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Deep crustal fabrics and a model for the extensional collapse of the southwest Norwegian Caledonides

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Abstract—The exhumed deep crustal rocks in the Western Gneiss Region (WGR) of Norway experienced Caledonian high-pressure metamorphism during the Silurian, Scandian continental collision between Baltica and Laurentia. The record of coesite-bearing eclogites and pressure–temperature estimates from the WGR demonstrate extreme burial of these rocks at P_{max}. Eclogite tectonite fabrics record coaxial deformation characterized by bulk horizontal shortening and vertical stretching. Many eclogites, particularly those with a high content of kyanite, quartz, phengite and clinozoisite have constrictional fabrics related to vertical stretching. Fabrics that developed during orogenic extensional collapse are of two main types. The deepest exposed sections are dominated by penetrative coaxial fabrics that are characterized by vertical flattening and horizontal, E–W, stretching. These fabrics developed during rapid decompression and were associated with, and locally enhanced by, partial melting of the deep crust. The collapse-related coaxial vertical shortening and horizontal stretching developed at granulite to amphibolite facies and is overprinted by non-coaxial deformation that formed thick mylonites along extensional detachments. The detachment zones are rooted in the coaxially deformed deep crust, and separate the exhumed deep-crustal rocks of the Lower Plate, from the rocks in the hanging-walls that are characterized by medium- to low-grade Caledonian metamorphism. Devonian basins were formed by extensional faulting in the upper crust, and the faults that controlled the sedimentation were rooted in the extensional detachments.

INTRODUCTION AND REGIONAL SETTING

TECTONIC denudation on extensional faults and detachments is a well-documented process for syn- to post-collisional exhumation of high-pressure rocks in orogenic belts (Selverstone 1985, Platt 1986, 1993, Dewey 1988). Extensional detachments are generally characterized by non-coaxial deformation and mylonite zones that in some areas, such as in western Norway, may be several kilometres in thickness (Norton 1987, Séranne & Séguret 1987, Chauvet & Séranne 1989, Andersen & Jamtveit 1990). Horizontal stretching and vertical thinning of a thick orogenic crust may occur by displacement along major extensional detachments in the middle and upper crust, as described in great detail from the Basin and Range Province in the Western U.S.A. (*cf.* Davis 1983, Wernicke 1985, Hamilton 1987, Howard & John 1987). It is less obvious how the deep eclogite-bearing crust is thinned contemporaneously with translation on the detachments. Some workers have suggested that detachments penetrate the entire crust (Wernicke 1985, Norton 1986, Séguret *et al.* 1989) whereas other have indicated that vertical thinning is related to a combined simple- and pure-shear model in which the upper crust is stretched non-coaxially by detachments rooted in the middle and lower crust. The lower crust in this model is characterized by overall non-rotational deformation (Hamilton 1987, Dewey *et al.* 1988, 1993, Andersen & Jamtveit 1990, Andersen *et al.* 1991b, Jolivet *et al.* in press).

In the large and coherent deep-crustal province of the Western Gneiss Region (WGR) in southwest Norway, Precambrian rocks underwent eclogite facies metamorphism during the Silurian, Scandian Orogeny (Griffin & Brueckner 1980, 1985, Gebauer *et al.* 1985, Tucker *et al.* 1987, 1992). The eclogites occur throughout an area of approximately 45,000 km^2 (Fig. 1). Pressure–temperature estimates from the eclogite facies rocks in the WGR show an increase in calculated equilibration temperatures from less than 600°C in the southeast to more than 750°C in the northwest and corresponding pressure estimates of P_{min} vary from 12 kbars in the southeast to a minimum of 28 kbars in the coesite-bearing eclogites in the northwest (Krogh 1977, Griffin *et al.* 1985, Jamtveit 1987, Smith & Lappin 1989). The eclogites from the southern part of the WGR discussed in this paper (Fig. 1), are low-temperature eclogites, generally with $T \approx 600 \pm 50$°C (Krogh 1980, Griffin *et al.* 1985, Andersen & Jamtveit 1990, Chauvet *et al.* 1992). The pressure–temperature estimates from the WGR are based mainly on studies in well-preserved eclogites that essentially are in mineralogical and textural disequilibrium with the surrounding gneisses. The details of the thermal evolution of the WGR during uplift is therefore still largely unknown and large-scale structural and metamorphic reworking post-dating the high-pressure metamorphism have occurred at conditions varying from sillimanite–granulite to greenschist facies metamorphism (Griffin 1987, Andersen & Jamtveit 1990). Mapping and geochronological evidence from the WGR (see Kullerud *et al.* 1986 for a summary of geochronology) indicate that parts of the gneisses underwent partial melting during decompression around 395–400 Ma.

The extensional detachments in the studied area of western Norway separate the rocks into Lower, Middle and Upper Plates, characterized by late-Caledonian high-, medium- and low-grade metamorphism, respectively (Andersen & Jamtveit 1990). The formation of the Devonian sedimentary basins was controlled by faulting within the Middle and Upper Plates (Hartz *et al.* in press, Osmundsen & Andersen in press), above the main detachment to the Lower Plate (Hossack 1984,

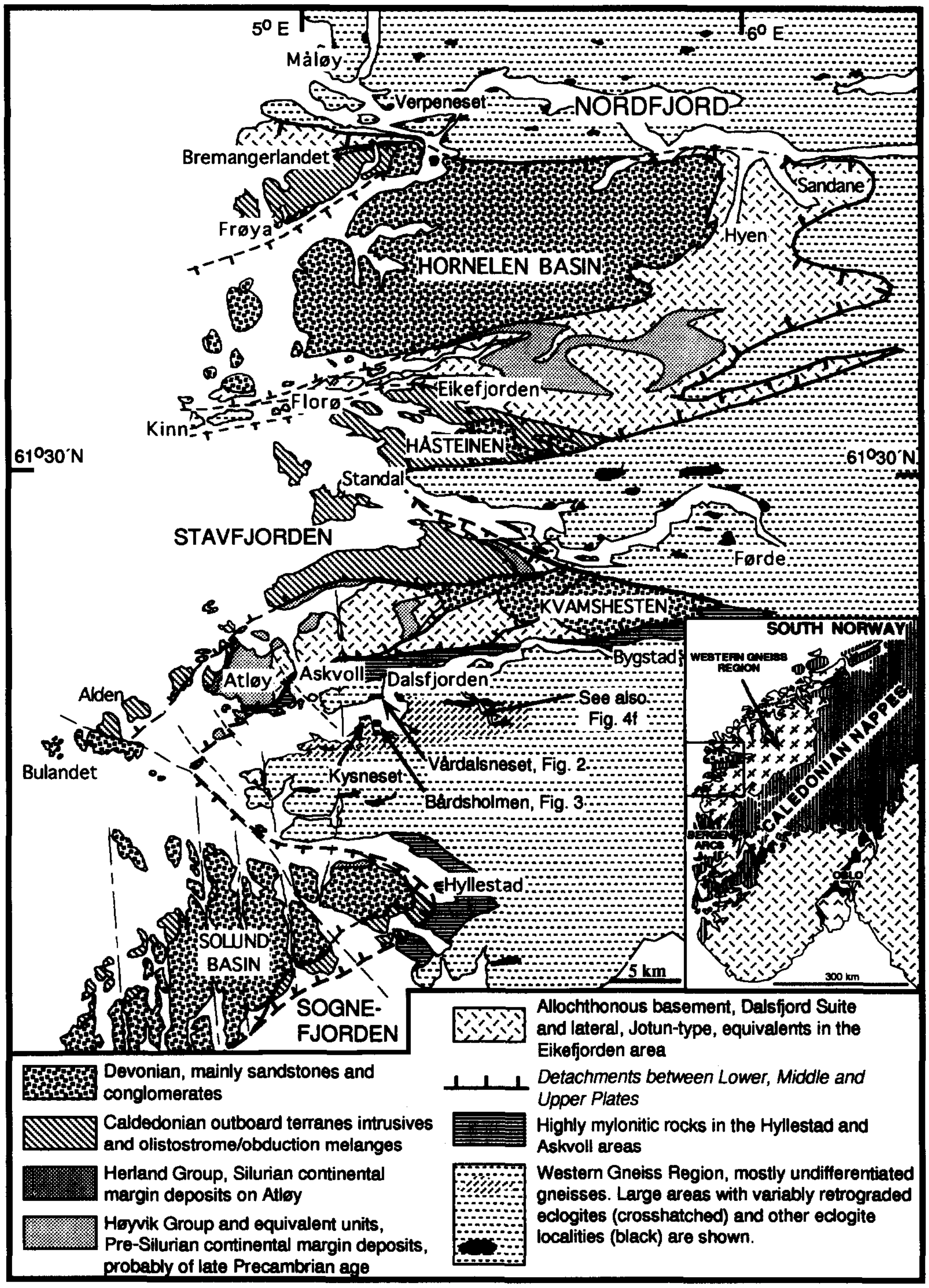

Fig. 1. Geological map, showing main tectonic units of the Sunnfjord area of western Norway between Sognefjorden and Nordfjord.

