Geological Survey of Norway
P.O.Box 3006 - Lade
N-7002 Trondheim, Norway
Tel.: 47 73 90 40 11
Telefax 47 73 92 16 20

REPORT

Report no.: 98.007	ISSN 0800-3416	Grading: Open

Title:

POLYPHASE BRITTLE FAULTING IN THE SUNNFJORD REGION, WESTERN NORWAY: KINEMATICS AND TIMING

Authors: Alvar Braathen	Client: NGU and industrial partners
County: Sogn og Fjordane	Commune:
Map-sheet name (M=1:250.000) Måløy	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 43 Price (NOK): 173 Map enclosures:

Fieldwork carried out: Summer 1996, 1997	Date of report: 12.02.98	Project no.: 2671.00/2685.00	Person responsible:

Summary:

Structural studies in the Sunnfjord region of western Norway, focused on faulting episodes that post-date the major period of Devonian extension, yield data that are relevant to the style and evolution of brittle faulting. Major brittle structures in the region generally divide into (i) E-W faults and (ii) N-S lineaments with subordinate NE-SW and NW-SE structures. In close association with these large-scale features, four distinct groups/populations of meso-faults can be distinguished.

Two reference areas, the eastern parts of the Kvamshesten and Hornelen Devonian basins, feature clear cross-cutting relationships of major faults and folds. Such cross-cutting relations and kinematic patterns of the distinct populations of meso-faults, and their relationship to dated fault rocks and dykes, form the basis for a four-stage history of post-Late Devonian brittle faulting. **Stage 1** is characterised by N-S shortening by thrusting and folding, related to either Late Devonian - Carboniferous transpression or compression. **Stage 2** is characterised by N-S shortening and E-W extension on conjugate strike-slip faults and bisecting normal faults. This fracture pattern could relate to the regional E-W folding (as ac- and hk0-fractures) during progressive shortening evolving from stage 1 to stage 2; **Stage** 3 is characterised by approximate E-W extension and is manifested as silicified fault breccias of possible Permian age that mainly bound the eastern margin of the Devonian basins. **Stage 4** features N-S extension on E-W striking normal faults that possibly relates to a regional Late Jurassic- Early Cretaceous extensional phase. In addition, n**eotectonic** reactivation may have occurred along some of the major structures.

Significant movements on some of the faults emphasise the importance of Late Devonian and younger faulting and leave the impression that these deformation episodes had a regional extent and, therefore, also occurred in the neighbouring offshore areas. The established four-stage fault evolution is examined in the light of known episodes of rejuvenation of faults on the nearby shelf and along the Møre-Trøndelag Fault Zone, emphasising the importance of movement on master faults with respect to local strain conditions in the Sunnfjord region.

Keywords: Strukturgeologi	Forkastninger	
Tektonikk		

CONTENTS

FIGURES

Fig. 1. (a) Outline map of Norway, with the Sunnfjord region indicated. (b) Simplified bedrock map of the Sunnfjord region, western Norway (modified from Osmundsen and Andersen 1992), locating sites were fault data have been collected. Each site is related to one of four populations of meso-faults. The lineaments are interpreted from a satellite image (Landsat TM scene, band 5) in scale 1:100,000.

Fig. 2. Population 1 data from the Sunnfjord region. The bedrock map (modified from Osmundsen & Andersen 1994) locates the sites where structural data have been collected. Three of the stereo-grams are slip-linear plots of recorded meso-faults, two are plots of poles to bedding in the footwall of the major faults. All stereo-plots are presented in lower hemisphere, equal area projection (Schmidt net).
The "slip-linear" plots, as described by Aleksandrowski (1985) and Goldstein and Marshak (1988), present the pole to the fault plane decorated by a line/arrow which indicates the direction and sense of slip of the hangingwall. The arrow is parallel to the horizontal trace of a plane (M-plane), which is defined by the pole to the fault and the slip-line.

Fig. 3. Photographs of structures in the Sunnfjord region. (a) Reverse fault of population 1 affinity at Skjerlie, bringing Caledonian rocks (left, NW) over Devonian metasediments (right, SE). The location of the photograph is indicated in Fig. 2. (b) Major thrust-fault and associated folds in the northern cliff-face of the Kvamshesten Devonian basin. Note that the view, from the NNE, is highly oblique with respect to the thrust-direction. See Fig. 2 for location. (c) The footwall syncline and narrow thrust zone of the major thrust-fault presented in (b), viewed from the ENE. (d) Typical population 2 conjugate strike-slip faults in foliated and banded anorthosite. The structures are displayed on a horizontal surface. (e) View from the south of the eastern nose of the Kvamshesten Devonian basin, which is bound by a low-angle, west-dipping fault (Kvamshesten fault) of population 3 affinity (arrow). A steep E-W fault (population 4) is also outlined. (f) Fault breccia and possible pseudotechylite on the Kvamshesten fault. (g) The Atløy red and green fault breccias, which have been dated to latest Jurassic - Early Cretaceous and Late Permian, respectively (Eide et al. 1997). Note the lower 0.5 m zone of young fault gouge. See Fig. 7 for location. (h) The Haukå fault, viewed from the west in Grøndalen. The steeply north-dipping fault of population 4 affinity juxtaposes Devonian rocks to the right and various Neoproterozoic to Early Palaeozoic schists to the left (south). (i) The southeast corner of the Hornelen Devonian basin, viewed from the east. The syncline in the basin (not on photograph) is truncated by the low-angle fault (population 3), which is cut by a steep E-W fault to the south (population 4). See Fig. 5 for location. (j) Zeolite (arrow) and breccia along young fractures in the central zone of a major N-S lineament/master-joint.

Fig. 4. Population 2 faults of the Sunnfjord region. Sites for data collection are located by dots. The meso-faults are plotted in slip-linear plots.

Fig. 5. Bedrock map of the southeast corner of the Hornelen basin and underlying metamorphic rocks, modified from Bryhni & Lutro (1991). Red and pink ellipses locate areas where meso-fault data, presented as slip-linear plots in the stereo-nets, have been recorded. Bedding orientations from the southeastern part of the Devonian basin are plotted as poles in the stereo-net.

Fig. 6. Simplified bedrock map of the eastern part of the Kvamshesten Devonian basin and underlying Nordfjord-Sogn Detachment zone. Red circles and ellipses locate areas where meso-fault data, presented as slip-linear plots in the stereo-nets, have been recorded. Bedding orientations from the Devonian basin are plotted as poles in the stereo-net.

Fig. 7. Population 4 fault data from the Sunnfjord region. Dots locate sites for data recording. The meso-faults are plotted in slip-linear plots.

Fig. 8. Diagram presenting a resume of observations related to the four structural populations. The M-plane plot of each population presents contoured poles to M-planes, and the average M-plane for the data-set.

Fig. 9. Diagram of documented tectonic events in western and northwestern South Norway. Timing of tectonic events are linked with the four populations/stages, as discussed in the text.

Fig. 10. Diagram presenting the shortening and extension directions, and suggested timing, for the four stages of brittle deformation in the Sunnfjord region. Possible regional implications and kinematics are indicated on the maps, and are further discussed in the text.

