Late-Caledonian structures, differential retrogression and structural position of (ultra)high-pressure rocks in the Nordfjord - Stadlandet area, Western Gneiss Region

MAARTEN KRABBENDAM & ALICE WAIN

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Late-Caledonian, amphibolite-facies structures in the Nordfjord-Stadlandet area comprise an 8 km-wide zone of non-coaxial shear below the Nordfjord-Sogn Detachment (NSD). Below this zone, coaxial structures dominate. The gneissic layering within the coaxial zone, in its present form, resulted mainly from pervasive late-Caledonian east-west extension. East-west trending fold hinges and prolate feldspar augen indicate substantial north-south shortening during east-west extension. This pervasive deformation played a significant role in the differential retrogression of eclogite-facies assemblages, so that most felsic rocks now have amphibolite-facies assemblages. Integration of petrological data with the structural data shows that attenuation of the crust is unevenly distributed and that locally ultrahigh-pressure (UHP) eclogites occur structurally above HP (P ~ 20-24 kbar) eclogites. Some 15 km of crust has been exhumed from above the NSD. 57 km of crust is now cut out by the NSD, but only about half of that has been exhumed by non-coaxial strain. Below the NSD attenuation to 72 - 86 % occurred. Locally, however, attenuation to 93-96 % has occurred as suggested by the occurrence of HP and UHP eclogites less than 1 km apart. Even so, no distinct high-strain zones occur in the vicinity of UHP eclogite pods.

Maarten Krabbendam & Alice Wain, Department of Earth Sciences, University of Oxford, Oxford OX1 3PR, UK.
Email: martink@earth.ox.ac.uk. *(Address for M.K. from 1/1-98: Department of Earth Sciences, Monash University, Clayton, Victoria 3168, Australia).*

Introduction

The Nordfjord - Stadlandet area is a critical area within the Scandinavian Caledonides because it contains some of the deepest buried rocks of the Western Gneiss Region (WGR), as indicated by the occurrence of coesite-eclogite bodies (Smith 1984, 1995) and also the most shallow rocks which were deformed during the Devonian, as exemplified by the Devonian Hornelen Basin (Steel et al. 1985). Bryhni (1966) provides a very useful description of rock types and structures of the southern part of the study area, whereas Lappin (1966) made a thorough study of the northern part. Since then, most work has concentrated on petrological and mineralogical studies of eclogite pods (e.g. Bryhni & Grimstad 1971, Smith 1988, 1995). The presence of coesite in eclogite in the area, indicating peak metamorphic pressures of ≥ 28 kbar (ultrahigh pressure or UHP hereafter) was reported by Smith (1984) and Smith & Lappin (1989). Wain (in press) describes many new coesite or coesite-pseudomorph-bearing eclogite occurrences in the area, which can be used to delineate a distinct ultrahigh-pressure (UHP) zone and a high-pressure (P < 25 kbar) zone.

The purpose of this paper is to describe the amphibolite-facies, late-Caledonian structures within the Nordfjord-Stadlandet area, the role of amphibolite-facies deformation in differential retrogression of eclogite-facies rocks during exhumation, and the relative structural position of the coesite-eclogite pods with respect to non-coesite bearing eclogites, granulitic bodies and the Devonian Hornelen Basin, and to discuss the uneven distibution of attenuation throughout the crust during the exhumation of (U)HP rocks in the area.

Geological setting

The study area is located in the western part of the WGR, a large basement window of Proterozoic gneisses, reworked during the Caledonian Orogeny (Dietler et al. 1985, Kullerud et al. 1986). The occurrence of eclogite and coesite-eclogite indicates that at least the western part of the WGR has been buried to great depth (>100 km, Smith 1984, Wain in press). In the east and southeast, the WGR is overlain by Scandian thrust nappes (e.g. Roberts & Gee 1985); in the northeast these thrust nappes have been traced in deep synclines into the WGR (e.g. Robinson 1995).

In the west, the WGR is separated from allochthonous rocks and Devonian sediments by the Nordfjord-Sogn Detachment (NSD), which has a top-to-the-west shear sense and has played an important role in the exhumation of the WGR and in the development of the Devonian basins (Norton 1987, Séranne & Séguret 1987, Andersen & Jamtveit 1990, Andersen et al. 1991). A second detachment, the Hornelen Detachment, lies structurally above the NSD, separating the 'Middle Plate' from the 'Upper Plate' (Andersen &

Jamtveit 1990, Dewey et al. 1993). The 'Upper and Middle Plate' terminology describes the tectonostratigraphic position of rock units after late-Caledonian extension, whereas the more classical 'Upper and Middle Allochthon' terminology (e.g. Roberts & Gee 1985) describes the tectonostratigraphic position of thrust nappes after Caledonian thrusting but before late-Caledonian extension. The exposed portion of the Upper Plate comprises mostly, but not exclusively, rocks of the Upper Allochthon and the Hornelen Basin itself; the Middle Plate comprises mostly, but not exclusively, rocks of the Middle Allochthon. None of the allochthonous rocks in the west have experienced Caledonian HP metamorphism. On Bremangerlandet, in the SW of the study area, the Hornelen Basin unconformably overlies the Kalvåg Melange (Bryhni & Lyse 1985, Steen & Andresen 1997) and a Caledonian gabbro-norite-granodiorite intrusion. This intrusion has been dated at 380 ± 26 Ma (Sm-Nd) and 390 ± 29 Ma (Rb-Sr) (Furnes et al. 1989), thus providing a rather loosely constrained, maximum age for the onset of deposition in the Hornelen Basin.

On the northern side of the Hornelen Basin, the NSD and the Hornelen Detachment converge and cannot be distinguished; here the Devonian rocks are juxtaposed almost directly against WGR rocks, separated by a mylonite zone, a few hundred metres thick (Plate 1, Dransfield 1994). West of Hornelen Mountain, the two detachments diverge (Andersen & Jamtveit 1990, Hartz et al. 1994) and the Dalsvatn Fault can be taken as a continuation of the Hornelen Detachment, whereas the Vetvika Shear Zone can be regarded as the continuation of the lower NSD. Both the NSD and the Hornelen Detachment are folded with the Devonian rocks occurring in the Hornelen Synform (Séranne & Séguret 1987, Andersen & Jamtveit 1990, Chauvet & Séranne 1994), so that, in the study area, the detachments are south dipping and have a dextral shear sense (Plate 1, Hartz et al. 1994, Dransfield 1994).

Lithologies and metamorphism in the Nordfjord-Stadlandet area

The Nordfjord-Stadlandet area of the Western Gneiss Region contains a wide variety of lithological-metamorphic units with parageneses corresponding to pre-Caledonian (granulite), peak-Caledonian (eclogite) and late-Caledonian (amphibolite-facies) stages, which can be related via progressive deformation and recrystallisation. Both ultrahigh-pressure (UHP) and non-ultrahigh-pressure (termed HP throughout this paper) eclogites are found in this area (Smith 1995, Wain in press) and the relationships between these and their country rocks can be examined. About 90% of the study area consists of pervasively deformed, compositionally heterogeneous, amphibolite-facies gneisses with minor metabasite, meta-anorthosite and/or ultrabasite. Eclogite or pre-Caledonian granulitic material is preserved in low-strain zones, surrounded by amphibolite-facies rocks.

Pre-Caledonian granulite enclaves

The Flatraket-Ulvesund HP granulite complex

Granulite-facies meta-igneous rocks of quartz-monzonitic, anorthositic to basic composition (the latter commonly present as cross-cutting sheets or dykes) are preserved within the Flatraket and Ulvesund bodies (Plate 1), mapped as 'mangerite' by Bryhni (1966) and as 'quartz-syenite' by Lappin (1966). In all those areas unaltered by later eclogite- or amphibolite-facies overprint, these rocks preserve a high-pressure granulite assemblage, of probable Proterozoic age, with garnet + clinopyroxene + plagioclase as the critical assemblage, and additional megacrystic K-feldspar, biotite, hornblende and accessory rutile or Fe-Ti oxides, depending on lithology. Rare orthopyroxene is a relic of an earlier (possibly igneous?) assemblage. Eclogite-facies and, more commonly, amphibolite-facies assemblages are found in Caledonian zones of fluid-infiltration and/or high strain, particularly on the margins of the Flatraket body. Eclogites and relics of eclogite-facies mineralogy in amphibolite-facies meta-anorthosite have been reported from Seljeneset, on the eastern margin of the Flatraket body (Cotkin et al. 1988, Cotkin 1997). On the western margin of the Flatraket body, a clear temporal progression from granulite through eclogite to amphibolite-facies assemblages is seen in anorthositic and basic rocks. Anorthositic and mafic granulite is transformed to eclogite in shear zones (consisting of kyanite, zoisite, quartz, omphacite, garnet, phengite for anorthositic rocks, and garnet, omphacite, quartz, rutile +/- phengite for mafic rocks). These assemblages may have a later, static, symplectitic amphibolite-facies overprint or are cut by amphibolite-facies shear zones. Amphibolite-facies material is rich in fine granular plagioclase, clinozoisite, biotite, white mica and amphibole with relict K-feldspar or garnet porphyroclasts in some lithologies. The Flatraket and Ulvesund bodies have experienced granulite-facies, eclogite-facies and subsequent amphibolite-facies conditions; the metastable preservation of pre- or peak-rogenic assemblages is related to the absence of subsequent deformation and fluid infiltration in unaltered areas.