Norton 1986, 1987, Séranne & Séguret 1987). The rocks of the WGR belong to the Lower Plate and underwent rapid decompression associated with the extensional collapse in the Late Silurian to Middle Devonian (Jamtveit 1987, Chauvet *et al.* 1992). The mineral assemblages that crystallized during the decompression are mostly syn-tectonic within the gneisses, but static symplectities are commonly preserved within partially retrograded eclogites.

Within the detachment zones in western Norway, eclogite-bearing rocks are structurally reworked and variably retrograded by mylonites characterized by amphibolite to greenschist facies metamorphism. The eclogites commonly occur as highly deformed, small lenses and boudins within the mylonites and mylonitic gneisses, but some relatively large (more than 100 m long) and exceptionally well-preserved eclogite-tectonites (Fig. 2) occur in the lower part (Zones 2 and 3 according to the description of Andersen & Jamtveit 1990) of the Kvamshesten Detachment Zone (KDZ). One of the best preserved bodies of eclogite-tectonite is found in Zone 2 of the detachment mylonites (Hveding 1992) at Vårdalsneset, and south of this body a very large coherent zone (several km long) with variously retrograded eclogites has been mapped (Fig. 1). The mineral assemblages of the generally amphibole-bearing eclogites in Sunnfjord vary from mafic, nearly pure garnet–omphacite lithologies to eclogites of more intermediate compositions, which also contain abundant quartz, phengite, kyanite and clinozoisite. The eclogites in Sunnfjord give temperature and pressure estimates of $T \approx 600–650°C$ at $P_{min} = 14–17$ kbars (Krogh 1980, Griffin *et al.* 1985, Andersen & Jamtveit 1990, D. Waters personal communication 1992). Some eclogites in the Førde area (Fig. 1), however, locally contain glaucophane and give temperatures less than 600°C (Krogh 1980). In the Hyllestad area to the south (Fig. 1) pressure–temperature estimates give $T \approx 550–600°C$ at $P \approx 11–15$ kbars (Chauvet *et al.* 1992), in general agreement with the regional *P–T* pattern of the WGR (Krogh 1977, Griffin *et al.* 1985).

Although a number of detailed mineralogical–petrological studies have been carried out on the Caledonian eclogite-bodies in western Norway (see review papers by Griffin 1987, Carswell 1990, Smith 1988), the internal structures and textures of the eclogites are still poorly understood. Field observations suggest that the rheology of mineralogically different eclogites was highly variable during the high-*P* deformation; the tectonite fabrics are particularly strongly developed in those that have a high content of the water-bearing phases phengite, clinozoisite and amphibole in addition to quartz and/or kyanite. The pure garnet–omphacite varieties are commonly massive or only weakly foliated/lineated and have apparently been less internally affected by strain under eclogite facies conditions. These eclogites, however, are commonly modally banded with garnet and omphacite rich bands. Studies by H. Austr-

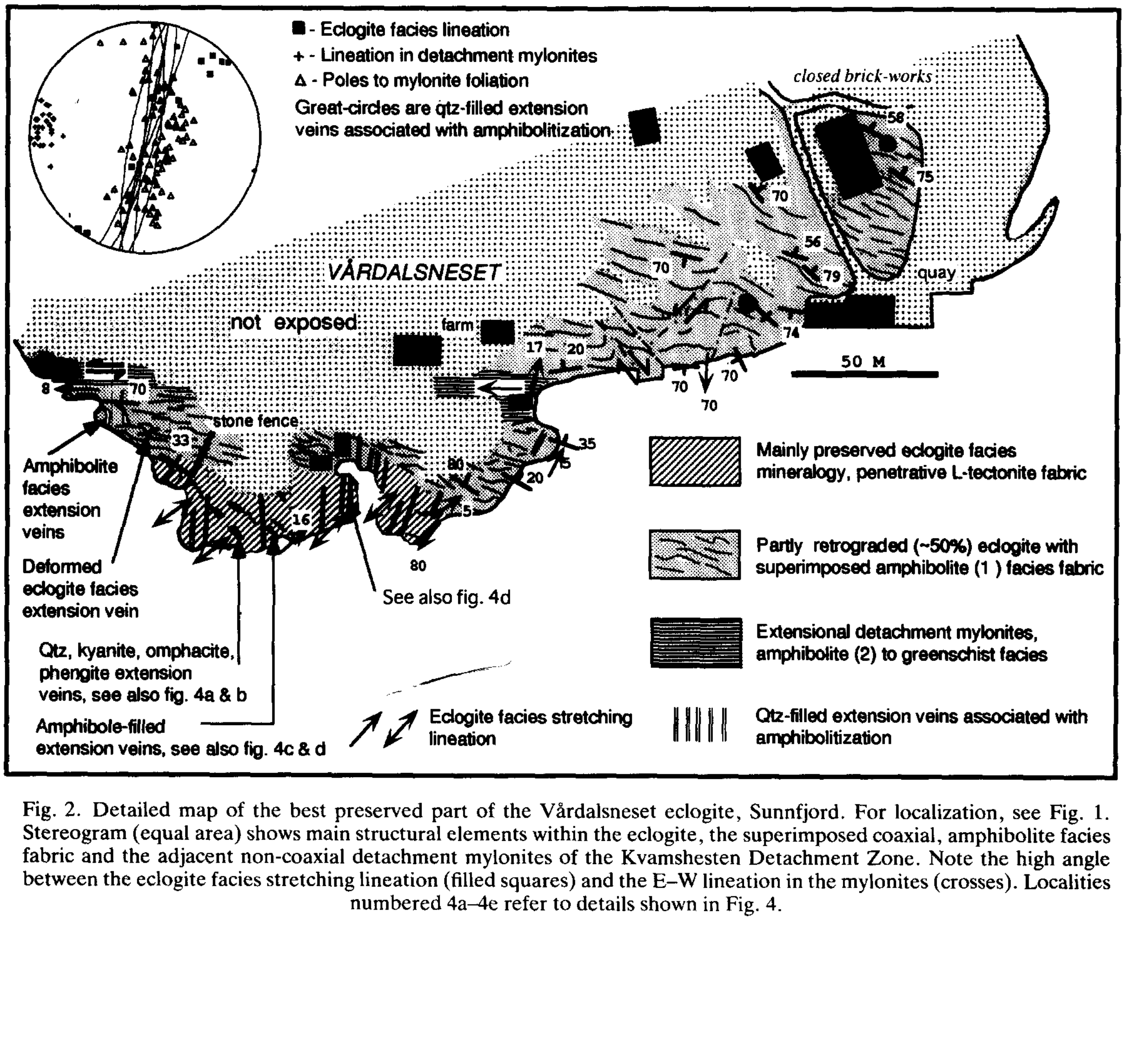

Fig. 2. Detailed map of the best preserved part of the Vårdalsneset eclogite, Sunnfjord. For localization, see Fig. 1. Stereogram (equal area) shows main structural elements within the eclogite, the superimposed coaxial, amphibolite facies fabric and the adjacent non-coaxial detachment mylonites of the Kvamshesten Detachment Zone. Note the high angle between the eclogite facies stretching lineation (filled squares) and the E–W lineation in the mylonites (crosses). Localities numbered 4a–4e refer to details shown in Fig. 4.