ABSTRACT

Structural studies in the Sunnfjord region of western Norway, focused on faulting episodes that post-date the major period of Devonian extension, yield data that are relevant to the style and evolution of brittle faulting. Major brittle structures in the region generally divide into (i) E-W faults and (ii) N-S lineaments with subordinate NE-SW and NW-SE structures. In close association with these large-scale features, four distinct groups/populations of meso-faults can be distinguished.

Two reference areas, the eastern parts of the Kvamshesten and Hornelen Devonian basins, feature clear cross-cutting relationships of major faults and folds. Such cross-cutting relations and kinematic patterns of the distinct populations of meso-faults, and their relationship to dated fault rocks and dykes, form the basis for a four-stage history of post-Late Devonian brittle faulting. **Stage 1** is characterised by N-S shortening by thrusting and folding, related to either Late Devonian - Carboniferous transpression or compression. **Stage 2** is characterised by N-S shortening and E-W extension on conjugate strike-slip faults and bisecting normal faults. This fracture pattern could relate to the regional E-W folding (as ac- and hk0-fractures) during progressive shortening evolving from stage 1 to stage 2; **Stage** 3 is characterised by approximate E-W extension and is manifested as silicified fault breccias of possible Permian age that mainly bound the eastern margin of the Devonian basins. **Stage 4** features N-S extension on E-W striking normal faults that possibly relates to a regional Late Jurassic- Early Cretaceous extensional phase. In addition, **neotectonic** reactivation may have occurred along some of the major structures.

Significant movements on some of the faults emphasise the importance of Late Devonian and younger faulting and leave the impression that these deformation episodes had a regional extent and, therefore, also occurred in the neighbouring offshore areas. The established four-stage fault evolution is examined in the light of known episodes of rejuvenation of faults on the nearby shelf and along the Møre-Trøndelag Fault Zone, emphasising the importance of movement on master faults with respect to local strain conditions in the Sunnfjord region.

1. INTRODUCTION

The kinematics of crustal scale deformation are, in many cases, directly reflected in accommodated small-scale structures. This is documented by numerous successful studies of small-scale fault data, which have been applied to evaluate kinematic and dynamic models (e.g., Marshak et al. 1982; Allmendinger 1982; Wojtal 1986; Braathen & Bergh 1995). Commonly applied methods of kinematic analyses have recently been quantified through numerical and geometrical techniques, such as the 'slip-linear/M-plane plot' analysis (Aleksandrowski 1985; Goldstein & Marshak 1988) and the 'stress tensor analysis' (Etchopar et al. 1981; Angelier 1984, 1994). For such analyses, the resolution of kinematically heterogeneous sets of meso-faults into homogeneous sets that signify a specific tectonic event is absolutely crucial (e.g., Etchopar et al. 1981; Marret & Allmendninger 1991; Braathen & Bergh 1995).

The Sunnfjord region of western Norway (Fig. 1; Kildal 1970) provides a good area for studying small-scale faults resulting from several brittle deformation events (e.g., Eide et al. 1997; Hartz & Andresen 1997) by applying the slip-linear/M-plane kinematic technique. The region has experienced pervasive Caledonian ductile deformation, followed by late Caledonian extension, the latter evolving from a ductile to a brittle style of deformation. Younger brittle events, well documented on the nearby continental shelf (e.g., Færseth et al. 1995), are robustly imaged in the Sunnfjord region, where Late Permian and Late Jurassic faulting can be demonstrated (Torsvik et al. 1992; Eide et al. 1997).

In the present report, the detailed chronology and kinematics of four post-Caledonian tectonic events, plus neotectonic activity, are established in the local context of the Sunnfjord region. The kinematic reconstruction is based on map-scale and mesoscale overprinting relationships in combination with fault-slip (based on fault: plane frictional wear, tool pit, cross fractures, growth fibres; see Hancock 1985 and Petit 1987) and fold data. The methods used embrace three main steps; (1) A classification of the regional lineaments (fault or master-joint zones), and the recording of meso-faults with slip-lines and the trends of folds (locally) on numerous sites along the major structures. (2) The establishment of homogeneous populations of successive finite strain elements. The meso-faults commonly have strikes subparallel to the first-order structures, and show slips that coincide with the associated major structures. Some lineaments show no evidence of fault movement, and here homogeneous sets of meso-faults are distinguished based on symmetrical patterns and cross-cutting relationships, if they exist. (3) An evaluation of the order and orientation of constructed strain axes.

In the last section of the report the established strain history of the Sunnfjord region will be compared with faulting events on the nearby continental shelf and in onshore areas, with an emphasis on the evaluation of regional kinematic models.

2. REGIONAL GEOLOGICAL SETTING

The rocks of western Norway can be conveniently divided into two major units; below and above the regional Nordfjord-Sogn Detachment (Norton 1986). This ductile fault zone is characterised by various mylonitised rocks which relate to both the underlying and the overlying units (Andersen & Jamtveit 1990; Wilks & Curtbert 1994). Beneath the detachment, the Western Gneiss Region (WGR) consists of various deep-crustal, quartzo-feldspathic gneisses that are commonly migmatitic; gneisses are intercalated with supracrustal rocks, and enclose numerous bodies of eclogite, anorthosite, amphibolite and ultramafic rocks (Kildal 1970; Milnes et al. 1997). The high-pressure metamorphism of the eclogite bodies indicates that parts of the WGR were exhumed from significant crustal depths during late stages of the Caledonian orogeny.

The Caledonian rocks in the hangingwall of the Nordfjord-Sogn Detachment can be divided into four main units (Roberts & Gee 1985; Andersen & Andresen 1994): (1) autochthonous/parautochthonous pre-Caledonian basement with (2) an attached, thin, Neoproterozoic to Lower Palaeozoic, mainly clastic cover sequence (e.g., Andersen et al. 1990), (3) several far-travelled nappes, some carrying ophiolites, of both Baltic and exotic affinity (Furnes et al. 1990), and (4) very low-grade, Devonian coarse-clastic sediments (Nilsen 1968; Steel et al. 1985; Cuthbert 1991). Transport of the Caledonian nappes was towards the SE, whereas late Caledonian deformation included a reversal in transport, towards the western hinterland, due to extensional collapse of the orogenic welt (Andersen et al. 1991; Fossen 1992; Wilks & Curtbert 1994; Osmundsen & Andersen 1994; Wennberg & Milnes 1994; Hartz et al. 1995; Wennberg 1996). The Devonian basins are thought to have formed during the extensional collapse, prior to folding of the Devonian sediments and other rocks into a series of E-W-trending, south-verging synclines and anticlines.