Peak-Caledonian enclaves: eclogite-facies rocks

Eclogites senso-stricto

Eclogite pods occur throughout the area and are commonly concentrated in trails along specific structural levels, best seen where coastal outcrops are parallel with the structural grain (Plate 1). The Gangeskardeneset eclogite trail (Lappin 1966) is exposed for some 500 m whereas a 15 km long trail stretches from Almenningen to Bryggja parallel to the northern shore of Nordfjord. The eclogites at Selje and Årsheimneset on either side of Stadlandet probably also form part of a trail. Eclogite pods vary in size from 1 m or less to up to several tens of metres across, with several bodies reaching >500 m length in the Nordfjord area. Eclogites occur: (1) within amphibolite-facies layered gneisses, possessing a foliated amphibolite-facies rim isofacial to the enclosing gneisses; (2)

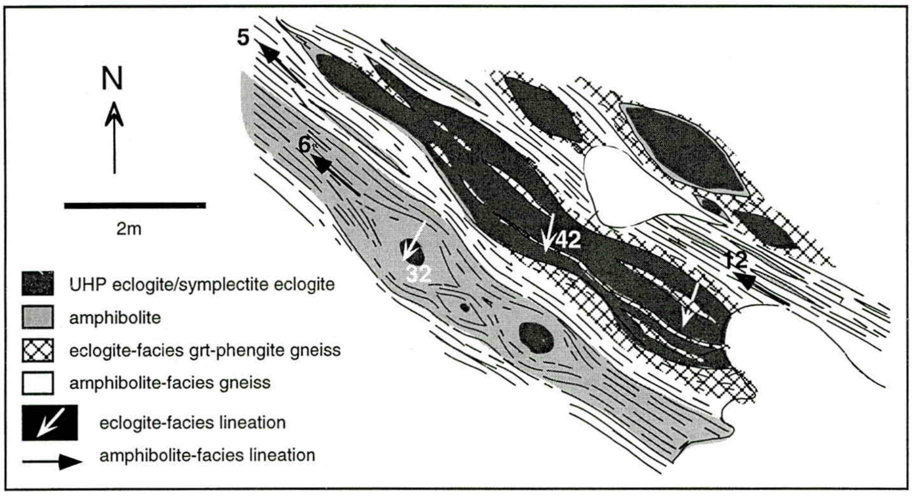


Fig. 1. Field drawing of an UHP eclogite occurrence, illustrating the co-existence of UHP-eclogite and eclogite-facies garnet-phengite gneiss and the preferential retrogression towards amphibolite-facies assemblages in high-strain zones. Location: 2.5 km west of Drage, LP 015 915.

within packages, up to 1 km in thickness, of eclogite-facies material including eclogite-facies garnetiferous gneiss or meta-anorthosite e.g. at Krokkenakken, Risnakken, Drage (Fig. 1) and Otnheim.

The mineralogy of the different eclogite pods is very variable (see Smith 1988 for an extensive overview). In addition to garnet and omphacitic clinopyroxene, eclogites contain variable amounts of either (1) quartz, phengite, kyanite, (clino-) zoisite, rutile, carbonate and/or amphibole or (2) quartz, phlogopite, orthopyroxene, rutile and/or amphibole. These correspond with the kyanite and orthopyroxene eclogite lineages (e.g. Smith 1988). Both types occur in association at Grytting, Årsheimneset and Gangeskardeneset. Compositional heterogeneity is found within some eclogites with mineral segregations forming layers or boudins within an individual eclogite body, e.g. phengite-clinopyroxene layers on the islet of Falken, near Almenningen (Plate 1). Both UHP and HP eclogites are found in the Nordfjord-Stadlandet area (Smith 1988, Wain in press) and belong to both the orthopyroxene and kyanite eclogite lineages. They are not distinguishable in hand specimen or by field relationships but can be distinguished by microstructure and mineralogy (Wain in press).

Retrogression of eclogite to amphibolite occurs via a symplectitic stage that is observable in the field. In the smaller pods, the core consists of the least retrogressed eclogite with increasing retrogression towards the margin. Long tails of amphibolite within enclosing amphibolite-facies gneisses are common. In the larger mafic bodies, however, several 'fresh' eclogite cores occur, separated by a network of amphibolite shear zones (e.g. at Drage (Fig.1), Grytting) (Plate 1).

Eclogite-facies gneisses and meta-anorthosite

Felsic eclogite-facies rocks, previously unreported from the area, are invariably associated with eclogite bodies and occur commonly along the northern shore of Nordfjord and locally on Stadlandet. These occur wrapping around or interlayered with both UHP and HP eclogites as part of eclogite-facies packages on the 10 m to km scale (Fig. 1).

Garnet-phengite-quartz gneiss contains up to 20% garnet and has an eclogite-facies mineralogy with accessory kyanite, zoisite, clinozoisite, rutile, carbonate and/or zircon. These rocks appear to have experienced the same conditions as the interlayered eclogites, and quartz pseudomorphs after coesite are observed in such gneiss interlayered with UHP eclogite at Totland and Drage (Wain in press). During amphibolite-facies metamorphism, phengite recrystallised to biotite-plagioclase symplectite, whilst other phases broke down to biotite, plagioclase, epidote and hornblende. Preservation of eclogite-facies mineralogy or textures is favoured only in amphibolite-facies low-strain zones associated with eclogite pods (e.g. at Krokenakken and Drage). In domains of amphibolite-facies high strain, the eclogite-facies assemblage recrystallised to a foliated biotite-plagioclase-quartz rich gneiss with relict garnet, and accessory sphene, Fe-Ti oxides, epidote or amphibole.

In addition to eclogite-facies meta-anorthosite in shear zones from the Flatraket-Ulvesund granulite complex described above, eclogite-facies meta-anorthosite is found interlayered with coesite-eclogite at Otnheim, Stadlandet. Here, eclogite-facies meta-anorthosite contains garnet, quartz, clinozoisite and minor kyanite and phengite, and quartz pseudomorphs after coesite are found in garnet and clinopyroxene, attesting to an UHP paragenesis. This is part of a larger (1 km^2) anorthositic-felsic-basic complex on the east Stadlandet coast (Plate 1), largely deformed and recrystallised at amphibolite facies.

Amphibolite-facies material

Layered granodioritic gneiss

The dominant rock type, comprising about 90% of the study area, is layered gneiss of broadly granodioritic composition with amphibolite-facies parageneses. The gneiss contains predominantly plagioclase and quartz with 10-20% biotite and/or white mica. In places, up to 10% epidote, K-feldspar

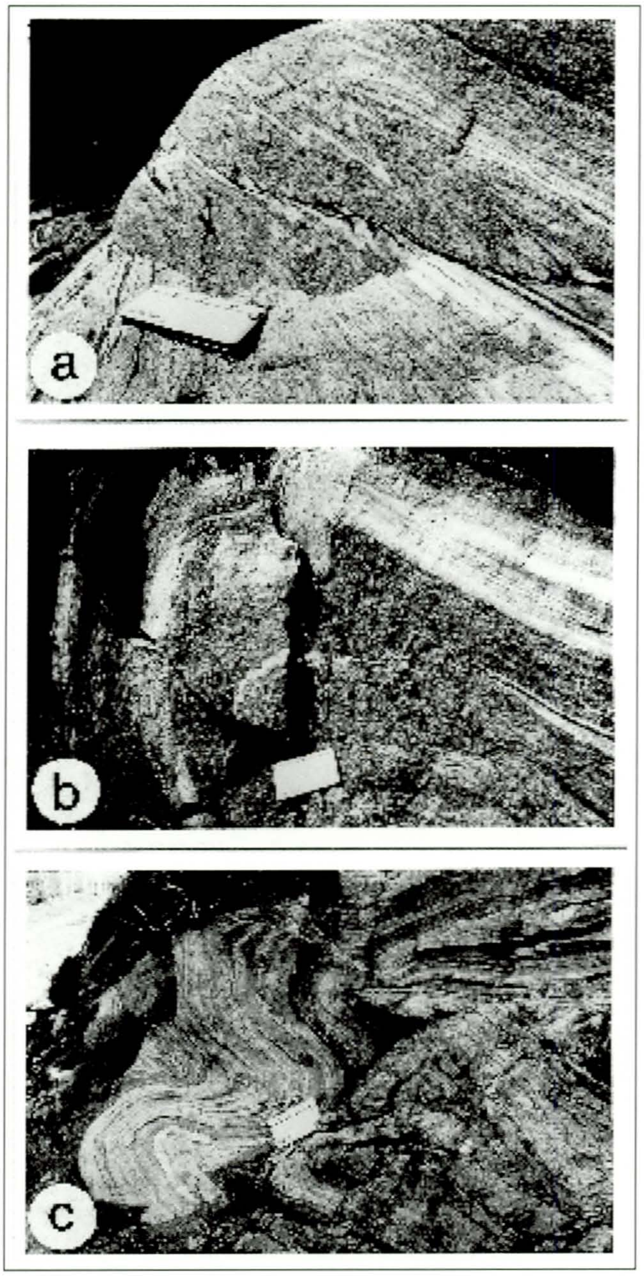


Fig. 2. Field photographs, illustrating strong deformation of layered gneiss. Much of the layer-forming flattening and all the folding are associated with late-Caledonian extension and constriction.