heim and co-workers on the eclogites of the Bergen Arc System also indicate a variable fabric development depending on their mineralogical composition. Eclogites from the same localities that recrystallized from mafic–ultramafic rocks are consistently more isotropic internally than those that recrystallized from anorthosite–mangeritic protoliths (Austrheim 1990, Boundy *et al.* 1992), and this is in general agreement with observations from the WGR. Felsic gneisses that contain eclogite boudins have locally preserved high-*P* assemblages (Griffin 1987). It has also been shown that igneous and granulite facies protoliths of the high-*P* rocks have been preserved in some areas, also in Sunnfjord (Gjelsvik 1952, Bryhni 1966, Cuthbert 1985, Mørk 1985, Austrheim & Mørk 1988) demonstrating a significant degree of disequilibrium during the high-pressure and later events. The eclogites and preserved Precambrian igneous protoliths occur as lenses within the gneisses in which the main structural fabric clearly post-dates the eclogite facies metamorphism.

This paper describes in detail the structures and textures in well-preserved eclogite-tectonites in Sunnfjord, briefly outlined and summarized by Dewey *et al.* (1993), that occur within the lower part and adjacent to the detachment mylonites of the KDZ (Figs. 1 and 2) and discusses their significance for understanding the dynamics in deeply buried crust during continental collision and orogenic extensional collapse. The Vårdalsneset eclogite is important because of its position within the detachment mylonites and its exceptionally well preserved structures and textures that enables characterization of the strain regimes that affected the rocks at maximum burial and during the subsequent decompression. The relationships between the internal eclogite-tectonite fabric and the subsequent retrograde fabrics dominated by early coaxial, and later non-coaxial, deformation, provide important information on the orientation of the principal strain axes during the progressive development of fabrics from eclogite facies through to the deformation and retrograde metamorphism that accompanied the vertical thinning of the orogenic crust and the formation of the detachment mylonites.

STRUCTURES AND FABRICS IN THE ECLOGITES

The Vårdalsneset eclogite, first mapped by E. Swensson in 1990 (Swensson & Andersen 1991), occur on the north side of Dalsfjorden in Sunnfjord (Fig. 1). It comprises the northernmost and structurally highest part of a large zone of eclogites and partially retrograded eclogites that can be traced several kilometres along Dalsfjorden (Fig. 1) between the KDZ and a region dominated by granitic rocks that, at least partly, intrude the eclogites. In the areas dominated by the granitic gneisses, the eclogites have been mostly retrograded and only variably assimilated ghost remnants of the amphibolitized eclogites occur as lenses and xenoliths within the highly deformed granitoid gneisses. Transitional

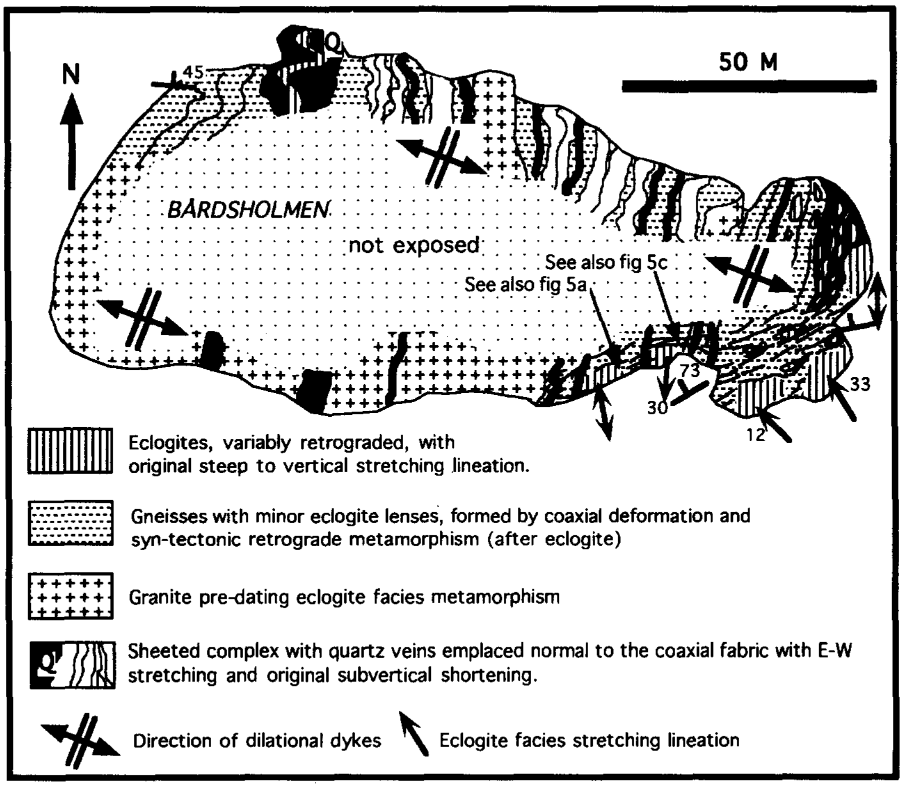

Fig. 3. Geological sketch-map of Bårdsholmen, Dalsfjorden, Sunnfjord. For localization, see Fig. 1. Note the high angle between the eclogite facies stretching fabric (average N–S) and the E–W fabric in the retrograded gneisses. The syn-tectonic dilational quartz veins (Q), dykes and composite pegmatites (P) were emplaced during the formation of the coaxial amphibolite facies fabric with E–W stretching and N–S shortening. Localities numbered 5a and 5c refer to details shown in Fig. 5.

contacts between variously retrograded eclogites, garnet–amphibolites, amphibolites, greenschists and banded gneisses demonstrate that a very large part of the characteristic banded amphibolite facies gneisses represent retrograded eclogites and highly reconstituted granitic orthogneisses andmtigmatites that locally was remobilized by partial melting during decompression. The coast-section (Map-sheet Dale, UTM 948062) west of the quay (Fig. 2) provides spectacular exposures of the eclogite, its internal fabrics, its syn-deformational retrograde products and the contact relationships between eclogite, retrograded eclogite and the detachment mylonites.

The eclogite facies fabrics

The interior, best preserved part (≈80 × 20 m) of the Vårdalsneset eclogite is only locally affected by retrograde deformation and metamorphism (Fig. 2). The eclogite is characterized by a subhorizontal to gently NNE-plunging (030–035°) linear fabric (Fig. 4a), which locally is deflected into retrograde steeply dipping E–W-trending high-strain zones resulting in steeper northeast or southwest plunges (Fig. 2). The very pronounced lineation is accompanied by a weaker sub-vertical foliation and the eclogite is a typical *L*- to $L \gg S$-tectonite. The lineation is defined by a penetrative crystal- and shape-preferred orientation (Fig. 4a) defined by eclogite facies fibrous and platy minerals omphacite, amphibole, kyanite, clinozoisite, phengite and by rods of mineral aggregates. In addition garnet or garnet aggregates and the symmetrical pressure shadows around them, have a shape preferred orientation, partly formed by a crack–seal mechanism in the garnet porphyroblasts. The weaker foliation is defined by modal variations, particularly in garnet, omphacite and phengite. The generally steeply dipping foliation that contains the lineation is locally folded by folds with subhorizontal axial surfaces and fold-axes parallel to the stretching lineation. There is no axial-planar foliation in these folds and their geometric relationship to the stretching direction and the folded foliation indicate that they were formed by two-directional shortening (subhorizontal WNW–ESE and subvertical in the present frame of reference), in a prolate, constrictional strain regime.

