictly forbidden**. Two physically separate and chemically and mineralogically distinct eclogite bodies outcrop at Grytting although, as shown on the accompanying map, these bodies are separated by only about 25 cm of quartzo-feldspathic gneiss.

(1) Grytting Coesite Eclogite Body

This small, unexceptional-looking, and partly symplectised eclogite lens provided the sample in which Smith (1984) discovered a relict coesite inclusion preserved within a clinopyroxene grain (see Fig. 1-1), as confirmed by raman spectroscopy. Smith (1988) reported that distinctive poly-crystalline pseudomorphs after coesite also occur as inclusions in garnets within this eclogite pod. Subsequent observations reported by Smith (1995) and confirmed by the present first author, have shown that polycrystalline quartz pseudomorphs after coesite (or even actual coesite relicts) are not infrequent as inclusions in clinopyroxenes and garnet amongst a suite of samples collected from other nearby pods of fine-grained, part-retrograded, eclogites enclosed within the commonly garnet- and phengite-bearing paragneisses on the foreshore to the north and west of this particular lens.

Smith (1988, 1995) described this original coesite-bearing eclogite pod as composed mainly of mm-sized garnet and clinopyroxene with minor coesite, dolomite, rutile, ilmenite and sulphide. Smith (1995) also emphasised that this eclogite body was distinctly different in its crystal-chemistry, rock chemistry and petrography from the closely adjacent orthopyroxene eclogite body described next.

(2) *Grytting Orthopyroxene Eclogite Body*

This spectacularly coarse-grained, although extensively retrograded, eclogite lens featured in the classic paper by Eskola (1921) “On the eclogites of Norway” and designated by him as the type locality of “Eclogite-pegmatite of the Gryting type”.

Eskola recognised this “eclogite-pegmatite” to be orthopyroxene-bearing and to also contain coarse carbonate, pale brown mica and pale green tremolitic amphibole in certain “schlieren”. In his accompanying sketch of this eclogite body he indicated that the original coarse-grained opx eclogite only survives as pod-like patches within a replacement coarse-grained amphibolite (see Fig. 1-2). Importantly he also indicated the eclogite-pegmatite, or more specifically its replacement amphibolite, to be in direct contact within this body with a darker, more Fe-rich, fine-grained opx-free eclogite, designated to be of Duen type – an essentially non-foliated type of bimineralic eclogite said to be common as lenses within the gneisses in this region.

Our more recent observations of this eclogite body indicate, as shown in the accompanying map, that the fine-grained bimineralic eclogite occurs as impersistent layers or patches within the coarse-grained opx eclogite (see Fig. 2-3) or its replacement amphibolite. This intimate rock association is apparent in the following generalised lithological log measured in a top to bottom margin section (A-B) marked on Figure 2-2:

Top Gneiss Contact

55 cm medium-grained retrograded amphibolite margin to the top medium-grained eclogite.

75 cm medium-grained dark, opx-free, eclogite with ca. 10 cm of symplectitic eclogite at the top.

12 cm medium-grained opx-bearing eclogite with an indistinct top margin to the dark, opx-free, eclogite and increasing grain size and opx content towards the base, with development further west of a distinct wedge of coarse-grained opx eclogite whilst to the east the opx content diminishes.

120 cm coarse-grained pegmatitic amphibolite containing relict patches and pods (up to 20 cm across) of pegmatitic opx eclogite.

100 cm coarse-grained pegmatitic opx eclogite containing isolated lensoid masses of medium-grained bimineralic eclogite (see Fig. 2-3).

150 cm coarse-grained pegmatitic opx eclogite locally containing pale brown phlogopite mica and carbonate.

80 cm coarse-grained opx eclogite containing distinctive, often ovoidal, mantled garnets of 1-2 cm size that have cores of dark red gemmy garnet and mantles of paler granular garnet (see Fig. 2-4) sometimes with quite abundant phlogopite mica and discrete dark green prisms of dark green amphibole. This lithology has a distinct flattening fabric in places defined by elongated garnet grain shapes and dimensionally-orientated clinopyroxenes.

280 cm coarse-grained pegmatitic amphibolite after earlier pegmatitic opx eclogite containing a possible infolded garnet-bearing gneiss layer as shown on the map

100cm discontinuous layer of medium-grained bimineralic eclogite with some garnet-rich and cpx-rich layers, the latter mostly replaced by secondary symplectite, and showing increased amphibolitisation close to the gneiss contact.

Bottom Gneiss Contact

We take the observed lithological associations in this Grytting eclogite body to indicate (as can also be demonstrated in the coarse opx-bearing eclogite body at Årsheimneset) that an original, fine-grained, essentially bimineralic eclogite body has been extensively replaced by the pegmatitic opx-bearing eclogite in response to a massive influx of aqueous and CO_2-bearing fluid. Compelling support for such an interpretation is provided by the high $^{87}Sr/^{86}Sr$ ratios reported by Brueckner (1977) and Griffin & Brueckner (1985) in all constituent minerals in sample S-19 of the Grytting Opx eclogite. Brueckner importantly emphasised that whereas the determined $^{87}Sr/^{86}Sr$ values in clinopyroxenes from the WGR orogenic peridotite bodies were low (0.701-0.703) and consistent with a mantle derivation, the isotopic ratios in clinopyroxenes and associated minerals in “country rock” opx-bearing eclogites from Selje(Grytting) and Eiksunddal directly enclosed in the gneisses were much higher (0.715-0.716) and also higher than determined in “country rock” opx-free eclogites (0.703-0.707). Brueckner (1977) also drew attention to the coarser grain size of the opx eclogites with higher $^{87}Sr/^{86}Sr$ ratios and postulated that it was likely that such eclogites were contaminated during eclogite-facies metamorphism by infiltration of water-rich fluid bearing radiogenic strontium from the surrounding crustal gneisses. From their enlarged isotopic data base, Griffin & Brueckner (1985) further emphasised that the high $^{87}Sr/^{86}Sr$ values of the opx-bearing eclogites are not supported by high Rb/Sr ratios and must have been open systems for Rb and Sr during eclogite-facies metamorphism. Consequently, the isotopic data signal the stabilisation of opx eclogites, such as at Grytting, within a deeply subducted continental crust slab rather than within the sub-continental lithospheric mantle as strongly advocated by Lappin & Smith (1978).

Mineral compositions for the assemblage garnet+clinopyroxene +orthopyroxene +/- phlogopite+/-magnesite observed within this eclogite body have been provided by Lappin & Smith (1978, 1981) and Carswell et al (1985). Opx grain cores have characteristically low Al_2O_3 contents (0.28-0.39 wt.%) that signal high equilibration pressures whereas the higher Al_2O_3 contents of opx grain margins adjacent to garnet (0.68-0.78 wt.%) that signal lower pressures (Carswell et al, 1985) are now recognised to reflect later diffusive re-equilibration. An updated evaluation based on the mean calculated P-T values for 7 samples (Cuthbert et al, 2000, Table 2) is that the Pmax assemblage in this opx eclogite formed at ca. 732^{o}C and 32.1 kbar. Such conditions are consistent both with the observed equilibrium coexistence of magnesite with enstatitic orthopyroxene and diopsidic clinopyroxene and with coesite stability within the adjacent eclogite pods that contain free silica.

For the opx eclogite at Grytting, Griffin & Brueckner (1985) reported a Sm-Nd garnet + clinopyroxene mineral age of 447+/-20 Ma, the oldest "Caledonian" age reported in their publication. However, as indicated in the lithological log above, at least some samples from this eclogite body show evidence of two distinct garnet growth stages. Hence the $^{206}Pb/^{238}U$ age of *ca*. 398 Ma for a zircon fraction from this eclogite reported by Gebauer *et al*. (1985) probably better reflects the timing of the opx-bearing eclogite-facies mineral growth under UHP conditions than the older Sm-Nd age that may be strongly influenced by the earlier growth of the garnet cores.

15.45-16.30: Proceed on foot from Grytting northwards along the shoreline outcrops of gneisses enclosing mostly rather heavily retrograded eclogite pods some of which contain obvious poly-crystalline quartz pseudomorphs after earlier coesites (note that sampling is now permissable) for roughly 1.5 km to the outcrops of the Liset eclogite.

16.30-17.30: STOP 2.2: LISET UHP ECLOGITE

The Liset eclogite has been described by Smith (1987) as an inconspicuous 60 meter long kyanite-lineage eclogite pod poorly exposed around the high-tide mark about 100 m NW of Liset hamlet. This pod was reported to display an extraordinary array of mineral textures and mineral compositions in its retrograded parts – including the newly discovered tectosilicates lisetite ($CaNa_2Al_4Si_4O_{16}$) and calcium-nepheline (Rossi et al, 1986; Smith et al, 1986). It is also noted for the first reported occurrence of eclogite-facies Al- and F-rich titanite containing up to 10 wt.% Al_2O_3 and 3 wt.% F (Smith 1980b; Oberti et al, 1985).

It was reported by Smith (1987) that the boundary between the Liset eclogite pod and the enclosing gneisses is difficult to trace in the field because of the thick microvegetation and the macroscale similarity of several of the nine principal rock types recognised that are as follows:

(1) Garnetite or garnet-rich eclogite, often rich in zoisite and titanite but without kyanite and rarely with quartz.

(2) Clinopyroxenite or clinopyroxene-rich eclogite, often rich in kyanite and quartz but without zoisite and titanite.

(3) Strongly retrogressed equivalents of (1).

(4) Strongly retrogressed equivalents of (2). Retrograded rocks (3) and (4) in fact make up most of the pod. In general the quartz-free layers were reported to be less retrograded. In some layers the clinopyroxene is replaced by an unusual texture of oligoclase + magnetite (as cubes) + minute micas and amphiboles and the high Al/Si ratio pseudomorphs after kyanite (+/- early paragonite) has given rise to a complicated series of retrograde reactions involving corundum, plagioclase, lisetite, calcium-nepheline and several micas (late paragonite, margarite and preiswerkite).

(5) "Internal gneisses" comprising garnet-quartzite, garnet-amphibolite and garnet-two mica schist that occur within the overall boundary of the eclogite pod.

(6) "External gneisses" of amphibolite-facies with minor garnet and abundant epidote that constitute the country rocks here.

(7) Pink-coloured quartz-albitite that often marks the position of the eclogite pod boundary.

(8) Late pegmatitic feldspathic veins and patches.

(9) Phengite-bearing eclogite that is chemically different from the Na- and Al-rich and K- and Mg-poor Liset eclogite - forming a separate small nearby pod, possibly just a buried loose block.

It was reported by Smith (1987) that the clinopyroxenite (1) is often wrapped around meter-sized garnetite (2) boudins which form small pods within the big pod and testify to a syn- or possibly pre-eclogite deformation event. In contrast the amphibolite- and greenschist-facies retrogression was static since most of the numerous kinds of mineral reactions displayed have conserved the forms of the preceding eclogite-facies crystals. The epidote-bearing amphibolite-facies "external gneisses" were reported to contain Mn-bearing garnets as relics of a previous metamorphic stage but without any direct evidence to relate that to the eclogite-facies stage in the eclogite unit. The "internal gneisses" were described as differing texturally and in the mineral chemistry of their silicates, oxides and sulphides from all the eclogites, retrogressed eclogites and the "external gneisses" and accordingly were taken to represent a different foreign material, in particular being devoid of clinopyroxene or symplectite after omphacite. From these observations Kechid & Smith (1985) imaginatively deduced that the Liset eclogite unit (presumed eclogitized crust) was first tectonically introduced into a deep continental gneiss unit and subsequently introduced along with a portion of the latter (now the "internal gneisses" unit) into the "external gneisses" unit. This instance of double tectonic introduction is accordingly in line with the "tectonic melange" model of "lithospheric interdigitation" of eclogites and gneisses as proposed by Smith (1980a).

Kechid & Smith (1985) deduced eclogite-facies temperature of 550-650^{o}C for the Liset eclogite and minimum pressures of 1.6 GPa from coexisting jadeite + quartz or of ca. 2.4 GPa if paragonite coexisted with jadeite and kyanite or even higher at ca. 2.6 GPa if some observed poly-crystalline quartz inclusions in garnets are interpreted as pseudomorphs after coesite.

Our more recent limited sampling of the Liset eclogite has revealed that certain kyanite-and quartz-bearing samples (collected from foreshore outcrops down from the sixth power pole to the NW of the Liset hamlet parking place) contain numerous convincing poly-crystalline quartz inclusions after coesites within large poikiloblastic garnets. Accordingly the UHP status of the Liset eclogite pod has now been confirmed. A noteworthy feature in our samples is that the larger silica-phase inclusions within the large garnets are invariably monocrystalline whereas the smaller inclusions often comprise fine-grained poly-crystalline quartz. There is no consistent spatial distribution of the two textural types of quartz inclusions within the largely chemically homogenous garnets and it appears that the larger monocrystalline quartz inclusions have just more thoroughly annealed probably because their more intense adjacent network of fractures within the garnet has permitted more ready access of recrystallisation-promoting fluids, hence eliminating obvious petrographic evidence that these larger inclusions were previously also of coesite.

17.30-18.30: Return on foot or by minibuses if available from Liset to the Selje Hotel.

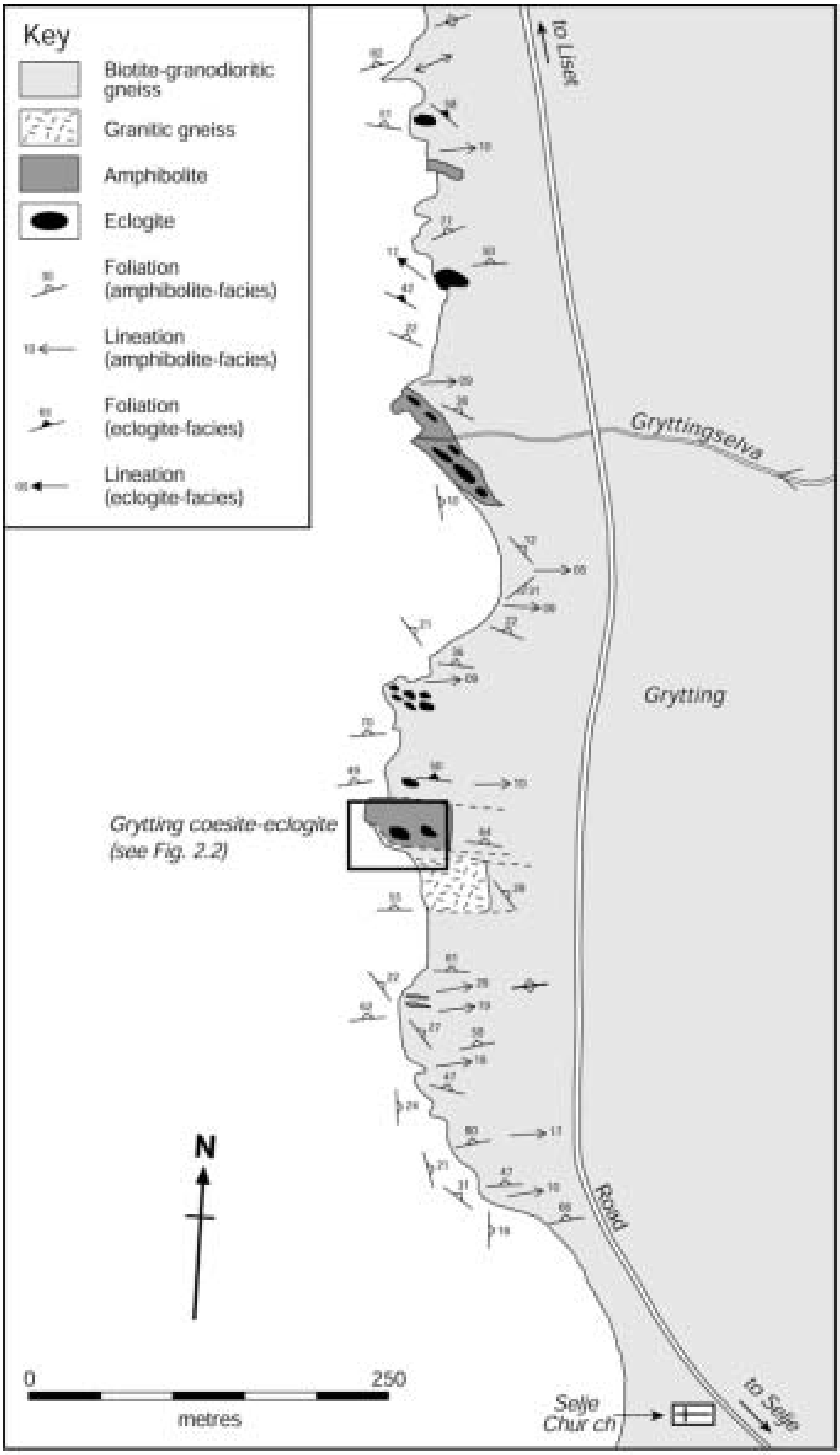


Figure 2-1: Geological map of the Selje-Grytting coast, Stadlandet by Maarten Krabbendam.

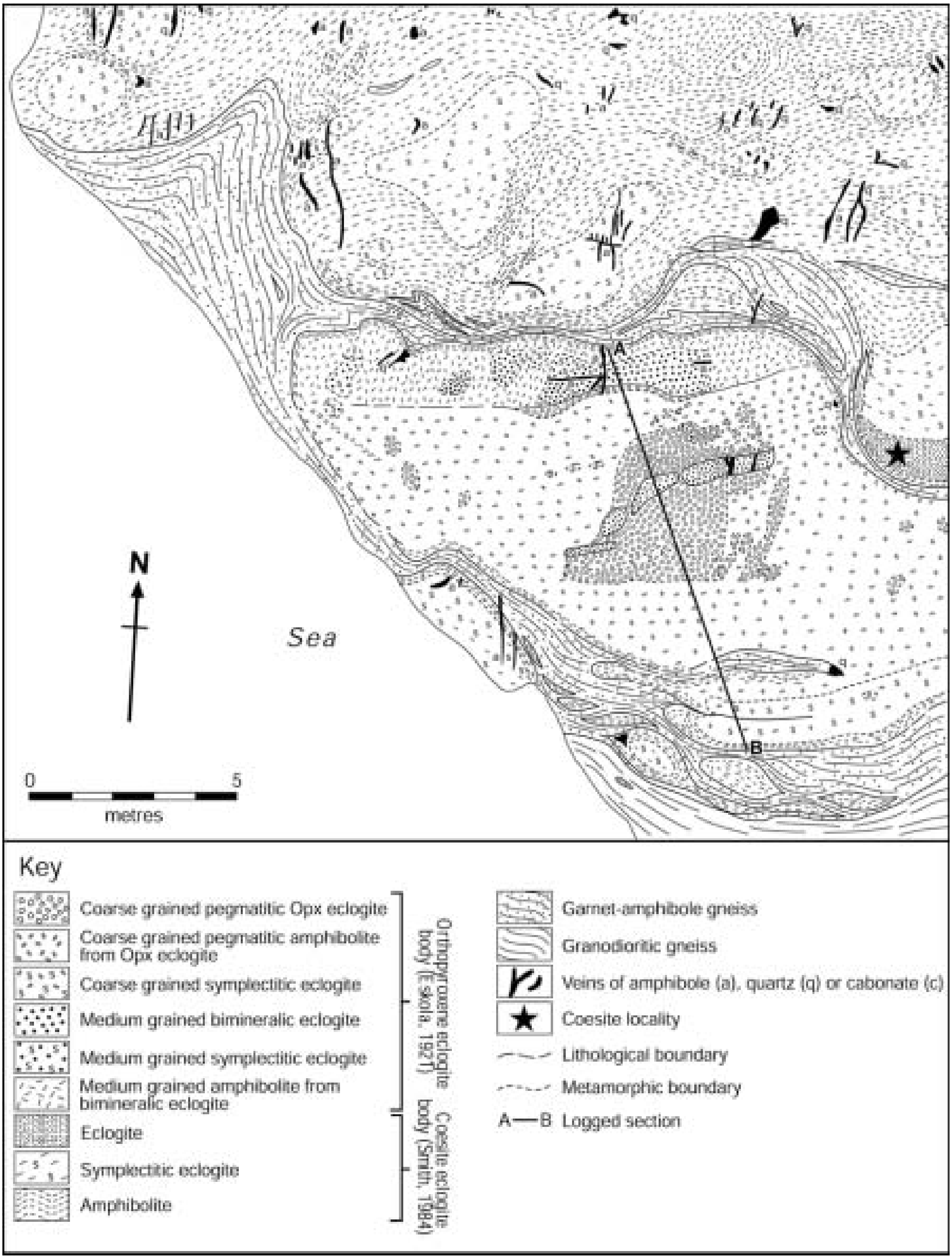


Figure 2-2: Detailed structural and metamorphic map by Maarten Krabbendam, with modifications by Tony Carswell and Simon Cuthbert, of the Grytting eclogite locality near Selje on Stadlandet. Random alignment of foliation symbols in amphibolite, symplectite and gneiss indicate undeformed state.

