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A computer model of sheath-nappes formed during crustal shear in the Western Gneiss Region, central Norwegian Caledonides

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Abstract—The eastern Western Gneiss Region of central Norway is part of the deepest exposed Norwegian Caledonides, where basement gneisses and an overlying thrust-nappe sequence have been folded into large fold-nappes. Structural analysis of a fold-nappe within the central part of the district (the Grøvudal area) suggests that it has a strongly sheath-like form, and that other fold-nappes of the Western Gneiss Region may also have sheath-like forms. The structural history within the Grøvudal area is dominated by intense east-directed subhorizontal shear in an overthrust sense, followed by asymmetric refolding with an easterly vergence. A computer-generated kinematic model was developed to test whether the regional interference patterns could be explained by sheath-fold development during this type of deformation. The computer model shows that the major regional interference patterns could have been formed by such a kinematic history, but does not rule out other possibile histories. The proposed kinematic history is, however, compatible with the regional tectonic history of the main Caledonian nappe pile, suggesting that the complex nappe interference patterns typical of the region were formed in a kinematically simple, but intense, ductile deformation associated with Caledonian continental imbrication.

INTRODUCTION

THE Caledonian mountain belt of Norway and western Sweden forms the eastern half of an orogenic belt formed during the Silurian–Devonian convergence of the present day Greenland and Scandinavian continental masses (Dewey 1969). This collisional event resulted in the eastward-directed emplacement of extensive thrust-nappes, comprised of diverse lithologies, including continental margin sediments, materials of oceanic affinity and continental basement, onto the Baltic Shield (Gee 1978, Roberts & Wolff 1981, Hossack 1983).

To the west of the main thrust-nappe pile lies the Western Gneiss Region, an area dominantly composed of complexly deformed high-grade basement gneisses (Sigmond *et al.* 1984, Fig. 1), which forms the deepest exposed portion of the orogen. The Western Gneiss Region is widest in western central Norway, but is exposed intermittently along the coast for most of the approximately 1500 km length of the orogenic belt. Metamorphism in the Western Gneiss Region is mainly eclogite grade to the west, falling to kyanite, and finally garnet and biotite grade to the east (Cuthbert *et al.* 1983, Krill 1985). The high-pressure eclogite metamorphism, a low velocity layer at 12 km (Mykkeltveit *et al.* 1980), and regional relationships suggest that major continental imbrication, or A-type subduction, occurred within the Western Gneiss Region as the Paleozoic continental margin of Greenland began to override the Baltoscandian continental margin (Gee 1978, Hodges *et al.* 1982, Cuthbert *et al.* 1983).

The existence of large, Pennine-style, fold-nappes within the Oppdal district was first recognized by Holtedahl (1938). Hansen (1971), working in the Trollheimen area, suggested mechanisms for fold and nappe formation involving complex flow patterns. Krill (1980, 1985, Fig. 2) made tectono-stratigraphic correlations in the district, and revised earlier interpretations of the regional nappe geometry. Krill's interpretation, in agreement with earlier workers, was that the regional interference patterns are due to the juxtapositon of fold-nappes with gneiss domes and gravitational basins. More recent structural analysis in the Grøvudal area (Vollmer 1985, Fig. 2), a central portion of the Oppdal district not previously mapped in detail, suggests that a major feature of the district previously described as a gravitational basin is a downward-facing nappe with a sheath-like form and that other nappes in the district may have similar forms. The purpose of the present paper is to suggest an alternative geometric interpreta-

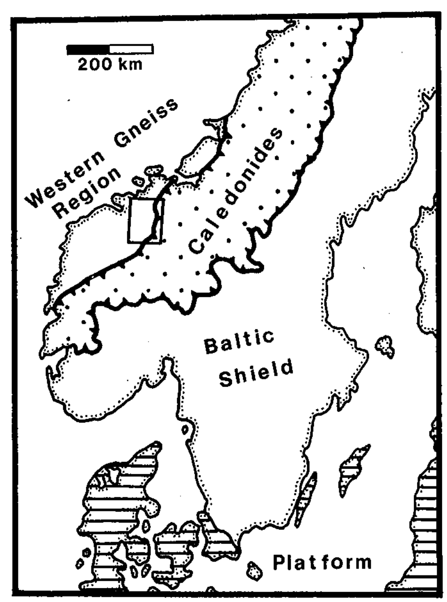

Fig. 1. Location of the Western Gneiss Region within the Scandinavian Caledonides. The rectangle outlines the area of Fig. 2 (from Oftedahl 1980).

tion of the nappes which takes into account these new data and to illustrate how a computer-generated model can be used to test this interpretation.

While an interpretation involving large sheath-like nappes is quite different from earlier models of the regional geology here, kilometer-scale sheath folds have previously been reported from the Alps (Cobbold 1979, Lacassin & Mattauer 1985), and the southern Canadian Rockies (Mattauer *et al.* 1983). As current models of the formation of sheath folds suggest that strong shear strains are involved (Cobbold & Quinquis 1980), the Western Gneiss district, where continental-scale overthrusting and shear has occurred, appears to be an ideal environment for such sheath-like nappes to form.