(a) Layered, granodioritic gneiss, with Fa folding. View to west; notebook is 20 cm long. Location: coastal point, 250 m south of the Verpeneset eclogite pod, LP 0066 6920. (b) Steep, near concentric Fb fold in layered gneiss. View to WNW, notebook is 20 cm long. Location: small, disused quarry, 600 m WNW of Åsmundsvåg, KP 9972 7875. (c) Recumbent, near-concentric Fb folds in sharply layered gneiss. View towards the east; notebook is 20 cm long. Location: along track, 2 km NNW from Almenningen, LP 0221 7120.

and/or blue-green hornblende are present. Opaques, sphene and zircon are common accessory minerals.

The gneissic layering in the study area is commonly defined by distinct pale, felsic layers and dark-grey, more mafic (biotite-muscovite-epidote-amphibole rich) layers on a mm to dm scale (Fig. 2a). Single layers of amphibolitic or granitic composition also occur, ranging in thickness from 1 - 10 cm. Epidote-rich layers also occur. The boundaries are sharp or more gradual (the 'wispy layering' of Lappin 1966). In this type of layering, there are, generally, no grain-size differences between layers of different composition.

This is in contrast to stromatic layering, which is observed in places on Stadlandet, around Sørpollen and between Gangeskardneset and Flatraket (Plate 1, Fig. 3). Stromatic layering typically comprises leucocratic segregations of trondhjemitic to granodioritic composition 5 - 30 mm wide, bounded by dark melanosome layers, <1 - 4mm thick, rich in biotite and, in places, garnet, amphiboles or epidote. Mesonome layers of intermediate composition can vary in width (2-10 cm) and relative amount. The layering is typically wavy, commonly with pinch-and-swell structures. The grain size in the stromatic gneisses is relatively coarse (0.5 - 2 mm, up to 4 mm in leucosome). The stromatic layering is interpreted as formed by anatectic migmatisation, based on the occurrence of melanosome, the different feldspar grain sizes in the leucosome (3-4 mm) and in the mesosome (<1 mm) and on perthitic exsolution features (indicative of formation at high temperatures) observed in many feldspars, in particular near Selje.

The gneissic layering commonly wraps around eclogite pods, truncating eclogite-facies structures. No evidence of eclogite-facies metamorphism is found in these gneisses in

Fig. 3. Stromatic migmatitic gneiss. Migmatitic layering is folded by tight-isoclinal Fa folds (e.g. just right of the hand-lens) and by close, steep, south-dipping Fb folds. View towards ENE, hand-lens is 5cm long. Location: road-cut along the Selje - Årsheimneset road, 2 km ENE of Selje, 230 m altitude. LP 1095 8512.

the study area but pervasive late-Caledonian amphibolite-facies deformation may have led to complete re-equilibration of possible former HP assemblages.

Granitic gneiss

In several places, notably between Måløy and Verpeneset, large bodies of granitic augen gneiss occur (Plate 1). The total content of mafic minerals (biotite, zoisite, muscovite and chlorite) is 5% or less, much less than in the layered granodioritic gneiss. Most of the granitic gneiss contains a rather uniform feldspar augen texture and layering is generally only very poorly developed, some layers enriched in K-feldspar occur in places. Undeformed pegmatitic patches occur within the granitic gneiss. An igneous origin for the augen gneisses seems probable, but the metamorphic mineral assemblage indicates, at most, amphibolite-facies metamorphism.

Garnetiferous gneiss

Different varieties of garnetiferous gneiss can be distinguished in the study area. Amphibolite-facies garnet-biotite-plagioclase rich gneisses are associated commonly with eclogites (e.g. at Drage or Krokkenakken, see Plate 1). The transition from eclogite-facies garnet-phengite gneiss to amphibolite-facies garnet-biotite-plagioclase gneiss via a symplectitic stage is thought to be related to deformation and re-crystallisation, as outlined above. The presence of garnet is the main distinguishing feature of this rock from the more common layered granodioritic gneiss. Final breakdown of eclogite-facies garnet may render this gneiss indistinguishable from the latter. However, it is not clear whether all garnetiferous gneisses represent relics of HP assemblages. Some garnet-K-feldspar-epidote rich gneisses appear to have purely amphibolite-facies parageneses.

Quartzite

Layers of quartzite occur in particular between Bortnen and Endal, south of Nordfjord (Plate 1, Bryhni 1966) and east of the study area in Hjelmelandsdalen (Bryhni 1974). Quartzite layers are generally 1 to 10 m thick but can extend for several hundreds of metres (Plate 1). The quartzite layers attest to a sedimentary origin for at least some of the lithologies occurring in the WGR.

Anorthosite

In addition to the granulite or eclogite-facies occurrences described above, anorthositic rocks are found more commonly as layers on a metre to 10 m scale within amphibolite-facies layered gneiss in the Nordfjord area. These invariably have an amphibolite-facies assemblage consisting of plagioclase with minor epidote, clinozoisite, zoisite, margarite, paragonite, chlorite, sphene, carbonate and rarely K-feldspar. They attest to an igneous origin for part of the WGR and occur, in particular, between Bortnen and Davik (Plate 1, Bryhni 1966), around Krokenakken and to the east of the study area in Hjelmelandsdalen and to the south of Nordfjordeid (Bryhni 1966, 1972, 1974).

Ultramafics

Large bodies of ultramafic rocks occur to the east of the study area in Sunndalen, Almklovdalen and Bjørkedalen (Bryhni 1966, Lappin 1966, Jamtveit et al. 1991). These are partly serpentinised dunite bodies and contain garnet-pyroxenite and eclogite pods. The tectonic implication of these bodies is a matter of dispute (Jamtveit et al. 1991). In the study area, a few smaller bodies occur (Plate 1); they are usually largely serpentinitised (e.g. Bryhni 1966) and are readily identified by their sandy-brown weathering. Veins, normal to the regional east-west extension trend are filled with acicular serpentine minerals with the fibres parallel with the extension trend.

Metamorphic evolution

As outlined above, the transition between pre-Caledonian (granulite-facies), peak Caledonian (either UHP or HP eclogite-facies) and late-Caledonian (amphibolite-facies) assemblages can be seen on the local scale across various lithological groups. Pre- and peak-Caledonian assemblages are preserved in local low-strain zones, whilst pervasively deformed amphibolite-facies material makes up ≥ 90% of the area.

Pre-eclogitic granulite-facies rocks are restricted to the Flatraket-Ulvesund body, corresponding to P-T conditions of 10-12 kbar, ~800 °C (Wain, in prep.). These plagioclase-bearing rocks were preserved metastably during eclogite-facies metamorphism. The age of granulite metamorphism is poorly constrained but predates the Caledonian eclogite-facies event and probably postdates the 1520 ± 10 Ma U-Pb upper intercept age of the Flatraket megacrystic quartz-monzonitic gneiss (Lappin et al. 1979).

Eclogite-facies P-T conditions, regarded to be Caledonian in age (Griffin & Brueckner 1980, Gebauer et al. 1985, Krogh & Carswell 1995), show marked variation through the study area, as shown on Plate 1. Wain (in press) suggests the presence of three zones with different peak pressures (Plates 1 and 2): (1) an UHP province, centred on Stadlandet, where eclogites contain coesite and/or coesite-pseudomorphs as part of a peak-pressure assemblage (P>28 kbar) and where no evidence of prograde textures and mineralogies has been found; (2) a HP zone, stretching from the NSD to the northern shore of Nordfjord, where eclogites commonly preserve prograde zoned garnets with amphibolite-facies cores (Bryhni & Grimstad 1971, Krogh 1982) and no evidence of (former) coesite has been found; a maximum pressure of 20-24 kbar at T ~ 650-800 °C has been calculated for these eclogites (Martin 1994, Wain, in press), (3) an ~ 8 km wide bimodal zone in between, stretching from the northern shore of Nordfjord to Rundarheim, where both UHP and HP eclogites occur, sometimes less than 1 km apart. Eclogite-facies gneisses or meta-anorthosite appear to be isofacial with associated HP or UHP eclogites. The Flatraket and Ulvesund granulitic bodies, metastable at HP, occur within the bimodal zone. Eclogite-facies shear zones within this complex correspond to HP metamorphism (20-22 kbar, ~750 °C, Wain in prep.) but show no evidence of having experienced UHP metamorphism.

Amphibolite-facies metamorphism is pervasive in the remaining rocks throughout the area, corresponding to relatively uniform conditions of 8-12 kbar, ~650 °C (Dransfield 1994). Other authors have estimated conditions of 11 kbar, 700-750 °C (Cuthbert 1991), and between 4.3-8.2 kbar, 520-610 °C (Cotkin et al. 1988), for points in the exhumation path of particular rocks.