Figure 2-3: Field photograph showing the disrupted portions of a sheet of medium-grained bimineralic eclogite that has been invaded by the enclosing pegmatitic orthopyroxene-, phlogopite and carbonate-bearing eclogite - from within the central part of the Grytting orthopyroxene eclogite body.

Figure 2-4: Field photograph of coarse-grained orthopyroxene eclogite with distinctive mantled garnets with dark red gemmy cores and paler granular overgrowth mantles - from within the central part of the Grytting orthopyroxene eclogite body.

CHAPTER 3:

EXCURSION TO THE UHP ECLOGITES AND SCHISTS AT ÅRSHEIMNESET AND OTNHEIM ON STADLANDET

Tony Carswell and Simon Cuthbert

14.00: Leave Selje on the road to Stadlandet and Vestkapp. This road climbs up over the Stad peninsula providing excellent views back westwards to Selje, Seljeøy and beyond and eastwards across Vanylvsfjorden during the descent to the eastern shore of Stadlandet. After 8 km turn right at the junction with route [620] towards Åheim, and drive ca. 600m to a roadside outcrop of eclogite (grid ref. 139872 Vanylven sheet) on a sharp right hand bend over Årsheimneset. There is parking for 3-4 minibuses (or a coach) in the left hand side lay-by ca. 100m past the outcrop, plus if necessary parking for 1 minibus 150m further east and further parking beyond.

14.30-15.45: STOP 3.1: ÅRSHEIMNESET ORTHOPYROXENE ECLOGITE

The roadside outcrop of this eclogite body *(PLEASE TAKE CARE TO WATCH OUT FOR PASSING TRAFFIC)* is ca. 11m long and 8m high, with the lower (western) contact with felsic gneisses well exposed. A petrographically-similar lens (ca. 40x50m size) containing opx-bearing eclogite outcrops on the shore of the Årsheimneset headland just to the east but will not be visited on this particular excursion. Opx eclogite from the latter outcrops was studied in depth by Lappin & Smith (1978) but the fact that they referred to this locality as **Sandviknaes** has caused some confusion in the literature since a conspicuous eclogite body (albeit kyanite-bearing and opx-free) is exposed on **Sandvikneset** point about 1.2 km to the NW. In all likelihood the roadside and foreshore outcrops of opx-bearing eclogite on **Årsheimneset** headland are disrupted portions of the same body.

Smith (1988) reported that phlogopite-bearing, opx-free eclogite samples from the Årsheimneset foreshore body contained poly-crystalline quartz pseudomorphs after coesite within garnets. The UHP status of the Årsheimneset roadside body has been confirmed by observations of poly-crystalline inclusions of quartz after coesite within garnet, opx and cpx grains, notably within phlogopite and opx-bearing eclogite samples.

An important observation in the Årsheimneset roadside outcrop, as illustrated in the annotated field photograph of Figure 3-1, is that the central part of the body comprises mainly essentially bimineralic (opx-free) eclogite whereas inside of the amphibolitised outer top and bottom contact margins to this body, the main rock type is an opx and phlogopite-bearing eclogite that becomes distinctly pegmatitic towards the lower margin. As the central bimineralic eclogite frequently contains conspicuous, up to cm-sized, prograde zoned garnets –see Figure 1-7, this body thus contains characteristics of both the HP and UHP eclogites in the Nordfjord/Stadlandet area, as characterised by Wain et al (2000), yet outcrops about 5 km within their recognised UHP zone. The coarser-grained Opx eclogite (see Fig. 1-11) contains more irregularly-shaped large garnets comprising early darker cores with blue-green amphibole inclusions extensively overgrown by later UHP garnet with poly-crystalline quartz inclusions after coesite as well as frequent inclusions of cpx and phlogopite, indicating that the latter was a stable UHP phase.

We interpret this Arsheimneset eclogite body to have evolved from an early HP (quartz-stable), essentially bimineralic, eclogite, with prograde zoned garnets that not infrequently contain bluish-green amphibole inclusions in cores, to a more siliceous opx- and phlogopite-bearing eclogite in which substantial new growth of garnet, opx and cpx took place under UHP conditions and consequently trapped coesite inclusions. Thus importantly in our opinion, the UHP mineral growth in this eclogite occurred in response to a substantial influx of fluid from the enclosing continental crust gneisses. The transformation of the early, essentially bimineralic, HP eclogite into a coarser-grained, even pegmatitic, UHP eclogite can be followed along hydraulic fractures penetrating the former (as shown in Fig. 3-1 - our annotated field photiograph of the distribution of rock types within this eclogite body). Field relationships give no support to an interpretation of tectonic mixing of HP and UHP eclogites as proposed to explain the close spatial association of these eclogites within the HP-UHP transition zone recognised between Nordfjord and Stadlandet by Krabbendam & Wain (1997) and Wain et al (2000).

Magnesite, albeit subsequently partly replaced by dolomite and/or calcite, was also introduced and stabilised as a minor UHP phase in the metasomatised phlogopite- and opx-bearing eclogite. Agrinier et al (1985) indirectly determined the carbon and oxygen isotope values of the magnesite in such a sample from the Årsheimneset roadside pod to be $\delta^{13}C$ = -4.5‰ and

$\delta^{18}O$ = +9.7‰. They were uncertain over a crustal versus mantle origin but on balance favoured crustal protoliths for such eclogites.

Some mica-rich veins and patches occur (see Fig. 3-1) that have been observed to preserve phengitic micas in their cores, overgrown and part replaced by darker coloured phlogopitic/biotitic micas. In addition to the phengitic mica, quartz (initially coesite?) and garnet have grown in these veins as have conspicuous accessory apatite and zircon, indicating metasomatic introduction of P and Zr as well as K. One especially well-developed vein within pegmatitic orthopyroxene-bearing eclogite has a phengitic mica-rich core and a garnet plus quartz-rich margin adjacent to the eclogite. This vein margin garnet contains some obvious poly-crystalline quartz inclusions confirming that the vein assemblage grew under UHP conditions with coesite as the stable excess silica phase.

Gebauer et al (1985) has provided U-Pb zircon and REE data for samples from the Årsheimneset Opx eclogite body, although unfortunately labelled as Sandviknaes. The dated sample from the roadside body (SAN1) is phlogopite-bearing and stated to contain large inclusion-rich subidioblastic garnets of up to 2 cm size. In this sample the zircon population comprises only about 5% of older magmatic zircons with substantial metamorphic growth having occurred at close to 400 Ma.

The low contents of Al_2O_3 in opx (0.30-0.49wt%, Lappin & Smith, 1978) in the Årsheimneset eclogite body are consistent with pressures sufficient for coesite stability. Our updated thermobarometric evaluation, using the coexisting grt+opx+cpx compositions for sample 68/88 in Lappin & Smith (1978) has yielded P-T values of 750+/-25^{o}C and 3.0+/-0.25GPa. On the other hand, Lappin & Smith (1978) took certain petrographic features in their samples as evidence for exsolution of garnet from the primary opx and also of opx from primary cpx. They accordingly employed reconstituted compositions for a “primary” pre-exsolution opx and cpx to derive values of 1220-1370^{o}C at 3.0-4.0GPa for their Stage A initial eclogite facies assemblage. Such a high temperature early eclogite-facies stage is, however, inconsistent with the much more compelling petrographic evidence for a prograde metamorphic evolution of this rock body from amphibolite-facies to HP (quartz-stable) and then UHP (coesite-stable) eclogite-facies conditions. In our opx-eclogite samples we have observed similar rational intergrowths of rather broad and irregular lamellae of garnet within opx and cpx and of opx within cpx to those described by Lappin & Smith (1978) but judge these intergrowths to have resulted from the rapid, sometimes epitaxial, growth of these co-existing minerals under fluid-present conditions.

15.45-16.00: Drive ca.4 km NW on route [620] from Årsheimneset to Otnheim. Turn left at the sign to the Otnheim hytte, park at the top of the gravel drive to the two cabins and walk down to the outcrops on the shore below the cabins (grid ref. 114897 Vanylven Sheet).

16.00-18.00: STOP 3.2: UHP ECLOGITES AND GNEISSES AT OTNHEIM

This is one of a number of localities on Stadlandet where Alice Wain importantly demonstrated that not just metabasic eclogite bodies but also intimately associated gneisses have experienced UHP metamorphism.

Accordingly, at this locality we shall follow the sketch map (Fig. 3-2) of the relationships between the exposed rock types by Wain (1996), who also provided the following description:

"A 20m wide composite body of eclogite and eclogite-facies gneiss occurs in a low-strain zone within mylonitic amphibolite-facies gneisses at Otnheim, East Stadlandet.

Mafic eclogite, and eclogite-facies gneiss, are interbanded on the centrimetre to metre scale. Eclogite contains garnet, omphacite and quartz, with minor biotite or amphibole. Coesite or poly-crystalline quartz pseudomorphs after coesite are common as inclusions in garnet, which is itself unzoned. Interbanded gneisses consist of garnet, clinozoisite and quartz, with variable phengite and kyanite. Polycrystalline radial-textured quartz inclusions are found in garnet, rarely in clinozoisite. Polygonal polycrystalline and multicrystalline (after Smith, 1988) quartz inclusions are common in clinozoisite. These textures are taken as evidence for former coesite, therefore both eclogite and associated gneiss have experienced UHPM.

The boundary of this composite body is defined by an amphibolite-facies deformatibn front, the external gneiss and metabasite strongly affected by late-orogenic deformation and metamorphism."

We offer the following additional comments, especially on the lithological association present. We suspect that all the rocks displayed at this locality are meta-igneous and probably belong to the mangerite-gabbro-anorthosite kindred, rocks that are quite widely exposed in the

Nordfjord-Stadlandet-Vanylvsfjorden area, albeit in a wide variety of deformation and metamorphic states. Westwards (and also immediately eastwards) of Alice Wain's map for this UHP eclogite body, the dominant rocks are platy, highly sheared K-feldspar-rich mangeritic gneisses that are garnetiferous in lower strain zones. These rocks, that are also well displayed in a rather less deformed state in the nearby road cuttings, were mapped as a discrete ca. 1x 0.5 km-sized body of garnetiferous gneiss by Krabbendam & Wain (1997).
We suggest that the irregular layers and lenses of garnet+clinozoisite+quartz+/-kyanite+/-phengite gneissic rock (with convincing petrographic evidence for previous coesite stability) that are intimately associated with the UHP eclogite at Otnheim were derived from original anorthositic rocks.

As such therefore these specific "gneisses" still do not provide conclusive proof that the more dominant quartzo-feldpathic granititic, grandioritic or mangeritic gneisses in the Stadlandet area also experienced UHPM conditions, although this is considered most likely.

18.00-18.30: Return to Selje by reversal of the outward journey route.

Figure 3-1 (opposite): Annotated field photograph of the roadside exposure of the coesite-bearing UHP eclogites at Åsheimneset on Stadlandet, west Norway.


Coesite-bearing UHP Eclogite
Årsheimneset, Stadlandet, west Norway
Opx
Eclogite
Bimineralic
Eclogite
Mica-cored
Symplectite
Opx
Eclogite
Amphibolite
Opx Eclogite
OPX-free
Bimineralic
Eclogite
Mica-cored
veins
Bi. Ecl.
Pegm. Opx Eclogite
Coarse Opx Amp.
Foliated Amphibolite
Gneiss
Bi. Ecl.
Opx
Eclogite
Gneiss
Gneiss

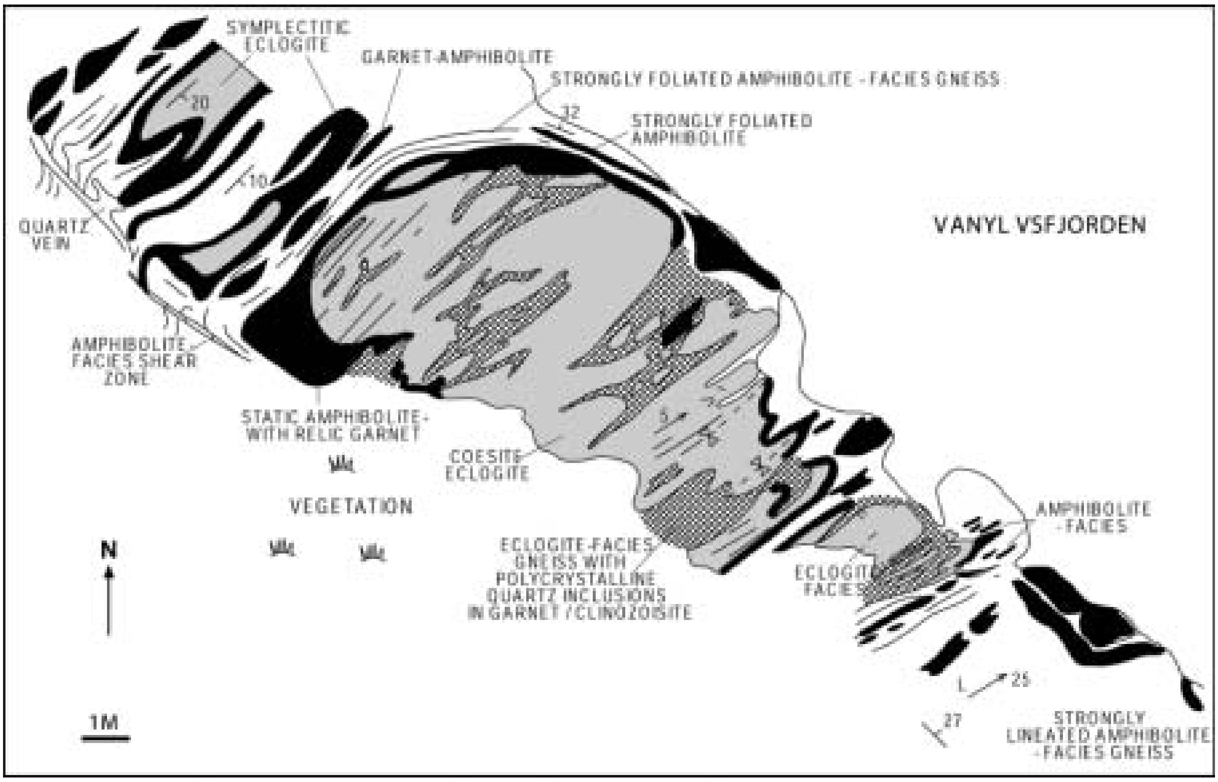


Figure 3-2: Field sketch of in-situ UHP metamorphism in the coastal exposure at Otnheim on Stadlandet, west Norway – after Alice Wain, 1996.

CHAPTER 4:
EXCURSION TO THE UHP ECLOGITES AND SCHISTS AT SALTA, VETRHUS AND FLISTER

Simon Cuthbert and Tony Carswell

Themes:

Temporal and spatial aspects of HP-UHP transitions, textural development of UHP eclogites, UHP metapelites.

Refer to Statens Kartverk 1:50 000 Topographic Map Series M711, sheets 1119 III (Vanylven) and 1118 I (Måløy).

14.00: *Leave Selje on route [518] towards Måløy and after about 11 km at grid ref. 088819 (Vanylven sheet) turn right at a bus stop along a minor road signposted SALT. Park minibuses in a grassy, graveled area on left 50 m from junction with main road. A coach is probably best left at the bus stop on the main road opposite the junction.*

14.15: *Walk ca. 300 m further north along the minor road to Salt, then turn left at a gravel drive* (089824) *leading to a white house, but immediately leave the drive and cross open, rough ground directly westwards to the rocky shoreline. Follow the shore northwards to find eclogite exposures after ca. 200 m at 087825.*

14.30–15.30: STOP 4.1: SALTA ECLOGITES

Eclogite at this locality was found by Wain (1997a) to be of UHP type, with poly-crystalline quartz. She placed it in her UHP zone 4.5 km north of the northern limit of her HP-UHP Transition Zone. At the back of the shore there is a conspicuous 1m wide eclogite layer within platey, porphyroclastic, mylonitic gneiss. Stretching lineations in the gneiss have shallow easterly plunges, co-linear with hinges of minor, intrafolial isoclines and later, large wavelength, open, upright folds and associated crenulations. The eclogite body pinches out eastwards, and strikes westwards for 20m before passing into the sea. It comprises a central, fine-grained, well-lineated eclogite with massive, coarse grained layers or pods of garnetite, plus some garnet-quartz layers.

20m inland to the east of these shore exposures is vegetated exposure of spectacularly layered eclogite (see Fig. 1-12) interlayered with phengite-quartz schists. Unusually for the WGR, well-preserved, palisade poly-crystalline quartz inclusions are common (Fig. 1-14) and relatively large (see Fig. 1-3) in this eclogite, especially within larger garnets in quartz-garnet layers and veins but also in omphacite in the eclogite host. Coesite has now been found here (Cuthbert et al., 2000). A vertical section through the layered sequence, exposed on the south side of the exposure, is shown below:

TOP OF EXPOSURE

Country-rock – layered, mylonitic biotite + feldspar + quartz gneiss.

Layer E – 180cm layered eclogite with a conspicuous, coarse-grained grt + qtz vein (presumably originally garnet+coesite) up to 1cm wide, together with finer, equigranular grt + qtz layers rich layers up to 5cm and thin phengite (+garnet) schist layers up to 3cm. The upper, exposed contact with the overlying gneiss lacks any clear retrograde amphibolitisation.

Layer D – 80cm well-layered omp + phe + qtz gneiss with quartz-rich lamellae up to 1cm thick.

Layer C – 32cm layered eclogite with omp-rich and grt-rich layers.

Layer B – 55cm dark grey-green finely layered and partly retrograded grt + ky + omp + phe + qtz gneiss.

Layer A – 100cm layered eclogite including 2-10cm thick grt + qtz layers and a layer of grt + phe + qtz up to 3cm thick.

BASE OF EXPOSURE

Layering in the eclogite has strike/dip 100/64N, concordant with that in the mylonitic gneiss country-rocks, but the omphacite lineation is moderately steep at 55.079, in contrast to the shallow easterly plunge of the stretching lineation in the country-rocks.

Garnet-quartz veins in the layered eclogite are discordant to the omphacite fabric in the host by up to 20^o. Garnets in these veins are xenoblastic and much larger than those in the host, with Ca-rich and Mg-poor cores and overgrowths of distinctly Ca-poorer and Mg-richer rims. The cores are slightly deeper red in colour than the overgrowths and contain abundant, minute rutile needles. The overgrowths are paler coloured and lack the small rutile inclusions. Patchy distribution of Ca in the cores suggests that they formed by aggregation of many small grains. Alternatively they may have been large porphyroblasts whose originally uniform composition has been modified along networks of fractures or dislocations. Also present in these veins are idioblastic garnets with identical compositions to the overgrowths; these also lack the small acicular rutile inclusions. The latter type of garnet has been used to produce a Sm-Nd mineral-WR isochron of 407+/-7Ma (Carswell et al., 2003a). Coesite and polycrystalline quartz inclusions are restricted to idioblastic or overgrowth garnet. This type of vein is spatially associated with high-strain seams in the adjacent clinopyroxenite layers, along which omphacite that has broken up into sub-grains. Where these seams meet the grt + qtz veins, such subgrains are isolated within quartz. The veins are interpreted as having formed by infiltration of a siliceous fluid along a fracture under UHP conditions and to have initially crystallized as grt + coesite.

15.45: *Retrace route back to vehicles and proceed a further 10km towards Måløy on route [518] (after 2 km UHP eclogites in roadcuts are passed near Runderheim – see Wain (1997a, 1998), and Wain et al., (2000) – these are not included in the excursion). Ca. 1km past the junction with a side-road to Venøya and 0.5 km NW of the hamlet of VETRHUS, park in a large, signposted roadside parking area and picnic site (grid ref. 053767 Måløy sheet) overlooking Nordpollen. Walk back north along route [518] (beware of traffic) past road cuts through orthogneisses until, after ca. 200m (051769), a swarm of eclogite pods in semipelitic gneisses and schists is encountered (see Fig. 4-1).*

16.10-17.30: STOP 4.2: VETRHUS UHP ECLOGITES AND SCHISTS.

The locality lies near the northern margin of the transitional HP-UHP zone recognised by Wain (1997a) and Wain et al. (2000). The eclogites form a swarm of pods within a 300m wide belt of phengite-quartz-garnet-kyanite schists and gneisses with thin anorthositic horizons close to its southern (lower) margin. This supracrustal unit is sandwiched between uniform, regionally extensive, migmatitic orthogneisses. This lithological association is common in the Nordfjord-Stadlandet area. Eclogites are much rarer within the orthogneisses, and none are found within them at this locality.

Eclogites at Vetrhus were described by Wain (1997a) as coesite-bearing UHP-type, enclosed in eclogite facies schist and gneiss containing prograde zoned garnets (Wain, 1998). The apparently contradictory association of UHP eclogite and HP-type schist led the authors to examine this site in detail, and it reveals interesting insights into the nature of the HP-UHP transition. The first obvious pod is on the NE side of the road, roughly opposite the roadsign to the picnic site, but this pod is heavily retrograded. Much fresher eclogite pods enclosed in phengite-garnet schists occur in cuttings on both sides of the road, commencing 30m further NW beyond a block retaining wall.