FOLD-NAPPES OF THE OPPDAL DISTRICT

Tectono-stratigraphy

Five main tectono-stratigraphic units have been delineated within the Oppdal district by Krill (1980, 1985). From structurally highest, these are the Tronget-Støren, Surna, Blåhø, Sætra, Risberget, Åmotsdal and Lønset units (Krill 1980, 1985). The Lønset unit forms the basement, comprising varied orthogneisses exposed in the area south and west of Lønset, much of the western Trollheimen range and areas to the west (Fig. 2). The highest of the units, the Tronget-Støren Nappe, is locally in post-metamorphic fault contact with the lower units

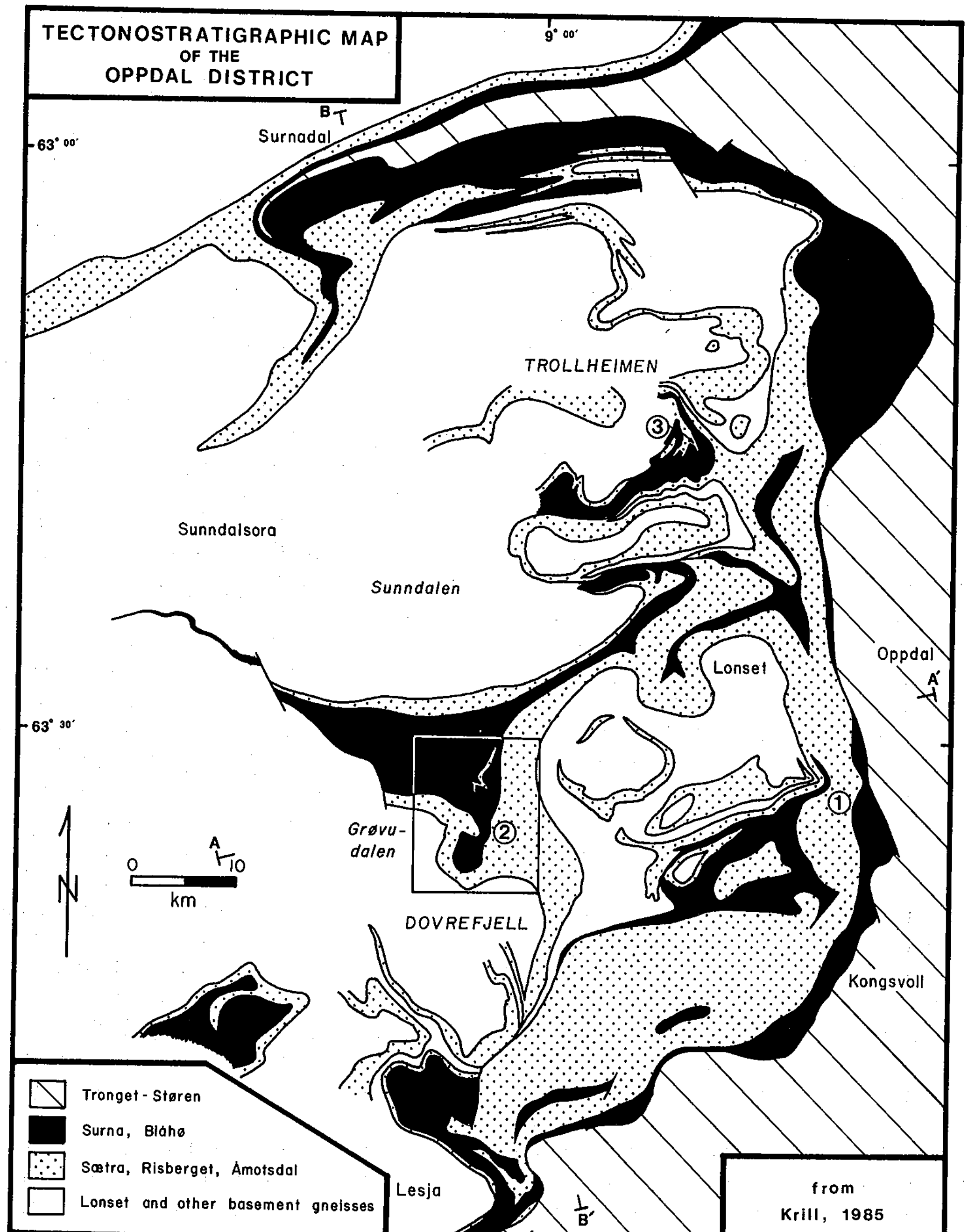

Fig. 2. Tectono-stratigraphic map of the Oppdal district simplified from Krill (1985). Rectangle indicates the location of Fig. 6. The three sheath-like nappes inferred to exist may be visualized by viewing down-plunge to the northeast. Locations referred to in the text: 1—relict cross-bedded sandstones in the Sætra unit cut by mafic dikes, 2—sheath fold A (Fig. 4, 3—sheath fold B (Fig. 4).

(Krill 1980) and is part of the Trondheim Nappe Complex of the main thrust-nappe sequence (Roberts & Wolff 1981). Krill (1980) has shown on the basis of lithological and intrusive relationships that these units form a sequence of stacked thrust-nappes overlying the Lønset basement orthogneisses. These tectono-stratigraphic units have been correlated with units of the main thrust-nappe sequence in Norway and western Sweden (Gee 1980, Krill 1980, Roberts & Wolff 1981), demonstrating large displacements along the nappe boundaries. While the early deformational history of these thrust-nappes is not addressed here, these units form a relatively consistent tectono-stratigraphic framework that has allowed the interpretation of the major fold-nappe interference patterns discussed below. A map of these units, simplified from Krill (1985), is shown in Fig. 2.

Conditions of deformation

Where observed in the Oppdal district, the boundaries of the tectono-stratigraphic units do not show direct evidence of the large displacements required by their present juxtaposition (Krill 1980). The contacts are typically sharp, but recrystallization has obscured or obliterated evidence of original localized cataclastic or mylonitic textures. Instead, the rock in general shows pervasive mylonitic textures (Higgins 1971, Sibson 1977), with no present indication of high localized strains at the nappe boundaries. Microstructural studies of 43 sections from the Grøvudal map area (Fig. 2) typically show a fine-grained, less than 0.5 mm, quartzo-feldspathic groundmass, which in many samples is largely equigranular, suggesting annealing. However, nearly all samples display elongate domains of recrystallized ribbon quartz, granulation of amphibole porphyroblasts, grain boundary mortar textures, deformation lamellae, subgrain development or other features indicative of dynamic recrystallization (Vollmer 1985). This suggests that during the latest phase of ductile deformation the lithologic boundaries were mechanically passive and that strain was distributed relatively homogeneously throughout the rock body.