A very significant correlation exists between late-Caledonian deformation and amphibolite-facies assemblages. All the rocks that have experienced late-Caledonian deformation show stable amphibolite-facies assemblages. However, domains where late-Caledonian deformation is absent or very weak show almost invariably either Caledonian peak eclogite assemblages or pre-Caledonian granulite assemblages or relics thereof.

Late-Caledonian structures

Most late-Caledonian structures are expressed by a deformation of the gneissic layering. The generation of the gneissic layering itself is the result of a long and complex history but an important part of this history is related to late-Caledonian extension. Only the late-Caledonian structures, formed under amphibolite to greenschist-facies conditions, are described in detail in this paper; structures within eclogite pods and granulite bodies will be described elsewhere. Andersen et al. (1994) described eclogite-facies structures from Sunnfjord in the southwestern part of the WGR; some of these observations are valid for the Nordfjord area (e.g. Dransfield 1994).

Structures related to east-west extension

The now classic sequence in extensional detachment zones, described from metamorphic core complexes in the Basin and Range Province, USA (e.g. Lister & Davis 1989), of cataclasites, greenschist to amphibolite-facies mylonites to mylonitic gneiss is characteristic of the NSD. However, unlike most Basin and Range metamorphic core complexes, in which the cores themselves experienced relatively little strain during extension, the WGR below the detachment zone has also been subjected to high strain. Andersen & Jamtveit (1990) demonstrated that this zone has been subjected to bulk coaxial east-west extension; Krabbendam & Dewey (in press) expanded on this idea and showed that the bulk finite strain ellipse is constrictional (rather than plane strain), with north-south and vertical shortening coeval with east-west extension.

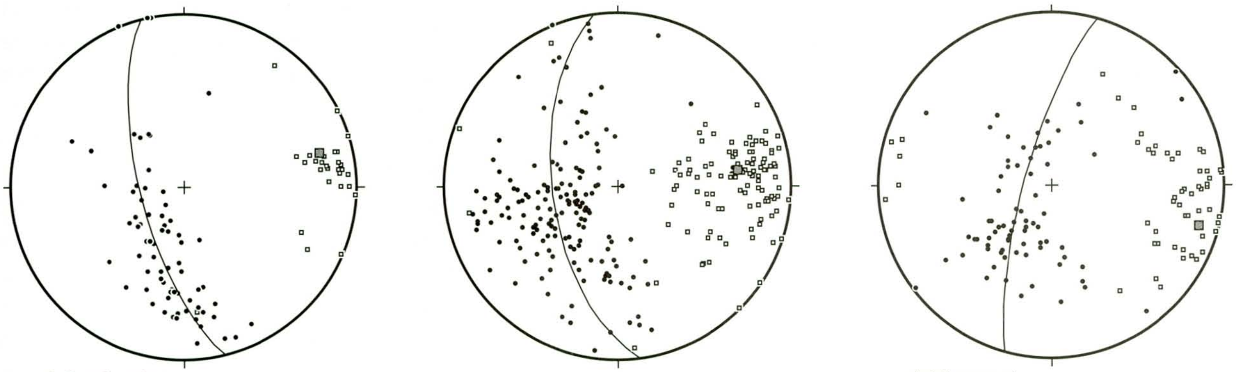
Structures related to the NSD zone, indicating strongly non-coaxial shear

In the study area, the NSD / HD is poorly accessible. In the far southeastern part of the study area, the detachment has been studied in detail (Plate 1). Here, steep SSE-dipping mylonites have a well-developed, sub-horizontal WSW-plunging lineation and contain abundant dextral / top-to-the-west shear sense indicators. The penetrative mylonitic foliation and lineation are oriented 10-20° clockwise from the trace of the brittle detachment itself. South of Borntepollen, the detachment zone can be studied only some 2-300 m below the base of the Devonian. Here, south-dipping mylonites occur with abundant σ-type feldspar porphyroclasts indicating a dextral (top-to-the west) shear sense (Dransfield 1994). A strong lineation, mainly defined by quartz rods, is sub-horizontal east-west. The metamorphic grade of these mylonites is upper greenschist facies; the protolith is granodioritic epidote-biotite gneiss. North of Borntepollen, the rocks grade into mylonitic, mica-rich gneisses with sub-horizontal east-west lineations, defined by quartz-rodding and prolate feldspar augen (aspect ratio 1:3:10). Shear sense indicators are abundant and include shear bands, extensional crenulation cleavages, internal oblique shape fabric in quartz-rich layers, σ-type feldspar porhyroclasts and an asymmetric wrapping of mica around garnet (see the reviews of Simpson & Schmid 1983, Hanmer & Passchier 1991), all indicating a top-to-the-west shear sense. In the Borntepollen - Leirgulen area, most shearing occurred under amphibolite-facies conditions but continued during greenschist-facies retrogression as shown by chlorite growth along certain shear planes. On Biskjelneset, on the north shore of Nordfjord, a highly sheared, granitic augen gneiss contains abundant σ-type feldspar porphyroclasts and asymmetric extensional shear bands, which cut an older gneissic layering. Thus, shear sense indicators, indicating strongly non-coaxial, top-to-the-west shear under amphibolite to greenschist-facies conditions, are abundant in a 5 km-wde zone north of the NSD, although a penetrative mylonite foliation is only developed in the top 2-400 m.

Structures in the coaxial zone below the NSD

North of Nordfjord, structures indicative of non-coaxial shear are rare and absent over large areas. However, the granodioritic granitic gneisses are highly and pervasively deformed by near-coaxial strain. East-west trending lineations can be found at almost every outcrop (Plate 1, Fig. 4) and include biotite mineral lineations and quartz-rodding in granodioritic gneisses and amphibole mineral lineations in amphibolites. The granitic augen gneiss near Verpeneset contains a fabric of symmetric, strongly prolate feldspar augen with an aspect ratio in the order of 1:3:8-10 to 1:1.5:8, implying general constrictional strain, similar to the strain regime observed along Førdefjorden further south in the WGR (Krabbendam & Dewey, in press).

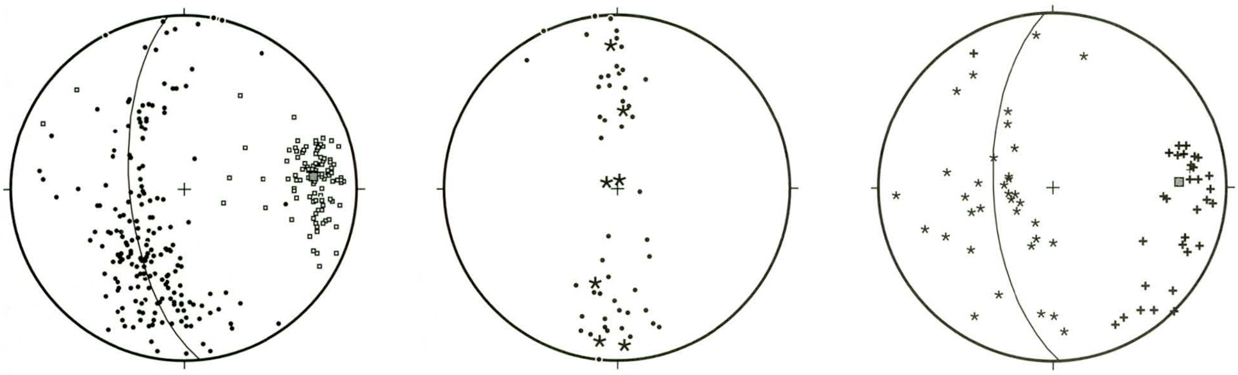
An amphibolite-facies mineral foliation is commonly very well developed and is parallel with the compositional layering, except in the hinge zones of tight folds (see below). This foliation, termed Sa, is defined by a preferred orienta-



a) Stadlandet
- Foliations: n = 76
▫ Lineations: n = 30

b) Sørpollen to Flatraket
- Foliations: n = 166
▫ Lineations: n = 111

c) Ulvesund
- Foliations: n = 76
▫ Lineations: n = 55



d) Verpeneset - Almenningen
- Foliations: n = 201
▫ Lineations: n = 106

e) Bortnepollen
- Foliations: n = 53
★ Fb axial plane n = 8

f) Nordfjord to Flatraket
+ Fb fold axes, n = 33
★ Fb axial planes, n = 35

Fig. 4. Equal-area diagrams of structural data, separated in different domains. Foliations are gneissic layering and amphibolite-facies foliation. Great circles are π planes of foliation data in Figs. 1a-d and of Fb axial planes in Fig. 1f. The grey squares are π poles of the same planar data.

tion of biotite, white mica and amphiboles and epidote (where present) but also by the shape orientation of quartz and feldspars and by quartz ribbons.

Orientation of gneissic layering, foliation and lineation
Because the gneissic layering and the mineral foliation are parallel, except in the hinge zones of small tight folds, they can be treated together in orientation analysis. The gneissic layering and foliation strike E-W but have variable dips (Fig. 4). The dip variation is attributed to late Fb folding (see below). Close to the NSD, lineations plunge gently west, whereas away from the NSD, east-plunging lineations become dominant with plunges up to 30° to the east (Plate 1, Fig. 4). This change from west to east plunging lineations occurs some 3 km north of the NSD and is probably related to a plunge culmination located structurally a few km below the NSD, also reported by Milnes et al. (1985, 1997) along the Sognefjord transect further south in the WGR. Note that the plunge culmination does not coincide with the transition from the non-coaxial to the coaxial zone.