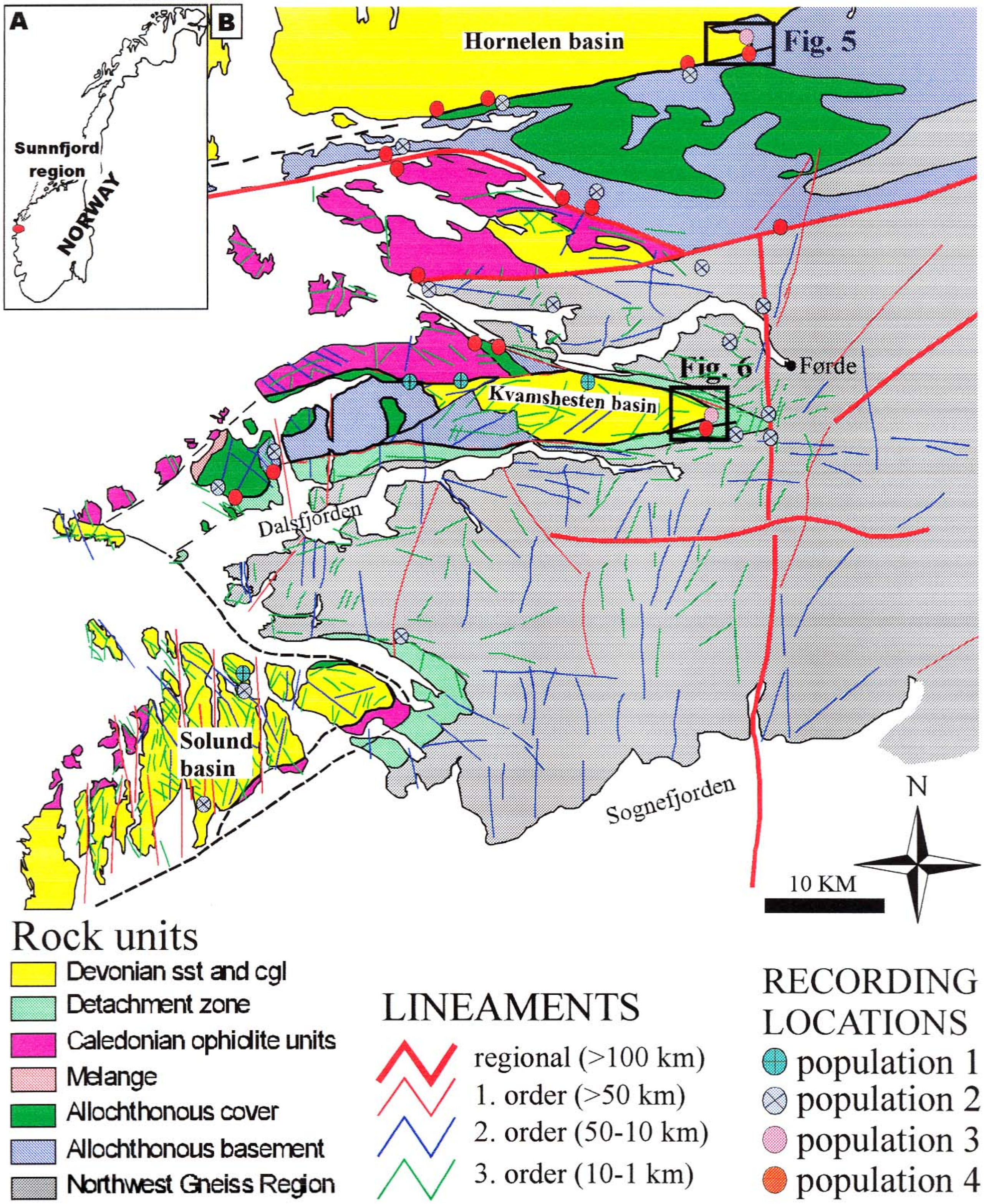


Fig. 1. (a) Outline map of Norway, with the Sunnfjord region indicated. (b) Simplified bedrock map of the Sunnfjord region, western Norway (modified from Osmundsen and Andersen 1992), locating sites were fault data have been collected. Each site is related to one of four populations of meso-faults. The lineaments are interpreted from a satellite image (Landsat TM scene, band 5) in scale 1:100,000.

3. BRITTLE STRUCTURES IN THE SUNNFJORD REGION

The late Caledonian extensional phase evolved from ductile to localised brittle deformation under decreasing P-T conditions (e.g., Norton 1986; Seranne & Seguret 1987). In rocks above the Nordfjord-Sogn Detachment several brittle faults related to deposition in the Devonian basins can be recognised (Bryhni & Skjerlie 1975; Osmundsen 1996, in press; Hartz & Andresen 1997). Yet younger faulting is also evident in the form of typically linear to semi-linear structures visible in satellite images (Fig. 1); these young faults/structures can be divided into two dominant sets (Ramberg et al. 1977; Gabrielsen & Ramberg 1978; Braathen et al. 1998): (1) Approximately N-S-striking lineaments with subordinate NE-SW and NW-SE structures, and (2) roughly E-W-striking lineaments.

The N-S lineaments transect all rocks of the region and, where mappable in three dimensions, have subvertical orientations. They vary in length from more than 100 km down to some hundred metres, and have been classified accordingly in Fig. 1. In most cases these lineaments show little or no displacement of bedrock markers, suggesting that they are fracture swarms or master-joints (Braathen et al. 1998).

The E-W lineaments define the fault boundary between the detachment zone and the overlying rocks. Commonly, these faults dip moderately to gently to the south or north, i.e. with a low angle or subparallel to the mylonite foliation of the detachment zone. However, dips exceeding 60° are quite common. These faults truncate the thrust sheets, the Devonian rocks of the hangingwall, as well as the detachment zone, and juxtapose the thrust sheets with the detachment zone (Andersen & Jamtveit 1992). Younger-on-older relationships suggest these E-W features are normal faults.

The E-W oriented structures have previously been regarded as part of the Nordfjord-Sogn Detachment zone, representing later and brittle stages of the top-to-the-west transport during extensional collapse of the Caledonides (Hossack 1984; Norton 1986; Seranne & Seguret 1987; Chauvet & Seranne 1994). Newer dating of fault rocks associated with these faults contradicts this interpretation (Torsvik et al. 1992; Eide et al. 1997), and has established that the faults were active in both Late Permian and Late Jurassic times. Local observations of non-lithified fault gouges indicate even younger reactivation, possibly within the latest 10,000 years. In this report it is argued that much of the offset found along the map-scale brittle faults of the Sunnfjord region may be attributed to Late Palaeozoic and Mesozoic episodes, and are, thus, not related to the late-Caledonian extensional phase.

4. KINEMATIC DATA

The observed heterogeneous structural elements have been split into four homogeneous, structural populations by comparing macro- and mesoscale field data, and by using intersection and overprinting relationships of distinct groups of faults as criteria for subdivision. The four populations can be ascribed to distinct tectonic events, ranging in inferred age from Late Devonian - Early Carboniferous to Early Cretaceous (Braathen 1997a,b; Braathen & Henriksen 1997). In addition, neotectonic reactivation has to be considered.

4.1 Population 1

Along the NW boundary of the Kvamshesten Devonian basin (Fig. 2; between Skjerlie and Oslandsbotn) a major fault defines the contact between Devonian sediments and various Caledonian rocks (Bryhni & Skjerlie 1975; Osmundsen 1996; Osmundsen et al. in press). This fault, consisting of numerous foliation-subparallel meso-faults in a >50 m-wide zone, dips at 40-60° to the north, and places metamorphic rocks of the hangingwall over Devonian sediments in the footwall (Fig. 3a). By placing older rocks on younger, the fault by definition is reverse. However, there is evidence for a partial reactivation of an older, syn-sedimentary normal fault (Osmundsen 1996; A.K. Svendby, pers. comm. 1997). Bedding in the Devonian rocks in the footwall of the major reverse fault is folded into a tight syncline, whereas the gently north-dipping foliation in the hangingwall rocks is partly truncated by the fault. Displacement on the structure cannot be quantified; however, the footwall syncline supports movement in excess of 200-300 m, and is probably significantly higher.