This style of penetrative ductile plastic deformation is consistent with the behavior of quartz-rich rocks at kyanite to eclogite metamorphic grade. Temperatures within the Grøvudal area have been estimated by single garnet–biotite pairs at approximately 550–650°C (Krill 1985). Farther west, eclogite grade metamorphism has occurred at temperatures between 550 and 750°C and pressures of 12.5–20 kb (Cuthbert *et al.* 1983).

If quartz is the rate controlling phase in the deformation of the quartz-rich gneisses, as has been suggested for granitic rocks (Carter *et al.* 1981), then experimentally derived flow laws for granite and quartzite should give an indication of typical stress–strain-rate relationships. Empirical and theoretical flow laws for quartzite (Koch *et al.* 1980) and granite (Carter *et al.* 1981) show that above 500°C strain rates greater than 10^{-13} are obtained at less than 10 MPa shear stress. Therefore, high orogenic strain rates (e.g. Ramsay & Pfiffner 1982) can easily be reached by moderate differential stresses under these conditions (e.g. Sibson 1983).

Regional relationships suggest an early history of thrust-tectonics involving the progressive stacking of outboard and continental margin lithologies onto the Baltic Shield (Gee 1978). This early phase of brittle thrust-nappe tectonics was probably transitional into the later phase of ductile fold-nappe tectonics in response to increased temperatures and pressures as the tectonic overburden increased during continental imbrication (e.g. Cuthbert *et al.* 1983).

Transposition, strain and sheath folds

Lithologic layering and contacts within the Oppdal district are typically transposed and are often repeated several times within a distance of meters or tens of meters. Where exposures are good, finger-like projections of one unit into another can be mapped near the unit boundaries (Hansen 1971, Vollmer 1985, fig. 2). In some cases these fingers are isolated from the main contact, and appear to have a sheath-like geometry in three dimensions.

Absolute strain magnitudes are difficult to estimate, as few reliable strain markers exist; however the extent of transposition gives an indication of the intense strain. The Sætra unit typically consists of centimeter-scale bands of meta-psammite and amphibolite (e.g. Fig. 4). However, locally, where exposed in flagstone quarries between Kongsvoll and Oppdal, this unit contains well preserved relics of cross-bedded sandstones cut at high angles by mafic dikes (Krill 1986). A simple model of layer-parallel simple shear causing reorientation of mafic dikes from 45° (as a conservative estimate) to between 0.5 and 2° from parallelism with bedding would indicate minimum shear strains of between 28 and 114. In the eastern portion of the Grøvudal map area (Fig. 2) a 5 km long boudin train of a calc-silicate horizon suggests minimum elongations in excess of 200% (Vollmer 1985). Other indications that strains are of these orders of magnitude are stretched pebble conglomerates found within the Åmotsdal unit, the mylonitic textures described above, colinearity of stretching lineations with several generations of fold axes, and sheath folds. Sheath folds, and coaxial fold generations and stretching lineations are commonly associated with high strain zones (e.g. Escher & Watterson 1974, Bell 1978, Williams 1978, Cobbold & Quinquis 1980, Bell & Hammond 1984). Strain measurements within other portions of the orogen show strong east–west elongations of up to several hundred per cent (Hossack 1968, Chapman *et al.* 1979).

Structural analysis within the Grøvudal area has demonstrated a minimum of three early phases of coaxial folding: initial isoclinal folding to form the transposition fabric (F_i), folding of the transposition fabric (F_{i+1}) and folding of F_{i+1} axial planes (F_{i+2}). All axes are variable, but are statistically parallel (Fig. 5). Coaxiality of folds of various styles has also been reported from other areas

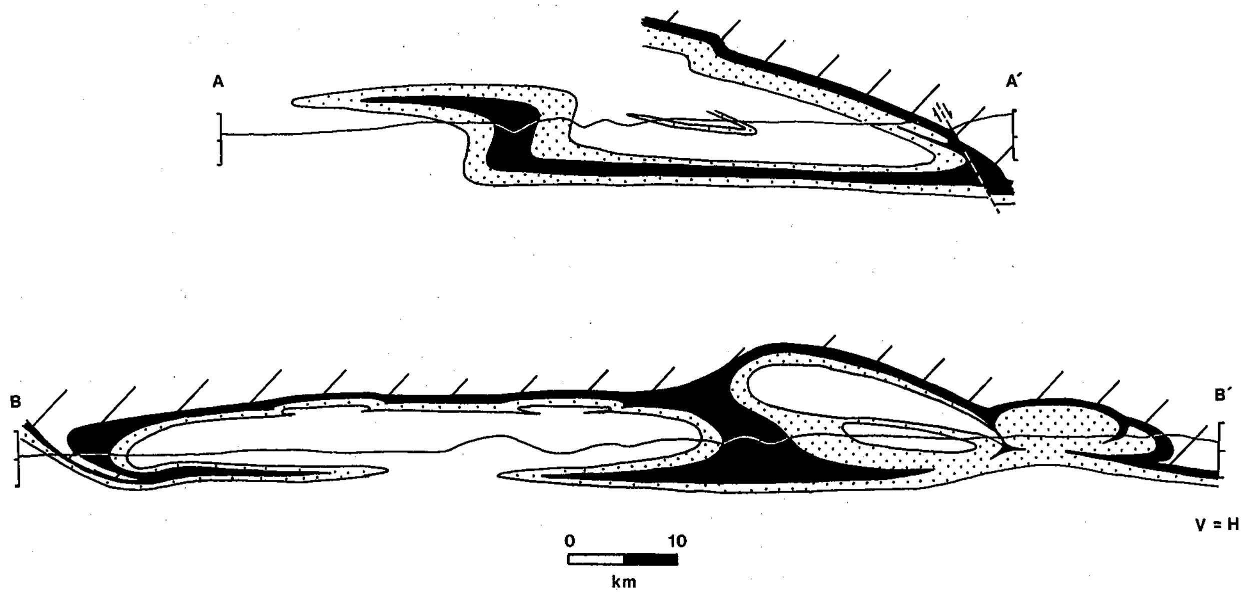

Fig. 3. Schematic cross-sections through the Oppdal district, with nappes interpreted as sheath folds. See Fig. 2 for locations.