These eclogite pods are phengite, zoisite and carbonate-bearing and show frequent evidence for coesite. Their deformation fabrics merit close examination: Strongly lineated eclogites (especially those on the SW side of the road) show streaked out, porphyroclastic grt + qtz layers (previously grt + coesite). Layering in this eclogite dips steeply NW and the omphacite lineation plunges equally steeply NW, both highly discordant to the amphibolite-facies fabrics in the orthogneisses on either side of the supracrustal belt. Eclogite with the most weakly developed omphacite lineation preserves subidioblastic, coarser-grained garnets with distinct prograde compositional zoning (see Fig.1-9) and commonly containing inclusions of hornblende in cores, hence resembling the VAK-type eclogites along Nordfjord. The latter type also contains more xenoblastic, not obviously zoned, garnets whose compositions are similar to the rims of prograde zoned grains. Poly-crystalline quartz inclusions are restricted to these latter garnet grains. Country-rocks along this road section are phengite-quartz-garnet schists and gneisses. Garnets are prograde zoned, and no poly-crystalline quartz or coesite inclusions have been found in them at these outcrops.

200m NW along route [518] from the picnic site sign at the SE end of the crash barrier access can be gained to the Nordpollen shoreline - walk across boggy ground on the seaward side of an old wire fence to reach rocky exposures at the shoreline (care is needed here as there is a risk of a slip into the fjord at some steeper and hold-free parts of this shoreline especially when wet, but good, safe exposures may be found without the need for scrambling on steep rock).

The excellent shoreline exposures display pelitic and semipelitic phe + qtz + grt +/- ky schists and gneisses enclosing numerous eclogite pods from a few cm to 4.5m across. The largest pod contains garnets with inclusions of palisade poly-crystalline quartz after coesite. The country-rocks are variably retrograded with replacement of coarse phengite by symplectites of plagioclase + biotite and fine grained white mica replacing kyanite. A well-developed quartz rodding lineation is co-linear to strings of garnet grains, both of which are developed coaxially to crenulations of the phengite foliation, considered to be a composite eclogite-facies fabric. Crenulations and lineation are variable due to deflection around eclogite pods, but generally plunge around 50^{o} N to NE, giving similar plunges to the amphibolite-facies stretching lineations in the nearby orthogneisses but with rather more northerly trends. Locally these coarse phengite schists are re-worked into finer-grained, well-foliated biotite-muscovite-plagioclase-quartz schists. The phengite schists display spectacularly large purplish-red porphyroblasts of garnet up to 4 cm in diameter, showing strong prograde zoning with Fe and Mn-rich cores and Ca and Mg-rich rims. Importantly, their rims have been found to contain rare poly-crystalline quartz inclusions after coesites.

Hence at this locality both eclogites and country-rocks show evidence for UHPM, with two distinct generations of garnet demonstrating a prograde evolution from amphibolite-facies or HP eclogite to UHP eclogite. The conclusion of Wain (1997a) and Wain et al. (2000) that eclogites in the transition zone are exclusively either “HP” or “UHP” is thus not upheld by observations at this locality; instead characteristics of both types are found within the same rock mass. This indicates an evolution from amphibolite-facies to UHP eclogite-facies during which the extent to which the rocks have transformed to a UHP paragenesis varies. A variety of mechanisms appear to have operated, including simple overgrowth of new garnet due to discontinuous reactions within the matrix, mechanical breakup of garnet and re-equilibration associated with recrystallisation, and possibly ingress of a silica-enriched fluid.

17.30–17.50: *Return to the vehicles and drive back towards Selje along route [518] for about 3 km. The route takes you north along the shore of Nordpollen, then east skirting Barmsundet, then south along the shore of a small, un-named fjord to a roadside eclogite exposure at FLISTER (065776 Måløy sheet). Parking is difficult but there should be space for 3 minibuses next to a red barn with a green door on the landward (W) side of the road, opposite a yellow house on the fjord side of the road. There are further smaller spaces suitable for minibuses between here and the southern end of this small fjord. Leave the buses and meet by the red barn.*

17.50–18.30: STOP 4.4: FLISTER FLASER ECLOGITE.

The exposure lies 10m N of the red barn in a grassy area by the landward side of the road. It is a 3m wide blasted exposure of eclogite with a distinctive flaser deformation fabric. Cuthbert et al. (2000) found coesite in this exposure and Wain (1997a) reported poly-crystalline quartz in an eclogite on Flister Hill above and to the west of here. The geology along the east side of the fjord (Fig. 4-2) is comprised of three main lithological associations; granitoid augen and layered gneisses, mostly in the form of porphyroclastic mylonites with only rare eclogite and biotite-epidote amphibolite pods; semipelitic phengite gneisses with thin horizons of meta-anorthosite and abundant pods of eclogite; and massive, grey, biotite-plagioclase-garnet-epidote +/- phengite gneiss with common layers of meta-anorthosite. The granitoid gneisses are similar to those at Vetrhuset and dominate the north and south ends of the fjord. The flaser eclogite here lies in one of three belts of phengite gneiss. Gneissic layering strikes E-W and stretching lineations in amphibolite-facies mylonites plunge about 35^{o}E. However, the omphacite lineation in the eclogite plunges more steeply to the NE.

The flaser eclogite is extensively symplectised and contains minor phengite and calcite. Garnet forms lensoid, granular streaks whose thicker parts are often cored by larger garnet euhedra. These have unzoned cores containing inclusions of hornblende. Surrounding this is a continuous, annular zone of higher Ca but unchanged Mg/Fe and lacking hornblende inclusions. The outer zone has a discontinuous annulus of low Ca and higher Mg/Fe, and a further, variably developed, zone of similar composition to the garnet core is locally developed. Hence these garnets show a complex type of prograde zoning similar to the VAK type eclogites. The remainder of this flaser-textured eclogite lens consists of granoblastic aggregates of finer-grained garnet and interstitial phengite, omphacite and rutile. These garnets lack inclusions of amphibole, but do contain omphacite, phengite and poly-crystalline quartz after coesite. They have compositions similar to the outer, Mg and Ca-rich zones of the larger prograde zoned garnets. Compositional variation is complex and rarely simply concentric, but many grains appear to show truncated concentric zoning, possibly indicating mechanical break-up of originally concentrically zoned crystals. Hence here we have another example of a coesite eclogite with at least two generations of garnet, the later garnet being associated with coesite. Textural relationships indicate that the later garnet formed at least in part by porphyroclasis and recrystallisation of earlier, larger grains.

If time permits, we can walk south along route [518] (beware the traffic) past the yellow house on the fjord side of the road, then descend to the shoreline into a bay between two headlands. North and south of the bay are pelitic gneisses with minor psammites, anorthosites, augen gneisses amphibolites, with swarms of eclogite pods. The largest of these on the southern headland has a phengite eclogite with a granoblastic texture and contains poly-crystalline quartz after coesite as inclusions in the margins of large garnets. Garnets have prograde compositional zoning, although the Ca and Mg-rich (UHP?) rims are very narrow. This is a common observation in eclogites in the WGR and the resulting lack of volume to contain coesite may explain why coesite is so rarely preserved in Norwegian eclogites, in contrast with those from Dabieshan, for example.

18.30: *Return to the vehicles and drive the remaining 18 km on route [518] back to Selje, to arrive at the hotel at ca. 19.00.*

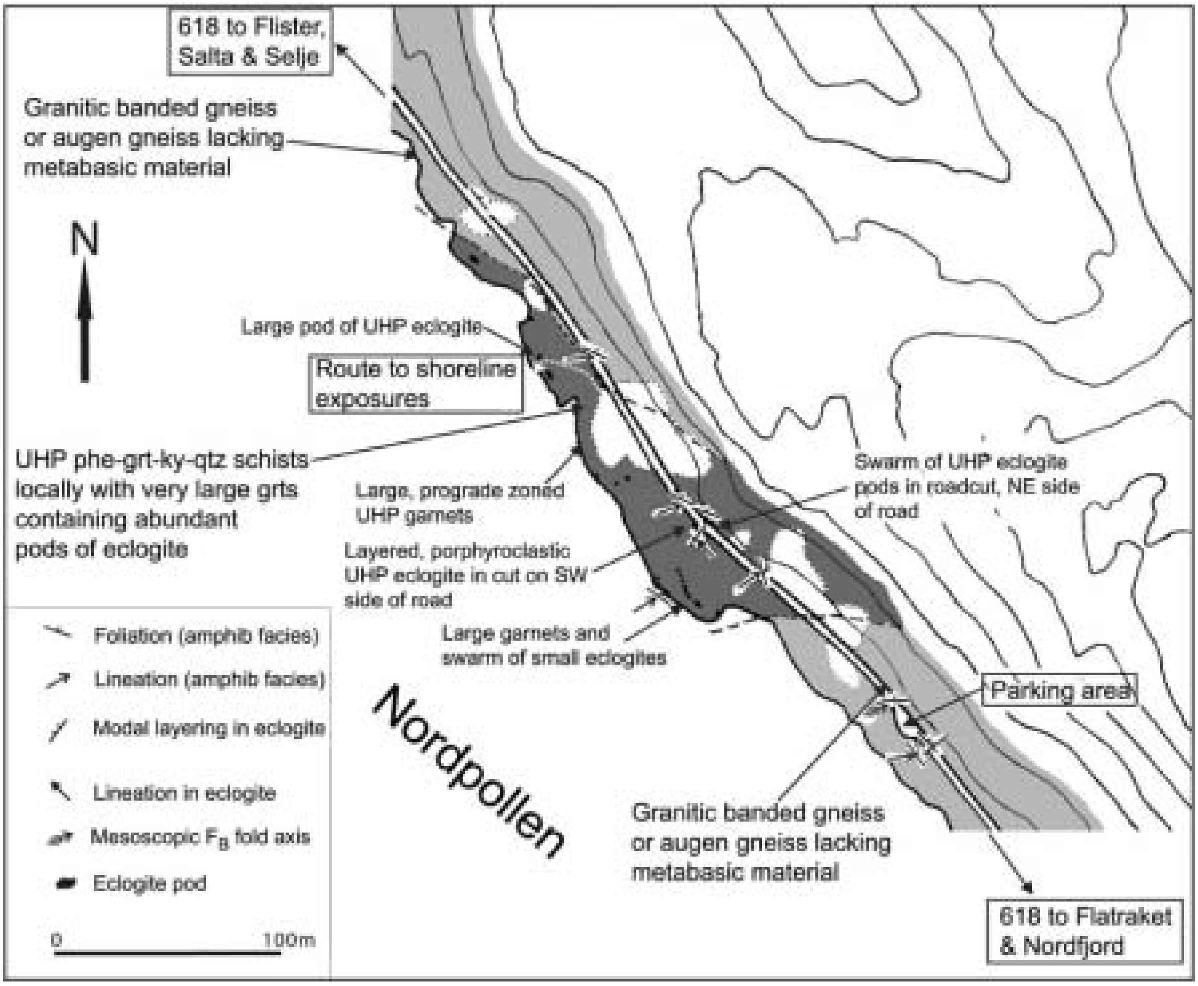


Figure 4-1: Geological map of Nordpollen shoreline at Vetrhuset (Stop 4.2).

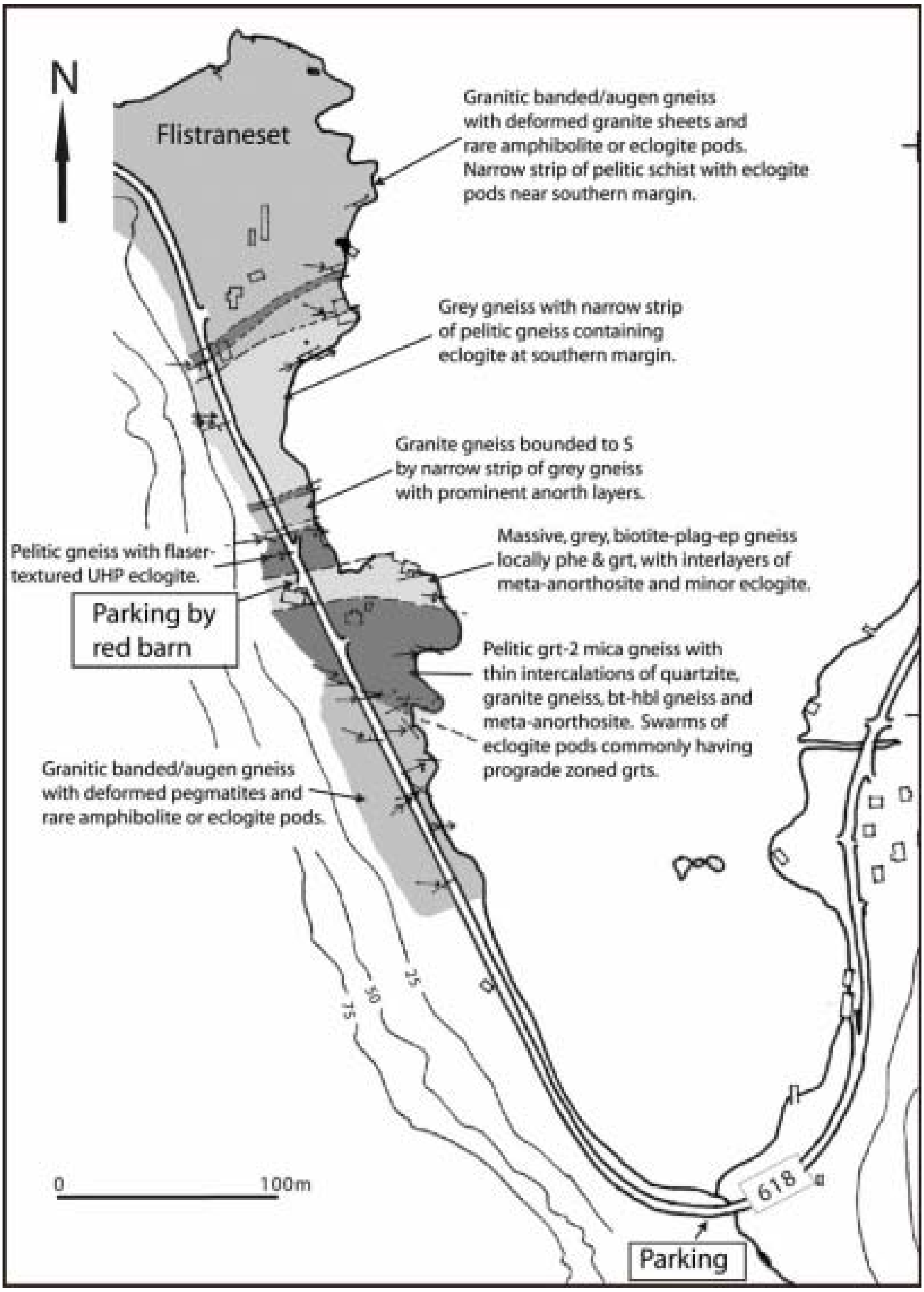


Figure 4-2: Geological map of the Flister area (Stop 4.3).

CHAPTER 5:
EXCURSION TO THE FLATRAKET MANGERITE BODY AND THE ECLOGITES AND GNEISSES OF OUTER NORDFJORD

Refer to Statens Kartverk Topographic 1:50,000 Series M711, sheet 1118I Måløy;
NGU Geological map sheet 1:250,000 Måløy (Kildal, 1971).

Themes

Conversion of felsic and mafic granulite to eclogite; plagioclase metastability; Flatraket UHP kyanite eclogite; Verpeneset, Kroken and Bryggia/Maurstad eclogites in the HP-UHP mixed zone; eclogite-gneiss relationships; retrogression of high-P gneisses during exhumation; exhumation tectonics related to the Nordfjord-Sogn detachment zone.

Logistics

This excursion is in two parts, each taking half a day. Part 1 visits the Flatraket mangerite body on the western side of Nordpollen. Part 2 goes to the north coast of outer Nordfjord. If the party is large it will probably need to be split into two groups, one going first to Flatraket and the other starting at Nordfjord. At lunch time the parties will swap over to visit the other site. The Flatraket visit involves a few hundred meters of walking on rough ground away from the roadside. All the Nordfjord sites are by the roadside. Some of the exposures are unstable cliffs and use of a protective hard hat is recommended. If there is good weather pleasant picnic spots can be found close to the field sites at Flatraket and near Almenningen, Nordfjord.

Part 1 – Flatraket

Prepared by Maarten Krabbendam

Introduction to Flatraket

Most rocks in the Nordfjord area (and indeed in much of the Western Gneiss Complex) are gneisses that were highly strained and (re)equilibrated at amphibolite-facies conditions, during late-Caledonian extension associated with exhumation from higher pressure conditions. These gneisses contain eclogite-bodies that attest to high to ultrahigh pressure conditions during the Caledonian. Thus, in most places in Nordfjord, one finds either peak-

Caledonian (eclogite-facies) or late-Caledonian (amphibolite-facies or lower) assemblages and structures, which makes it difficult to look beyond the Caledonian.

The Flatraket body is a 2 km^2 low-strain enclave that is an exception to this, in that it preserves igneous and granulite-facies assemblages and textures that *pre-date* Caledonian orogenesis. The Flatraket body is located within the mixed HP-UHP transition zone of Wain (1997). Two other low strain bodies further west in Nordfjord, the Ulvesund body and the Kråkenes metagabbro, also display pre-Caledonian assemblages (Krabbendam et al. 2000).

The Flatraket body is mainly composed of a quartz-monzonite with megacrystic K-feldspar in its core, surrounded by a layered transition zone containing felsic granulite gneisses with layers and pods of dioritic, anorthositic and mafic composition. Lappin et al (1979) obtained a U/Pb zircon upper intercept age of 1520 +- 20 Ma from the quartz monzonite, believed to represent magmatic crystallisation and a lower intercept of ~ 400 Ma.

Most of the body contains granulite-facies assemblages, such as cpx + plag + grt + qtz for meta-anorthosite; for which P-T conditions of 9-11 kbar and 700 - 800 º C were calculated by Wain et al (2001). During the Caledonian HP event, these assemblages behaved metastably and failed to react, so that pre-Caledonian plagioclase is widely preserved. This metastability is associated with lack of fluid and (more visible in the field) lack of Caledonian deformation (Krabbendam et al. 2000; Wain et al. 2001).

Locally (probably about 5% of the body) the Flatraket body was transformed into eclogite in zones of fluid infiltration and deformation, commonly focussed along lithological contacts in the margins of the complex. Where eclogitisation occurred in the absence of deformation (eg in the mafic ‘Pod 916’ in the stream section – see stop 5.3d) it never led to complete equilibration: remnants of plagioclase are still present, and garnets and clinopyroxene show strong zonation in their mineral chemistry. Garnet has grossular-rich rims and the jadeite contents in the clinopyroxenes jump from <6% to ~ 50-60%; this also shows that eclogite-facies metamorphism post-dates granulite-facies metamorphism (Wain et al. 2001). Strong local disequilibrium exists in such rocks; plagioclase breakdown occurred both via anhydrous reactions (producing grossular + ky + jadeite + qtz) and hydrous reactions (producing zoisite + ky + qtz + jd) although hydrous reactions dominate, attesting to the importance of fluid infiltration (Wain et al. 2001).

In contrast, complete eclogitisation of granulite occurred in shear zones, commonly at the contact between mafic and felsic rocks (Wain et al. 2001). In these rocks, hydrous HP phases (phengite, zoisite) are common, demonstrating a significant fluid influx coeval with deformation. This may also explain why eclogite-facies metamorphism is more common in the margins, rather than the core of the Flatraket body. Strain is commonly higher in felsic parts of shear zones than mafic ones, possibly because the plagioclase breakdown to zoisite + kyanite + quartz is associated with reaction softening. Wain et al (2001) calculated P-T conditions of P ~ 20 – 23 kbar, T = 650 – 800 º C, in both felsic and mafic eclogite shear zones. These pressure estimates show that plagioclase survived metastably 5-6 kbar above its anhydrous breakdown and 8-9 kbar above its hydrous breakdown.

Much of the Flatraket body has been affected by partial amphibolite-facies retrogression, even in undeformed areas, producing minerals such as clino-zoisite, sericite, amphiboles and biotite. Curiously, eclogite appeared to have been more resistant to amphibolite-facies retrogression than granulite-facies rocks; nevertheless, symplectisation is typical of many eclogitic rocks. This amphibolite-facies retrogression would have required a large amount of fluid: one source available during exhumation may have been the external gneisses as they retrogressed from phengite- and zoisite-rich eclogite-facies rocks to less hydrous feldspathic gneisses (Krabbendam & Wain 1997, Wain et al. 2001).

Coesite-bearing eclogite has been found ~200 m structurally above (Stop 5.2) and ~ 1 km below the Flatraket body on the east shore of Nordpollen (Wain, 1997). It is unclear how and when the coesite-bearing eclogite and the Flatraket body (with its apparent maximum pressure of ~23 kbar) were juxtaposed. However, the eclogite-facies shear zones that form the margin of the body (see Stop 5.3b) may suggest that juxtaposition occurred under HP conditions. These shear-zones are related to local and temporary fluid infiltration and deformation events that may not have occurred under peak P conditions (Wain et al 2001). This leaves open the possibility that the Flatraket Body was also buried to UHP conditions. Burial to UHP conditions, however, would represent a rather enormous amount of overstep (8 – 14 kbar for anhydrous and hydrous breakdown respectively) and unprecedented metastability; it would also beg the question why no coesite has been found (not for want of trying!), since the quartz-coesite transition is independent of fluid as a component (Wain et al. 2001).