A marked feature of the eclogite fabric is the occurrence of extensional veins orientated normal to the *L*-fabric (Figs. 4b, c & d). The veins are of two main types, dominated by either (1) quartz or (2) hornblende. The quartz-dominated veins have variable amounts of garnet, omphacite, kyanite, phengite, clinozoisite, rutile and locally also tourmaline. Several veins consist of nearly pure fibrous kyanite where individual kyanite crystals may be more than 10 cm long (Fig. 4b). The vein-fill minerals, particularly omphacite, kyanite and mica, define a strong fibrous growth-fabric normal to the vein walls, clearly demonstrating that they crystallized continuously from the margins towards the central parts as the veins opened as a result of the constrictional deformation and a high fluid pressure that must have equalled the lithostatic pressure of 15–17 kbars (D. Waters personal communication 1992). At Vårdalsneset, individual veins may be tens of centimetres long, their width is typically less than 5 cm, although some of the veins are up to 20 cm wide. Individual omphacite crystals may be 3–5 cm long and fibers in an aggregate of large kyanite crystals in one of the veins affected by later deformation is close to 20 cm in length. Some of the early omphacite-bearing veins show small-scale buckling of the vein walls indicating shortening normal to the eclogite facies stretching lineation (Fig. 4b). Eclogite-facies extension veins also occur several places across the fjord, south and southeast of Vårdalsneset, locally with omphacite crystals more than 15 cm long (Fig. 4f).

Most of the amphibole-dominated veins consist of fibrous hornblende±phengite±quartz (Figs. 4c & d). They are generally larger than the veins described above and one vein at Vårdalsneset is approximately 1 m long and 30 cm across (Fig. 4d). Internally the fibrous hornblende crystals have grown across the vein with their long axes in continuation with the eclogite stretching fabric in the wall-rock. Their orientation and relationships to the eclogite fabric are indistinguishable from type 1 veins and cross-cutting relationships between the two generations have not been observed. The quartz-dominated veins were apparently formed first as some of the amphibole veins have an outer early zone adjacent to their walls that also contain quartz, omphacite, kyanite, clinozoisite and phengite (Fig. 4c). It is presently not known if the amphibole-rich veins reflect a significant change in the *P–T* conditions or whether they only represent a change in the fluid compositions. The kinematic significance is, however, indistinguishable from those with undoubted eclogite facies assemblages.

Some of the veins (both types) have been shortened normal to the weak vertical eclogite facies foliation during their formation as some vein margins are gently folded by small-scale folds without retrograde effects on the vein minerals (Figs. 4b & c). The well preserved structures and textures show that in the present frame of reference, the eclogite facies principal axes of stretching and shortening are subhorizontal with stretching along a NE–SW (average 033°) direction (Fig. 2, stereogram). The occurrences of some folds with subhorizontal axial surfaces also suggest subvertical (in the present frame of reference) shortening. The eclogite facies stretching lineation at a high angle to the later fabrics (see below) is preserved in a number of small boudins outside the best preserved part of the eclogite at Vårdalsneset and regionally in both Sunnfjord and Nordfjord; the later fabric is characterized by general E–W lineations (Fig. 2, stereogram). The structures and textures that provide the qualitative strain markers do not enable quantitative strain measurements. The very pronounced lineation, two directional shortening and the parallel orientation of different generation extension veins normal to the stretching lineation, however, suggest that a relatively homogenous, non-rotational, constrictional-type deformation affected the Vårdalsneset eclogite. Eclogite facies lineations orientated at a high angle (between 40°

and 90°) to extensional veins, modal layering in eclogites and the later amphibolite facies fabrics are very common in well-preserved eclogites in both Sunnfjord and the Nordfjord–Stadt area (observations by T.B. Andersen & M. Dransfield personal communication 1992). Because of the geometric relationships to the later amphibolite facies coaxial fabrics and the non-coaxial detachment fabrics, it is clear that the coaxial stretching reflected by the eclogite tectonite fabrics must have had a subvertical orientation and that it probably was related to bulk horizontal shortening and vertical stretching during continental collisional tectonics as suggested by Andersen *et al.* (1991b).

Amphibolite facies fabrics

The amphibolite facies fabrics affecting the Vårdalsnes eclogite and the surrounding rocks can be distinguished in two main categories on the basis of their relative age and kinematic characteristics: (1) a coaxial fabric with bulk vertical shortening sub-parallel to the eclogite facies stretching direction; and (2) non-coaxial fabrics related to the extensional detachments and other top-to-the-west shear zones. The earliest reworking of the eclogite fabric is found internally in the best-preserved parts of the eclogite and in a zone of variable thickness (max. *ca* 50 m) around this body. Because of the excellent exposures, cross-cutting relationships, different geometries and kinematic characteristics, the relative age and orientations of these fabrics can be determined with confidence adjacent to, and within, the Vårdalsneset eclogite. At structurally deeper levels in the WGR, the earliest coaxial amphibolite fabrics are most common, both in Sunnfjord and elsewhere in the WGR south of Stadt (Fig. 1).

In the best preserved parts of the Vårdalsneset eclogite, the initial amphibolitization is associated with a system of nearly parallel, vertical extensional quartz veins with an average NNE (010°) orientation (Fig. 2 stereogram and 4e). The veins are dilational, mostly with sharp margins to the eclogite (Fig. 4e). Individual veins can be traced several metres along strike and their width is normally between 5 and 20 cm. They are spaced at irregular intervals, but have locally resulted in an WNW elongation of nearly 40%, although the total elongation normal to veins in the best preserved part of the eclogite is less than 2.5%. Retrograde, dark-green zones (up to 15 cm in width), characterized by static symplectitization (Fig. 4e), have typically developed along the margins of the dilational veins. These veins are mostly relatively straight margined, but locally segments may be arranged en échelon. The symplectites after omphacite are of amphibole and plagioclase. There is no consistent displacement along the veins, and consequently they are taken to be oriented normal to the stretching direction at the time of their formation. As is seen from the stereogram in Fig. 2, this implies that the principal stretching direction (≈100°) in these rocks had changed by approximately 65–70° from its initial orientation (030–035°) during formation of the eclogite *L*-tectonite fabric. Within the best preserved parts of the eclogite, the E–W extension and N–S shortening is clearly reflected by the dilational quartz veins and with the formation small-scale conjugate shear zones.

The best preserved part of the eclogite is surrounded by a carapace where the eclogite is partially retrograded to amphibolite±garnet. The retrograde metamorphism in this zone was accompanied by syn-deformational segregation of quartz–plagioclase–garnet–amphibole–epidote–phengite veins. There are transitional contacts within composite veins that may vary from a high content (more than 95%) of sugar-textured quartz, clearly related to fluid migration, to those with a granitic composition and igenous texture that probably crystallized from fluid-saturated melts. The earliest granitoids (see also Figs. 5a & b) are usually highly garnetiferous, often with atoll garnets, and they always contain abundant epidote–clinozoisite and white mica. The feldspar is mainly albite, but perthite and mesoperthite occur in some specimens. Similar granitoid veins in eclogites have also been described from the Bergen Arc eclogites, although in this case the granites were interpreted to have formed by partial melting during eclogite facies metamorphism (Andersen *et al.* 1991a). Formation of partial melts in the eclogites during the initial stages of the amphibolitization in the Sunnfjord region may have been associated with a slight increase in temperature as suggested from other parts of the WGR (Jamtveit 1987, Chauvet *et al.* 1992).