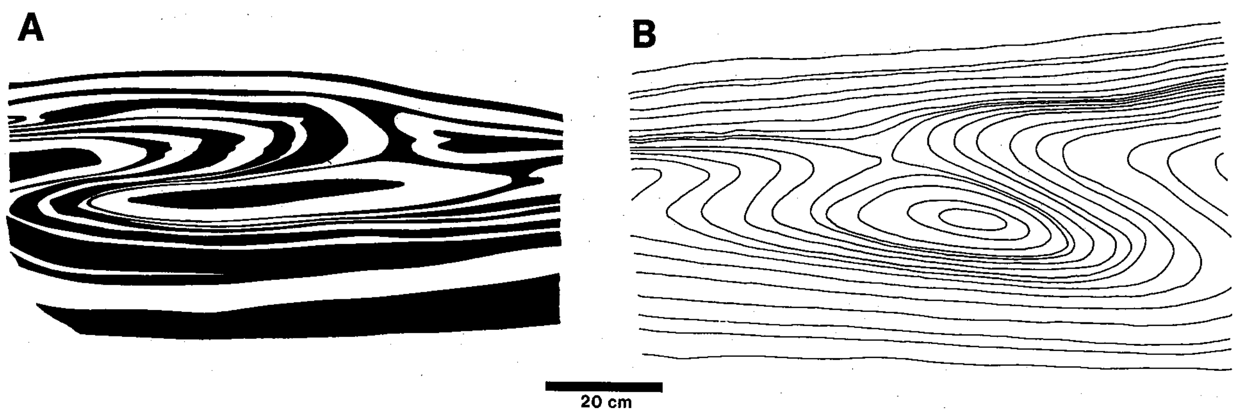

Fig. 4. Line drawings of sheath folds of the Oppdal district traced from photographs. Fold A is in banded amphibolite–psammite of the Sætra unit, from central Grøvudalen in the Dovrefjell range (UTM grid zone 32V–MQ965212). Fold B, in psammite of the Åmotsdal unit, Blåhø Mountain, eastern Trollheimen range (NQ158594), was described by Hansen (1971).

of the Oppdal district (Hansen 1971, Krill 1986). Coaxiality of the fold phases suggests a cogenetic relationship and transitional styles suggest a continuum of fold development rather than distinct episodes of folding (Vollmer 1985).

This continuous development and modification of fabric elements is also demonstrated by the relationship between planar fabrics. Planar foliations (S_{i+1}) secondary to the dominant transposition foliation (S_i) are developed locally as axial-planar fabrics where the transposition foliation is folded. Statistically, however, these secondary foliations remain parallel to the dominant transpositions layering. Similar relationships have been described by Bell & Hammond (1984) in a study of folded mylonitic rocks, where folds in the mylonitic foliation formed with the mylonitic foliation as an axial plane. These relationships suggest continuous fabric and fold development during a progressive deformation, where total finite strains were large. Such a polyphase folding history may occur in a progressive deformation if episodic perturbations occur within the flow due to local anisotropy (Platt 1983) or changes in boundary conditions.

Locally, within outcrop, folds show a consistent pattern of vergence leading to a 'separation-arc' pattern (Hansen 1971); however, in general, fold axes of S- and Z-symmetry are parallel. This is consistent with a sheath-fold regime, and several spectacular examples of sheath folds have been described from the area (Hansen 1971, Vollmer 1985, Krill 1986). Two examples are shown in Fig. 4, one from the Grøvudal area and one described by Hansen (1971) from Trollheimen. The sheath-fold axes are parallel to stretching lineations within outcrop.

Refolding of the Grøvudal fold-nappe

Within the Grøvudal area this early phase of multiple folding has been overprinted by a later refolding event (Figs. 5 and 6). This refolding event was analyzed using a computer-aided domain search (Vollmer 1985), essentially an analysis for cylindrical domains (Turner & Weiss 1963) using eigenvectors of orientation data and a

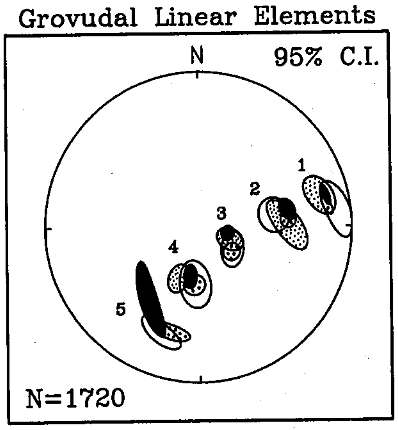

Fig. 5. Synoptic equal-area projection of orientation data from the Grøvudal area, illustrating the colinearity and refolding patterns of fold axes and other linear elements. Black = minima from 957 foliations, coarse stipple = maxima from 439 lineations, white = maxima from 199 fold axes, fine stipple = minima from 125 axial planes and secondary foliations. Ellipses are 95% confidence regions based on a Bingham distribution. Confidence region clusters marked 1–5 correspond to domains 1–5 of Fig. 6. Unfolding about a northwest-trending axis results in a single cluster of fold axes and lineations trending approximately east.

methodical search procedure to locate domains of cylindrical folding. In the Grøvudal area cylindrical domains run approximately northwest (Fig. 6). These domains are the result of the antiformal refolding of an early east-trending recumbent fold, with east-trending linear features, about a northwest-trending axis. This is clearly illustrated in Fig. 5, where the 95% confidence interval regions of fold axes and other linear elements (maxima to lineations, maxima to fold axes, minima of poles to the main foliation and minima of poles to fold axial planes and axial plane foliations), all form a small circle pattern about a northwest-trending axis. If the effect of this refolding is removed, fold axes and lineations plunge gently to the east, parallel to the lineations in domain 1. This refolding is also reflected in the pattern of poles to foliations.