Summary of geological evolution of the Flatraket Body

The geological evolution of the Flatraket body can be summarized as follows:

Pre-Caledonian (Proterozoic)

- intrusion of megacrystic quartz monzonite (~1520 Ma)
- intrusion of doleritic dykes
- granulite metamorphism (Sveconorwegian?)

Caledonian

- The Flatraket body was buried to pressures of at least 23 kbar. However, most rocks failed to equilibrate under these conditions. Some mafic dykes did equilibrate as did some felsic rocks, the latter mainly in shear zones that operated at HP conditions. The Flatraket body behaved largely as a low strain zone during burial and subsequent exhumation.
- Meanwhile, rocks just outside the Flatraket body were buried to pressures exceeding 28 kbar, accompanied by the crystallisation of coesite. It is unclear how these UHP rocks and the Flatraket body were juxtaposed.

History of research

The Flatraket body was first described in some detail by Bryhni (1966) and Lappin (1966). Further work was reported by Bryhni et al (1977) and Lappin et al (1979). The rocks at Seljeneset are described by Cotkin et al (1988) and Cotkin (1997). Alice Wain and I worked extensively in and around the Flatraket body in the summers of 1995 and 1996 and our field descriptions and structural analyses are published in Krabbendam et al. (2000). One day in 1995, I showed Alice the eclogite-body at Flatraket Harbour and she took some samples. During many weeks in the winter of 1995-1996 Alice was hunting coesite through her microscope without finding any, until a single day she found coesite in five or six different thin sections of different pods, Flatraket being one of them, which led to her paper in Geology (Wain, 1997). Further petrological work, detailing the story of metastability at HP in Flatraket was, fortunately, published in Wain et al (2000) and Wain et al. (2001). In her thesis, Alice Wain used the Flatraket Body and its evidence to demonstrate that granulite-facies metamorphism is not isofacial with eclogite-facies metamorphism and does pre-date rather than post-date eclogite-facies metamorphism, as had previously been suggested in areas elsewhere in the WGC.

Route:

Leave Selje on route [618] towards Måløy and drive about 28 km to Flatraket.

Stop 5.1: Megacrystic quartz-monzonite and mafic dykes.

Quarry along route [618], about 1 km east of Flatraket village. Spacious parking is available at the picnic site on the prominent bend in the road at the north end of Nordpollen fjord, above Flatraket point (grid ref. 033776) from where there are excellent views towards the imposing sea cliffs of Stadlandet. The quarry is located on the south side of the road (take care with traffic) and can be accessed directly from the road.

This quarry, more or less in the core of the Flatraket body, consists of megacrystic quartz-monzonite, characterized by large (3-10 cm) ovoidal megacrysts of K-feldspar, with smaller (5-10mm) ovoids of plagioclase in a matrix of plagioclase, quartz, garnet, biotite and hornblende and/or augite. The overall texture is akin to Rapakivi granites and shows that the original igneous texture is more or less preserved. The K-feldspar ovoids are ideal strain markers. Although the megacrystic gneiss is sheared in places (the northern wall of the quarry shows a very good example of a steep shear zone) what is striking in the quarry is how many K-feldspar ovoids are near-spherical, attesting to a lack of deformation, especially when compared to gneisses outside the Flatraket body. Using a variety of methods, Wain et al (2001) estimated a pressure of 8 – 10 kbar at a temperature of 700 – 850^{o}C for the granulite-facies metamorphism that these rocks experienced after intrusion.

Dolerite dykes cut the megacrystic quartz-monzonite and two of such dykes occur across the road from the quarry (*take care with traffic*). Although some dykes have eclogite-facies assemblages, these particular dykes have been equilibrated under granulite-facies conditions and show the assemblage cpx + plag + grt +- qtz. Relic ophitic textures, partially reacted to granoblastic textures occur in some mafic dykes (see also Bryhni et al. 1977). Most of these features, however, can only be appreciated in thin section: in the field eclogite-facies and granulite-facies mafic dykes cannot be reliably distinguished.

Stop 5.2: Coesite-eclogite outside Flatraket Body.

Drive 0.5 km west along highway [618] to Flatraket village (grid ref. 026771), then turn right onto a minor road to the harbour, where there is parking next to the harbour wall (grid ref. 027776). Follow the harbour wall. About halfway, there is a large rock (much larger than the boulders from which the harbour wall is constructed) on the sea-side of the wall.

This large rock, which is presumed to be a small islet, now incorporated into the harbour wall, is a coarse grained, unfoliated eclogite, with shows a beautiful symplectitic margin towards felsic gneiss outwith the eclogite. The eclogite has the assemblage grt + omph + ky (visible with the naked eye) + phe +/- amph +/- carb +/- rut +/- zircon +/- qtz +/- coesite (Wain, 1997; Wain et al. 2000). Coesite relicts occur as inclusions in garnet, whereas polycrystalline radial quartz occurs in both garnet and omphacite (Wain et al. 2000). Wain (1997) calculated peak pressure of around 28 kbar for the eclogite here. It is worth appreciating how close this eclogite body is to the Flatraket body (less than 200 m), given the different P-T conditions of the eclogite here and within the Flatraket body: Wain et al (2001) calculated a maximum pressure of 23 kbar for an eclogite-facies shear zone within the Flatraket Body, whereas plagioclase is still (metastably) present within the body.

Stop 5.3: Western margin of Flatraket Body.

Drive back to the main road, turn left then immediately right into a residential area in the far southeast of the village. After ~300m turn left then right to arrive at a stream crossing the street (grid ref. 027765) at the base of the hill Lyngahornet (334m). Behind the houses, cross the fence with care and follow the stream uphill.

The megacrystic gneiss (see Stop 5.1) is flanked by sheared megacrystic gneiss and then by layered garnetiferous gneiss with mafic and anorthositic layers and pods. This marginal zone contains very interesting features and is best seen in this stream section.

Stop 5.3a. Just after crossing the fence, there is a zone about 50m wide of micaceous quartzo-feldspathic gneiss, with occasional eclogite pods. These rocks are representative of other rocks in the Nordfjord area. The micaceous quartzo-feldspathic gneiss here has an amphibolite-facies assemblage (plag + qtz + k-fsp + biot + epidote +/- sphene +/- grt). The gneiss here has an intense banding and strong fabric, suggesting intense deformation. Biotite and epidote define an east-dipping lineation.

Stop 5.3b. Some 100m east of the fence is a shallow north-south trending drain.
In this drain there are small (<1m) pods and slivers of mafic eclogite, in a matrix of pale-green felsic to intermediate eclogite – much eclogite is now symplectitic. The pale-green eclogite is sheared and the mylonitic matrix of these shear zones has the assemblage ky + zo + qtz + phe + omph. It is from a similar (possibly same) shear zone further to the north that the P-T estimates (P ~ 20 – 23 kbar, T ~ 650 – 800ºC) from Wain et al (2001) were obtained.
The main lineation in this shear zone is shallow north-south plunging, at right angles to the east or west plunging lineations outwith the Flatraket body, which is interpreted to be related to late-Caledonian exhumation. Further outcrops of shear zones containing felsic eclogite occur higher up the stream.

Stop 5.3c. *Just above the first waterfall*. Here is a coronitic meta-anorthosite, surrounded by eclogite-facies and amphibolite-facies shear zones. The meta-anorthosite is white to pale-pink with large (~1 cm) garnet – clinopyroxene – quartz coronas that separate granoblastic plagioclase from igneous orthopyroxene. The margin of the anorthosite has been substantially recrystallised and has been partially eclogitised. A mafic band some 10 cm thick just to the east of the pod has thin felsic eclogite mylonite on either side. Wain (1998) showed that these felsic eclogite mylonites have completely equilibrated with the assemblage qtz + zo + ky +/- phe +/- paragonite. The eclogite mylonite shows a N-S trending lineation.
It appears that the gneisses not affected by eclogite-facies shearing (and retaining presumably at least some of their granulite-facies assemblage) were particularly affected by recrystallisation and shearing under amphibolite-facies conditions.

Stop 5.3d. *Just below the second waterfall* ('Pod 916')
Just below the second waterfall is a large pod (about 10m wide) of dioritic composition. The core of this pod locally contains relics of an igneous, ophitic texture with plagioclase laths still present. Most of the pod, however, has the granulite-facies assemblage grt + cpx + plag, with a relict granoblastic texture and garnet coronas separating feldspar from clinopyroxene. This assemblage has been strongly affected by amphibolite-facies retrogression. A sample from the margin of the pod contains the eclogite-facies assemblage grt + omph + qtz + zo.

Thus, this dioritic pod contains four assemblages: igneous, eclogite-facies, granulite-facies and amphibolite-facies.

Stop 5.3e. *Above the second waterfall and beyond.* Above the second waterfall, the dominant rock type is a coarse, foliated, finely-spaced layered garnetiferous gneiss, with mafic layers that occur parallel to the foliation. Some mafic layers have a pale-brown eclogitic core (grt + omph + qtz +//- rut +/- phe) and dark green, strongly symplectitic margins. Other mafic layers have a granulite-facies core (grt + cpx + plag) but eclogite-facies assemblages (grt + omph + qtz +- rut) developed along their margins.

Some of the folding and shearing that affects the rock here overprints the eclogitisation and must, hence, be late-Caledonian. Assemblages in these rocks are commonly a mixture of granulite-facies relics (plag + cpx + grt) and fine-grained minerals (e.g hbl, biotite, qtz, epidote) that presumably crystallised under amphibolite-facies.

Stop 5.3f. *A dioritic granulite, exposed in the southern side of the stream, 70 m beyond the second waterfall.*
About 70m upstream from the second waterfall a large (~10m) dioritic pod, surrounded on all exposed sides by felsic, layered granulitic gneiss. Most of the dioiritic pod has a granulite-facies assemblage (plag + cpx + grt). In the margin of this pod is a good example of incipient eclogite-facies metamorphism. At the margin, large garnets and symplectised cpx can be seen. Just inside the body is a narrow (2 cm) pink-green band (?vein) consisting of Grt + Cpx +- Ky . Wain (1998) and Wain et al (2001) detected grossular-rich garnet and small kyanite needles in this rock, and concluded that this is one of the few occurrences of anhydrous plagioclase breakdown with the reaction An Č Gros + Ky + Qtz, in addition to the hydrous plagioclase breakdown reaction, i.e. An + H_20 Č Zois + Ky + Qtz. This eclogitisation occurred in the absence of significant deformation.

Return down the hill to the vehicles. If the party is to return to Selje, reverse the outbound route. If continuing to Nordfjord, follow the instructions after the introduction to Nordfjord in Part 2 below. It may be desirable to have lunch at the Flatraket picnic site, otherwise another picnic site is passed on the way to Nordfjord that could be used instead.

Part 2 – Outer Nordford area

Prepared by Simon Cuthbert & Tony Carswell

Introduction to the Nordfjord area

The northern shore of Nordfjord provides an almost completely exposed east-west traverse through the Western Gneiss Complex (WGC) from the coast near Måløy to the Jostedal mountains east of Stryn. The westernmost part of Nordfjord from Maurstad to Verpeneset displays many of the classic, beautifully preserved, eclogites for which Norway is famous. The three localities that we shall visit along Nordfjord provide opportunites to explore several of the key issues relevant to the genesis, development and preservation of HP and UHP eclogites and gneisses in the "mixed zone" of Wain (1997a), and the panoramas to the south across Nordfjord place the eclogite facies rocks in the context of the tectonic system responsible for their exhumation. Due to the pivotal role of the Nordfjord rocks in the development of ideas about HP and UHP metamorphism, a rather extended introduction to the area is given here.

The Nordfjord eclogites were first mentioned by Irgens et al. (1864) and Reusch (1877). Eskola (1921), in his important study of Norwegian eclogites, described occurrences at "Bryggen" (Bryggja?) that display the typical mode of occurrence of smaller eclogite masses in the Nordfjord area, as swarms of pods having selvages of amphibolite, lying within "vein gneiss". He also described modal layering in the Nordfjord eclogites, and quartz or quartz-garnet veins. The origin of such layering and veining is of considerable interest for understanding the protoliths and petrogenesis of eclogites, and we shall see examples on the excursion.

Bryhni (1966) undertook the first detailed geological mapping in the Nordfjord area. He found that the predominant lithology in the region north of Nordfjord is a banded, granodioritic gneiss. Within this, horizons could be mapped out in which pelitic gneisses, psammites, granitic or monzonitic ("mangeritic") augen gneisses, and meta-anorthosites predominate. Pods and larger masses of serpentinite or dunite show a close spatial association with these supracrustal belts. One such dunite, which is mined for olivine sand, lies just east of our field area for this excursion, at Levdal. Bryhni noted that the Levdal body was one of a belt of ultramafic pods that extends along strike to the southwest across Nordfjord, and to the northeast to include the Almklovdalen garnet peridotite (the subject of Day 6 excursion). Lappin (1966) found a similar suite of lithologies around Almklovdalen just to the north of the excursion area. These reconnaisance surveys have remained the definitive description of Nordfjord lithology and structure until the 1990’s (see NGU 1:250K sheet “Måløy” of Kildal, 1970). In contrast to the Moldefjord area of the northern WGC, no coherent tectonostratigraphic framework has yet been established in the region north of Nordfjord, so only the most generalised structural and lithological correlation with adjacent regions has been possible. The belts of supracrustals with sheets of anorthosite and augen gneiss may be equivalents of the Lower and Middle Allochthons in the Jotunheim mountains to the southeast of the WGC, as infolds and/or imbricates within the Baltica basement gneisses (Bryhni, 1989). The recent regional structural mapping of Krabbendam & Wain (1997) and Labrousse et al (2002) emphasise the “mega-lens” form of the major anorthosite, mangerite, eclogite and peridotite masses to the north of Nordfjord (including the Flatraket granulite and the Almklovdalen peridotite), lying within a “matrix” of banded, granodioritic gneiss.

A spectacular feature of the scenery in outer Nordfjord is the mountain Hornelen on the island of Bremangerlandet immediately south of the field area visited on this excursion. Hornelen gives its name to a late orogenic molasse basin – the Hornelen Basin (Steel et al., 1985). The northern faulted margin of the basin lies roughly parallel with Nordfjord along its southern shore. In the basin, Middle Devonian conglomerates lie unconformably on a basement of outboard terrane material of the Upper Allochthon metamorphosed at greenschist-facies that has probably not experienced pressures higher than 4+/-2 kbar during the Scandian orogeny (Cuthbert, 1991). This has a thrust contact with underlying middle/?lower allochthon rocks lacking high pressure rocks. These, in turn, lie above a major detachment fault – the Hornelen Detachment (Seranne & Seguret, 1987; Wilks & Cuthbert, 1994; Andersen, 1998). On Bremangerlandet this appears as a 4 km thick zone of mylonite and ultramylonite showing consistent top-west shear sense (the Vetvika Shear Zone of Harz et al., 1994). The shear zone is part of the Nordfjord-Sogn Detachment Zone (NSDZ) (Norton, 1987), a major late orogenic, low angle, extensional detachment system outcropping from south of Bergen to Nordfjord, and probably merging with the Møre-Trondelag Fault Zone offshore to the west of Vågsøy. The base of the NSDZ is marked by the top of the WGC eclogite-bearing gneisses. Eclogites giving P ca. 20 kbar lie only 1 km below the base of the NSDZ, implying excision of nearly 60 km of crust across this normal-sense shear zone (Krabbendam & Wain, 1997). It may be argued that the total relative motion may be the result of several tectonic transport processes, including coaxial vertical shortening, and is not solely due to detachment faulting (Wilks & Cuthbert, 1994; Krabbendam & Wain, 1997).

In the WGC below the NSDZ the lack of regionally continuous marker horizons makes mapping out of large-scale structures difficult (Bryhni, 1966). Based upon mesoscopic structures deforming the gneissic layering, Krabbendam & Wain (1997) recognised two sets of folds. Early F_A isoclinal folds have axial planar foliation S_A parallel to the general gneissic layering away from fold hinges, and are associated with a mineral lineation L_A parallel to fold hinges. Open to tight, concentric folds F_B fold both gneissic layering and S_A and have a local crenulation cleavage S_B. F_B folds are grossly co-axial to F_A and L_A. Mesoscopic F_B folds appear to be related to the kilometre-scale E-W folds between Nordfjord and Sognfjord to the south, including the major synform containing the Hornelen Basin, so F_B folding must have continued until at least Middle Devonian time.

Mineral foliations and lineations in the predominant banded grey gneisses of the WGC in the Nordfjord area are defined by amphibolite-facies parageneses. On the margins of eclogites, and in some high-P pelitic gneisses, these amphibolite-facies fabrics can be seen to overprint earlier eclogite-facies fabrics. To the south of Nordfjord, and in the southern and westernmost part of the field area near Verpeneset, fabrics indicate strong non-coaxial top-west shear, while further north and east the fabrics indicate coaxial, constrictional strains (Krabbendam & Wain, 1997). As the Nordfjord rocks lie on the northern limb of the major F_B Hornelen synform, the rocks on either side of Nordfjord and as far north as Almklovdalen represent, broadly speaking, a tilted crustal section with progressively deeper levels towards the north. Structurally immediately below the Hornelen Detachment and the NSDZ, foliations have a sigmoidal pattern described by Labrousse et al (2002) as a "ductile shear band" indicating top-west motion, and coincident with Krabbendam & Wain's (1997) zone of non-coaxial shear fabrics. North and east of Maurstad (Stop 5.6) foliations turn to a consistent E-W trend, so the eastern Nordfjord gneisses lie close to the base of this shear band. North and west of Maurstad the foliation forms an east-closing arc encompassing Vågsøy and Stadlandet, and appears to define a complex west-plunging major fold culmination structurally below the shear band. At these lower levels, roughly coincident with the north shore of Nordfjord, coaxial, constrictional fabrics appear (Krabbendam & Wain, 1997). Hence each of the field sites in this excursion lies in the transition zone between upper zone of non-coaxial top-west shear and the underlying zone of coaxial E-W horizontal constriction. Both of these strain regimes operated under amphibolite facies conditions and were related to exhumation. The northern, co-axial zone, incorporating Vågsøy, Flatraket and Almklovdalen has been described by

Labrousse et al (2002) as a “crustal-scale boudin” containing large, relict masses of eclogite- and granulite-facies rocks.

Lappin (1966) and Bryhni (1966) were the first to notice that the eclogites and garnet peridotites are generally not co-facial with their enclosing country-rocks, although they came to very different interpretations. Bryhni considered that the eclogites were basic intrusions that were metamorphosed at high P along with their gneissic hosts, but at different P_{H2O} (see also Bryhni et al., 1970). In contrast Lappin concluded that the eclogites are “foreign inclusions” introduced into the gneisses as solid masses and broken up into boudins by later tectonism. Lappin and Bryhni agreed that the ultramafic masses in the Nordfjord-Stadlandet region are solid tectonic introductions, but, along with their respective co-workers and protagonists, they continued to argue for their respective “foreign” versus “in situ” origins for the Nordfjord eclogites for over two decades (Bryhni et al., 1977; Cuthbert et al., 1983; Griffin et al., 1985; Griffin 1987; Griffin & Mørk, 1981 pp. 53-55; Lappin, 1974; Lappin & Smith, 1981; Smith, 1980, 1988).

The discovery of HP and UHP relics in a variety of lithologies in the Nordfjord area (Griffin et al., 1985; Wain, 1997a) seems to confirm the in-situ origin for eclogites. The different metamorphic facies may then be explained by differential retrogression. Griffin (1987) and Krabbendam & Wain (1987) followed Heinrich (1982) in postulating that high-P granodioritic gneisses will have been phengite-bearing, and will have retrogressed by spontaneous dehydration reactions, while relatively anhydrous metabasic eclogites tend to retrogress via hydration reactions and, therefore, require an influx of water. The net flux of water from dehydrating gneiss into hydrating eclogite may explain the common amphibolitised rims to the eclogites in Nordfjord. An important example of preserved eclogite-facies felsic rock in the Nordfjord area is a phengite-garnet-kyanite-quartz gneiss, which occurs as a discontinuous belt along the north shore of Nordfjord between Almenningen and Maurstad (Bryhni, 1966; Kildal, 1971; Krabbendam & Wain, 1997). It often encloses swarms of eclogite pods, or envelopes large eclogite masses, as at Kroken (Stop 5.5). Identical rocks at Vetrhus (see Chapter 4) have been found to contain evidence for coesite and preserve rare examples of HP or UHP deformation fabrics in gneiss (Carswell & Cuthbert, 2003 – see Chapters 1 & 4). Transitions from this lithology into the granodioritic banded gneisses play an important, but controversial role in understanding the exhumation-related retrogression of the gneisses; this can be a subject of discussion at Kroken (Stop 5.5).