Some kilometres further west (at Skogafjellet), a significant low-angle to subhorizontal, north-dipping fault is visible in the northern cliff face of the Devonian basin (Fig. 3b). Associated structures include a hangingwall anticline and a footwall syncline (Fig. 3c). Both folds display local overturned bedding, and the total structural geometry is that of a thrust fault with associated fault-propagation folds. Shortening on the entire structure is estimated to be in excess of 1 km (Osmundsen 1996, 1997; Braathen 1997a). Actually, this fault may be a continuation of the reverse fault further west, in this case requiring a total length of 20 km.

The bedding in the footwall of the reverse fault(s) is folded into tight synclines. When plotted on a stereonet, bedding data from two sites show near-cylindrical folding around moderately east-plunging fold axes (Fig. 2).

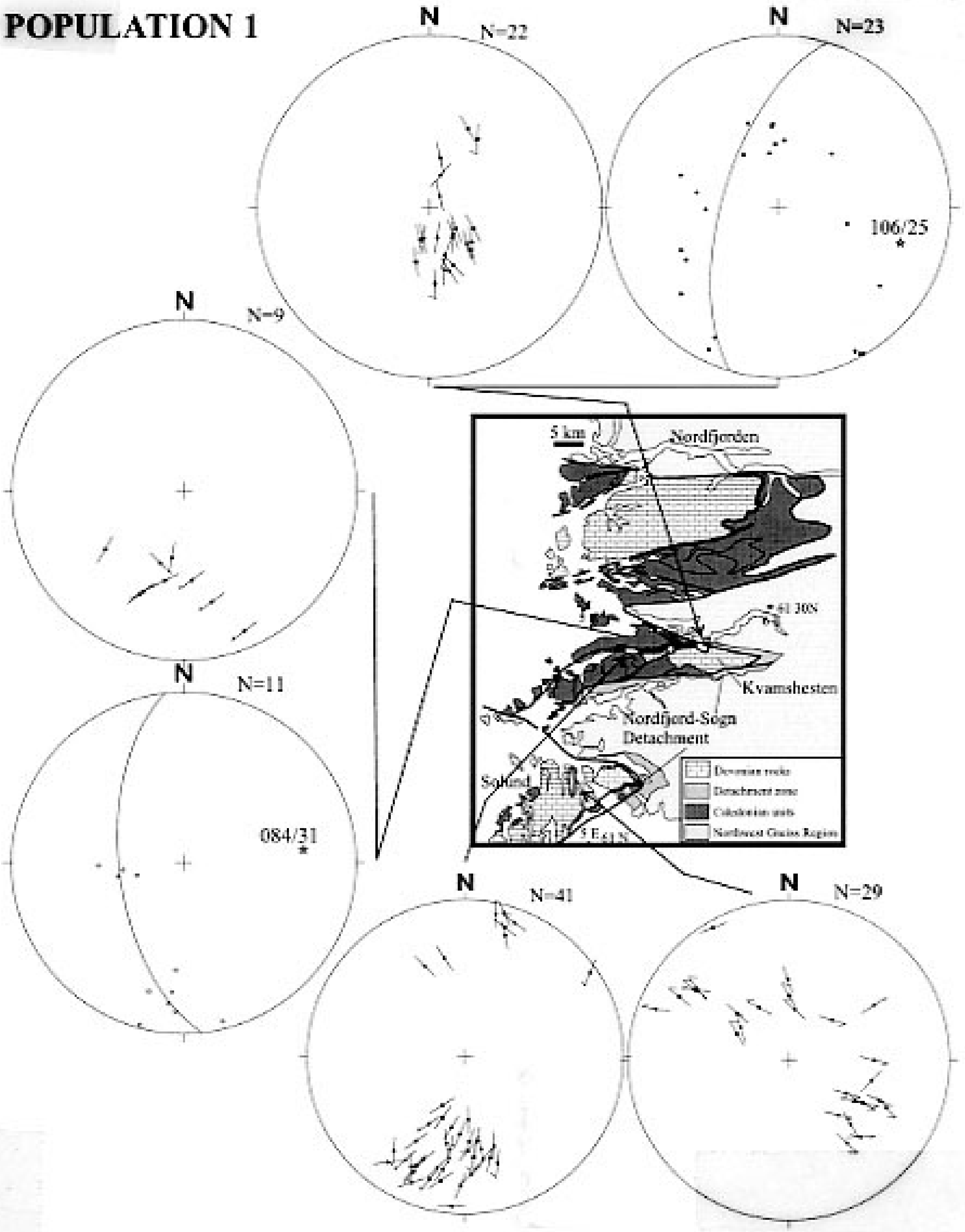


Fig. 2. Population 1 data from the Sunnfjord region. The bedrock map (modified from Osmundsen & Andersen 1994) locates the sites where structural data have been collected. Three of the stereo-grams are slip-linear plots of recorded meso-faults, two are plots of poles to bedding in the footwall of the major faults. All stereo-plots are presented in lower hemisphere, equal area projection (Schmidt net).
The "slip-linear" plots, as described by Aleksandrowski (1985) and Goldstein and Marshak (1988), present the pole to the fault plane decorated by a line/arrow which indicates the direction and sense of slip of the hangingwall. The arrow is parallel to the horizontal trace of a plane (M-plane), which is defined by the pole to the fault and the slip-line.

The first-order thrusts are made up of a 0.5-1 m-thick cataclasite with a thin overlying veining breccia, both silicified and hosting secondary epidote; numerous meso-scale faults are commonly coated with quartz. These meso-faults are recorded at three sites along the major structure(s), and have E-W strikes and subhorizontal/gentle to moderate north or south dips. When the slip direction on the meso-faults can be deduced, it commonly shows a south-directed reverse sense of slip, in accordance with the first-order thrust; the north-directed faulting probably represents backthrusts.

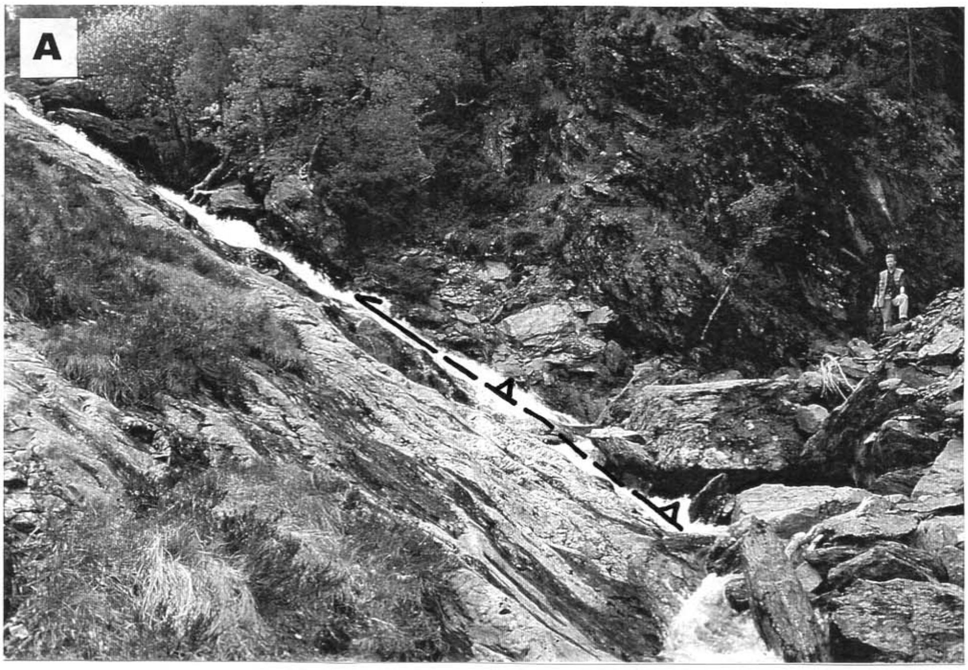
Contractional structures are also present at other locations of the Sunnfjord region, e.g., in the Solund Devonian basin. On Utvær (Fig. 1b), bedding in Devonian coarse clastic sediments are tightly folded and transposed into parallelism with a penetrative foliation (Sturt & Braathen in prep.). The cleavage/bedding relationship suggests that folding occurred around a NW-SE axis, and with a vergence towards the southwest. Furthermore, the growth of chlorite and white mica in the cleavage indicates lower greenschist-facies conditions during the deformation. Further east, numerous meso-faults truncate subhorizontal Devonian bedding (Fig. 2). These structures, recorded on one site, strike NE-SW and dip moderately to the southeast and northwest. Slip-lines on the fault surfaces indicate both top-to-the-NW and SE reverse senses of slip.