Structures indicating N-S shortening: E-W folds

Structures relating to two types of late-Caledonian folding, differing both in style and in relative timing, can be observed in the study area. Because a long and presumably complex tectonic history preceded these folds, we do not use an F1, F2 order; rather, we refer to the folds as Fa and Fb. Although Fb overprints Fa in every locality where both folds occur (e.g. Fig. 3), it is not necessarily the case that all Fb folds are younger than all Fa folds in the area as a whole.

Early folds (Fa)
Fa folds are tight to isoclinal folds, folding the gneissic layering (Fig. 2a). Fa folds are commonly near-similar and rootless Fa folds are common. The strongly developed amphibolite-facies mineral foliation (Sa) is axial planar to the Fa folds, indicating that Fa folds developed under amphibolite-facies conditions. Because Sa and the gneissic layering appear to be (sub)parallel in the Fa fold limbs, the axial planar fabric relationship of Sa and Fa can commonly only be reliably established in the Fa fold hinges. The wavelength of Fa folds is generally 1-20 cm and rarely exceeds 1 m; the fold ampli-

tude, however, can be several metres or more. The Fa fold hinges are either east- or west-plunging and everywhere parallel with the mineral lineations (La), indicating that the E-W extension (responsible for the strong lineations) was coeval with N-S shortening. Although Fa folds are generally strongly asymmetric, no regionally dominant vergence is observed, attesting to a near-coaxial strain regime.

Late folds (Fb)

Fb folds are open to tight, commonly near-concentric folds, folding the gneissic layering, the earlier Fa folds and the Sa mineral fabrics (Figs. 2b-c, 3). This deformation has commonly resulted in an intense crenulation of micas in the tighter parts of Fb fold hinges. The axial planar fabric of Fb folds is therefore a crenulation cleavage, which tends to be well developed only in the fold hinges of mica-rich rocks. The metamorphic grade of this deformation stage is somewhat lower than the amphibolite-facies metamorphism that prevailed during the formation of Fa folds, as no significant new mineral growth is associated with Fb. Fb fold hinges are generally E-W trending and are grossly parallel with the regional mineral lineation and the Fa fold hinges (compare Fig. 4f with Figs. 4a-d). At many localities, however, Fb can be seen to fold the mineral lineations (La) and angles up to 15° between Fb and La occur locally, for instance in road-cuts north of Almenningen (cf. Chauvet & Séranne 1994).

Two sets of Fb folds occur: recumbent and upright folds (Figs. 2b & c, 4e & f). The upright Fb folds, mapped within the WGR gneisses, have amplitudes and wavelengths varying from 1 m to 1 km (Plate 2). If the synforms containing the four Devonian basins in the WGR are also Fb folds, which is likely, then the Fb wavelength under these basins is several kilometres. Recumbent folds are less common and generally smaller with a wavelength of a few metres at most. Along Borntepollen, recumbent folds have wavelengths of up to 10 m. No overprinting relations between recumbent and upright Fb folds have been observed and it is not clear whether they were formed synchronously or not. If the former is the case, Fb folds may have formed during bulk east-west general constriction.

In an 8-9 km-wide zone, from the NSD to the north shore of Nordfjord, upright Fb folding is intense with numerous close to tight folds resulting in steep, vertical and locally overturned gneissic layering (Plate 2, Fig.4d). North-south shortening by Fb folding in this zone is estimated at about 50% by line balancing.

Along the coast from Falkevik to Almenningen, many recumbent folds occur. It is, however, not clear whether these folds are Fb folds or possibly earlier folds related to accommodation of strain around the numerous eclogite bodies at this structural level, which acted as low-strain zones.

Along Sørpollen, Fb folding is rather open and the gneissic layering is gently east dipping (Fig. 4b). However, structurally above the Flatraket granulite, east and southeast of Nordpollen, Fb folding is again abundant and steep attitudes are common (Plates 1 and 2). These differences may be attributed possibly to the Flatraket granulite body, having inhibited homogeneous N-S shortening.

Between Flatraket and Rundarheim, Fb folding is also common and attitudes are steep. On large parts of Stadlandet, Fb folding is rare and the gneissic layering is sub-horizontal (Fig. 4a) with the exception of a 2-3 km-wide steep zone near Selje, bounded by two moderately steep south-dipping monoclines (Plates 1 and 2). The classic Grytting coesite-eclogite pod occurs in this steep zone. North-south shortening by Fb on Stadlandet is estimated at 10% maximum by line balancing.

Structural positions of eclogite and granulitic bodies

The layered granodioritic gneisses, forming the bulk of the WGR, record only late-Caledonian metamorphic conditions, whereas peak-metamorphic conditions are only recorded in the relatively rare eclogite pods. Therefore, the relative structural positions of eclogite pods, recording different peak-pressures, are important in assessing the tectonic relationships and evolution of eclogite-facies rocks in the Western Gneiss Region. Overall, there is a gross increase in recorded peak pressures from the NSD towards the north. In detail, however, complications occur, as indicated by the close occurrence of UHP and HP rocks within the bimodal zone (see section on Metamorphic Evolution).

The Ulvesund and Flatraket granulite bodies are most likely parts of the same body, connected via a N-S trending, open anticline along Sørpollen (see also Bryhni 1966). In a N-S cross-section, this body has a rather flat-lying attitude (Plate 2). Eclogite-facies shear zones suggest that the body has experienced HP (20-22 kbar) but it apparently contains no evidence for UHP metamorphism. The Straumen coesite-eclogite pod in Sørpollen (Smith & Lappin 1989) occurs structurally below the Flatraket body, as does the newly discovered Flatraket coesite-eclogite pod, the latter only 200 m away from the Flatraket granulite (Plates 1 and 2); this represents an inverted metamorphic zonation. The coesite-eclogite pod in Nordpollen is structurally above the Flatraket Body. Thus, the Flatraket body has UHP eclogites both structurally below and above, indicating both inverted and right-way-up metamorphic zonations. Other close occurrences of UHP and HP eclogites include (Plates 1 and 2): Gangeskardeneset (HP) - Flatraket (UHP); UHP and HP eclogites along the northern shore of Nordfjord, and at Straumen, where HP and UHP eclogites are probably separated by less than 1 km although the exact location of the UHP eclogite at Straumen (Smith & Lappin 1989) could not be found. UHP and non-UHP eclogites are always separated by >100 m of pervasively deformed amphibolite-facies gneisses with no evidence, however, for discrete shear zones separating the two suites. The exact tectonic relationship between UHP and non-UHP eclogites in the UHP-HP bimodal boundary zone is obscured by the amphibolite-facies overprinting, but the P-T jump in this area suggests zones of extreme attenuation or a distinct tectonic break, pre-dating regional amphibolite-facies metamorphism and deformation and separating an UHP province from the rest of the WGR (Wain in press). It is unclear from our cross-section whether the UHP province as a whole is structurally above or below the HP zone of the Western Gneiss Region.

Discussion

Three issues will be discussed below: the formation and modification of gneissic layering by pervasive late-Caledonian strain; the in-situ versus foreign eclogite metamorphism models from a deformational point of view and the heterogeneous attenuation of the crust causing differential exhumation and tectonic juxtaposition of HP and UHP rocks.

Formation and modification of gneissic layering by pervasive late-Caledonian strain

Some elements of the gneissic layering may be of primary origin, such as original sedimentary layering or layer-parallel intrusions. However, most of the gneissic layering in the WGR is of tectonic origin, formed by flattening of originally discordant rock contacts. Passchier et al. (1990) have described this process in some detail and argue that this is a very common origin of gneissic layering. That the tectonic flattening, which played such a major role in the formation and modification of gneissic layering in the study area (and indeed in most of the western part of the WGR), is Caledonian rather than Proterozoic, can be argued as follows. First, in the eastern and southern part of the WGR, many discordant contacts of igneous rocks can be seen concomitant with low strain, for instance at the excellent exposures below Nigardsbreen (part of Jostedalsbreen) and also those reported by Milnes et al. (1988, 1997) in the Sognefjorden transect. Such highly discordant contacts are not present in the western part of the WGR, where the compositional differences are now planar, except in those domains which show older deformation and metamorphism, e.g. near Flatraket and on Bardsholmen in Sunnfjord (Andersen et al. 1994). Thus, from east to west, contacts become more concordant, concomitant with the westward increase of Caledonian strain (Dietler et al. 1985, Milnes et al. 1988). Secondly, the late-Caledonian mineral foliation (biotite, muscovite, epidote, amphiboles) is generally parallel with the compositional layering. Thirdly, amphibolite-facies material wraps and/or truncates eclogite-facies structures, and thin layers of deformed amphibolite (retrogressive after eclogite) containing layer-parallel amphibolite-facies fabrics are continuous with eclogite pods, indicating that these layers where formed by deformation that post-dated the eclogite-forming event. The last two arguments also indicate that a substantial part of the strong deformation responsible for the formation of the gneissic layering was late-Caledonian. In the southwestern part of the WGR, bulk near-coaxial strain below the NSD has been taken up by anastomosing shear zones, surrounding low-strain zones (Andersen & Jamtveit 1990), whereas in the study area bulk near-coaxial strain has been taken up in a far more pervasive and mesoscopically homogeneous way. This pervasive late-Caledonian deformation and related pervasive amphibolite-facies retrogression may account for the scarcity of relics of HP-assemblages in the layered granodioritic gneiss in the study area; elsewhere in the WGR, such relics appear to be more common (Griffin 1987, Andersen et al. 1994).