Dilational quartz veins may be traced continuously from eclogites into the deformed and retrograded envelope, where the veins are folded by small-scale folds or off-set by minor shear zones. The folding of the veins is related to anastomosing shear zones with variable sense of shear, and a general N–S shortening normal to the composite fabric in the carapace of the eclogite (Fig. 2). The orientations of the fold-axes are controlled by the dip and shear sense of the individual, generally E–W-striking, shear zones that deform the veins (Fig. 2). North–south shortening of dilational quartz veins, with the same orientation as those at Vårdalsneset, have also been obseved in the large zone of partially retrograded eclogites on the south side of Dalsfjorden (Figs. 1, 3 and 5). The composite amphibolite facies fabric around the best preserved part of the eclogite has a general WNW–ESE orientation, and the dips are both to the north and south (Fig. 2). There is no consistent sense of shear across this fabric, and individual high-strain zones may show both top-to-the-west and -east displacements. There are also many examples of high-strain zones where no consistent asymmetry can be distinguished even on a small scale, and where lenses and boudins apparently are symmetrically deformed within the strong fabric (Fig. 5a). An E–W, sub-horizontal stretching lineation which is parallel to the lineation in the detachment mylonites can be observed on most localities. In small lenses (≈15–30 cm across) between the retrograde high-strain zones, the earlier eclogite tectonite fabric, with its characteristic oblique northeasterly trending lineation is frequently preserved (Figs. 3 and

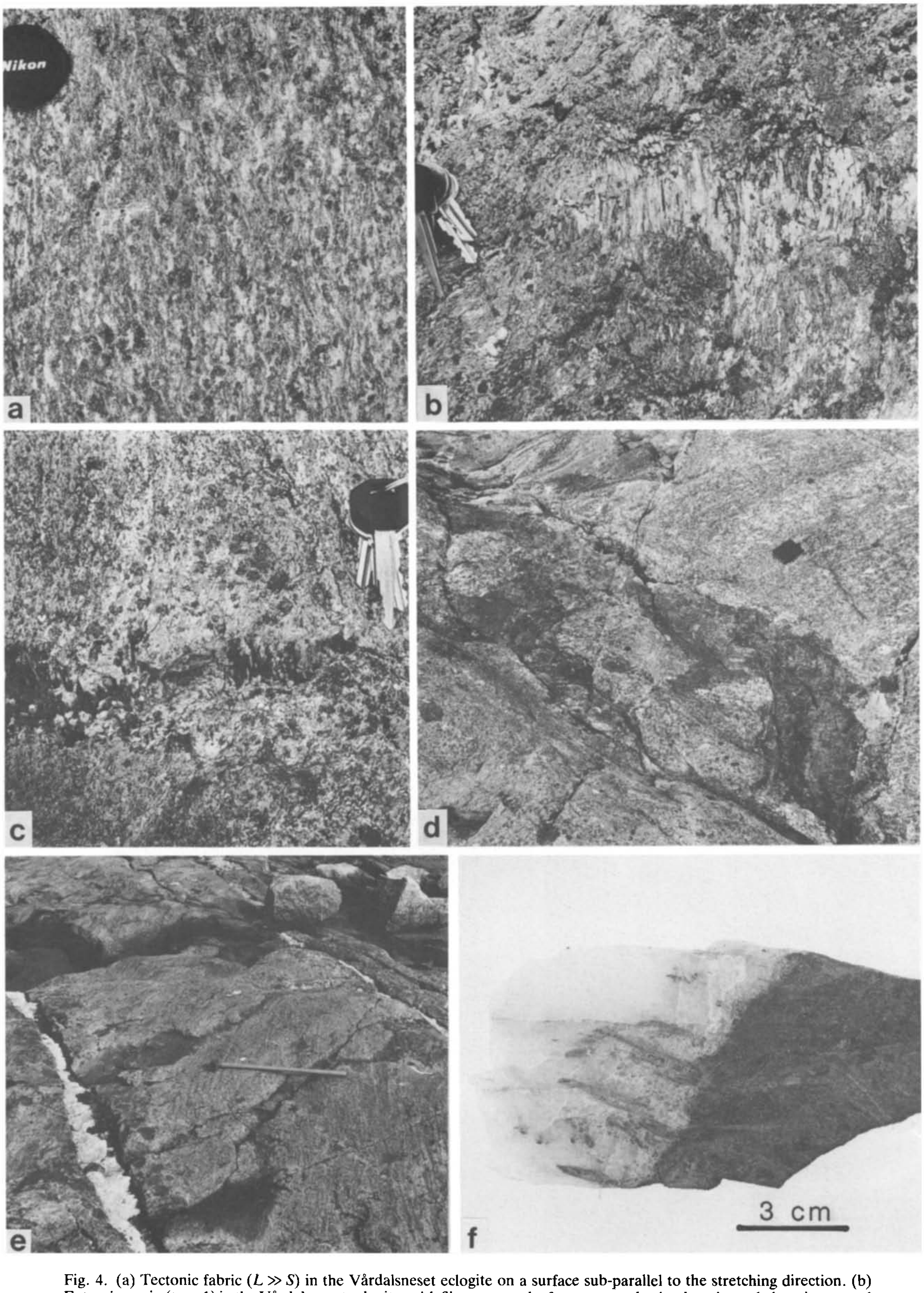

Fig. 4. (a) Tectonic fabric ($L \gg S$) in the Vårdalsneset eclogite on a surface sub-parallel to the stretching direction. (b) Extension vein (type 1) in the Vårdalsneset eclogite, with fibrous growth of quartz, omphacite, kyanite and phengite normal to the vein walls and parallel to the stretching fabric in the eclogite. Individual crystals of kyanite and omphacite are 4–6 cm long. (c & d) Extensional veins (type 2) in the Vårdalsneset eclogite, dominated by fibrous aggregates of hornblende and quartz. In (c), the margins of the vein also contain omphacite, kyanite and phengite, and hence show a transitional mineralogy to the type 1 veins. Compass for scale in (d) is 10 cm long. (e) Eclogite facies $L \gg S$-tectonite fabric in the Vårdalsneset eclogite cut by N–S-trending dilational quartz veins associated with retrograde symplectitization along their margins. Hammer for scale 60 cm. See text for discussion. (f) Eclogite facies extensional quartz vein with preferred orientation, normal to the vein-walls, of large omphacites. The omphacites are partly pseudomorphosed by amphibole–plagioclase symplectites. Locality southeast of Vårdalsneset, Sunnfjord (see Fig. 1).