The major structure represented in the Grøvudal area is thus a previously east-trending, north-opening, recumbent fold, refolded into an asymmetric fold overturned to the northeast. This refolding, while of a different style than earlier folding, still represents a general west–east sense of vergence, and is believed to be a later stage of the same orogenic phase with somewhat different conditions of temperature, pressure and stress.

Interpretation of regional interference patterns

The major 'trumpet-shaped' interference pattern in the central portion of the district, of which the Grøvudal closure forms the southern part, also closes to the northwest (Fig. 2), suggesting that the structure as a whole represents an easterly plunging nappe with a strongly sheath-like form. This interpretation can be seen by viewing Fig. 2 down regional plunge to the northeast (i.e. by viewing the map at an inclination of about 10° to the northeast), and comparing this view with the sheath folds illustrated in Fig. 4. A geometry of the nappe which is consistent with this is illustrated in the schematic cross-sections through the Oppdal district (Fig. 3). These cross-sections are drawn to retain the surface geometry from Krill (1985), while taking into account the new data from the Grøvudal map area; they are approximately parallel and perpendicular to the inferred transport direction.

This interpretation, while not unique, takes into account a number of important constraints from the regional geometry. The structure within the Grøvudal area has previously been considered to be a synclinal basin. However, the data summarized in Figs. 5 and 6 show that fold axes and linear features plunge in south-easterly directions and not to the north as required by a synclinal interpretation. As the fold closes to the south, this requires that the major fold closure is antiformal and downward-facing. Although this differs from the previous interpretation as shown by Krill (1985), it is consistent with structures described in the Oppdal area, where Krill showed that a synform–antiform pair of north-trending folds along the eastern margin of the district are also downward-facing. These are shown in Fig. 3 as forming a large parasitic fold on the upper limb of the downward-facing, basement-cored Lønset Nappe.

At the northern edge of the district the large Surnadal synform verges to the north and plunges to the east, in contrast to the east-verging, north-trending folds along the eastern margin of district. Krill (1985) suggested that this wrapping around of the fold axes is related to the emplacement of central gneiss domes. However, this geometry can also be explained as large, gently east-plunging sheath folds. The southern portion of the NNW–SSE section (B–B′), northeast of Lesja, appears more complex and includes some fault-related discon-

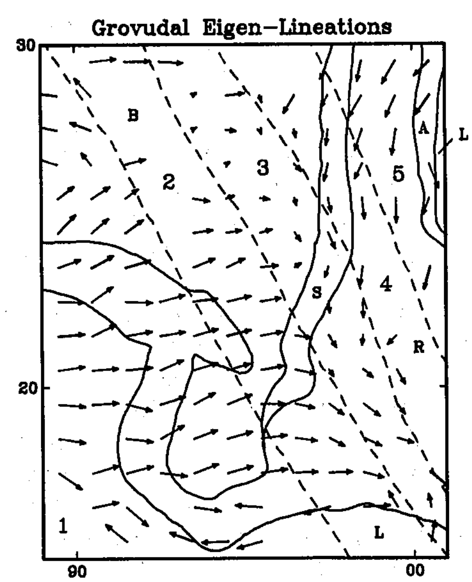

Fig. 6. Best-fit lineations (eigen-lineations) in the Grøvudal area calculated for each square kilometer, illustrating the map pattern of refolded lineations. Fold axes parallel these lineations and indicate a southeasterly plunge of the structure as a whole. Fold and lineation data from domains 1–5 are shown in Fig. 5. The length of arrows is proportional to the cosine of the plunge of the lineation, giving the map projections of the unit vectors. Tick marks are 10 km UTM grid co-ordinates in zone 32V–MQ.

tinuities. Fold axes trend mainly southwest–northeast and major recumbent folds verge towards the southeast (Wheeler 1973, Krill 1985).

Thus, major fold axes plunge to the east in the western portion of the district, and wrap around to the north along the eastern margin. The folds verge away from the two central areas of basement gneisses towards the north, east and south, and generally plunge to the east or northeast. This could be explained by a model of gneiss dome emplacement; however the Grøvudal Nappe plunges to the southeast beneath the basement gneisses, suggesting that the basement gneisses of the Lønset area root farther to the west and have been carried *east* (rather than west) over rocks of the cover sequence.

It is suggested that a model involving sheath-like nappes more simply accounts for these major features than does a model involving gneiss domes. In this interpretation three major nappes define the large-scale features of the district, from north to south: the basement-cored Trollheimen Nappe, the cover-cored Grøvudal Nappe and the basement-cored Lønset Nappe. These sheath-like fold-nappes plunge gently to the east, and are therefore slightly downward-facing. This interpretation can be seen by viewing Fig. 2 down regional plunge to the northeast. Geometrically, this interpretation is not a radical departure from earlier interpretations, the main differences being that the Grøvudal structure is downward-facing and plunges east, and that much more of the Trollheimen and Lønset gneiss areas are underlain by the cover sequence.

Aside from geometrical considerations, this model is kinematically consistent with the emplacement of the overlying Caledonian thrust-nappes, having combined eastward displacements of many hundreds of kilometers (Gee 1978). In this interpretation the major interference patterns can be related to these orogenic movements and no additional episodes of gneiss dome formation or more complex orogenic movements seem to be required.