Late-Caledonian deformation and the in-situ versus foreign eclogite models

Two models of eclogite formation in West Norway have been proposed, an 'in-situ' and a 'foreign' model. The 'foreign model' involves the tectonic introduction of eclogites, formed at mantle depths, into the host gneisses, which never experienced HP or UHP (Lappin 1966, Lappin & Smith 1978, Smith 1984). Smith (1988, 1995) proposed a variation on this theme, the FIF (foreign, in-situ, foreign) model. This model envisages tectonic introduction of UHP rocks into HP rocks and subsequent tectonic introduction of HP rocks into LP rocks.

Many authors, including Bryhni (1966), Cuthbert et al. (1983) and Griffin & Carswell (1985), have argued that the eclogites formed in-situ in their present host gneisses, so that all rocks were subjected to the same P-T conditions. Compatible P-T conditions for some eclogites and gneisses (with high-pressure granulite assemblages) were previously argued (Krogh 1980) but it is now widely accepted that there is a significant pressure difference between the dominantly amphibolite-facies gneisses and both HP and particularly UHP eclogites (as argued by Smith 1988). Thus, an in-situ origin for the eclogites must imply either metastability of felsic rocks at depth or differential retrogression whereby retrogression was favoured in felsic rocks, or a combination of those processes.

In the study area, evidence for metastability of felsic rocks at eclogite facies is restricted to the Flatraket-Ulvesund granulite complex, which has clearly experienced eclogite-facies conditions but preserves pre-orogenic granulite-facies assemblages in low-strain zones. The extremely strong correlation of amphibolite-facies assemblages with late-Caledonian extensional deformation suggests that differential retrogression has been operative in the majority of the country rocks, so that mainly undeformed and mafic rocks tend to retain their eclogite-facies assemblages, whereas strongly deformed, mainly felsic rocks are preferentially retrogressed. The pervasive, late-Caledonian, extensional deformation within the felsic gneisses would greatly favour retrogression of HP assemblages. An eclogite-facies assemblage with a granodioritic composition is more hydrous than an amphibolite-facies assemblage of the same composition (e.g. Bousquet et al. 1997), so that the retrogressive reaction from HP to LP in a rock with granodioritic composition is kinetically favourable, as the rock tends to retain its most dehydrated state (e.g. Heinrich 1982). The preservation of eclogite-facies garnet-phengite gneiss in late-Caledonian low-strain zones with a direct correlation between retrogression and late-Caledonian deformation, provides strong evidence for in-situ metamorphism, for both HP and UHP eclogites (e.g. Fig. 1).

There is no evidence for specific high-strain zones, linking UHP or HP eclogites, as proposed by Smith (1988, 1995), in existence today. The steep zone, linking the Grytting and Årsheimneset UHP eclogite pods, is the result of Fb folding (Plate 2) in a very late stage of exhumation and is not a specific high-strain zone (cf. Smith 1988). Therefore, field evidence in this area is not compatible with simple subvertical solid introduction of foreign rock bodies (cf. Smith 1995).

It remains possible, however, that such shear-zones have existed but that their fabrics have been obliterated during the pervasive late-Caledonian amphibolite-facies metamorphism. This would imply that any foreign introduction, if it did occur, must have happened prior to this amphibolite-facies event. Thus, the second stage of tectonic introduction of Smith's (1988) FIF model, that of HP rocks into LP rocks, is incompatible with the data presented in this paper. The first stage of introduction, that of UHP rocks into HP, cannot be ruled out, although all field and metamorphic relationships can be explained by metastability or differential retrogression with late-Caledonian deformation playing a key role in the latter and in the juxtaposition of HP and UHP rocks. Another argument against foreign introduction is that the gneisses within the UHP province are effectively the same as those in the HP zone; in other words, lithologically the UHP province is not exotic.

Differential amounts of exhumation

The exhumation of the UHP rocks in the WGR can be partitioned into three domains: exhumation from above the NSD, attenuation across the NSD by non-coaxial strain, and attenuation by pervasive coaxial strain below the NSD. By comparing the vertical distance between individual rock samples prior to exhumation (as constrained by peak-pressure estimates) with the current structural distance between those samples, we can constrain the contribution of each of these domains to the total attenuation of the crust. This comparison indicates that attenuation is not distributed uniformly throughout the crust (Fig. 5).

The amount of exhumation which occurred from above the NSD is constrained by the highest Caledonian pressure estimate in the allochthon. Cuthbert (1991) calculated a P of 4.1 ± 1.8 kbar and T = 510 ± 40°C for a sillimanite-garnet hornfels in the Kalvåg melange, within the thermal aureole of the granodioritic intrusion on Bremangerlandet. This pressure estimate can be taken as Caledonian, as the related Gåsøy intrusion has been dated at 380 ± 26 Ma (Sm-Nd) / 390 ± 29 Ma (Rb-Sr), (Furnes et al. 1989). The calculated maximum P of 9.2 ± 1.4 kbar for a mica schist on Marøy (Cuthbert 1991) at a lower tectonostratigraphic level than the Kalvåg melange, is regarded by some as pre-Caledonian (T.B. Andersen, pers. comm. 1997). Thus, the peak Caledonian pressure of the allochthonous units is taken as 4.1 kbar; the occurrence of andalusite and cordierite in the thermal aureole of the granodioritic intrusion on Bremangerlandet (Bryhni & Lyse 1985) supports this low-pressure estimate. Such a pressure suggests that some 15 km of crust was removed from above the NSD/Hornelen Detachment. The Kalvåg melange and the granodiorite intrusion are overlain unconformably by the Devonian Hornelen Basin (Plate 1). A number of normal faults occur below this unconformity and are truncated by it (Hartz et al. 1994, Hartz & Andersen, in press) indicating that the 15 km of crust was removed by a combination of erosion and extension (Fig. 5), partly prior to deposition of the Devonian sediments, very similar to the tectonic evolution of the allochthonous units in the Sunnfjord area (Osmundsen & Andersen 1994).

The eclogite pod nearest to the NSD and the allochthon occurs along Borntepollen, structurally less then 1 km below the NSD. A pressure of 20 kbar has been calculated for this eclogite (Martin 1994). A pressure difference of 16 kbar, equivalent to 57 km of crustal section, is now represented by about 1 km of structural thickness across the NSD, implying an attenuation of 98% (defined as shortening: $(l-l/l_0) \times 100\%$). It is doubtful, however, if all this exhumation was achieved solely by simple shear along the NSD. The maximum horizontal displacement of the NSD is equal to the distance between the eastern edge of the NSD and the western edge of the Jotun Nappe (50-60 km), plus the distance which the Jotun Nappe has moved back to the west along the thrust plane (estimated at 20-35 km, Fossen & Holst 1995), plus the horizontal displacement along the Laerdal-Gjende Fault Zone (~35 km, Milnes et al. 1997); that is, a maximum total displacement of 105-130 km. If exhumation ('vertical displacement') of 57 km was achieved solely by simple shear along the NSD this would require a dip of 26-33° of the NSD and a subsequent rotation of 16-23° to the current dip of 10°. Such a steep original dip of the NSD and later rotation is unlikely becaus: -

- the dip of the NSD is very constant over a distance of ~ 80 km, making both wholesale rotation or a rolling hinge rotation hard to conceive;
- the SSOC ophiolite was obducted along a shallow dipping plane, as is the case for most ophiolites (J.F. Dewey, pers. comm. 1997);
- a substantial difference in metamorphic grade would be expected between the Devonian rocks in the eastern and in the western part of the Hornelen Basin;
- the metamorphic grade of the most westerly allochthonous rocks would be expected to be substantially higher.