Overall, the significance of Scandian tectonic versus metamorphic factors remains a key issue in understanding the origins of the peridotite, anorthosite and mangerite massifs, the grey banded gneisses and, indeed, the relationships between HP and UHP eclogites.

Bryhni & Griffin (1971), Bollingberg & Bryhni (1972) and Krogh (1982) examined zoning in eclogite garnets from Nordfjord. Compositional zoning corresponds to changes in the types of solid inclusions present, defining a "prograde" zoning pattern with relict amphibolite-facies garnet cores having high Fe/Mg, Mn and Ca with inclusions of magnesio-hornblende, paragonite, quartz, clinozoisite and rutile, and eclogite-facies rims having lower Fe/Mg, Mn and Ca and inclusions of omphacite, tremolite, kyanite, clinozoisite, quartz and rutile. Bryhni et al. (1977) and Krogh (1977) found a gradient of increasing T to the north and west across the WGC based upon grt-cpx Fe/Mg thermometry. They noted that eclogites giving equilibration temperatures of <750^{o}C tend to show prograde zoning, while those giving >750^{o}C tend to have flat zoning profiles lacking amphibolite-facies inclusions but have a narrow, retrograde-zoned rim zone. This transition occurs in outer Nordford. They attributed this to the effect of enhanced intragrain diffusion at higher T.

Griffin & Brueckner's (1985) geochronological study of WGC eclogites failed to acquire a meaningful isochron from the Nordfjord eclogites. Interestingly, and consistent with the observations above about the relationship between zoning profiles and peak T, they found that lower T eclogites with prograde zoning from Nordfjord (Verpeneset, Almenningen and Totland) showed disequilibrium for Sm-Nd between garnet and omphacite, while those from the higher T area further north with flat or retrograde garnet profiles gave reasonable Sm-Nd mineral isochrons. The Verpeneset eclogite gave a Rb-Sr isochron age for zoisite – cpx – whole rock - kyanite – phengite of 398 +/- 1 Ma, consistent within error with more recent U-Pb zircon data of Root (see symposium abstracts). $Ar^{40/39}$ muscovite ages from outer Nordfjord are in the range 385-390 Ma (Berry et al., 1993, 1995) identical to a Rb-Sr whole-rock-phengite age of 385+/- 8 Ma for a HP garnet mica schist at Kroken (Cuthbert, 1991), indicating cooling through ~350^{o}C. Biotite Ar and Rb-Sr ages cluster around 375 Ma (Lux, 1985; Mearns, 1984 in Kullerud et al., 1986) indicating that cooling through ~300 ^{o}C took place during the middle Devonian.

Early attempts at thermobarometry in the Nordfjord area (Krogh, 1977, 1982; Griffin et al., 1985) were hampered by the lack of useful barometers capable of estimating absolute pressures. Opx eclogites, which might give absolute P values, have complex petrography due to the development of late amphiboles and early estimates were widely divergent. Carswell et al. (1985) derived values from 15-21 kbar from opx eclogites along Nordfjord (Kvalneset and Hornindal), but Lappin & Smith (1978) found much higher pressures (>30 kbar) for similar eclogites further north on Stadlandet. The discovery of coesite at Grytting by Smith (1984) tended to corroborate the higher values. The regional mapping out of coesite occurrences by Wain (1987) and her widespread application of the new omphacite-phengite-garnet barometer (Waters & Martin, 1993) led to the recognition of a transition zone along Nordfjord between a southern HP eclogite terrain and a northern UHP terrain (see the Chapter 1 review). Wain (1997), Cuthbert et al. (2000) and Wain et al. (2000) recognised that quartz-stable, HP eclogites tend to have the prograde-zoned garnets recognised by Bryhni & Griffin (1971), while coesite-stable, UHP eclogites tend to have garnets with flat zoning profiles. The HP-UHP transition zone was recognised by Wain (1997a) as a “mixed” zone of both HP and UHP eclogites. This was corroborated by the database of Cuthbert et al. (2000). For example, two of the eclogites visited on this excursion lie close to eclogites yielding significantly different pressures. The Maurstad UHP eclogite lies within 2 km map distance of the Levdal HP eclogite, with a pressure difference of 6+/-2 kbar. The Kroken HP eclogite lies 2.5 km map distance from the UHP Totland eclogite and also gives a pressure difference of 6 kbar. Given likely vertical structural distances between these eclogites, the apparent pressure gradients between them are certainly much greater than lithostatic. Krabbendam & Wain (1997) appealed to tectonic juxtaposition to explain these pressure breaks. Carswell & Cuthbert (2003 – see Chapter 1) found that the situation is more complex and the petrographic criteria for distinguishing HP from UHP eclogites apparantly too simplistic, as shown by the discovery of good evidence for coesite at the classic, prograde “HP” eclogite locality of Verpeneset, and documented evidence for the existence of “hybrid” eclogite bodies that display both HP and UHP characteristics. This leads to the idea that adjacent eclogites, or even different parts of the same eclogite body, have equilibrated at different times along the same P-T-t path.

Route:

Continuing from Flatraket, take highway [618] west, then south along Sorpollen, until after about 8 km you reach the junction with highway [15]. Turn left (southeast). If a lunch stop is required, a picnic site is located by a small lake on the right about 400 m from the junction on highway [15]. Continue to Almenningen 2 km from the junction and take the minor road towards Vemmelsvika (signposted to Falkevika camping cabins). This very narrow road skirts the steep coast of Nordfjord, and requires some care. After 4 km park at the top of the drive to the Fjord Seafood factory at Verpeneset (grid ref. 005690). Please take care not to obstruct access.

Stop 5.4: Verpeneset Eclogite

The exposures are roadcuts immediately opposite the parking place. ***Please note that the landowner does not permit hammering or collecting at this site***. Two-mica + garnet gneisses giving T=745+/-50^{o}C and 11.4 +/-2.0 kbar (Cuthbert, 1991) enclose a spectacularly well-preserved mass of bright green/red kyanite eclogite of about 20x30m in outcrop, 15m southwest of which is a separate 8m wide pod of darker, more amphibolitised flaser-textured eclogite. The larger eclogite body, the most well-known of the two, is an L>S-tectonite showing a well-developed omphacite linear shape fabric with attitude 03.112 at a high angle to the foliation in the host gneiss.
Two types of layer are visible in this eclogite body (Bryhni & Griffin, 1971; Griffin & Mørk, 1981):-

1) Coarse grained, paler aluminous eclogite with bright green omphacite (Jd_{35}) + garnet + kyanite + clinozoisite + quartz.
2) Medium-grained, darker more siliceous eclogite with garnet + omphacite (Jd_{35}) + quartz.

Phengite and talc are accessory phases in type (1) layers, and talc + phengite +/- kyanite +/- tremolitic amphibole segregations are found in both layer types. Large garnets in type (1) layers can be seen in the exposure to have darker red cores with dark green magnesio-hornblende inclusions. Paragonite inclusions are also present here. Rims are paler red and locally include omphacite and kyanite (Krogh, 1982). These represent the classic style of “prograde” garnets found in the Nordfjord and Sunnfjord areas, showing evolution to eclogite from an amphibolite-facies protolith.

The smaller, western pod has more extensively symplectised omphacite within a flaser fabric defined by anastomosing layers of granular garnet. In contrast to the larger kyanite eclogite body, omphacite is randomly orientated in the foliation, hence this eclogite is an S>L tectonite. Omphacite and garnet are overgrown by coarse prismatic, poikiloblastic hornblende. The pod is split by a vertical zone of fault gouge cored by a milky quartz vein, associated with a zone of amphibolitisation in the adjacent eclogite. It is texturally and mineralogically identical to the coesite eclogite at Flister (see Chapter 4 excursion). Pallisade-textured polycrystalline quartz has recently been found as inclusions in garnet in this eclogite (Carswell & Cuthbert, 2003 – see Chapter 1), providing convincing evidence for UHP metamorphism and making this body the most southerly exposed UHP eclogite in the WGC. The presence of a coesite eclogite so close to the prograde-zoned kyanite eclogite here at Verpeneset, previously considered to be a classic “HP” eclogite, is intriguing and adds to a growing body of evidence that UHP eclogites in the WGC have experienced a prograde history that involve a preceding HP eclogite stage (Cuthbert & Carswell, 2003 – see Chapter 1). No evidence for coesite in the kyanite eclogite body at Verpeneset has yet been published, but D Root (personal communication 2003) claims to have found poly-crystalline quartz pseudomorphs after coesite and we have observed other possible examples as inclusions within omphacite in the darker, more quartz-rich, interlayers. Current P-T estimates using grt-cpx-phe analyses of kyanite-eclogite sample VP3 from Krogh (1982) are 709^{o}C at 2.87 GPa (E. Ravna, personal communication 2003), just within the stability field of coesite.

Looking south across Nordfjord at this stop we get a spectacular view of Hornelen mountain rising above the western end of the island Rugsundøya. The following description is based upon Cuthbert (1991), Wilks & Cuthbert (1994) and Hartz et al. (1994). The upper crags around the summit are Middle Devonian conglomerates. These lie upon a clearly visible unconformably on greenschist-facies upper allochthon olistostromes and greenstones, which in turn lie upon gneisses and quartzites of the middle allochthon and possible lower allochthon forming the wooded slopes in the lower part of the mountain. These units give Ar^{39}-Ar^{40} muscovite cooling ages of 404-409 Ma (Andersen, 1998). All these basement units to the Hornelen basin were juxtaposed by south or east-directed thrusting during the Scandian phase of the Caledonian orogeny, but have subsequently been affected by ductile and then brittle extensional faulting, some of which may have controlled deposition of the Middle Devonian sediments.

Looking through the gap between Rugsundøya and Gangsøya the coast of Bremangerlandet is visible (weather permitting!). Just above the coast road the lower/middle allochthon gneisses are bounded below by the Vetvika Shear Zone: The top of shear zone is marked by a brittle fault trending parallel to the coast. This fault passes eastwards onto the mainland to merge with the Hornelen detachment, the bounding fault of the Hornelen basin. Below this brittle structure is a zone of fault gouge and cataclasite, above greenschist-facies ultramylonites, which in turn pass down into a sequence of amphibolite-facies mylonites that reaches 4 km in thickness on the western part of Bremangerlandet. The mylonite foliation dips steeply south here and kinematic indicators give a consistent top-west shear sense. Structurally below the shear zone in the islands between Bremangerlandet and Nordfjord are WGC gneisses with eclogites (the latter have not yet been studied in detail). The section below Hornelen represents an extremely attenuated section through the Scandian nappe pile, with large-scale excision at several levels between the unmetamorphosed Devonian sediments and the top of the WGC. This section above the Vetvika shear zone is termed the “Upper Plate” of the Nordfjord-Sogn Detachment system by Andersen (1998). The WGC is the lower plate, and at least some of the upward transport of the WGC is thought to have taken place by upthrow or “eduction” along the base of this detachment system. It is amazing to reflect that at Verpeneset you are standing on a coesite eclogite formed at ~400 Ma only 4 km map distance from low grade metamorphic rocks that were no deeper than 15 km at the same time!

Return along the same minor coast road to the junction with highway [15] at Almenningen. Turn right (east) and drive 3 km along highway [15]. At grid ref. 060701, about 200m west of the entrance to Krokeberget tunnel, a section of old road branches off on the left (north) side, providing parking and turning space suitable for several vehicles. Cross the main road with care opposite a track entrance at the end of a crash barrier, then descend the grassy slope on your left to reach the old coast road. Walk east along this road. The high cliffs and roadcuts above the road are unstable – wearing of a hard hat is recommended at this site. Avoid standing directly below obviously loose areas and avoid hammering the rock face – there is plenty of fallen material available on the road.

Stop 5.5: Kroken Old Road Eclogite

The first good exposures display the typical grey, layered, amphibolite-facies, granodioritic plag-qtz-epidote-biotite+/-grt+/-Ksp+/-white mica gneiss typical of outer Nordfjord. Some pale layers could be deformed trondjhemitic leucosomes. Pods of foliated biotite amphibolite and garnet amphibolite up to 2m are commonly found in the gneiss, some having small cores of symplectised eclogite. A sharply defined boundary separates the grey gneiss from an eclogite-facies phe-qtz-grt-czo-ky gneiss with a static, symplectitic overprint of bt+mu+plag replacing phengite and garnet. Eclogite pods become increasingly common to the east in this unit, which is about 10 m thick. These pods are also symplectised, but generally lack amphibolitic margins. Some have rather diffuse contacts with the phe-gneiss, implying some mixing at their margins. At the east edge of this unit the eclogite pods are numerous enough to coalesce and form a coherent mass of eclogite in which screens of phengite gneiss are present, but become less common eastwards. The main eclogite mass extends at least 200m eastwards, but the eastern end is obscured by rockfall netting. The rock is a handsome, coarse grained, qtz-phe-czo-dol eclogite with accessory sulphide. Lappin & Smith (1981) provided analyses of the essential phases. Modal layering in this eclogite has strike/dip 100/40N with a well-developed omphacite lineation plunging 20.055. Layer dip is essentially identical to that of the foliation in both the phengite gneiss and the grey gneiss, so eclogite-facies and amphibolite-facies fabrics are concordant in this case.

Garnets show similar patterns of zonation in composition and of mineral inclusions to those at Verpeneset, and to date no coesite or polycrystalline quartz inclusions have been found. Wain (1998) obtained P&T of 2.3 GPa at 712^{o}C, and Cuthbert et al. (2000) obtained 607^{o}C at 2.4GPa, both consistent with stability of quartz. The eclogite at Totland, only 2 km northeast of this locality is a coesite-bearing UHP eclogite giving 759 ^{o}C at 2.9 GPa (Cuthbert et al., 2000; Wain et al., 2000).

Variants on the normal eclogite at Kroken include granoblastic quartz eclogite and thin garnet-quartz layers (a common feature of WGC eclogites). Veins rich in colourless, glassy quartz associated with very coarse phengite, kyanite and omphacite are common, with phengite-rich varieties spatially associated with screens of phengite gneiss. Some contacts between phengite gneiss and eclogite are marked by diffuse-edged veins of plagiogranite with coarse hornblende, possibly indicating localised partial melting at the contact.

Some points of interest at this locality are:-

1) The gneiss-eclogite contact zone is a clear example of in-situ eclogite facies metamorphism.

2) What is the nature of the contact between the amphibolite-facies grey gneiss with its biotite-dominant foliation and the eclogite facies phengite gneiss? Wain (1998) considered the phengite gneiss to be the HP equivalent of the grey granodioritic gneiss, with the boundary between them marking a “deformation front”, the phengite gneiss having been protected from retrogressive recrystallisation in the strain shadow of the eclogite. Support for this interpretation comes from preservation of some phengite grains in the cores of large zoned clinozoisite-epidote grains in the grey gneiss and in claimed geochemical similarities between the two lithologies. However, the garnet-phengite gneisses might well be pelitic or semipelitic metasediments, in which case the boundary could mark a simple lithological boundary – possibly a basement-cover or orthogneiss-paragneiss contact? In this case, to what extent are the coarsely-unmixed feldspar clasts in the grey granodioritic gneiss metastable relics of a pre-Scandian paragenesis?

3) The grey gneisses have a migmatitic aspect, but the phengite gneiss shows no sign of migmatisation, except possibly at localised gneiss-metabasite contacts. What is the age of migmatisation here – Proterozoic or Scandian? How does this fit into the spatial and temporal pattern of anatexis in the WGC?

4) The proximity of prograde, quartz-stable eclogites and coesite eclogites (such as here and at Totland, respectively) defines the mixed HP-UHP transition zone of Wain (1997a). To what extent have tectonic and metamorphic factors influenced the juxtaposition of eclogites that have equilibrated at such different conditions?

5) What is the significance of the quartz-rich and phengite-rich veins in the eclogite? Can they provide any information about the role of fluids during eclogitisation?

Return to the vehicles, crossing the road with care. Continue east for 8.5 km to Maurstad. Just after crossing a bridge over a stream, and immediately west of the turning to Bryggja, turn left into the bus stop bay in front of the community hall / school at grid ref. 136727. Either park in the bus bay, or if open, the large community car park beside or behind the hall. There are extensive rock cuttings by the main road and bordering the car park. Begin by walking west back along highway [15] over the stream bridge – take great care as this is a *fast road and there is no footpath over the bridge. There is no need to cross the road as the best exposures are on the north side, in an embayment next to the road sign "Måløy".*

Stop 5.6: Bryggja and Maurstad UHP Eclogites

In the embayment and by the roadside are exposures of variably fresh, heterogeneous, layered quartz eclogite with minor kyanite, phengite, dark amphibole and biotite. This was called the Bryggja eclogite by Cuthbert et al (2000). The rock is equigranular, granoblastic with a weak omphacite lineation. Garnet-quartz layers up to 10 cm thick, some of which extend into coarse quartz-phengite-omphacite veins. Griffin & Mørk (1981) suggested that such layers might be metasedimentary in origin, but could they be due to metamorphic differentiation? The modal layering has variable dips about from 45-90^{o} to the NW. Eclogite from this locality contains scarce poly-crystalline quartz pseudomorphs after coesite within both garnets and omphacites, consistent with grt-cpx-phe thermobarometry estimates of 730^{o}C and 29.8 kbar (Cuthbert et al, 2000).

Returning to the cuttings by the driveway to the hall car park, the same eclogite mass re-appears as a 12m wide pod, but is more intensively retrograded here, with only local cores of fresh quartz eclogite. At the south margin of the pod it is bordered by well-layered bt-plag-ep-qtz migmatitic gneiss, within which biotite-rich and quartzitic layers suggest a metasedimentary origin. F_A isoclines have an axial planar schistosity. Steeply E-plunging F_B (?) folds are coaxial with a rodding lineation. To the north of the eclogite are further migmatitic grey gneisses, here rich in garnet, with trondhjemitic leucosomes and biotite-garnet-rich melanosomes. Local plagioclase-quartz-hornblende pegmatite layers are present. Griffin & Mørk (1981) reported calcic garnets in these gneisses in association with kyanite and sodic plagioclase, possibly indicating equilibration pressures >20kbars. Could these garnets be a product of anatexis of an omphacite-bearing UHP gneiss?

Now walk from the hall for ~500 m along a paved cycle track running parallel to highway [15]. Go through the underpass crossing route [61] (the Åheim road) and continue past the Statoil fuel station (toilets and a shop available here and parking if it is decided to bring vehicles) and cross a river bridge at grid ref. 143728. Just after the bridge is a 90 m long rock cutting adjacent to the cycle track. Start at the eastern end:

The eastern end of the exposure is dominated by similar streaky, migmatitic, granodioritic gneisses to those by the community hall, containing leucogranitic sheets and lenses up to 30 cm thick. The layering is folded around near-isoclinal folds with axes plunging moderately steeply E. The gneisses are rather granular textured and lack the strong feldspar rodding lineation commonly found in the Nordfjord gneisses. Mafic bodies are rare at this end of the exposure, except for a few pods of biotite-hornblende schist. About half way along the cutting to the west a 2 m pod of retrograded eclogite marks the appearance of considerably more mafic material. The grey granodioritic banded gneiss is absent and a more massive leucogranite is the main felsic component. From here west, mafic material varies from amphibolite to variably symplectised eclogite. Eclogite is sometimes layered with glassy quartz segregations bearing greenish kyanite. Locally, metabasite is dominant, and the felsic component takes the form of schleiren of phengite-quartz schist grading via a garnet-rich selvage into phengite eclogite by an increase in omphacite (now symplectite). At the west end of the exposure eclogites are better preserved with layers rich in garnet, omphacite or quartz. The eclogite masses take the form of pods with lobate margins separated by streaks of phengite-rich gneiss or schist. Eclogite from this site was named “Maurstad” by Cuthbert et al. (2000), who found polycrystalline quartz after coesite and obtained P&T of 694^{o}C at 28.2 kbar. It lies only 2.5 km SE across strike from a prograde quartz-eclogite at Levdal that gives 646^{o}C at 22 kbar, again illustrating the wide range of eclogite-facies P-T conditions recorded along the Nordfjord coast.

Possible questions that could be posed at the Bryggja and Maurstad localities are:-

1) Why do we find UHP eclogites (as at this stop) and HP eclogites (as nearby at Levdal) so close together in the Nordfjord area. Interestingly, the Bryggja eclogite garnets are often found as granular streaks or flasers, while the Levdal eclogite has more discrete, idioblastic garnets. Could the Bryggja eclogites have undergone deformation-related recrystallisation at UHP, while the Levdal eclogites escaped this?