COMPUTER MODEL OF FOLD INTERFERENCE PATTERNS

The geometrical analysis outlined above suggests that

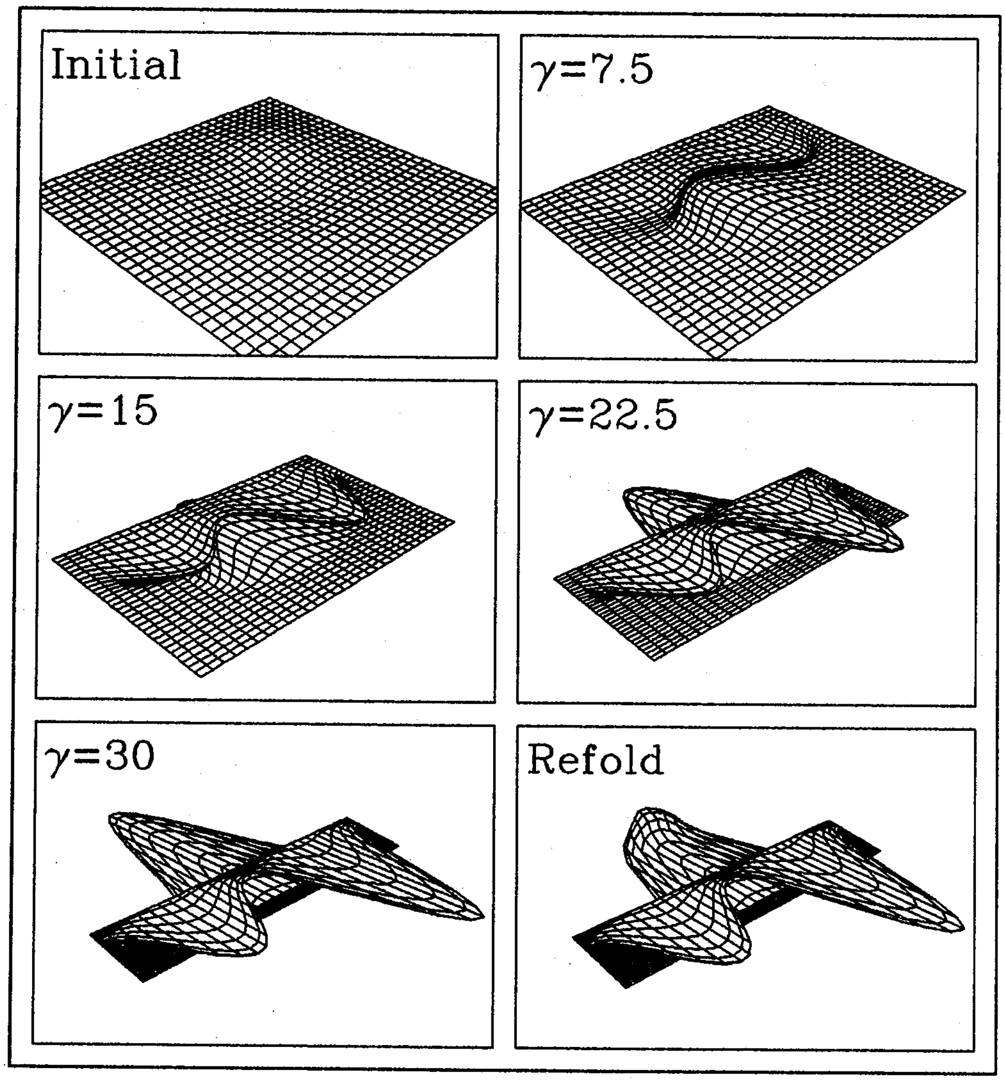

Fig. 7. Single-surface kinematic model of sheath-nappe formation. The initial surface is parallel to the shear plane, with the addition of three perturbations. The initial perturbed surface was subjected to a 1.5° rotation into the shear direction, followed by progressive homogeneous simple shear to $\gamma = 30$, and a final refolding as described in the text. Sections through a three-surface model are shown in Figs. 8 and 9. The shear direction is out and to the right.

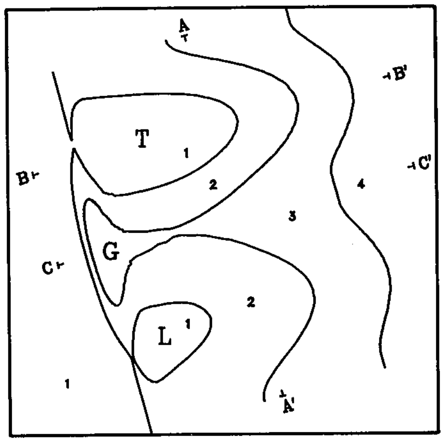

Fig. 8. Map-view section through the three-surface kinematic model of Fig. 7. The model has been rotated 15° about Y to illustrate the correlation of map features with Fig. 2, so the sheath folds plunge gently to N075°E. Labelled features are correlated with the following features of Fig. 2: T = Trollheimen Nappe, G = Grøvudal Nappe, L = Lønset Nappe. Numbers 1–4 represent simulated stratigraphic units. Indicated cross-sections are shown in Fig. 9.

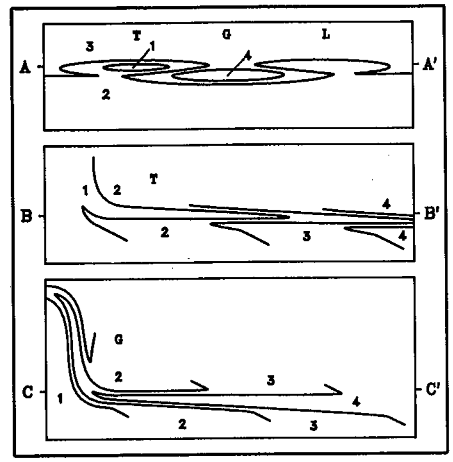

Fig. 9. Cross-sections through the three-layer kinematic model. Numbers 1–4 refer to the simulated stratigraphic layers of Fig. 8 and T, G and L to the three sheath-nappes, as in Fig. 8. Tick marks indicate the plane of the map-view section (Fig. 8). Section A–A′ is a transverse section through the three sheath folds. Section B–B′ is a longitudinal section through the northern basement-cored sheath (T), and section C–C′ is a longitudinal section through the central cover-cored sheath (G). Vertical exaggeration is ×3.

the nappes of the Oppdal region are sheath-like in form and that these may have formed during a simple kinematic history involving horizontal shear and refolding. In order to test whether this proposed history can explain the observed regional interference patterns, a dimensionless computer model was developed which allows the superposition of homogeneous strains and sinusoidal folds on bodies defined by grid surfaces. Cross-sections through the body can be calculated as intersections of the grid surfaces with the section plane. The body is assumed to be homogeneous and isotropic with layering serving as purely passive markers. Folds are imposed as portions of sinusoidal waves. The model presented here is the result of hundreds of trials using different surface spacings, rotations, fold amplitudes and wavelengths, and section planes.