It is likely, therefore, that the NSD originated with very much its current dip (see also Andersen & Jamtveit 1990, Dewey et

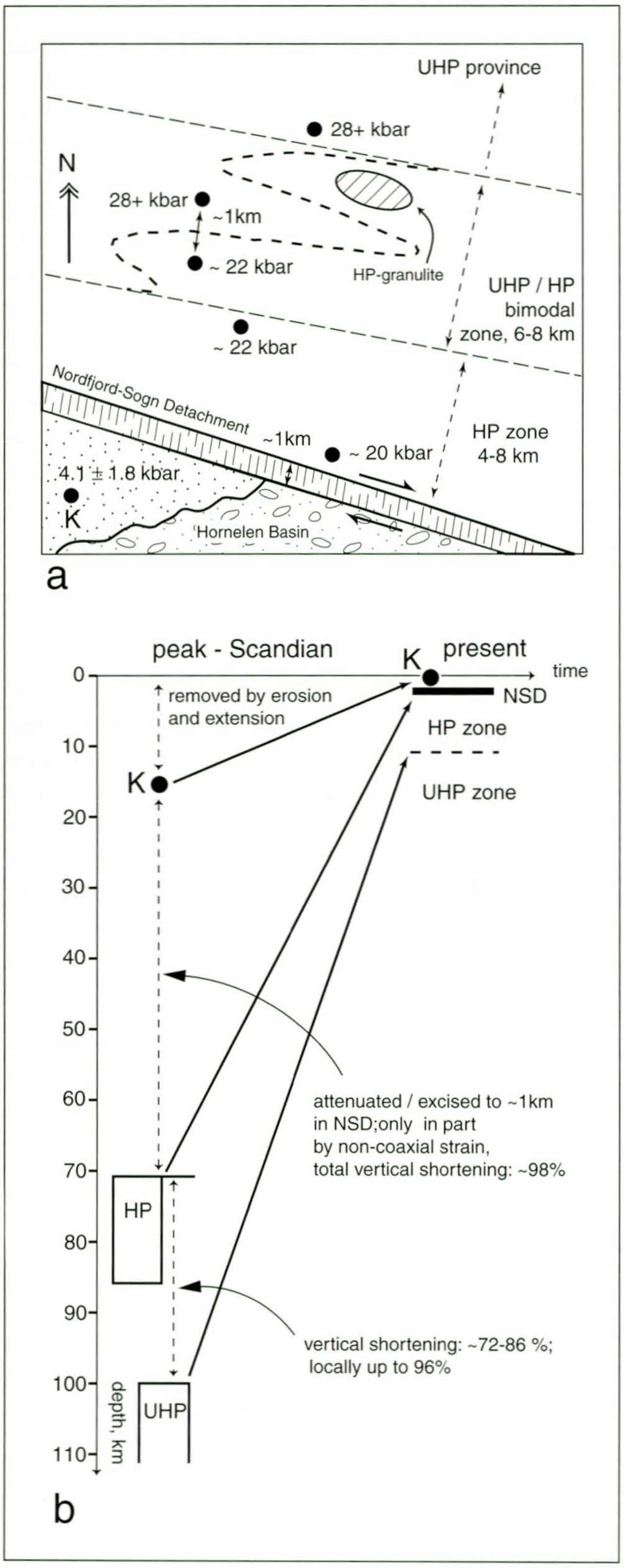


Fig 5. Differential exhumation and attenuation of isobars. a) Schematic map, not to scale, showing domains with different peak pressures. b) Diagram showing differential exhumation and attenuation of isobars. K = Kalvåg melange, pressure after Cuthbert (1991). Other pressure data after Wain (in press). For further explanation: see text.

al. 1993, but see Fossen 1992), that the exhumation taken up by non-coaxial deformation along the NSD probably did not exceed 25 km, and that a substantial part of the exhumation was taken up by coaxial vertical shortening below the NSD (e.g. Andersen & Jamtveit 1990, Dewey et al. 1993, Krabbendam & Dewey in press) with the highest level sections of the crust thus attenuated subsequently cut out by the NSD.

The most southerly and structurally highest UHP eclogites occur along the north shore of Nordfjord near Totland (Wain in press, Plate 1). This level occurs about 8 km from the NSD. However, because of Fb fold repetition, the true structural thickness of the 'HP zone' may be as little as 4 km (Plate 2 and Fig. 5). With the minimum pressure of coesite-eclogites taken as 28 kbar, the difference in recorded peak pressure from Bortnepollen to Totland is ≥ 8 kbar, equivalent to at least 29 km of crustal section, which is now attenuated to 4-8 km. Therefore, an overall attenuation of 72-86 % took place across the HP zone. This attenuation, however, is very unevenly distributed throughout, as HP and UHP eclogites occur very close together along the north Nordfjord coast. A similar situation occurs within the 8 km-wide bimodal UHP-HP zone, where UHP eclogites (P ≥ 28 kbar) and HP eclogites (P ~ 20-24 kbar) occur as close as 1 km from each other. With a minimum pressure difference of 4-8 kbar, equivalent to ≥ 14-28 km of crust, the local attenuation between such eclogite occurrences amounts to ≥ 93-96 %.

Thus, attenuation of the crust was not homogeneous but varies locally by a factor of 8 or more. Even so, no specific high-strain zones have been discerned between occurrences of HP and UHP rocks with the exception of the high-strain zone that bounds the Flatraket granulite body separating it from the coesite-eclogite just to the west. Therefore, both the model of the WGR as a coherent unit during subduction and exhumation (e.g. Fossen 1992, Wilks & Cuthbert 1994) and the foreign introduction model (e.g. Smith 1988) are too simple. A possible scenario for producing the close juxtaposition of HP and UHP rocks and the locally inverted metamorphic zonation may necessitate the juxtaposition of an UHP domain close to an HP domain (both forming part of the same terrane but one part more deeply buried than the other) during the first stages of exhumation. Further exhumation, by continuing E-W extension concomitant with N-S shortening (Fa folding) under amphibolite-facies conditions (Krabbendam & Dewey in press) brought UHP and HP rocks closer together but also folded the already attenuated metamorphic pile, so that locally the UHP rocks occur at structurally higher levels than the HP rocks (Plate 2, Fig. 5) within the bimodal UHP-HP boundary zone north of Nordfjord.

Summary and conclusions

Amphibolite-facies, late-Caledonian deformation in the felsic gneisses in the Nordfjord-Stadlandet area is remarkably pervasive, and has been responsible for the formation and modification of the gneissic layering in its present form. All the rocks that experienced late-Caledonian high strain show amphibolite-facies assemblages, whereas virtually all late-Caledonian low-strain zones display older assemblages, either peak-Caledonian (eclogites) or pre-Caledonian (granulite). Thus, late-Caledonian deformation has assisted differential retrogression. No specific high-strain zones, linking eclogite pods, have been identified. These conclusions support an in-situ origin for HP and UHP eclogites. If foreign introduction of UHP eclogites occurred it must have been prior to the late-Caledonian amphibolite-facies extension, but foreign introduction is not required to explain the field and metamorphic evidence and the similar lithologies surrounding the UHP and HP eclogites do not support foreign introduction.

Occurrence of HP and UHP rocks in the WGR requires the removal of 70 to 100 km of crustal overburden. Some 15 km of this overburden was removed by a combination of erosion and extension in the hangingwall of the NSD, partly prior to depostion of Devonian sediments. The bulk of the exhumation was achieved by E-W extension. The resultant crustal attenuation is unevenly distributed with a large part of the crust now attenuated and/or excised in the NSD, at least in part by strongly non-coaxial shear. Significant attenuation, however, occurred below the NSD by more pervasive coaxial strain. This E-W extension was apparently constrictional and accompanied by N-S shortening, as indicated by L>>S fabrics in augen gneisses and lineation-parallel folding in the layered gneisses. Locally, very strong attenuation is suggested by the close (≤ 1 km) occurrence of HP and UHP eclogites. Inverted and right-way-up metamorphic zonation (UHP rocks structurally on top of and below HP eclogites) may be the result of tight folding of an already attenuated metamorphic sequence. This attenuated boundary may be the tectonic contact between an UHP province and the rest of the WGR with juxtaposition pre-dating the regional amphibolite-facies late-Caledonian exhumation stage.

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Geological map Nordfjord - Stadlandet area, West Norway