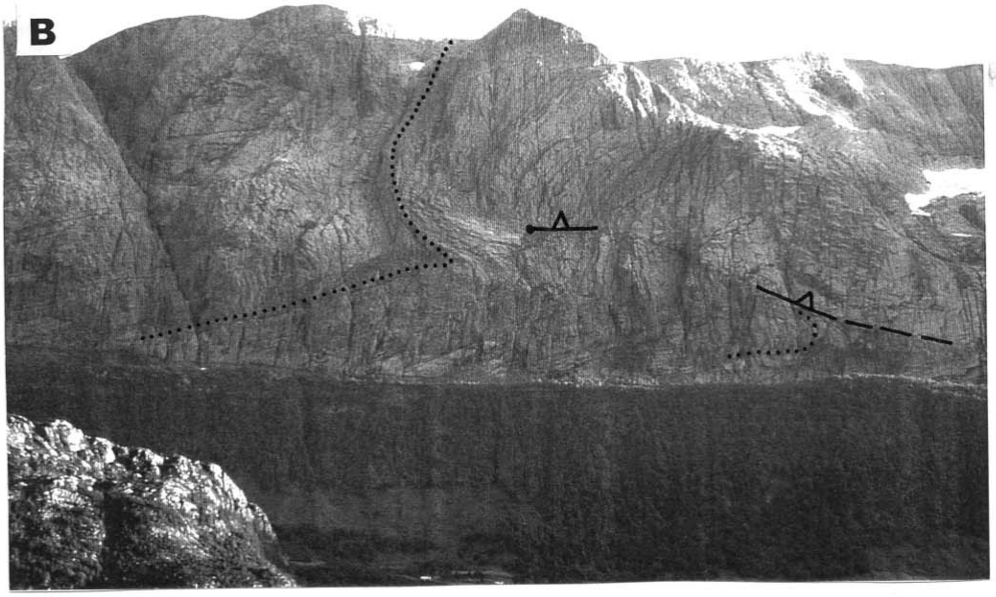
4.2 Population 2

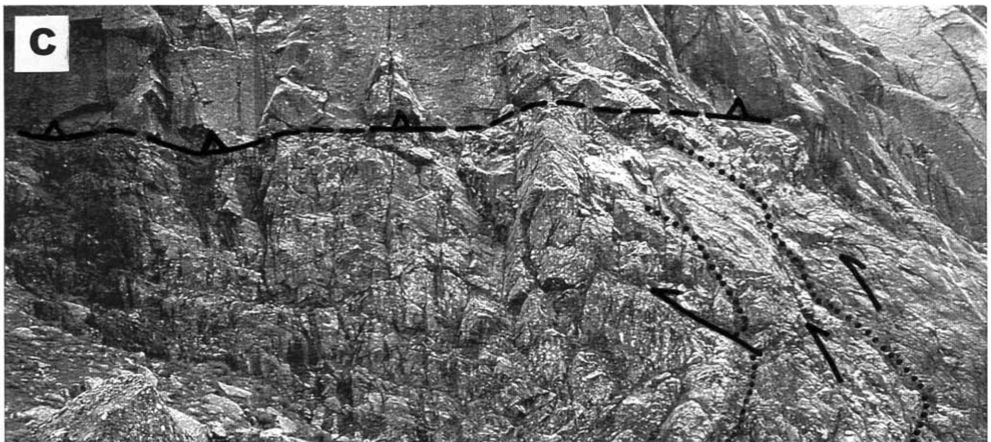
The N-S striking lineaments with subordinate NE-SW and NW-SE structures, of population 2 affinity, do not displace bedrock markers to any significant extent. Typically, the lineaments appear as >100 km down to 1 km long zones of intense fracturing, commonly 400-500 m wide, and with a symmetric fracture distribution around the centre of the lineament. The central zone commonly contains breccia (Braathen et al. 1998).

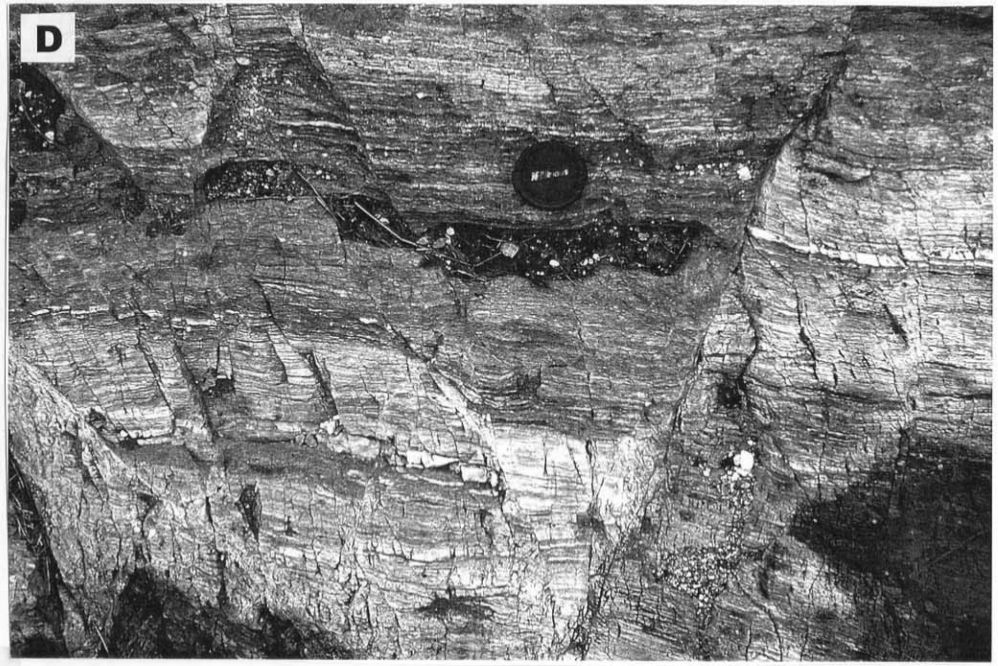
Abundant population 2 meso-faults, commonly covered with epidote and/or quartz, are found adjacent to the lineaments. These faults, recorded at 17 sites, can be separated into three sets based on orientation and sense of slip (Figs. 3d, 4): (i) N-S-striking, steeply dipping faults with normal displacement; (ii) NE-SW to NNE-SSW-striking, subvertical faults with subhorizontal to moderately plunging slip-lines, supporting strike/oblique-slip and sinistral movements; and (iii) NW-SE to NNW-SSE subvertical faults with subhorizontal to moderately plunging slip-lines, indicating strike/oblique-slip, dextral movements. The three sets of faults appear to have formed simultaneously, because no consistent cross-cutting relationships can be documented. This supports an interpretation of the NE-SW and NW-SE subvertical faults as conjugate strike/oblique-slip faults, bisected by N-S normal faults, the latter subparallel to the first-order lineament.