In this model the body was defined by three grid surfaces, each defined by the X, Y and Z co-ordinates of 16,384 points, where X and Z varied uniformly between −100 and 100, and the initial values of Y were $Y_i = -2.56$, 0.0 and 2.42 units. These three surfaces represent the contacts between four homogeneous layers. Three single wavelength perturbations in the form of sinusoidal bumps:

$$Y = Y_i + A\cos\left[(2\pi/W)\left((X - X_p)^2 + (Z - Z_p)^2\right)^{1/2}\right] + A$$

were introduced at locations $(X_p, Z_p) = (-50, -50)$, $(-50, +50)$ and $(0, 0)$, to form the initial perturbed state (Fig. 7). The amplitude to wavelength ratios for these three perturbations (A/W) were 2:100, 1:100 and −2.5:120, respectively. The low A/W ratios were chosen to simulate primary geological irregularities or secondary perturbations introduced by buckling (e.g. Smith 1975) or flow irregularities (Hudleston 1976, 1977).

This perturbed surface was then rotated $\theta = -1.5°$ about the Z axis and subjected to various amounts of simple shear, γ, parallel to X in the XZ plane:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

as shown in Fig. 7. A final asymmetric refold was simulated by the addition of a half-wavelength sine wave at a 70° angle and a final rotation of 2.6° was added about the Z axis, so that the structures plunge gently in the X direction ('east'). A map-view section and two cross-sections are shown in Figs. 8 and 9 for the planes: $Y = 1.87$, $X = -1$, $Z = -50$ and $Z = 0$.

Note that sheath folds produced in this model are purely passive folds of the type described by Hudleston (1976, 1977); they are the result of the homogeneous deformation of a perturbed surface, not heterogeneous shear or slip folding (e.g. Turner & Weiss 1963, Hobbs *et al.* 1976).

DISCUSSION

It is necessary in most geologic studies to relate observations to a model or hypothesis. In this case the Grøvudal structure was initially thought to have a synclinal form, as earlier reconnaissance work had suggested. A more complete structural analysis, as outlined above, showed that this model was inconsistent with field data and required revision. A regional model involving refolded sheath-like nappes evolved through equal-area net and map pattern analysis, and by analogy to small-scale structures. It was felt, however, that if a kinematic model could be made which recreated the observed geometrical properties and map patterns by a deformation related to known orogenic movements, this interpretation would be strengthened. It was with this in mind that the computer model was developed.

It is important to realize that while such a computer

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A computer model of sheath-nappes formed during crustal shear in the Western Gneiss Region, central Norwegian Caledonides: Discussion

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VOLLMER (1988) has presented an insightful re-interpretation of Caledonian fold-nappes in the Oppdal district as large-scale sheath-folds. However, his statement contrasting basement–cover relations at Oppdal with those in northern Norway (citing my 1982 paper) is not entirely correct. It may be true that basement involvement in the Caledonian nappes is volumetrically greater at Oppdal than in the Lofoten-Tysfjord area where I worked, but the difference is probably one of magnitude only and not of process. Basement deformation in the Lofoten-Tysfjord area certainly is not "more brittle" than at Oppdal. As summarized below, relations along the basement–cover contact are quite similar in the two areas. When placed in the context of regional relations in north Norway, this fact has important implications for the nature of Caledonian A-type subduction. In the interests of clearing up any misunderstanding, I briefly recapitulate the main points of my work on this problem and add some new remarks in the light of more recent data and ideas.

Maps and cross-sections from the Lofoten-Tysfjord area in Bartley (1982, 1984) and Steltenpohl & Bartley (1988) show km-scale recumbent folds that interdigitate basement and cover and isoclinally fold cover-nappe boundaries. The folds resemble those at Oppdal in style and in their timing relative to stacking of cover nappes and to metamorphism, though the folds are somewhat smaller in size. At Tysfjord and probably elsewhere, the folds have sheath-like forms (e.g. Steltenpohl & Bartley 1988, fig. 5). Fabric analysis and pelite thermobarometry indicate that the folds formed at kyanite-grade conditions (about 550°C and 8 kb; Hodges & Royden 1984, Steltenpohl & Bartley 1987), similar to metamorphic conditions at Oppdal according to Vollmer (1988). In thin section, the mylonitic basement rocks in the folds show intense uniform grain-size reduction and thorough recovery and recrystallization, consistent with deformation at high temperature. In short, basement involvement in Caledonian nappes at Lofoten-Tysfjord closely resembles that at Oppdal.

If there is a major difference between the areas, it is the regionally continuous exposures in Lofoten of parautochthonous Precambrian basement rocks that underlie the Pennine-like nappe complex (Bartley 1982). The Lofoten basement is composed of medium-pressure granulites that represent a westward continuation of the Baltic craton (Griffin *et al.* 1978). The granulite-grade mineralogy of the basement formed in the early Proterozoic, and in the field, in thin section and in moderately resistant isotopic systems (e.g. Rb–Sr whole-rock), the rocks show a general lack of Caledonian structural or metamorphic overprinting, although Rb–Sr and K–Ar mineral systems were partially or wholly reset (Hakkinen 1977, Griffin *et al.* 1978, Malm & Ormaasen 1978, Bartley 1981, 1982). The downward disappearance of Caledonian strain is spectacularly exposed on a regional scale and is completely gradational. The mylonitic basement rocks in Caledonian fold-nappes are geochemically identical to the mangerites that predominate in the underlying Lofoten basement complex (Bartley & Schubert unpublished data). These relations indicate conclusively that a high degree of ductile strain localization in the basement near the basement–cover contact was responsible for the detachment-like style of nappe transport in the Lofoten-Tysfjord area. Although the actual deformation mechanisms were highly ductile, the large-scale kinematics of this system, in which the cover and sheets of subjacent basement were sheared off a relatively undeformed deeper basement, strikingly resemble foreland thrust systems.