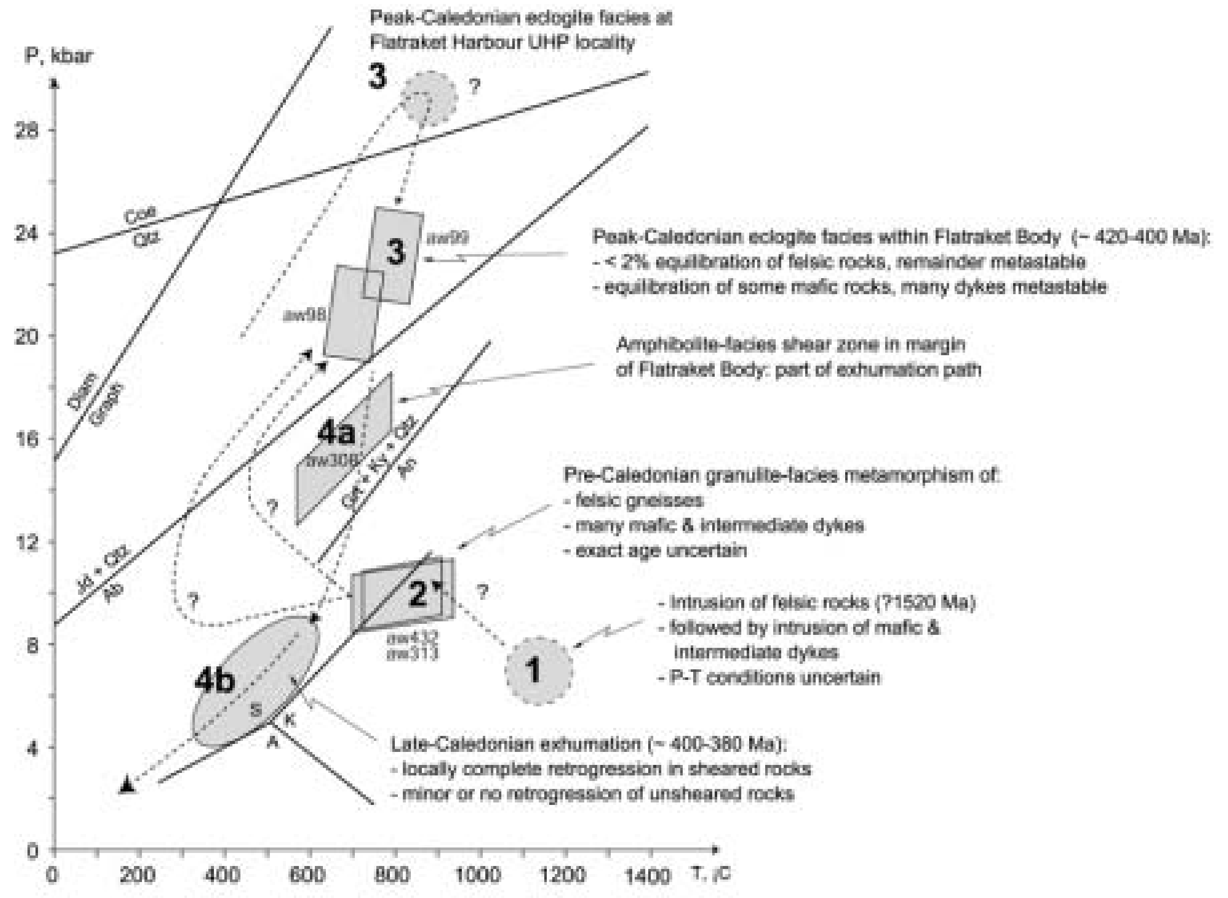
2) What is the origin of the layering in these eclogites? Is it a feature inherited from the protolith, or a metamorphic effect? What does it tell us about the processed by which eclogites form and are subsequently modified at UHP?

3) What is the origin of the swarms of small eclogite pods or “pillows” in these gneisses? They closely resemble the forms of mafic enclave swarms commonly observed in granitoid intrusions, so in this case could the pods be protolith feature, and not due to boudinage as is often claimed for eclogite lenses?

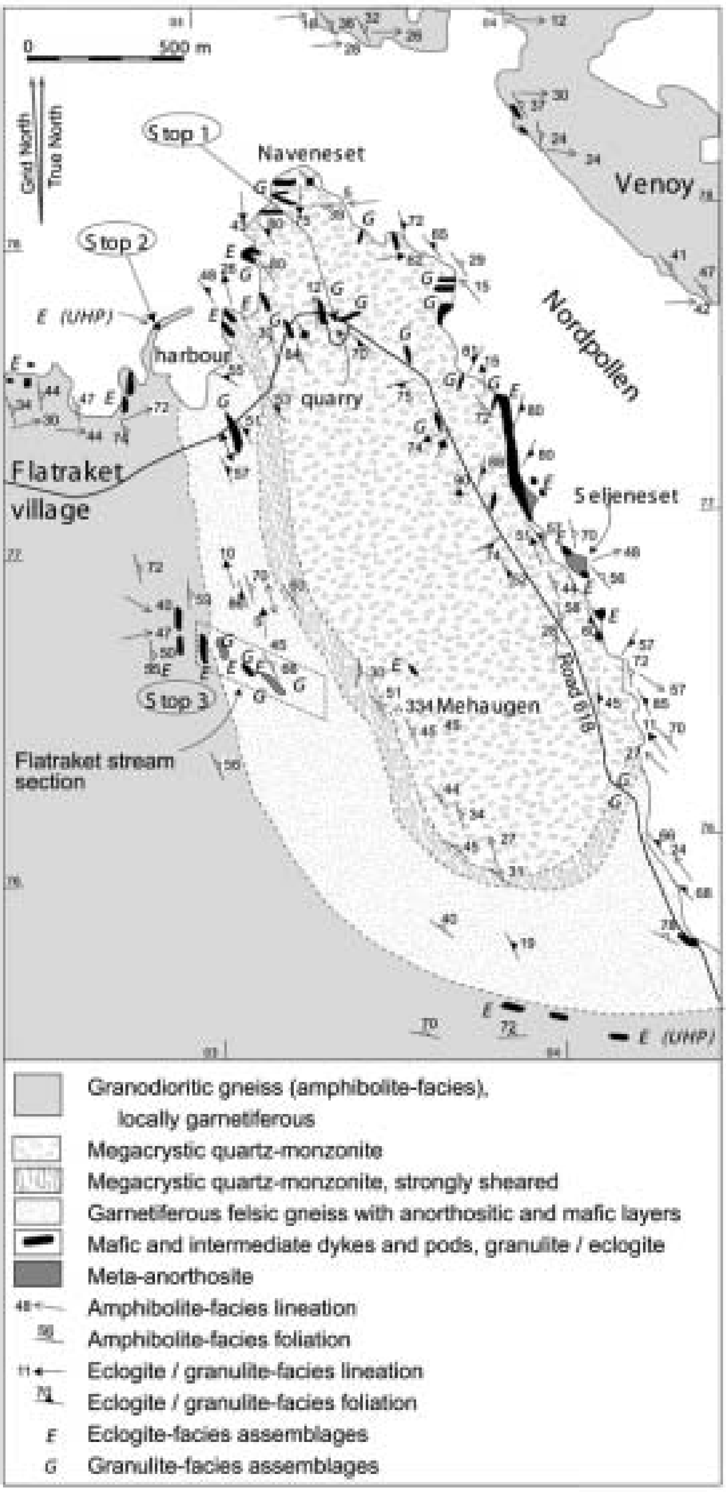
4) Why do we find that the felsic material here tends to be eclogite-facies phengite gneiss close to or within eclogite, but a granodioritic, amphibolite-facies, migmatitic gneiss at a greater distance from eclogite?

5) When did the migmatisation take place? During exhumation or prior to the Scandian UHP event? What would be the consequences of anatexis for the mechanical behaviour of the WGC during exhumation?

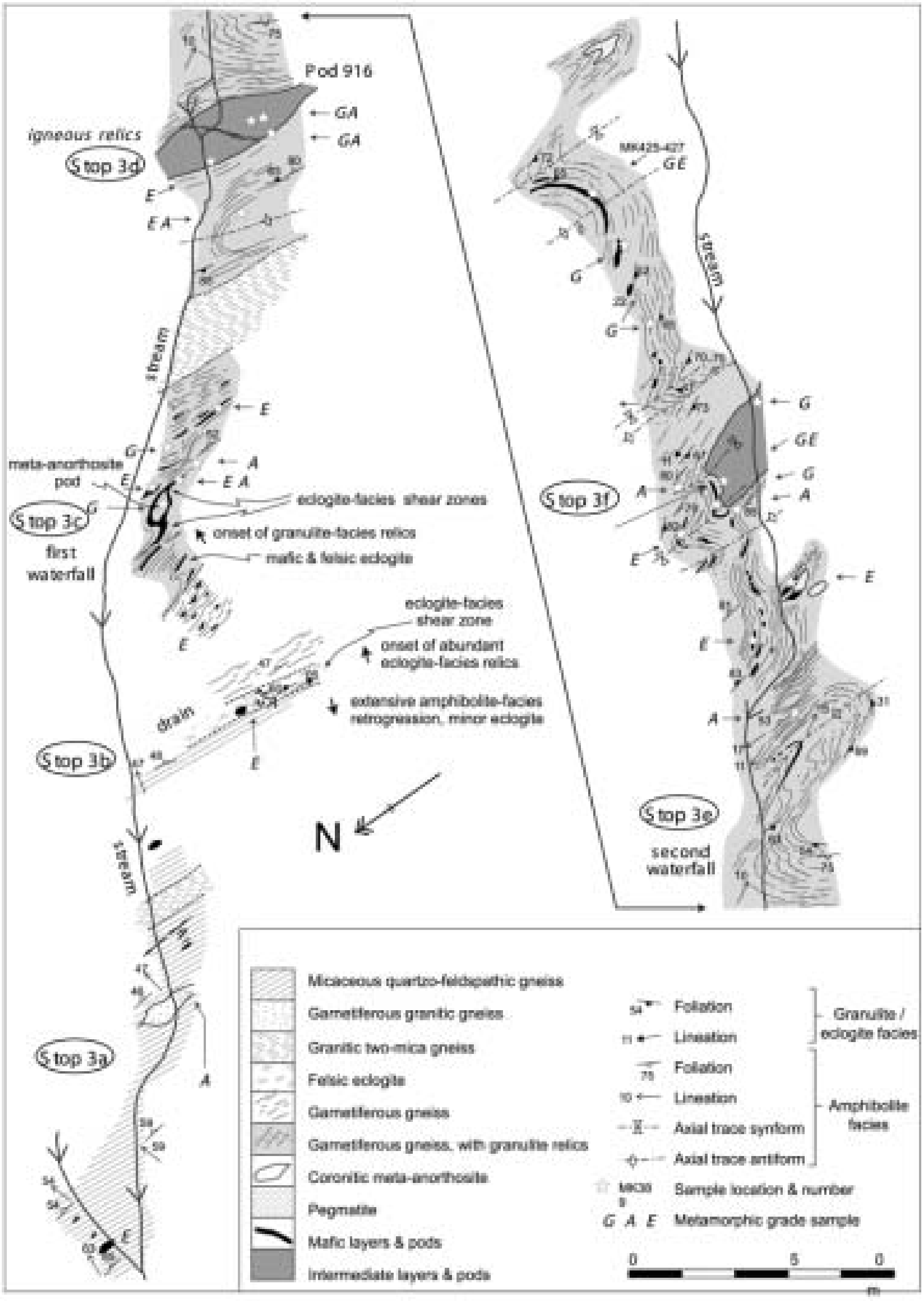
Return to the vehicles at the community hall. If the party is to return to Selje from Maurstad, drive east for about 300 m and take the left turn onto highway [61]. After 14 km at Åheim take a left turn onto highway [620], which skirts the inner end of Vannylvsfjorden, taking the left fork after 8 km to climb over the neck of the Stadlandet peninsular, still on the [620] road. After a further 4 km a junction is reached with highway [618] at Eide. Turn right along the north shore of Moldefjorden to reach Selje after 5 km. If continuing to Flatraket, retrace your route back west 13 km to Almenningen on highway [15], turning right onto highway [618] to reach Flatraket after 8 km. A lunch stop may be made at the picnic site on highway [15] above Almenningen, as mentioned above. For parking instructions at Flatraket, see the first part of the guide for this day's excursion.



M. Krabbendam, Flatraket excursion.
Figure 5-1: Intrusive, metamorphic and P-T-t evolution of the Flatraket Body, modified after Krabbendam et al (2000). P-T conditions of samples aw98 etc. after Wain (1998) and Wain et al (2001); the decompression part from stage 4a to 4b is also constrained in the Seljeneset rocks by Cotkin et al (1988) and Cotkin (1997). Age of the Flatraket quartz-monzonite after Lappin et al (1979).



M. Krabbendam, Flatraket excursion.
Figure 5-2: Geological map of the Flatraket Body and surroundings, modified after Krabbendam et al (2000). UHP localities after Wain et al (2001). Excursion stops are indicated.



M. Krabbendam, Flatraket excursion.

Figure 5-3: Geological map of the stream section at the western margin of the Flatraket Body, modified after Krabbendam et al (2000). Described excursion stops are indicated.

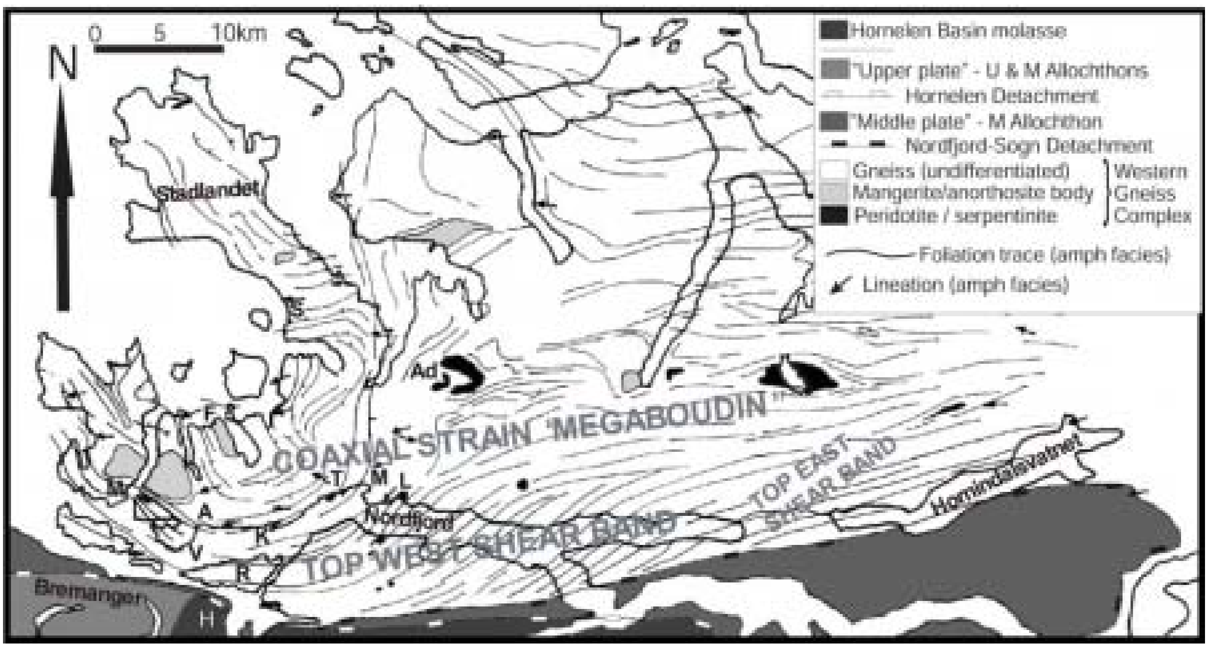


Figure 5-4: Simplified tectonic map of the Nordfjord-Stadlandet region, modified after Labrousse (2002) with information from Krabbendam & Wain (1997) and the authors. A – Almenningen, Ad – Almklovdalen, F – Flatraket, H – Hornelen, K – Krokken, L – Levdal, M – Maurstad, R – Rugsundøy, S – Selje, T – Totland, V – Verpeneset.

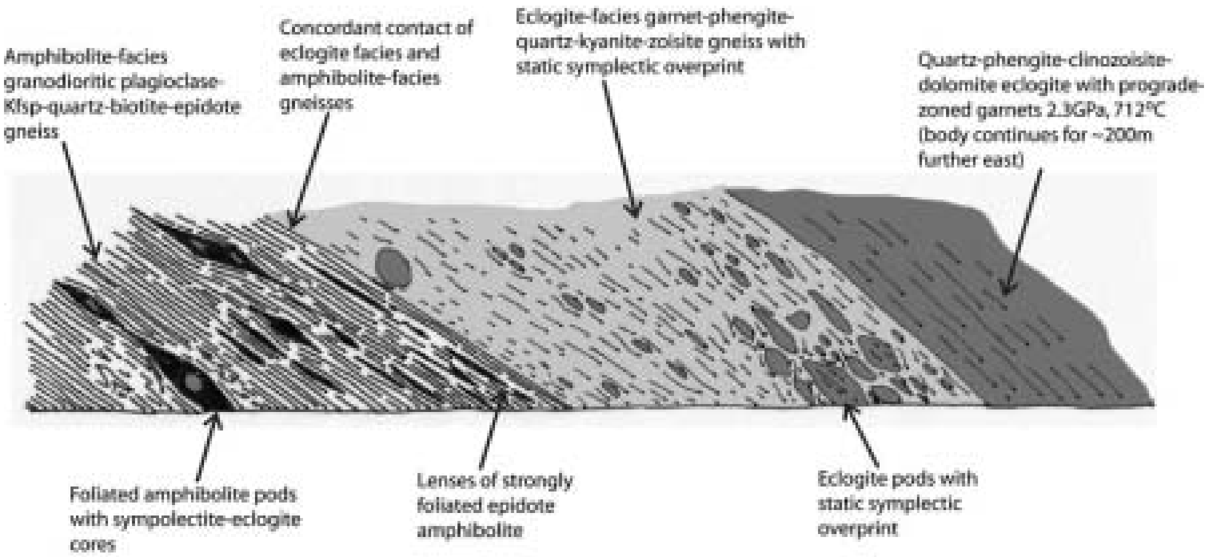


Figure 5-5: Roadcut section at Kroken Old Road, Nordfjord (Stop 5.5), showing metabasite-gneiss relationships. Drawn facing north. Length of section about 40 m. Modified after Wain (1998).

CHAPTER 6:
EXCURSION TO THE ALMKLOVDALEN PERIDOTITE

L. Gordon Medaris, Jr. and Hannes K. Brueckner

Introduction

The Almklovdalen peridotite, located about 5 km southeast of the village of Åheim, is one of the largest, best exposed, and most thoroughly studied peridotite bodies in the Western Gneiss Region (WGR), and it has important bearing on the Proterozoic and Caledonian interaction of mantle and crust in western Norway. Garnetiferous ultramafic rocks from Almklovdalen were first described by Eskola in his classic 1921 paper, "On the Eclogites of Norway", and subsequent detailed investigations were carried out at Lien (Medaris, 1980), Rødhaugen (Carswell, 1981), Raudleivane (Griffin & Qvale, 1985), and the Gusdal quarry (Osland, 1997) (Fig. 6-1).

The most abundant rock types in the Almklovdalen peridotite are chlorite peridotite (ol + opx + chl + amp) and dunite, which are exposed in an ellipsoidal outcrop pattern approximately 4.0 x 3.3 km in size (Fig. 6-1). Relict garnet peridotite and associated garnet pyroxenite are most extensively preserved in four outcrop areas at the Lien locality, but also occur at Rødhaugen, Raudkleivane, and the top of the Gusdal Quarry. Eclogite boudins occur in surrounding gneiss ("external" eclogite) and within, but near the margin of, the peridotite body ("internal" eclogite) at Raudkleivane, along the northern edge of the Gusdal quarry, and at Ekremsaeterfoss, between Ekremsaeter and Rødhaugen.

Field mapping (Lappin, 1966, 1967; Cordellier et al., 1981) and gravity measurements (Grønlie & Rost, 1974) indicate that the peridotite is a bowl-shaped sheet around a central gneiss area. Three main stages of deformation have been recognized: D1 (Proterozoic) folds in garnet peridotite; D2 (Caledonian) isoclinal folds in chlorite peridotite, which are associated with recrystallization of garnet peridotite to chlorite peridotite; and D3 (Caledonian) foliations and lineations in chlorite peridotite, which are thought to be related to gravitational sinking of the peridotite body in the enclosing gneiss (Cordellier et al., 1981). In the Lien area, chlorite peridotite and the surrounding amphibolite facies gneiss share the same D2 structural elements and represent equivalent grades of metamorphism (Medaris, 1980).

Anhydrous dunite is a major constituent of the Almklovdalen body, and it is estimated that approximately two billion tons of high-quality olivine are present. In 1948, following the pioneering research by V. M. Goldschmidt on the industrial use of olivine, the Norwegian Parliament established A/S Olivin, which has become the world's largest manufacturer of olivine products. Initially, olivine was produced primarily for foundry sand, but today the main use is as slag conditioner in blast furnaces, and in 1995 3.1 million tons of olivine were shipped throughout Europe for this purpose. Another important use of olivine is in the fabrication of a variety of refractory products. See Sturt et al. (2002) for further information on the Almklovdalen body and other ultramafic rocks in Norway that have been exploited for industrial use.