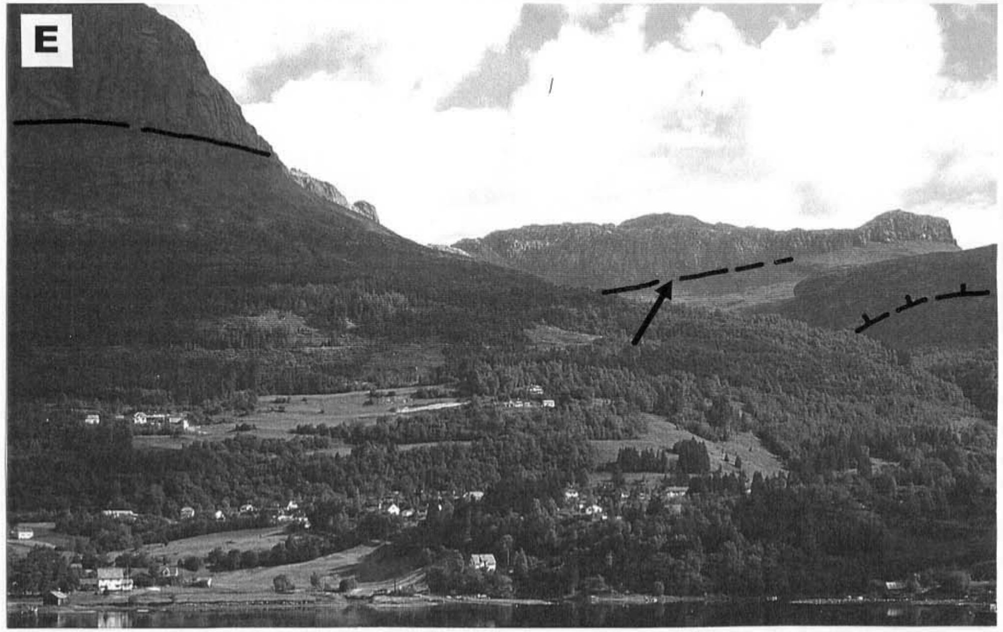
Fig. 3. Photographs of structures in the Sunnfjord region. (a) Reverse fault of population 1 affinity at Skjerlie, bringing Caledonian rocks (left, NW) over Devonian metasediments (right, SE). The location of the photograph is indicated in Fig. 2. (b) Major thrust-fault and associated folds in the northern cliff-face of the Kvamshesten Devonian basin. Note that the view, from the NNE, is highly oblique with respect to the thrust-direction. See Fig. 2 for location. (c) The footwall syncline and narrow thrust zone of the major thrust-fault presented in (b), viewed from the ENE. (d) Typical population 2 conjugate strike-slip faults in foliated and banded anorthosite. The structures are displayed on a horizontal surface. (e) View from the south of the eastern nose of the Kvamshesten Devonian basin, which is bound by a low-angle, west-dipping fault (Kvamshesten fault) of population 3 affinity (arrow). A steep E-W fault (population 4) is also outlined. (f) Fault breccia and possible pseudotechylite on the Kvamshesten fault. (g) The Atløy red and green fault breccias, which have been dated to latest Jurassic - Early Cretaceous and Late Permian, respectively (Eide et al. 1997). Note the lower 0.5 m zone of young fault gouge. See Fig. 7 for location. (h) The Haukå fault, viewed from the west in Grøndalen. The steeply north-dipping fault of population 4 affinity juxtaposes Devonian rocks to the right and various Neoproterozoic to Early Palaeozoic schists to the left (south). (i) The southeast corner of the Hornelen Devonian basin, viewed from the east. The syncline in the basin (not on photograph) is truncated by the low-angle fault (population 3), which is cut by a steep E-W fault to the south (population 4). See Fig. 5 for location. (j) Zeolite (arrow) and breccia along young fractures in the central zone of a major N-S lineament/master-joint.