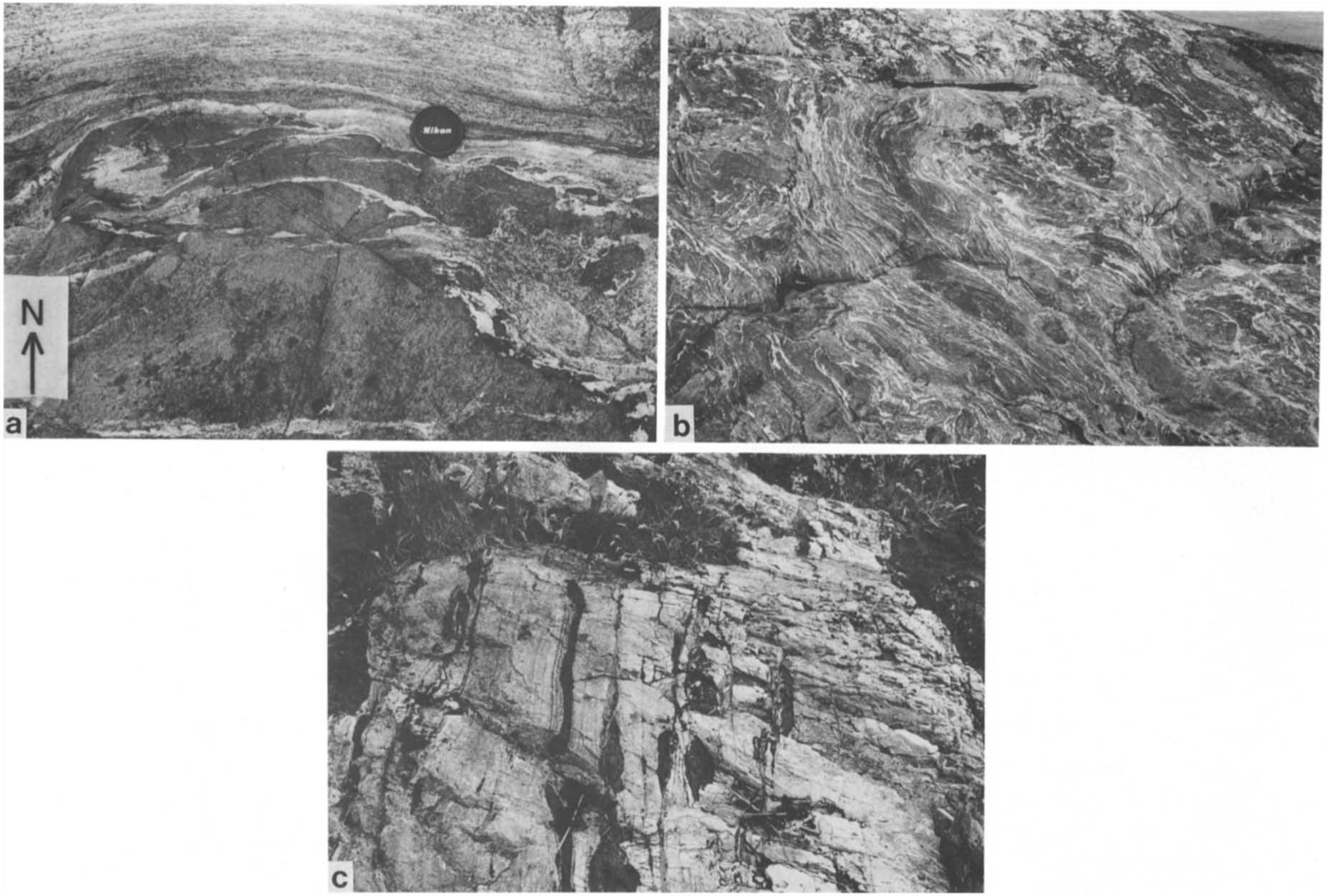

Fig. 5. (a) Lenses of preserved eclogite on southeast coast of Bårdsholmen (Fig. 3). Note the N–S-trending linear fabric in the interior of the eclogite and the superimposed, E–W-trending amphibolite facies fabric. Note also progressive opening of N–S-trending extensional cracks in the eclogite. (b) Migmatites developed from net-veining and partial melting of eclogite during decompression. This migmatitic lithology from Kysneset is very characteristic of the large area of partially retrograded eclogites on the south side of *Dalsfjorden in Sunnfjord* (see Fig. 1) and *elsewhere in the WGR*. Note lens-cap for scale to the left in the photograph. (c) Sheeted complex of extensional, N–S-trending quartz-veins on Bårdsholmen. The dykes–veins on Bårdsholmen vary from a few cm to several m in width, and are emplaced syn-tectonically at right angles to the amphibolite facies stretching direction (see also Fig. 3). The dilational veins and dykes records E–W 'spreading', much similar to the sheeted dykes in an ophiolite. Note the 'rafts' or partial to completely retrograded eclogites as wall-rock. Lens-cap for scale below vegetation in central parts of the photograph.

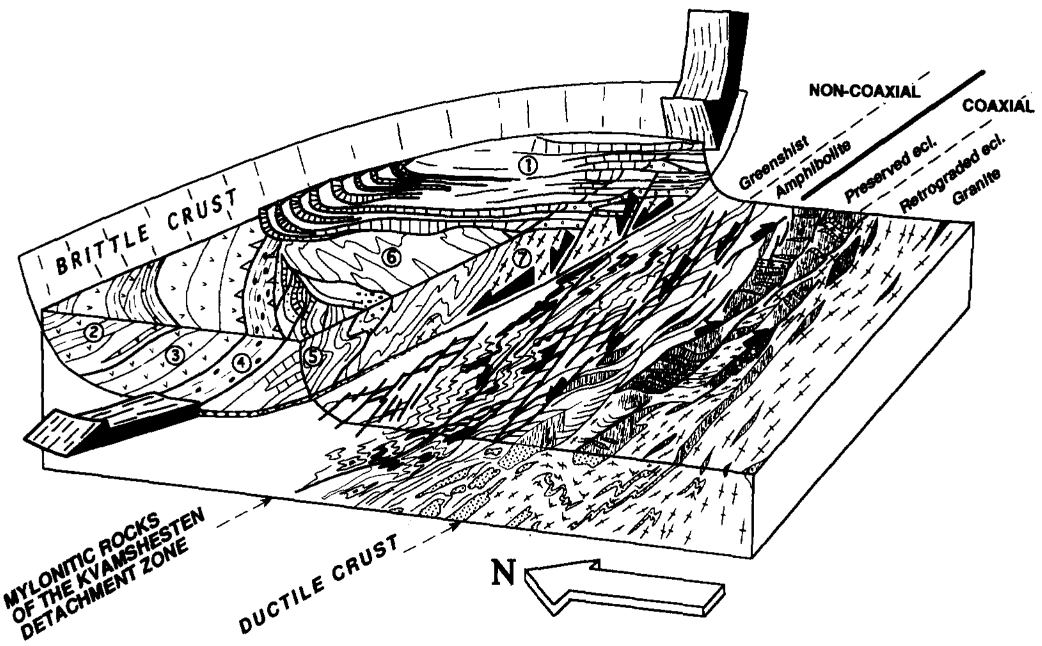

Fig. 6. Generalized block diagram (not to scale) for the geology and the structural relationships between the Upper and Lower Plate in the Sunnfjord region of the southwest Norwegian Caledonides. Note W-vergent folds and extensional reactivation of contractional faults in the Upper Plate and that sedimentation in the Devonian Kvamshesten Basin was partly controlled by normal faults in the Upper Plate that are rooted in the Kvamshesten Detachment Zone. The detachment is characterized by a several kilometres thick zone of mylonites formed by non-coaxial, top-to-the-west shear at amphibolite to greenschist facies metamorphism. The extensional mylonites are rooted in the lower crust that underwent coaxial vertical flattening and E–W extension. Legend: (1) Devonian sediments; (2) Staveneset Group, cover to the Solund–Stavfjord Ophiolite Complex; (3) Solund–Stavfjord Ophiolite Complex; (4) Sunnfjord Mélange; (5) the Herland Group, Silurian continental margin deposts with W-vergent folds related to the extensional collapse; (6) the Høyvik Group, Late-Precambrian (?) continental margin deposits; and (7) the Dalsfjord Suite, Precambrian (?) allochthonous basement. See the text for a detailed discussion of the fabrics in the Lower Plate.

5a). The observations of the earliest post-eclogite facies structures and fabrics suggest that the composite fabrics around the eclogite developed at amphibolite facies metamorphism associated with some partial melting, in a deformation regime characterized by overall coaxial deformation with N–S flattening and E–W stretching in the present frame of reference.

The second stage non-coaxial amphibolite facies fabrics are related to the mylonites that partly cut across the eclogite (Fig. 2) and forms its boundary towards the detachment mylonites of the KDZ. These fabrics are found throughout the lower part of the detachment (Zones 2 and 3 of Andersen & Jamtveit 1990). The detachment mylonites show consistent top-to-the-west, deformation, that apparently developed continuously during uplift and cooling from amphibolite to low-greenschist facies conditions (Swensson & Andersen 1991, Hveding 1992). The orientation of mylonite fabric in the Askvoll area is shown in Fig. 2 (stereogram). This fabric has been described and discussed in detail in several studies dealing with the extensional collapse in West Norway and will not be repeated here (Norton 1986, 1987, Chauvet & Séranne 1988, Andersen & Jamtveit 1990, Swensson & Andersen 1991, Hveding 1992, Torsvik *et al.* 1992).