Mineral Assemblages and Pressure-Temperature Conditions

The mantle-derived, Mg-Cr peridotite bodies in the WGR record a long, complex tectonothermal history, and Carswell & Van Roermund (2003) have recognized eight stages in their metamorphic evolution (Fig. 6-2), many of which are recorded in the Almklovdalen peridotite. The two most prominent mineral assemblages in the Almklovdalen peridotite are ol + opx + cpx + grt (Stage 2, mid-Proterozoic garnet peridotite) and ol + opx + chl + amp (Stage 7, Caledonian chlorite peridotite). The Stage 7 assemblage can be seen to replace the Stage 2 assemblage on all scales, from outcrop to microscopic. The abundant chlorite-rich layers in chlorite peridotite most likely represent preexisting garnet pyroxenite layers.

In detail, garnet peridotite is a multi-stage rock, consisting of medium- to coarse-grained, strained porphyroclasts of ol + opx + cpx + grt (Stage 2), which reside in a fine-grained, strain-free groundmass of ol + opx + spl + amp ± cpx. The Stage 2 assemblage is generally regarded as having formed during mid-Proterozoic time, while the peridotite was still in the mantle (see age discussion below). It is uncertain whether the groundmass is equivalent to a Stage 3 assemblage, to which amphibole has subsequently been introduced, or whether it represents a transitional Stage 5 to 6 assemblage. Garnet porphyroclasts are typically surrounded by kelyphite, which contains radiating, tiny grains of amp + spl ± px. Such kelyphite is probably equivalent to Stage 6 and results from reaction between olivine and garnet during Caledonian decompression. However, secondary garnet has been reported to occur in some kelyphite in garnet peridotite from Lien (Griffin & Heier, 1973), which indicates the possible presence of a Stage 4 assemblage that may have resulted from late Proterozoic (Sveconorwegian) or Caledonian HP metamorphism.

Further evidence for Caledonian HP metamorphism is provided by eclogite boudins in peridotite at Raudkleivane (Griffin & Qvale, 1985). Garnet grains in the eclogite exhibit prograde compositional zoning and contain inclusions of amphibole, K-feldspar, apatite, ilmenite, and pyrite, none of which occur in the eclogite matrix. Such features suggest that amphibolitization of the basic rocks at Raudleivane preceded prograde metamorphism to eclogite facies and imply that the enclosing peridotite experienced the same prograde metamorphic event. Similar prograde features are characteristic of the external eclogites of the area and are interpreted as reflecting prograde metamorphism related to subduction of the WGR during the Scandian phase of the Caledonian Orogeny. That similar features occur within internal eclogites, such as those at Raudkleivane, raise the questions of whether peridotite bodies of the WGR were in the mantle or the crust prior to the Caledonian Orogeny, and why internal eclogite records the effects of prograde Caledonian metamorphism, but associated garnet peridotite rarely does so.

P-T conditions for garnetiferous assemblages in the Almklovdalen peridotite and other peridotites in the WGR have been estimated from a combination of the Al-in-opx geobarometer and Fe-Mg exchange geothermometers for ol-grt (peridotite) and opx-grt (pyroxenite) (Fig. 6-3; see Medaris, 1999, for a full discussion of the methods involved). The Stage 2 assemblage in eleven Almklovdalen samples yields a range of values from ~680 ^{o}C, 20 kbar, to ~900 ^{o}C, 38 kbar, which is consistent with the pattern of results from other WGR peridotite samples. Although the P-T array defined by all WGR samples coincides approximately with a steady-state geotherm for 200 km-thick lithosphere, such a simple relation is improbable, because the pressure (depth) range shown by the Almklovdalen body far exceeds its thickness.

Van Roermund et al. (1998, 2000, 2001) have described the presence of pyroxene lamellae in garnet from peridotite bodies on Oterøy, which is thought to represent the prior existence of majoritic garnet (Stage 1, Fig. 6-2) at pressures of 60 to 70 kbar (Fig. 6-3). The Stage 2 P-T array may thus be a consequence of decompression and cooling as deep-seated mantle rose to shallower depths, and may represent the result of a complex interplay between the cooling history of individual samples, different blocking temperatures for the geobarometer and geothermometers, and the difficulty in selecting portions of grains that represent equilibrium compositions. Although evidence is lacking so far for the presence of majoritic garnet at Almklovdalen, garnet lamellae have been described in clinopyroxene from an orthopyroxene-bearing eclogite lens (garnet pyroxenite?) in the southwestern part of the peridotite (Lappin, 1973), presenting the intriguing possibility that the Almklovdalen body may also have experienced an early, high P-T stage.

The Stage 4 assemblage in samples from Fjørtoft and Raudhaugene (Jamtveit et al., 1991) and Sandvik (Medaris, this conference) yields a temperature of ~715 ^oC and pressures from 15 to 21 kbar (Fig. 6-3). These results are consistent with the Caledonian P-T path for the Eiksunddal mafic-ultramafic complex (Jamtveit, 1987) and with minimum temperatures and pressures for the Raudkleivane eclogite (calculated from analyses given by Griffin & Qvale, 1985). Note, however, that the Stage 4 assemblage in the Bardane peridotite on Fjørtoft contains microdiamond and is estimated to have stabilized at 34 to 41 kbar and 840 to 900 ^oC (Brueckner et al., 2002; Van Roermund et al., 2002).

Geochemistry

Major and trace elements

Peridotite from Almklovdalen and elsewhere in the WGR shows a wide range in MgO content, from about 37 to almost 53 wt% (Fig. 6-4), and a pronounced negative correlation of CaO and Al_2O_3 with MgO, similar to that for the well-documented Ronda peridotite in the Betic Cordillera, Spain (Frey et al., 1985). Such compositional variation has been ascribed to partial fusion of peridotite and extraction of melt, in which higher degrees of fusion and extraction result in progressively more depleted solid residua. The large number of analyses, in which MgO is > 45%, CaO is < 2%, and Al_2O_3 is < 1%, reflect the prominence of dunite in the WGR and illustrate the high degree of major element depletion in these mantle rocks. FeO also is negatively correlated with MgO in most WGR peridotites, but seven Almklovdalen samples, all of which are closely associated with pyroxenite layers, lie well above a depletion trend, probably due to cryptic metasomatism by transient melts from which the pyroxenites crystallized.

Normalized REE patterns in Almklovdalen peridotite plot below, but parallel to, those for associated pyroxenite layers (Fig. 6-5). Peridotite and pyroxenite have relatively flat MREE to HREE patterns, and both are enriched in the LREE, with values of La/Sm ranging from 1.5

to 2.2 in peridotite, and from 1.3 to 2.6 in pyroxenite. The REE pattern for Almklovdalen peridotite probably resulted from cryptic metasomatism by melts that produced the associated pyroxenite layers. The LREE enrichment and major element depletion trends (except for FeO) illustrate the decoupling of trace and major elements during the geochemical evolution of the Almklovdalen peridotite, which is a well established phenomenon in subcontinental mantle massifs elsewhere.

Some Almklovdalen samples, however, have a complex, Z-shaped REE pattern, in which peridotite again plots below, but parallel to, pyroxenite (Fig. 6-6). The origin of this type of pattern is unclear, but it may be the result of an early stage of LREE enrichment, followed by a small amount of partial fusion and extraction of the LREE.

Geochronology and Nd and Sr isotopes

The garnet-bearing Stage 2 assemblage within the Almklovdalen peridotite has been subjected to several dating attempts, primarily by the Sm-Nd mineral isochron technique (Jacobsen & Wasserburg, 1980; Mearns & Lappin, 1982; Rubenstone et al., 1986; Mearns, 1986; Jamtveit et al., 1991; Brueckner, et al., 1996, and Brueckner, unpublished data). The “ages”, shown on a histogram on Fig. 6.7, scatter from a high of 1703 Ma to a low of 1040 Ma. Several of these ”dates” coincide with major tectonothermal events recorded in the host gneiss, including the Svecofennian (1600-1750 Ma) and Sveconorwegian (950-1300) Orogenies, as well as an unnamed intrusion event at around 1.5 Ga. While it is likely that these important crustal events also had a major effect on the rocks of the underlying mantle, implying that the crust and mantle were coupled throughout much of Proterozoic time and had a shared history, it seems improbable that some ages in the peridotite body would be reset, and others not. It is also possible that the oldest date of 1703 Ma (Mearns, 1986) most closely approaches the formation of the Stage 2 assemblage and that the younger ages reflect partial re-equilibration of the Sm-Nd system during sequestration of the garnet peridotite in relatively shallow levels of the mantle, where temperatures were high enough for limited diffusion, but not high enough to completely reset the Sm-Nd system. If so, this is further evidence for a complex interplay between the cooling history of the peridotite, blocking temperatures, grain size and recrystallization. Under either interpretation, the ages are much older than the Scandian (400 – 415 Ma) Sm-Nd and U-Pb ages obtained from the external eclogites of the WGR (Griffin & Brueckner, 1980; Gebauer et al., 1985; Terry et al., 2000; Carswell et al., 2003), suggesting a long history for the peridotite bodies in the mantle prior to their incorporation into the WGR during Caledonian subduction. Some peridotite bodies from Nordøyene and Oterøy contain possible Stage 4 garnet-bearing assemblages. Attempts to date these phases (Jamtveit et al., 1990; Brueckner et al., 2002) yield ages that are close to the Scandian phase of the Caledonian Orogeny (Fig. 6.7) suggesting, again, two episodes of HP metamorphism within WGR peridotite bodies.

Sm-Nd model ages for clinopyroxene grains from twelve samples, representing all four Almklovdalen garnet peridotite/pyroxenite localities, consistently range between 1.3 and 1.8 Ga (T_{chur}) and 1.7 and 2.1 Ga (T_{DM}). The clinopyroxene grains at Lien define a strikingly linear array on a Sm-Nd isochron diagram that, if interpreted as an isochron, gives an age of 1.8 Ga, although with a large error because of low dispersion in Sm/Nd ratio. These data suggest that the melts, which fertilized the previously depleted peridotite and resulted in the formation of the pyroxenites, probably filtered through the Almklovdalen body in mid-Proterozoic time. If the oldest (1703 Ma) Sm-Nd mineral age for the garnet-bearing assemblage at Lien is correct (Mearns, 1986), it would imply that the melts and adjacent fertilized peridotite crystallized directly as garnet-bearing assemblages, or did so shortly after the cryptic metasomatism.

Sr and Nd isotopes of clinopyroxene grains from the Almklovdalen body are characterized by very unradiogenic values for both $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ (Fig. 6.8). The ratios from the Almklovdalen body occupy the lower left corner of a trend defined by most other peridotite bodies in the WGR, which show a large variation in $^{143}Nd/^{144}Nd$ (i. e. ε_{Nd} ranges from + 57 to – 36), but little variation in what are very unradiogenic $^{87}Sr/^{86}Sr$ ratios (0.7015 to 0.7033; see also Brueckner, 1977). If this trend is the result of two-component mixing, it is reasonable to identify one component as very depleted mantle with high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$. Presumably, peridotite bodies of the WGR underwent extreme melt extraction early in their history, possibly during the Archean (Jamtveit et al., 1991). But the second component, represented by the pyroxenite layers (see discussion above) and characterized by the very low $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values that characterize the clinopyroxene grains from the Almklovdalen body, is less easy to identify. The melts that produced the pyroxenite layers would have been derived from a source region characterized by very low, long term, Parent/Daughter ratios. Few terranes in either the crust or mantle are characterized by both low Sm/Nd ratios (i.e. light REE enriched) and low Rb/Sr ratios (i.e. alkali poor). In addition, the positively correlated trend defined by the Almklovdalen pyroxene suite (Fig. 6.8) is equally difficult to model, because these ratios usually are negatively correlated.

The Almklovdalen peridotite appears not to have been affected by a later, Caledonian metasomatism, which is characterized by a striking increase in $^{87}Sr/^{86}Sr$ ratio in clinopyroxene, and which seems to be restricted to a few peridotites in the extreme NW corner of the WGR on the islands of Otrøy and Nordøyene (Brueckner et al., 2002; Van Roermund et al., 2002). It is not clear why this metasomatism did not affect the Almklovdalen body and other peridotite bodies in the central WGR, such as Kalskaret, Aldalen and Raubergvik.

Localities

(1) Lien

Excellent peridotite outcrops are exposed in the upland between Lien farm and Sundalsvatnet in the vicinity of Helgehornvatnet (Figs. 6-1 and 6-9). The predominant ultramafic rock type is foliated chlorite peridotite, which contains the Stage 7 mineral assemblage, forsterite + low-Al enstatite + tremolitic amphibole + clinochlore ± Cr-rich spinel. Tight to isoclinal folds are common, and the associated penetrative axial plane foliation strikes ENE and dips ~70^{o} to the south, parallel to that in the surrounding amphibolite facies quartzofeldspathic gneiss.

Garnet peridotite and locally abundant garnet pyroxenite, representing relicts of the earliest discernible mineral assemblages in the Almklovdalen body, occur in four areas around the east end of Helgehornvatnet (Fig. 6-9). The garnetiferous rocks are predominantly wehrlite and olivine clinopyroxenite, although orthopyroxene is abundant enough in places for the rocks to be classified as lherzolite and olivine websterite. As described previously, garnet peridotite is a multi-stage rock, consisting of strained porphyroclasts of ol + opx + cpx + grt in a fine-grained, strain-free matrix of ol + opx + spl + amp ± cpx. A common feature is the presence of amp + spl kelyphite around garnet. Recrystallization of garnet peridotite to chlorite peridotite is displayed clearly along the margins of the garnet peridotite masses, where garnet has been replaced by chlorite and there is incipient development of penetrative foliation, which is an integral part of the chlorite peridotite fabric.

Garnet pyroxenite is most abundant in the northernmost occurrence of garnet peridotite (Fig. 6-9, locality 1), where (prior to blasting) garnet peridotite and pyroxenite could be seen to be interlayered for a distance of approximately seven meters across strike on one limb of a fold (Fig. 6-10). 58% of the former outcrop was garnet peridotite, and 42%, garnet pyroxenite. The layers are generally continuous along strike for a distance of about 50 meters, except for several garnet- and pyroxene-enriched pods and lenses within thicker peridotite layers.

NB! LOCALITY 1 AT THE NORTHEAST END OF HELGEHORNVATNET IS PROTECTED, AND COLLECTING IS FORBIDDEN!

This locality has already been severely damaged by blasting for mineral collecting.

(2) Raudkleivane

Fe-rich eclogite boudins and relict garnet peridotite occur in chlorite peridotite at the Raudkleivane locality (Fig. 6-11). Subsequent to mapping of the locality by Griffin & Qvale (1985), much of the garnet peridotite and some of the eclogite were removed by quarrying, and the road was relocated. However, small areas of partly chloritized garnet peridotite still occur on the hillside above the present road, and three eclogite boudins, ranging from 1 to 3 meters in thickness, are well exposed in the roadcut along the eastern side of the road.

Individual eclogite boudins commonly show a cm-scale layering of omphacite- and garnet-rich types. Eclogite generally consists of omphacite + garnet + rutile + apatite in a medium-grained, mosaic texture, although pyroxene-rich layers tend to be coarser-grained and lineated. Retrogression is extensive, involving breakdown of omphacite to symplectite and widespread development of secondary amphibole.

The importance of the Raudkleivane locality lies in the evidence for prograde metamorphism of eclogite within peridotite. Several eclogite samples contain garnet grains with rims that have higher values of Mg/Fe than do the cores. Although the rims of such garnet grains contain omphacite and rutile inclusions, the cores contain inclusions of Cl-rich ferropargasite, K-feldspar, apatite, ilmenite, and pyrite. Griffin & Qvale (1985) suggested that amphibolitization of the basic rocks at Raudkleivane preceded prograde metamorphism to eclogite facies and, therefore, that the enclosing peridotite must have experienced the same hydration, followed by high-pressure metamorphism. However, the only evidence so far for Caledonian HP metamorphism of Almklovdalen ultramafic rocks is the report by Griffin & Heier (1973) of secondary garnet in kelyphite in Lien garnet peridotite.

(3) Gusdal Quarry (If time permits!)

The Gusdal Quarry is the most recent excavation in the Almklovdalen peridotite. It contains rocks that are ideal for processing by A/S Olivin, consisting largely of fresh, anhydrous dunite, which is relatively free of chlorite and serpentine. However, at the top (i.e. north end) of this rather steep quarry are some more internal eclogite boudins, as well as a fresh garnet pyroxenite layer and some garnet peridotite. These rocks have not been the subject of any detailed investigation. However, we will visit the site if there is enough time left in the day and if permission can be obtained, depending on quarrying operations. We will take a bus to the top if possible, but it may prove necessary to hike to the top, which may be strenuous for some. There are no restrictions on collecting at this site and it provides the best opportunity for legally collecting some of the beautiful rocks that characterize the Almklovdalen body!

(4) A/S Olivin Plant

We will either start or finish our trip at the plant where the olivine is crushed, sieved and made into refractory bricks. There will be a brief (20-30 minute) presentation on the properties and use of olivine as an industrial mineral.

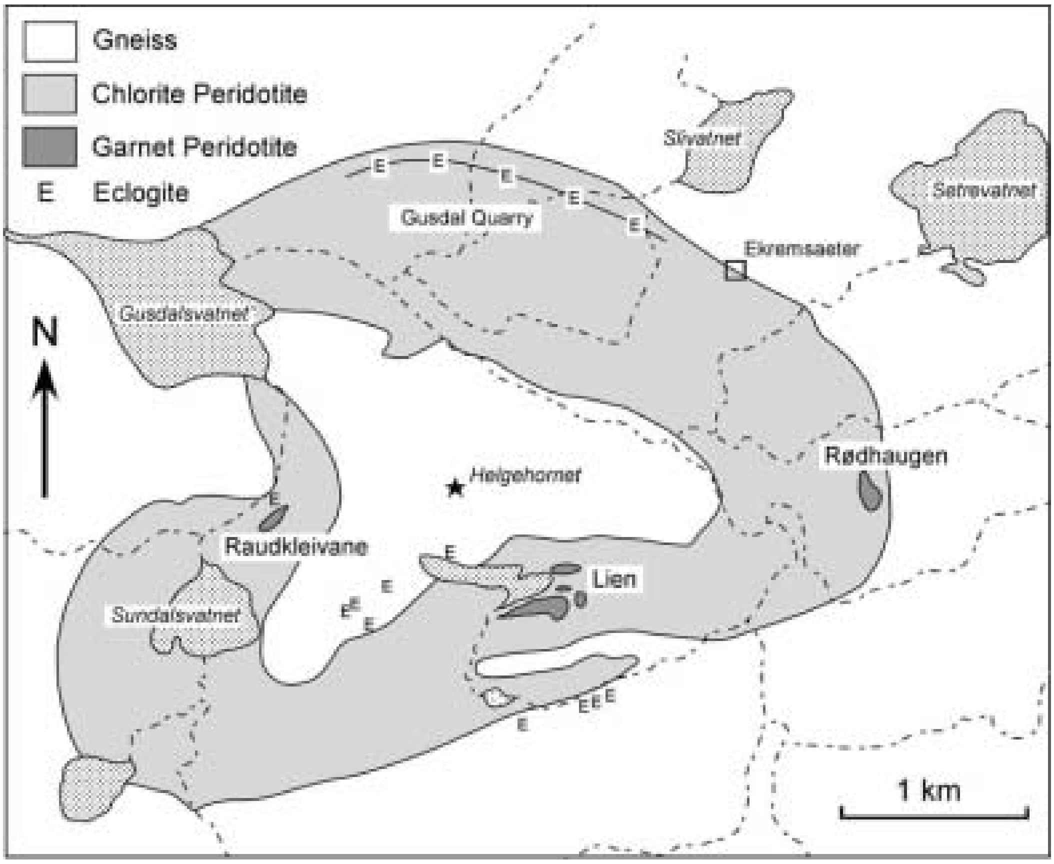


Figure 6-1: Simplified geological map of the Almklovdalen peridotite (modified from Cordellier & Boudier, 1981, and Osland, 1997).