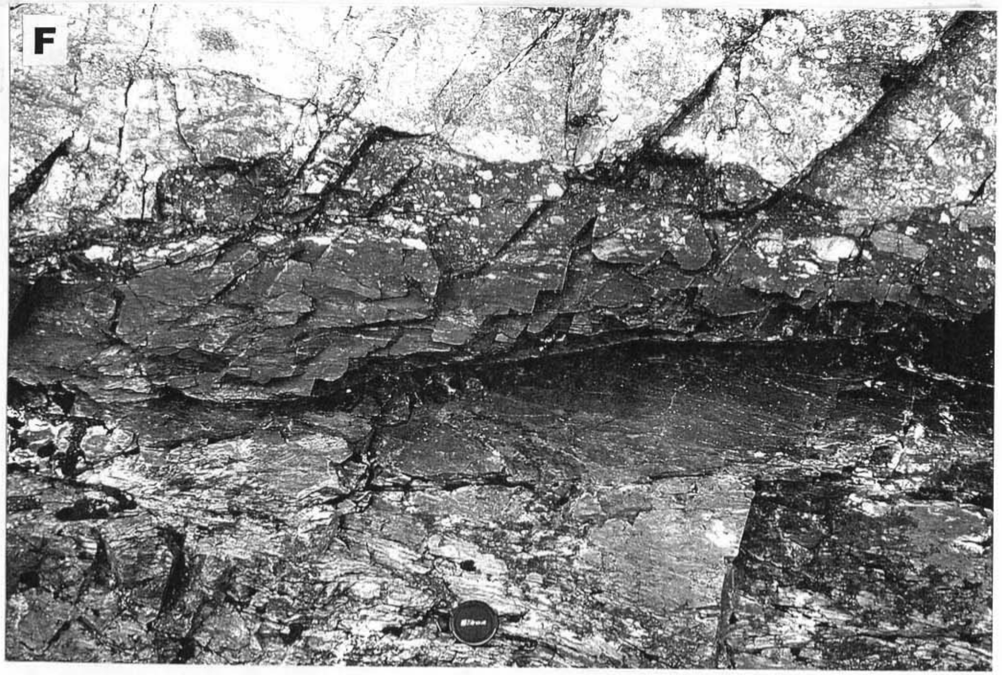

A


B

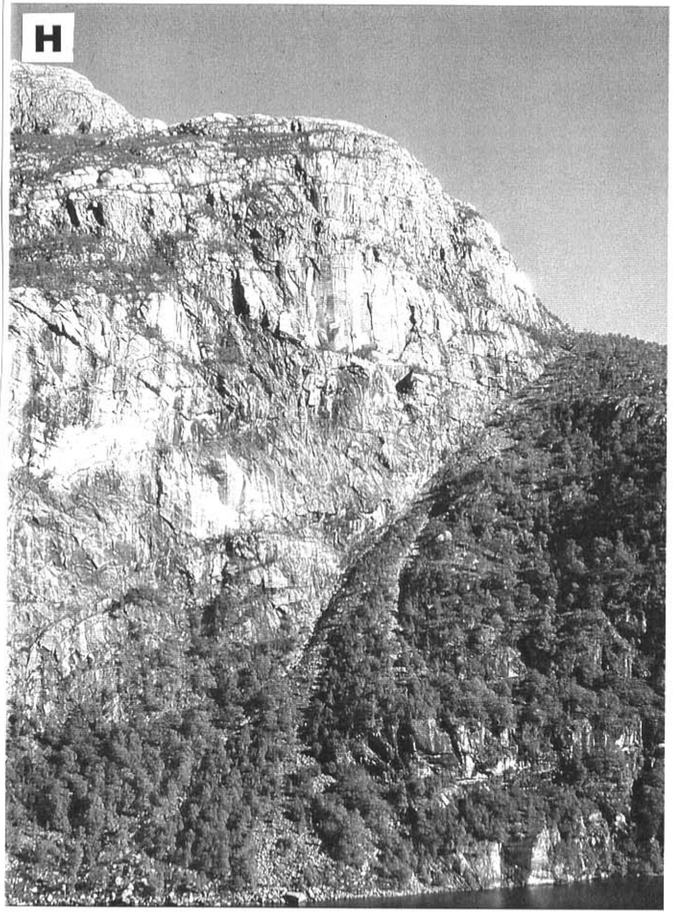

C

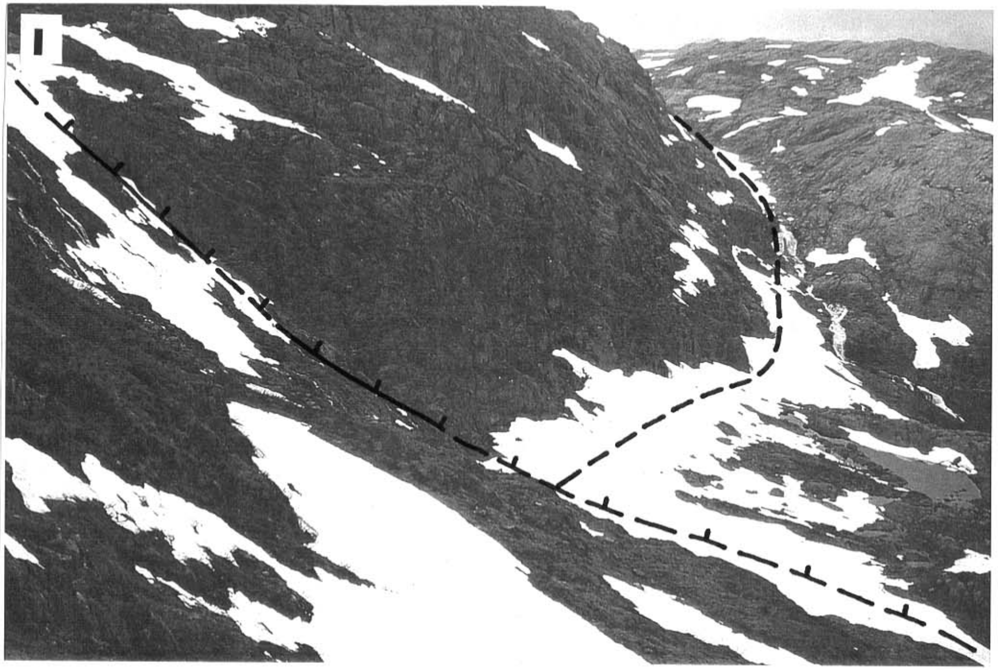

D

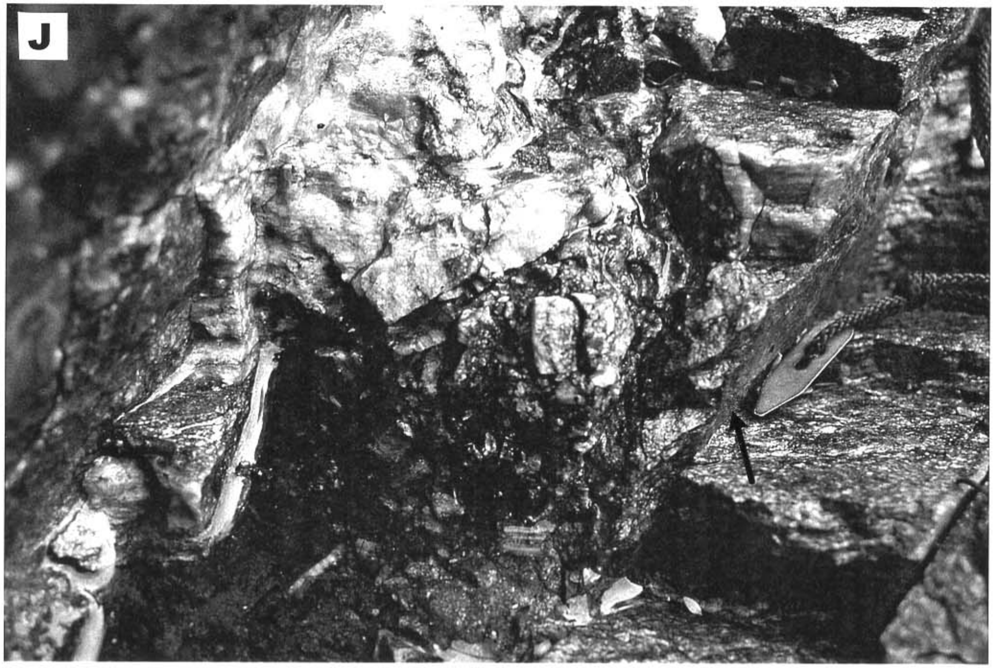

E


F


G
WORLD CUP 1982 OFFICIAL CAMERA OF THE FOOTBALL
Canon


H


I


J

4.3 Population 3

Map-scale structures of population 3 affinity are evident in two (or more) areas; the southeastern corner of the Hornelen Devonian basin and the eastern nose of the Kvamshesten Devonian basin (Fig. 1). Typical for both areas is the presence of a low-angle fault at the base of folded Devonian rocks, bounding the basins on the east side, and separating the Devonian rocks from underlying, intensely folded and foliated metamorphic units (e.g., Andersen & Jamtveit 1990). These low-angle faults (population 3 affinity) are cut by steep, E-W-striking faults related to population 4, which generally form the northern and southern margins of the Devonian basins.

Devonian sediments of *the SE corner of the Hornelen Devonian basin* are folded into an E-W oriented, open to tight, upright syncline-anticline pair (Bryhni & Lutro 1991; Wilks & Cuthbert 1994; Torsvik et al. 1997). These moderately east-plunging folds are clearly truncated in the east by the low-angle Hornelen detachment fault (Fig. 5), which apparently is gently folded as well (e.g., Torsvik et al. 1997). Folding of the fault is indicated by a change from a gentle SW dip to a moderate NW dip as it is followed northwards. However, the trace of the hangingwall anticline in the Devonian rocks intersects the underlying fault more than 500 m northeast of the bend in the fault; above this bend the bedding has a consistent SSE dip. Therefore, no link exists between the anticline in the Devonian rocks and the bend of the underlying fault, suggesting that the present shape of the low-angle fault reflects its initial geometry, and not a superimposed folding.