The field relationships between the coaxially deformed and retrograded eclogites and granitic veins indicate that local partial melting occurred in the Proterozoic granites and granitic gneisses that occupies the core of the large-scale antiform which lies between the Kvamshesten and the Solund basins (Figs. 1 and 6). These granites and gneisses displays an early coaxial flattening fabric overprinted by shear zones characterized by *S–C* fabrics with top-to-the-west sense of shear. The granitoids contain an increasing number of inclusions of mafic rocks toward the well-preserved eclogites. The eclogites crop out as coherent large-scale boudins with the successive fabrics described above, or as small pods of highly foliated rocks in various stages of preservation within the foliated granites. These pods have E–W-trending long axes parallel to the regional amphibolite facies stretching lineation. Larger boudins display a succession of N–S-trending veins which opened progressively during E–W stretching (Figs. 3, 4e and 5c). There is a gradual transition from the mafic gneisses with abundant eclogites and minor granitic intrusions towards the granites and granitic gneisses with ghosts of retrograded eclogites at deeper structural levels in the core of the antiform. This suggests that the rocks with abundantly preserved eclogites forms a carrapace to an lower granitic–granodioritic crust. Detailed geochronological and structural studies are in progress (J.P. Gromet & T.B. Andersen personal communication 1993) in order to evaluate to what extent remobilization by partial melting has affected the Precambrian granitic rocks of the WGR during the orogenic collapse. Preliminary results from these studies demonstrate that conclusions on the age relationships between the emplacement of granitoids and the high-P metamorphism, based on field and petrographic studies, frequently are equivocal; hence extreme care should be taken before firm conclusions on the amount and significance of partial melting during decompression are presented.

Summary of the structural geometries

The tectono-metamorphic history of the eclogites in the WGR is particularly well illustrated by the structural fabrics and geometries of Vårdalsneset eclogite in Sunnfjord. The exhumed high-P rocks are characterized by a three-stage sequence of events, each characterized by syn-tectonic mineral assemblages and progressive evolution of fabrics that developed and identifies different tectonic regimes and P–T environments. The present paper does not present new data on mineral chemistry. The petrography and mineralogy of the Vårdalsneset eclogite, however, show that the mineral assemblages in the eclogite and its retrograded carapace are comparable to those that have been described previously from other amphibole-bearing eclogites in the southwestern part of the WGR. Hence, already published P–T estimates are used in the present description and discussion (Krogh 1980, Cuthbert 1985, Andersen & Jamtveit 1990, Chauvet *et al.* 1992).

Stage 1 comprises the eclogite facies structures and fabrics. At Vårdalsneset, it is not possible to study events related to the initial stages of Caledonian crustal thickening, but it is likely that the protolith was part of a large Precambrian gabbroic-anorthositic to intermediate intrusive complex (Cuthbert 1985) intruded by a suite of Grenvillian granites (Gromet & Andersen personal communication 1993). The eclogite fabric is principally a penetrative $L>>S$-tectonite fabric. The lineation is presently sub-horizontal (033°) and a weak vertical foliation is developed in the eclogites. Lack of asymmetrical structures and formation of parallel extensional veins of different generations (quartz- or amphibole-dominated) normal to the L-fabric suggest that the eclogite experienced coaxial, constrictional-type deformation at P_{max}. Its orientation, at a high angle to the steeply dipping (present orientation) fabrics that were formed during the extensional collapse, and which most likely was related to sub-vertical thinning/shortening and sub-horizontal stretching of the thickened crust, shows that the original orientation of the stage 1 L-fabric must have been near vertical. The sub-vertical eclogite facies fabric is tentatively related to bulk vertical thickening of the lower crust during collisional tectonics and slab-pull by eclogitized subducted material.

Stage 2 is represented by amphibolite facies coaxial deformation patterns in interior parts of well-preserved eclogite lenses and in the abundant retrograded eclogites. This fabric further dominates the structure throughout the western parts of the WGR structurally below the detachment mylonites. Within many eclogites, hydrofracturing and fluid-migration occurred in vertical, parallel quartz-filled extension veins that produced static amphibole–plagioclase symplectite reaction rims after clinopyroxene in the eclogite. The extension veins can be traced into the garnet–amphibolite around the preserved eclogites. Both the veins and the amphibolitized eclogite are coaxially deformed by N–S shortening (present orientation) and anastomosing, E–W-striking high-strain zones. The high-strain zones have no consistent sense of shear, and most are without noticable asymmetrical structures. This suggests that they were developed in an overall coaxial strain regime presently orientated with N–S shortening and sub-horizontal E–W stretching. The hydrofracturing and segregation of fluid-rich granitic leucosomes by partial melting locally altered the rheology and enhanced the deformation in the zones where they were formed/introduced. Partial melting was more abundant at low structural levels in the WGR, structurally below the detachment mylonites. The presence of granitoid partial melts also indicate some increase in the regional temperature after P_{max}. Quartz veins were emplaced syn-tectonically and occur as *lit-par-lit* veins normal to the bulk stretching and parallel to bulk shortening directions, analogous to the sheeted dykes in an ophiolite.

Stage 3 in the retrograde tectono-metamorphic history of the Vårdalsneset, and other eclogites, is represented by formation of amphibolite, and finally greenschist, facies mylonites of the extensional detachments. The mylonite fabric (not described in detail here) in which shear strains of more than 20 have been estimated across the 1–2 km thick KDZ (Hveding 1992), was formed by rotational deformation with consistent top-to-the-west displacement. The shear sense is documented by a variety of kinematic indicators which have been described in several previous papers (see above). The KDZ mylonites on the south side of the Kvamshesten Devonian basin, dip to the north on a regional scale, although at the scale of outcrop the mylonites are folded by upright, open to tight folds with E–W-trending axes (Swensson & Andersen 1991, Hveding 1992). Folds with the same geometry also deform the Devonian sediments and are probably of Late-Devonian age (Torsvik *et al.* 1987). It is likely that the late folds were superimposed on already existing E–W-trending folds in the detachments. The late folds produced the girdle (Fig. 2) that the poles of the mylonite foliation define in stereograms (cf. Swensson & Andersen 1991).

DISCUSSION

Eclogite facies tectonite fabrics that are found within the best preserved part of the eclogites, particularly those with abundant quartz, kyanite, phengite and other fibrous minerals, demonstrate that coaxial constrictional deformation affected some of the rocks in the WGR at P_{max} during the Scandian Orogeny. The extension direction is well defined by penetrative mineral lineations and orientation of extensional veins. Within well-preserved eclogites, such as the Vårdalsneset eclogite in Sunnfjord and the Verpeneset eclogite in Nordfjord (Fig. 1), the coexistence and well-defined geometric relationships between fabrics of different generations, provide good evidence for the inversion of the principal strain axes from bulk horizontal coaxial shortening and vertical stretching at eclogite facies (stage 1) to bulk horizontal coaxial stretching and vertical flattening during the orogenic collapse (stage 2). It is also clear that on a regional scale, the stage 1 fabrics must have been highly inhomogeneous, both qualitatively and quantitatively as the homogeneous constrictional strains that commonly are observed within the eclogite lenses are incompatible as a regional deformation pattern. The eclogite facies tectonite fabric we have observed cannot be related to deep-crustal contractional shear zones as these would have been associated with non-coaxial deformation geometries.

The amphibolite facies fabrics of stage 2 were related to vertical shortening and E–W stretching, also in a coaxial strain regime. The very penetrative formation of fabrics during this event is related to rapid removal of overburden that caused decompression of the rocks in Sunnfjord from a pressure of more than 16 kbars at approximately 415 Ma (average of best eclogite facies age determinations) to approximately $P \approx 10$ kbars at around 400 Ma (average of best amphibolite facies cooling ages) corresponding to a vertical shortening at an average strain rate of slightly less than 0.5×10^{-15} s^{-1} (allowing for some erosional denudation). As stage 1 and 2 fabrics are found together within the eclogite, it is demonstrable that the principal direction of stretching was changed by approximately 70°, from ≈030–035° during eclogite facies to ≈100° (present orientations) at stage 2 amphibolite facies. Because no transitional deformation can be identified between these two stages, and because the strain regime also changes from constrictional- to flattening-type deformation, it appears that the principal stress vectors (σ_1 and σ_3) affecting the deeply buried rocks must have changed abruptly, both in direction and relative magnitudes during the initial stages of the decompression. As the decompression was associated with vertical shortening, crustal thinning and removal of overburden, it is likely that the orientation of the principal compressive stress axis (σ_1) at the earliest stages of the orogenic collapse was near vertical.