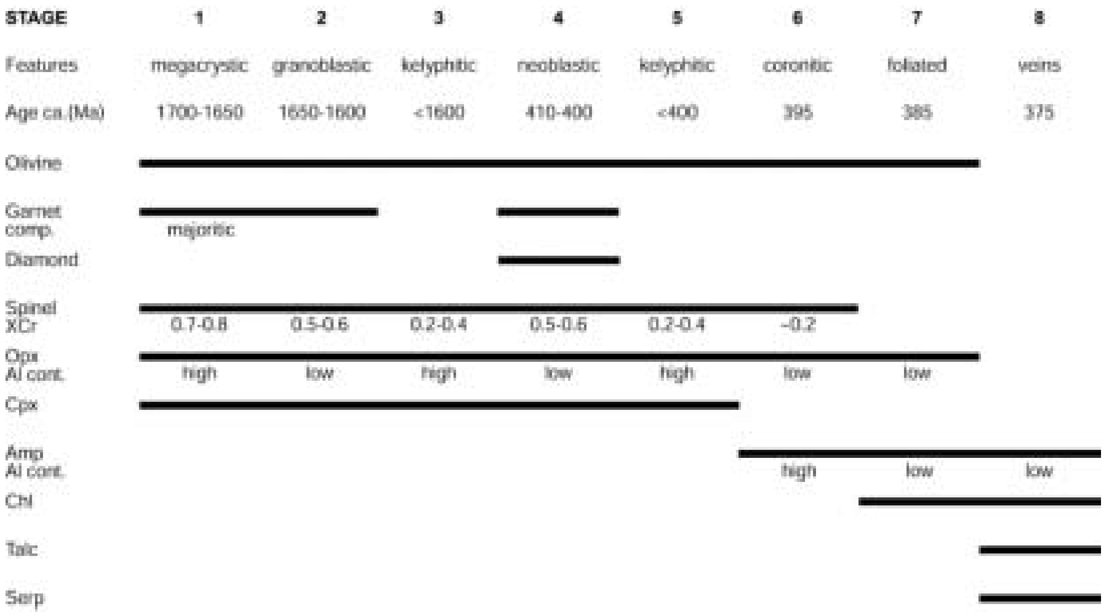


Figure 6-2: Summary of the multi-stage metamorphic evolution of the mantle-derived, Mg-Cr type, garnet-peridotite bodies in the Western Gneiss Region, Norway (from Carswell & Van Roermund, 2003).

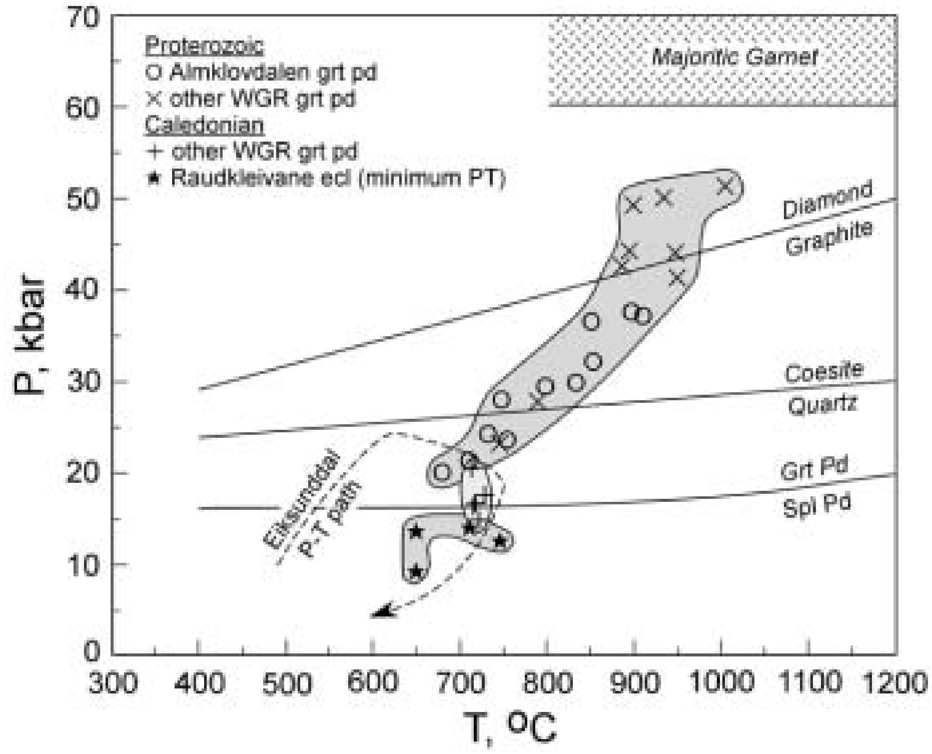


Figure 6-3: P-T conditions for garnetiferous assemblages in the Almklovdalen peridotite, peridotite bodies elsewhere in the WGR, and eclogite at Raudkleivane. The Eiksunddal P-T path is from Jamtveit (1987), and the field for majoritic garnet at Otrøy is from Van Roermund & Drury (1998).

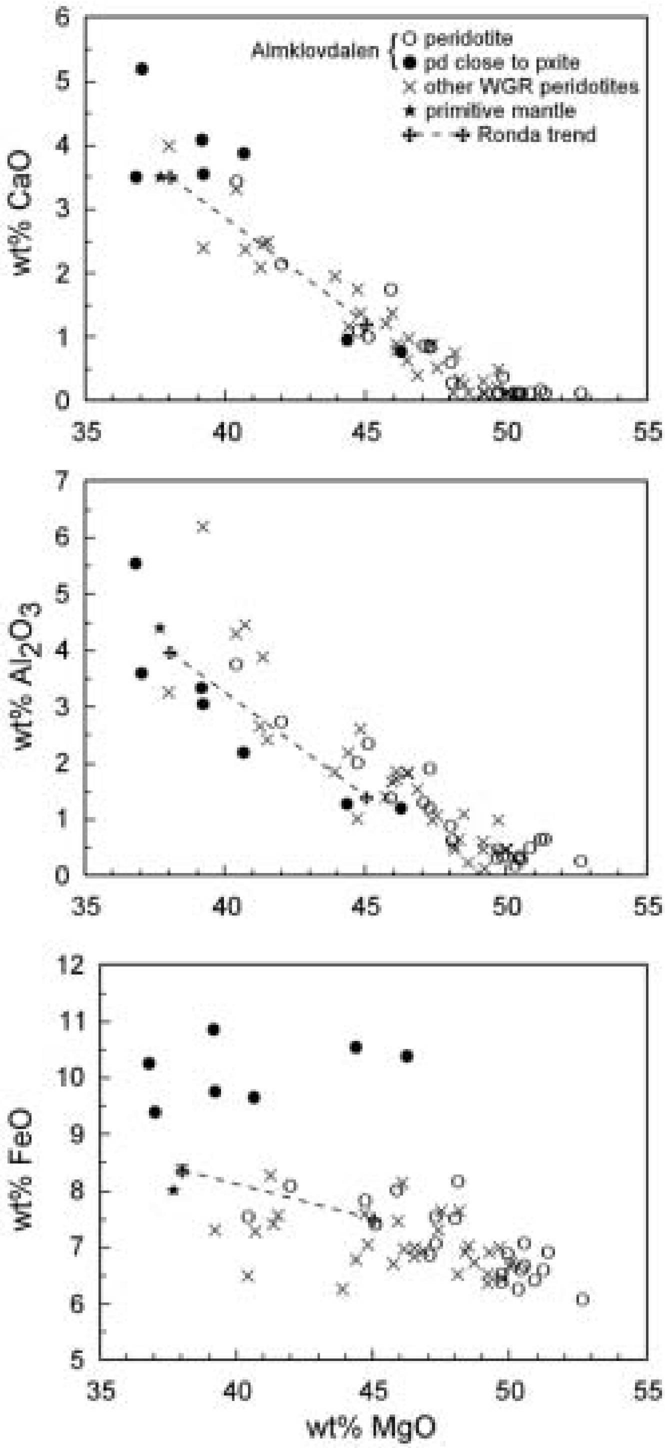


Figure 6-4: Harker diagrams for selected major elements in the Almklovdalen peridotite and other WGR peridotites. The composition of primitive mantle and the Ronda trend are shown for comparison.

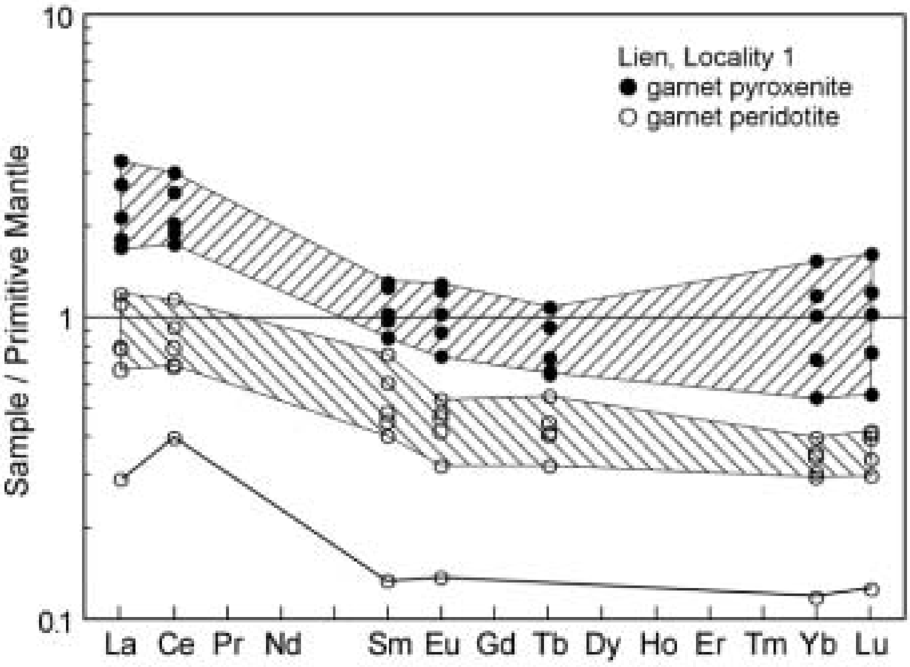


Figure 6-5: REE patterns (normalized to primitive mantle) for five samples of garnet pyroxenite and six samples of garnet peridotite from Lien, Locality 1.

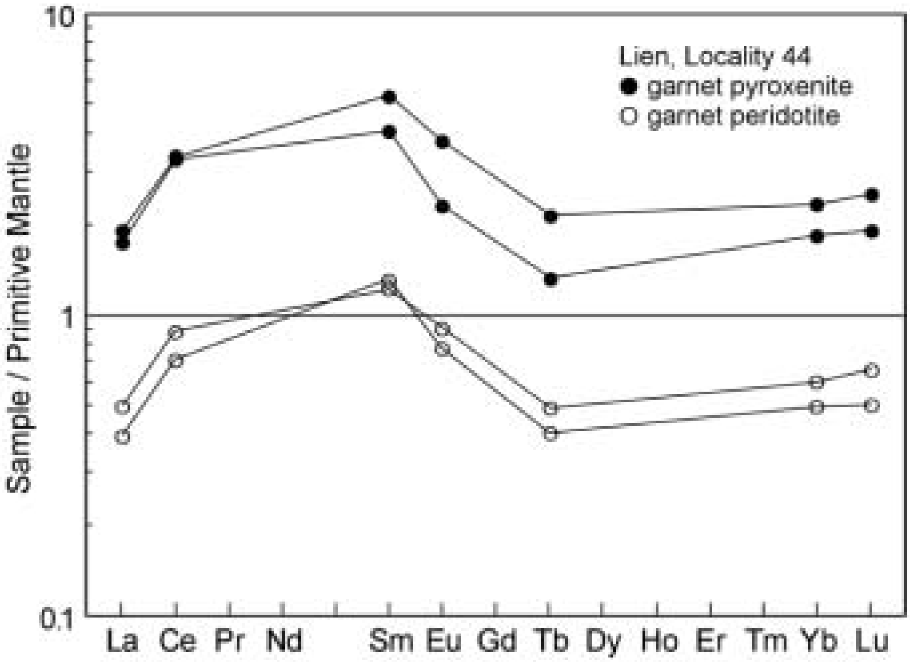


Figure 6-6: REE patterns (normalized to primitive mantle) for two samples of garnet pyroxenite and two samples of garnet peridotite from Lien, Locality 44.

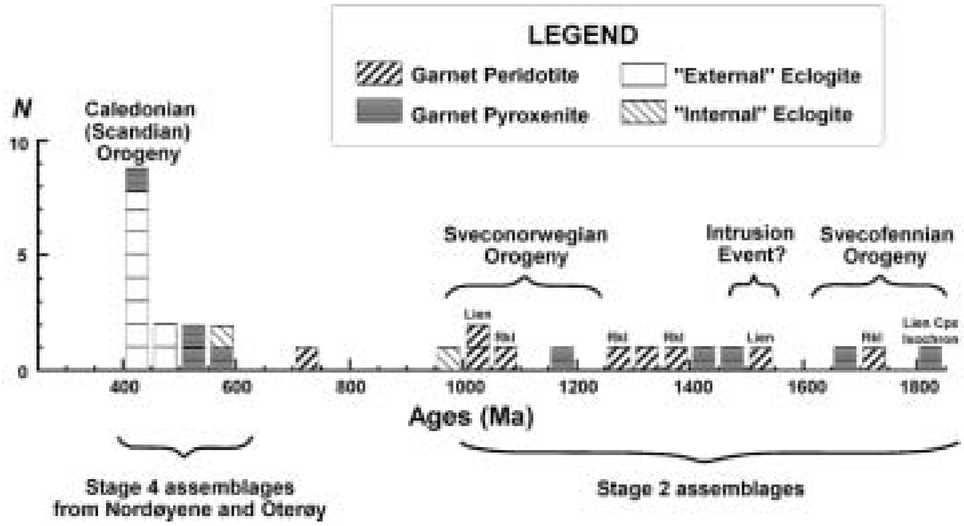


Figure 6-7: Histogram of Sm-Nd mineral ages from garnet peridotite, garnet pyroxenite and internal eclogite from the Almklovdalen peridotite, WGR. The ages from Almklovdalen are labeled Lien and Rkl for samples collected from the Lien and Raudkleivane localities, respectively. Sm-Nd mineral ages for external eclogite are shown for comparison.

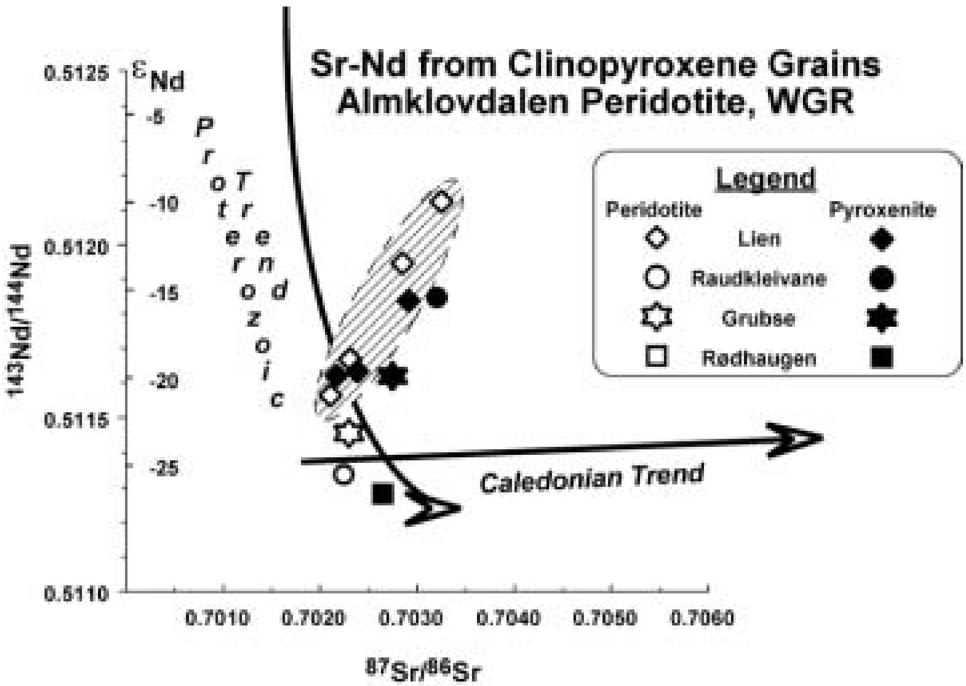


Figure 6-8: Sr-Nd covariance diagram of clinopyroxene analyses from the four garnet-bearing localities in the Almklovdalen peridotite, WGR. Present-day ratios are plotted. The trends shown by arrows are defined by clinopyroxene from other peridotites bodies in the WGR (see Brueckner & Medaris, 1998; Brueckner et al., 2002).

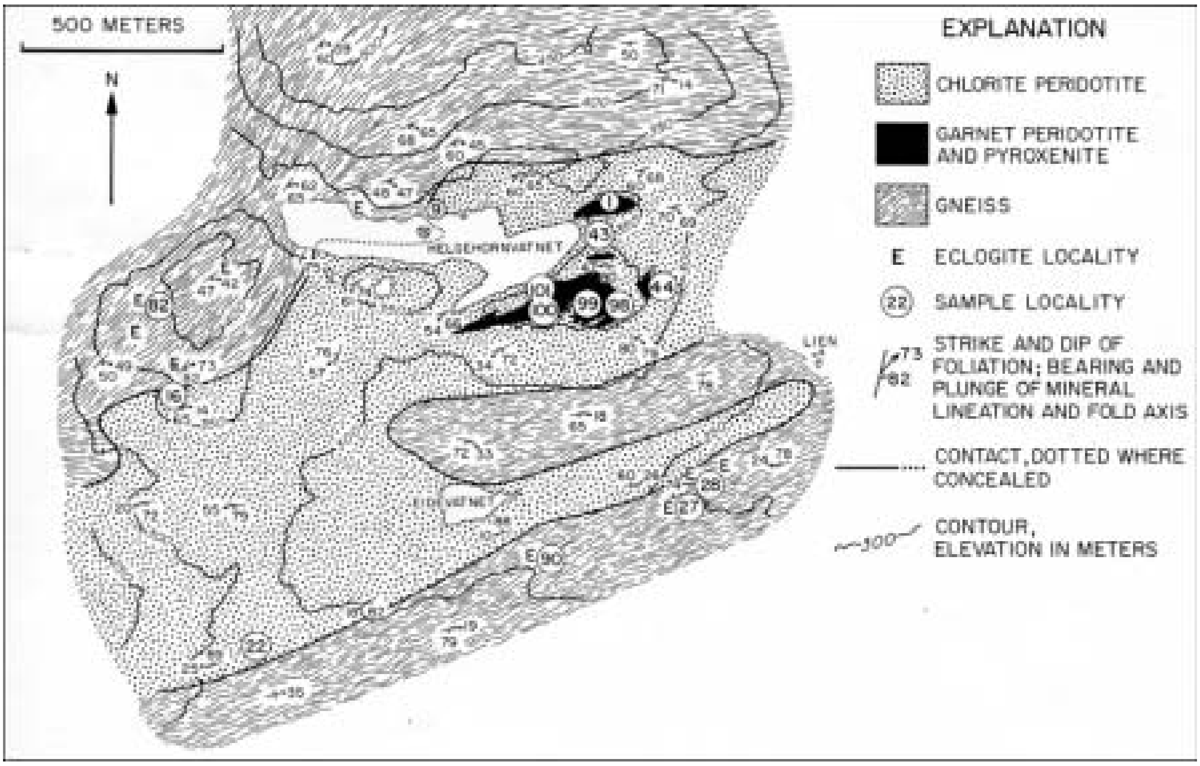


Figure 6-9: Geological map of the Lien area, Almklovdalen peridotite (from Medaris, 1980).

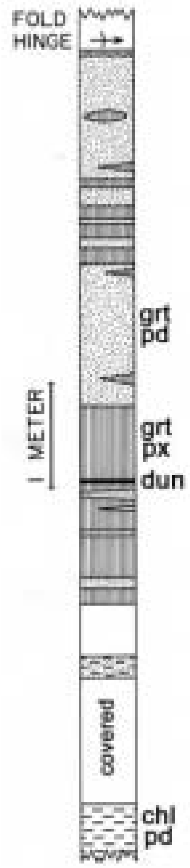


Figure 6-10: Section of interlayered garnet peridotite and pyroxenite at Lien, Locality 1 (from Medaris, 1980). Stipple, garnet peridotite; black, dunite; vertical lines, garnet pyroxenite; dashes, chlorite peridotite; stipple and dashes, garnet peridotite partly altered to chlorite peridotite; blank, not exposed.

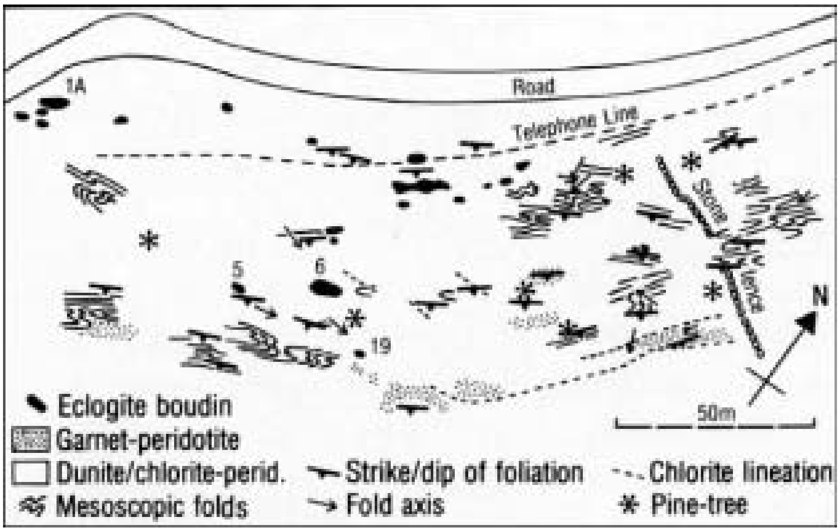


Figure 6-11: Geological map of the Raudkleivane area, Almklovdalen peridotite (from Griffin & Qvale, 1985).

CHAPTER 7:
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