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

Key

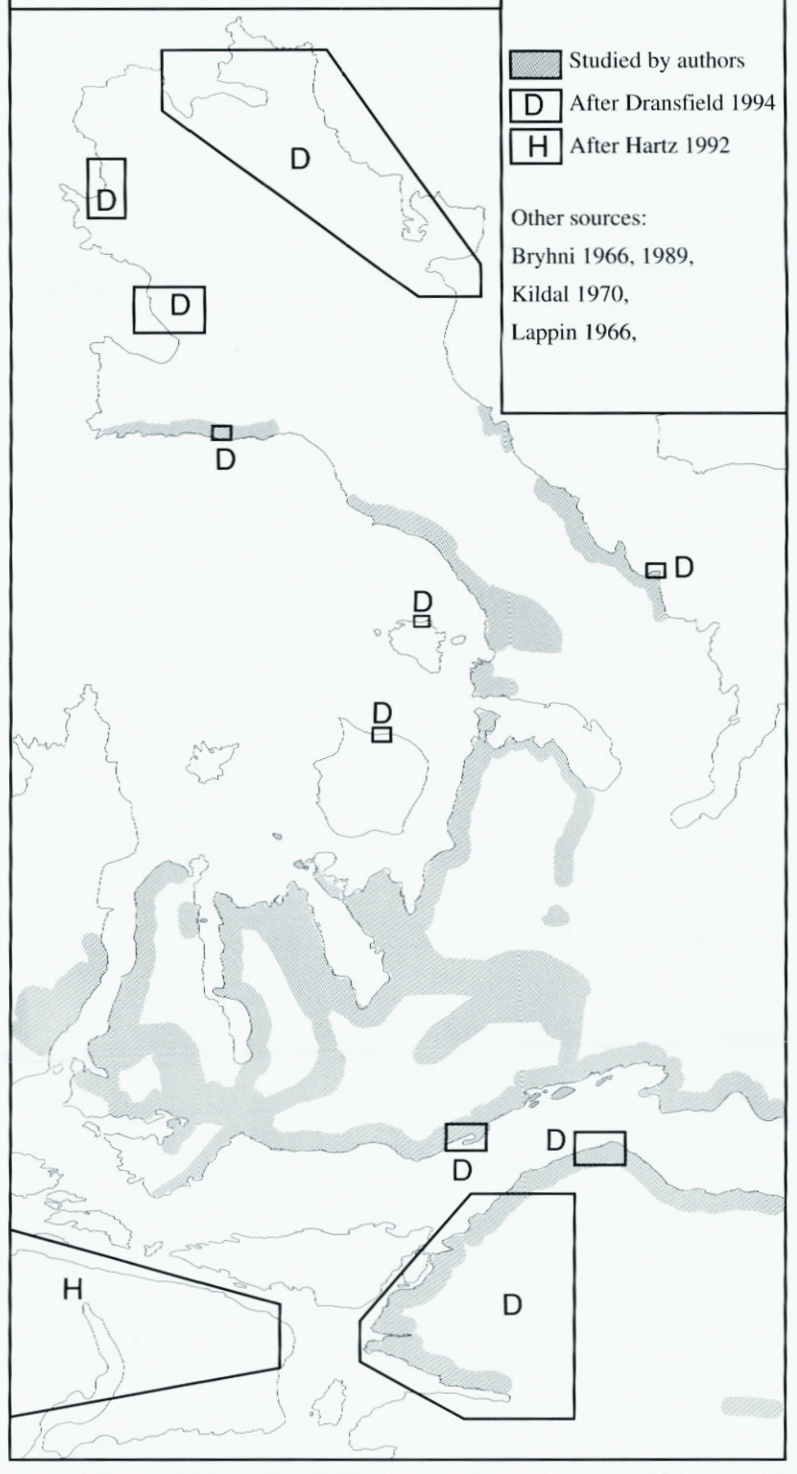
Symbol	Description		
	Conglomerate & sandstone	Devonian	Upper Plate
	Granodiorite	Upper Allochthon	
	Kalvåg Melange		
	Mafic and metasedimentary rocks		
	Quartzite	Middle Allochthon	Middle Plate
	'Bremanger Gneiss', undifferentiated		
	Mylonite	Western Gneiss Region	Lower Plate
	Layered granodioritic gneiss, undifferentiated, .locally with anorthosite, amphibolite, quartzite & granitic augen gneiss		
	Granitic gneiss, mostly with augen texture		
	Gneiss, where migmatitic		
	Garnetiferous gneiss		
	Quartzite, mostly feldspathic		
	Anorthosite		
	HP granulite (partially retrogressed)		
	HP granulite with megacrystic K-feldspar		
●	Eclogite		
	Amphibolite		
● U	Ultramafic rocks: dunite & serpentinite		
C	Coesite - eclogite (28 + kbar)		
P	Coesite-pseudomorph locality (28 + kbar)		
N	Eclogite with prograde zoning (~20-24 kbar)		
	Extensional detachment		
	Unconformity		
	Other geological contact, dashed where conjectural		
80	Amphibolite-facies foliation		
25 ←	Amphibolite-facies lineation		
80	Eclogite / granulite-facies foliation		
25 ←	Eclogite / granulite-facies lineation		
25	Fold axis, minor fold (Da)		
82	Axial plane, minor fold (Da)		
15	Fold axis, minor fold (Db)		
60	Axial plane, minor fold (Db)		
20	Fold axis, minor fold (Dc)		
25	Fold axis with direction of vergence		
80 ⇆	Sense of shear on foliation plane		
	Axial trace, major synform (Db)		
◆	Axial trace, major antiform (Db)		
	Axial trace, major monoclinal synform (Db)		
	Axial trace, major monoclinal antiform (Db)		

Grid North, 3.5° W of true north
True North

0 5 km

Note: gridlines refer approximately to ED50

Coverage and sources



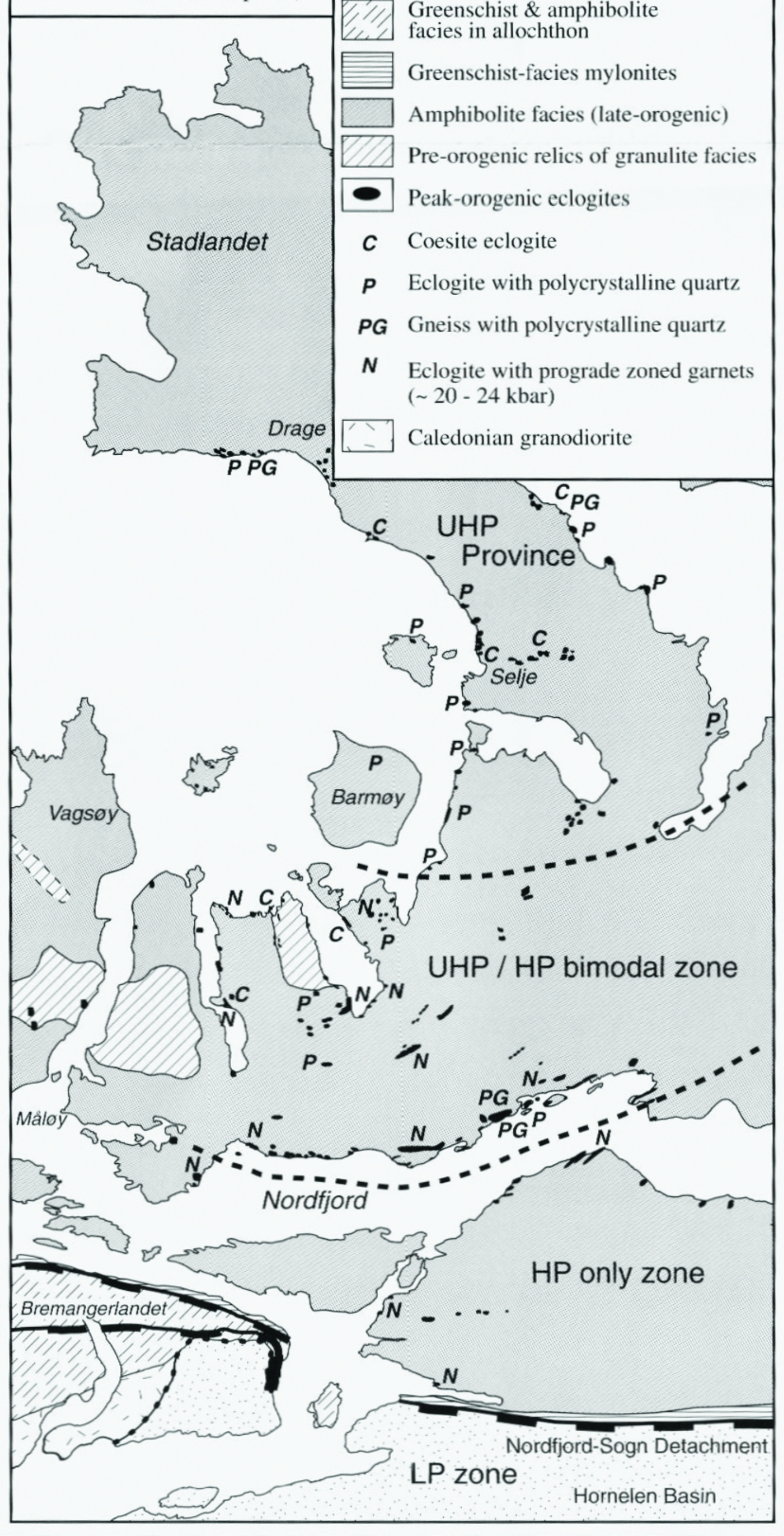
Key

- ▨ Studied by authors
- D After Dransfield 1994
- H After Hartz 1992

Other sources:
Bryhni 1966, 1989,
Kildal 1970,
Lappin 1966,

Metamorphism

(after Dransfield 1994
Smith 1995, Wain in press)



Key

- Devonian sediments (lower greenschist facies)
- Greenschist & amphibolite facies in allochthon
- Greenschist-facies mylonites
- Amphibolite facies (late-orogenic)
- Pre-orogenic relics of granulite facies
- ● Peak-orogenic eclogites
- **C** Coesite eclogite
- **P** Eclogite with polycrystalline quartz
- **PG** Gneiss with polycrystalline quartz
- **N** Eclogite with prograde zoned garnets (~ 20 - 24 kbar)
- Caledonian granodiorite

Plate 1. Structural map of the Nordfjord-Stadlandet area. Compiled by the authors with additional information from (Bryhni 1966), Dransfield (1994), Kildal (1970) and Lappin (1966). The metamorphic map contains data from Krogh (1982), Dransfield (1994), Smith (1995), Wain (in press) and T.B. Andersen (pers. comm. 1997).

Plate 2. North-south cross-section from the Hornelen Basin to Stadlandet, indicating Fb folding, and estimated shortening by Fb folding. Different eclogite zones are indicated. Where lineations are east-dipping, the cross-section is a down-plunge projection.