Because the undeformed basement probably reached temperatures in excess of 500°C during the Caledonian (Bartley 1984), the downward disappearance of Caledonian deformation probably cannot be attributed to an inverted temperature gradient caused by thrusting. The basement rocks that record large Caledonian strains appear to be somewhat hydrated compared to their undeformed counterparts (amphibolite instead of granulite facies), leading me to propose (Bartley 1982) that strain localization primarily was caused by hydrolytic weakening and reaction softening in the basement adjacent to the cover. I hypothesized that the requisite water was derived from synkinematic metamorphic dehydration of the cover, and was introduced downward into the basement by a mechanism similar to that recently proposed in more detail by McCaig (1988). This led to the further suggestion that the distribution of water (and not, for example, the thermally activated brittle–ductile transition) may have controlled the detachment of basement thrust sheets in the Scandinavian Caledonides (Bartley 1982).

However, regardless of the mechanism of strain localization, the large-scale geometry of the Lofoten-Tysfjord area implies that Caledonian A-type subduction occurred by *en bloc* underthrusting of an effectively rigid Baltic lower crust and subjacent mantle beneath the nappe complex (Bartley 1982, Hodges *et al.* 1982). The effective rigidity of the Lofoten basement probably was not because it was particularly strong (compared to cold upper crust or underlying upper mantle), but rather because the high-strain zone in which the sheath-nappes formed was extraordinarily weak. The result is that the A-type subduction zone was still in effect thin-skinned to a depth of at least 30 km and far into the 'metamorphic core' of the orogen, even though deformation along and above the detachment in this position was under conditions far into the ductile field.

These considerations lead me to suggest that the sheath-nappes at Oppdal may well be larger examples of precisely the same process recorded at Lofoten-Tysfjord. As the lower boundary of the main Caledonian shear zone migrated downward with time (following an infiltration front of metamorphic water?), basement rocks were sheared ductilely into fold-nappes that refolded thrusts in the cover. This process had the result, certainly at Lofoten-Tysfjord and quite possibly at Oppdal, that the entire Pennine-type nappe complex is underlain by lower continental crust that scarcely participated in Caledonian nappe tectonics.

A computer model of sheath-nappes formed during crustal shear in the Western Gneiss Region, central Norwegian Caledonides: Reply

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I thank Dr Bartley for his comments and for his lucid summary of the relationships between basement and cover in the Lofoten-Tysfjord area. Bartley has pointed out many important similarities between the interpretations I made for the Oppdal area (Vollmer 1988), and the interpretations made for the Lofoten-Tysfjord area (Bartley 1982, Steltenpohl & Bartley 1988). I believe this emphasizes the importance of these interpretations for the deformational histories of the Caledonian and other collisional orogens. The major differences between the two areas appear to be the presence of the rigid basement exposed in Lofoten, and the scale of the basement-cored nappes.

Bartley refers to a sentence in my paper (Vollmer 1988) that compares the style of deformation in the Oppdal district with the style of deformation described by Bartley (1982) on east Hinnøy, north Norway. In that sentence I stated that the deformation in the northern Norwegian Caledonides appeared to be a "more brittle detachment-style deformation" (Vollmer 1988, p. 742). This referred to Bartley's (1982) observation that ductile fold-nappes in the Lofoten-Tysfjord area appear to be essentially detached from the lower, rigid basement gneisses. As clarified by Bartley in his Discussion, the detachment is a gradational mylonite zone, which he does not believe is a major structural discontinuity between two genetically distinct basement blocks.

I am not aware of any similar evidence from the Oppdal area to suggest that a rigid basement block exists below the fold-nappes there, although it may be possible. It seems that within the Oppdal district the deformation began as thin-skinned thrust tectonics, resulting in the formation of the regional tectonostratigraphic framework (Krill 1985), followed by the downward migration of increasingly ductile deformation into the basement gneisses (Vollmer 1988). This appears to be similar to what Bartley has described for the Lofoten-Tysfjord area. However, much of the basement in the western portion of the Oppdal district appears to have been migmatized during Caledonian deformation (Krill 1985), suggesting ductile deformation extends well down into the basement gneisses. It is possible that the deformation within the Oppdal area represents a later stage in the progressive development of these basement-cored nappes. Further mapping within these problematic lower gneisses will be required to clarify their deformational histories.

Steltenpohl & Bartley's paper (1988), which had not been published when my manuscript (Vollmer 1988) was prepared, illustrates many of the similarities Bartley refers to in his present Discussion, including the apparent presence of a refolded sheath-nappe in the Tysfjord area. In terms of regional deformation processes, it is notable that they interpreted gneiss domes in that area to be the result of crustal shortening and fold interference rather than diapirism. This is similar to the suggestion I made for the Oppdal district (Vollmer 1988), although I argued that the major interference patterns there could be explained by a simpler deformation history than they describe from the Ofoten-Tysfjord area.

As Bartley suggests, however, the main fold-nappes in the Lofoten-Tysfjord area may well be smaller examples of the same types of nappes I described from the Oppdal area, and the differences between the two areas could largely be a matter of scale. It is further possible that the deformational processes responsible for the formation of these basement-cored nappes occurred over a longer period of time, or were more intense, in the Oppdal area, resulting in larger nappe structures with more extensive basement involvement.

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