In several papers, it has been argued that fabrics in the deep crust during extensional collapse are characterized by vertical flattening and sub-horizontal stretching (Hamilton 1987, Dewey 1988, Dewey *et al.* 1988, 1993, Andersen & Jamtveit 1990, Jolivet *et al.* in press). In these models, horizontal stretching–vertical thinning of the upper and middle crust occur by normal faults and rotational deformation on extensional detachments. The extensional shear zones are rooted in the deep crust that undergoes contemporaneous vertical shortening and horizontal stretching by overall coaxial deformation. Andersen & Jamtveit (1990) assumed that the non-rotational fabrics in eclogites were formed essentially in a sub-horizontal position, and that the later coaxial amphibolite facies fabrics formed sub-parallel to the eclogite facies fabric. This model, however, does not explain the high angle between eclogite and amphibolite facies coaxial fabrics that is seen within the eclogites at Vårdalsneset and elsewhere in the Sunnfjord and Nordfjord areas. The change in orientation of principal strain axes from stage 1 to stage 2 cannot be explained by rotation of the eclogite bodies as a rigid bodies within a shear zone because the geometric relationships between the fabrics remain constant within the eclogites. Furthermore, the orientation of the principal strain axes developed during the stage 2 syn-tectonic retrogression within the rigid eclogite bodies is parallel to that of the surrounding amphibolites. In the case of the Vårdalsneset eclogite as well as several other well-preserved eclogites in Sunnfjord and Nordfjord, it has been demonstrated that the principal stress vectors (σ_1 and σ_3) that formed the coaxial fabrics must have had nearly reciprocal orientations at eclogite and early amphibolite facies deformation and that geometrical relationships between the eclogite fabrics and the later coaxial and non-coaxial detachment fabrics show that the initial orientation of the eclogite L-fabric probably was near vertical.

In the low P–T part of the WGR, it is likely that the eclogites reached amphibolite facies conditions relatively shortly after the rapid uplift, vertical shortening and removal of overburden commenced during the extensional collapse. Consequently, if the model presented above is generally applicable, original sub-horizontal eclogite facies high-strain zones should be rare in this part of the WGR. Further to the north, however, where subducted crust may have been educted from below the geophysical Moho (Andersen *et al.* 1991a), a considerable part of the decompression must have occurred at high-T eclogite and subsequently granulite facies conditions (Griffin & Mørk 1981, Griffin 1987, Jamtveit 1987). Thus, the original steep fabrics may have had a more limited preservation potential in these areas. Detailed investigations in progress north of the Hornelen Devonian basin, however, show that eclogite facies tectonites that have a marked fabric discordance to the penetrative amphibolite facies coaxial flattening fabrics, are common. The non-rotational amphibolite facies fabrics in Nordfjord were apparently also formed by vertical shortening–horizontal stretching as the detachment mylonites are superimposed and rooted in the coaxial fabrics similarly to the structural relationships described above from the Sunnfjord area.

In the Bergen area, the prograde formation of Caledonian eclogites from Middle Proterozoic granulites have been studied by Austrheim and co-workers (Austrheim 1990). The eclogite facies high-strain zones in this area have often been referred to as shear zones; however, the detailed mapping of original lithological boundaries that are cut by the eclogite high-strain zones show that the displacements across these zones are small. Boundy *et al.* (1992) indicate that some kinematic indicators show right-lateral displacement, but the small-scale displacement indicates a dominant flattening across the high-strain zones. Because of the structural complexity it is not yet known what the original way-up direction in these rocks was during eclogitization. It is, however, of interest to note that the eclogite fabrics in many places cross-cut lithological boundaries and the Precambrian (Austrheim 1987, 1990) granulite facies tectonic fabrics at a high angle. By comparison with deep-seismic reflection studies of continental crust (Meissner 1989) it is reasonable to assume that the main anisotropy of these rocks was a sub-horizontal or gently dipping before the Caledonian orogeny. If these assumptions are correct the prograde, coaxial eclogite high-strain zones in the Bergen area may have been near vertical during the crustal thickening and hence comparable to the stage 1 fabrics of the eclogites in the WGR. The details of the kinematic and structural geometries that accompanied the decompression of the high-*P* rocks in the Bergen area are not known, although it is clear that the middle and upper crust, including the Caledonian nappes, were affected by widespread extensional tectonics with top-to-the-west displacement along previous thrusts (Fossen 1993).

In conclusion, detailed structural studies of the Vårdalsneset eclogite and other eclogites in the gneisses of the West Norwegian eclogite provinces suggest that eclogite facies tectonite fabrics were formed by bulk coaxial horizontal shortening and vertical stretching of the deep crust, related to plate convergence and slab-pull by subducted cold lithosphere. Rapid decompression during the orogenic extensional collapse was associated with bulk coaxial vertical shortening and horizontal stretching in the deep parts of the thickened crust. The vertical flattening occurred at granulite to amphibolite facies conditions and was associated with some remobilization of the crust and a large number of quartz veins were emplaced normal to the horizontal stretching. The veins were folded contemporaneously with their emplacement by the vertical shortening. Formation of syntectonic partial melt granitoids in the Lower Plate in zones that have undergone syn- to post-orogenic extensional collapse is well documented from the post-Alpine extended crust in areas such as the Corsica–Tyrrhenian Sea region and in the Aegean (Jolivet *et al.* in press). It is likely that the extensional collapse was triggered by removal (Houseman *et al.* 1981. England & Houseman 1988) of the lower part of the thickened lithosphere; a model that has been suggested as an underlying mechanism for extensional collapse in several orogenic belts (Dewey *et al.* 1988, 1993, Platt & Vissers 1989, Andersen & Jamtveit 1990, Andersen *et al.* 1991a). Removal of the lower part of the thickened lithosphere and replacement by asthenosphere will increase the heatflow in the collapsing orogenic crust (Houseman *et al.* 1981, Dewey 1988). Because of the limited petrological studies of the ordinary and most common gneisses within the WGR, the post-eclogite facies history is not well understood. A number of geochronological investigations (see review by Kullerud *et al.* 1986) by a variety of methods (Lux 1985, Tucker *et al.* 1987), as well as palaeomagnetic studies (Torsvik *et al.* 1987, 1988, 1992) demonstrate a slow thermal relaxation of the WGR and thermal overprint of the Devonian sedimentary basins through the Upper Devonian and Permian.

In the model (Fig. 6) proposed for the orogenic extensional collapse of the southwest Norwegian Caledonides, we envisage that the Lower Plate, below the main detachment, comprised a lower, highly ductile crust in which the non-coaxial extensional detachments were rooted. The penetrative amphibolitization of the Proterozoic rocks in the deepest exposed structural levels of the WGR explains the lack of major geophysical (gravity and magnetic) anomalies across the exhumed deep crustal province (Anonymous 1992). The crustal thinning in the middle crust occurred by the non-coaxial deformation expressed by the several km thick extensional mylonites in the detachments. As previously suggested by Andersen & Jamtveit (1990), the detachments were rooted and progressively cut into the lower crust that underwent contemporaneous coaxial deformation (vertical shortening and horizontal stretching). The extension in the uppermost crust occurred initially by semi-ductile re-activation of previous contractional faults and shear zones (Osmundsen 1990, Fossen 1993, Hartz *et al.* in press, Osmundsen & Andersen in press). Brittle normal faults that branched from the main detachments were superimposed on the already stretched and tectonically exhumed rocks in the Upper Plate and controlled the sedimentation in the Middle Devonian basins.

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