The southern boundary of the Hornelen Devonian basin (Fig. 5) is defined by the steeply north-dipping Haukå fault (Bryhni & Lutro 1991), with folded and foliated gneisses and schists in the footwall (Fig. 3e). Associated fault-rocks are seen in a 0.5-3 m-wide zone that consists of an upper veined breccia in Devonian rocks and a lower proto- to ultracataclasite, both cemented by carbonate. In the east, where displacement can be demonstrated to exceed 500 m, this major steep fault clearly cuts the low-angle fault (Figs. 3i and 5).

Meso-faults associated with the low-angle fault of population 3 affinity, recorded at two sites, dip NNW and reveals slip-lines with variable dip-slip and oblique-slip sense of movement (Fig. 5). The first-order fault at these sites dips gently SSE, indicating that the recorded meso-faults are antithetic structures of the hangingwall. The overall geometry, with the youngest rocks in the hangingwall, in association with the inconsistent slip pattern, indicate top-to-the-SE normal movement on the low-angle fault. In contrast, meso-faults, recorded at two sites along the major WSW-ENE steep fault of population 4 affinity, show a consistent moderate to steep dip to the north. These meso-fault data reveal down-to-the-north slip-lines consistent with the displacement on the major fault and, in addition, down-to-the-south slip representing antithetic structures.

Devonian sediments of *the eastern nose of the Kvamshesten basin* (Fig. 6) are underlain by the planar, 22-25^o west-dipping Kvamshesten detachment fault of population 3 affinity (Fig. 3e). Associated brittle fault rocks occur in a 2-3 m-wide zone, consisting of a veining breccia in the Devonian rocks above c. 0.5-1.5 m of ultra-cataclasite and local, possible psedotachylite (Fig. 3f; Torsvik et al. 1988). Beneath this there is a 10-20 m-thick zone of ultramylonites. All of these fault rocks are silicified.

The Devonian rocks are folded into an open syncline that plunges sub-horizontally to the NW. In places, an axial plane cleavage is evident (Torsvik et al. 1986, 1987). Both the fold and the cleavage, as well as underlying mylonitic units of the Nordfjord-Sogn Detachment, are truncated by the low-angle fault. The footwall mylonitic rocks are folded around E-W axes; in the north they are folded into an open synform, followed by a tight antiform-synform pair, and in the south, into a tight and overturned, south-verging antiform. A steeply north-dipping, E-W-striking brittle fault (population 4), the Dalsfjorden fault, truncates the overturned fold limb. Where this steep fault intersects the low-angle fault to the west, the steep fault appears to truncate the low-angle structure (Kildal 1970).

Meso-scale faults associated with the first-order structures can be assigned to two sets: Population 3 faults, recorded at three sites along the low-angle fault, showing NNE-SSW strikes and various, gentle to moderate WNW and ESE dips. Slip-lines on the faults are subparallel to the dip-line and, in cases where the sense of slip can be deduced, they indicate normal movement. The meso-faults are interpreted as WNW-dipping synthetic normal faults, in accordance with the first-order low-angle fault and ESE-dipping antithetic faults. Population 4 faults have been recorded on one site, along the major WSW-ENE fault. At this locatity, meso-faults dip steeply to the north, subordinately to the south, and show dip-parallel slip-lines and, where detectable, a normal displacement. Thus, they record down-to-the-north movement in accordance with the major fault.

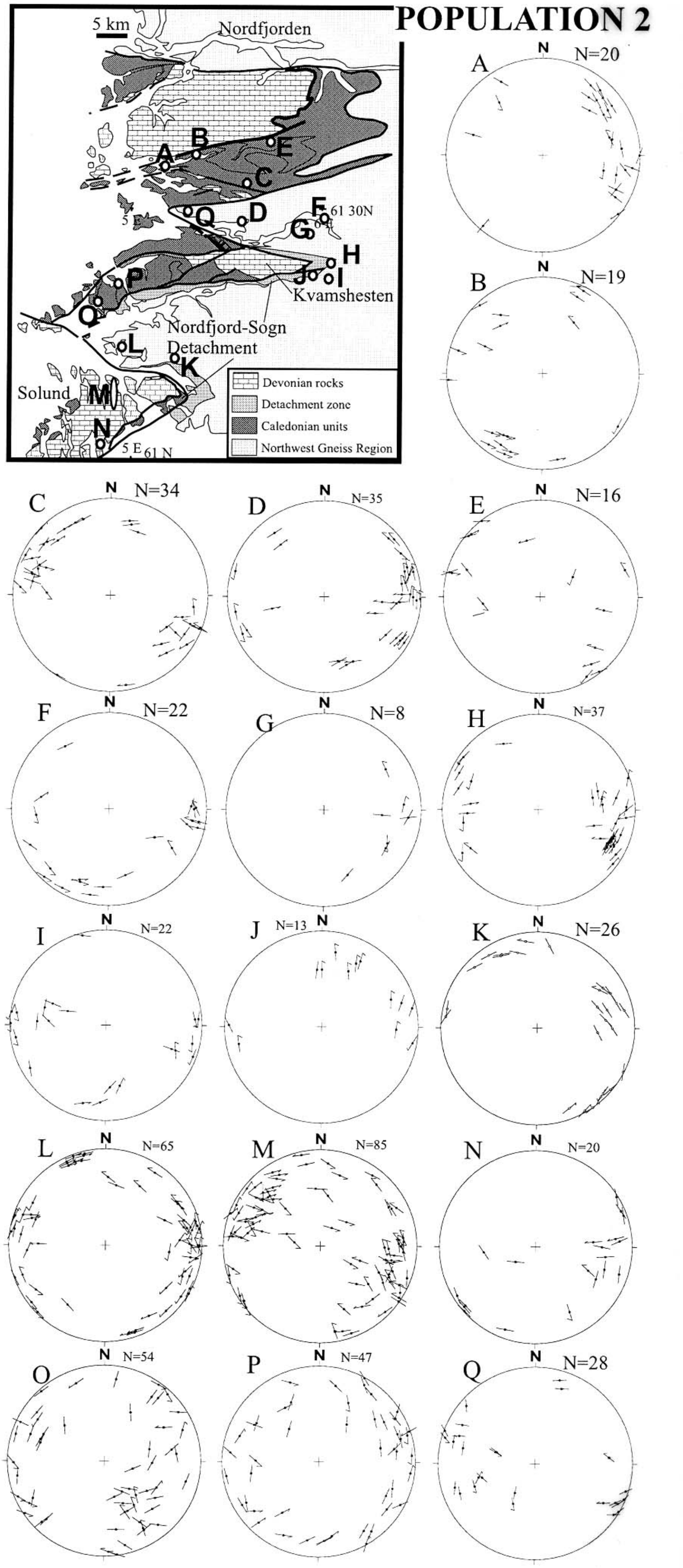


Fig. 4. Population 2 faults of the Sunnfjord region. Sites for data collection are located by dots. The meso-faults are plotted in slip-linear plots.

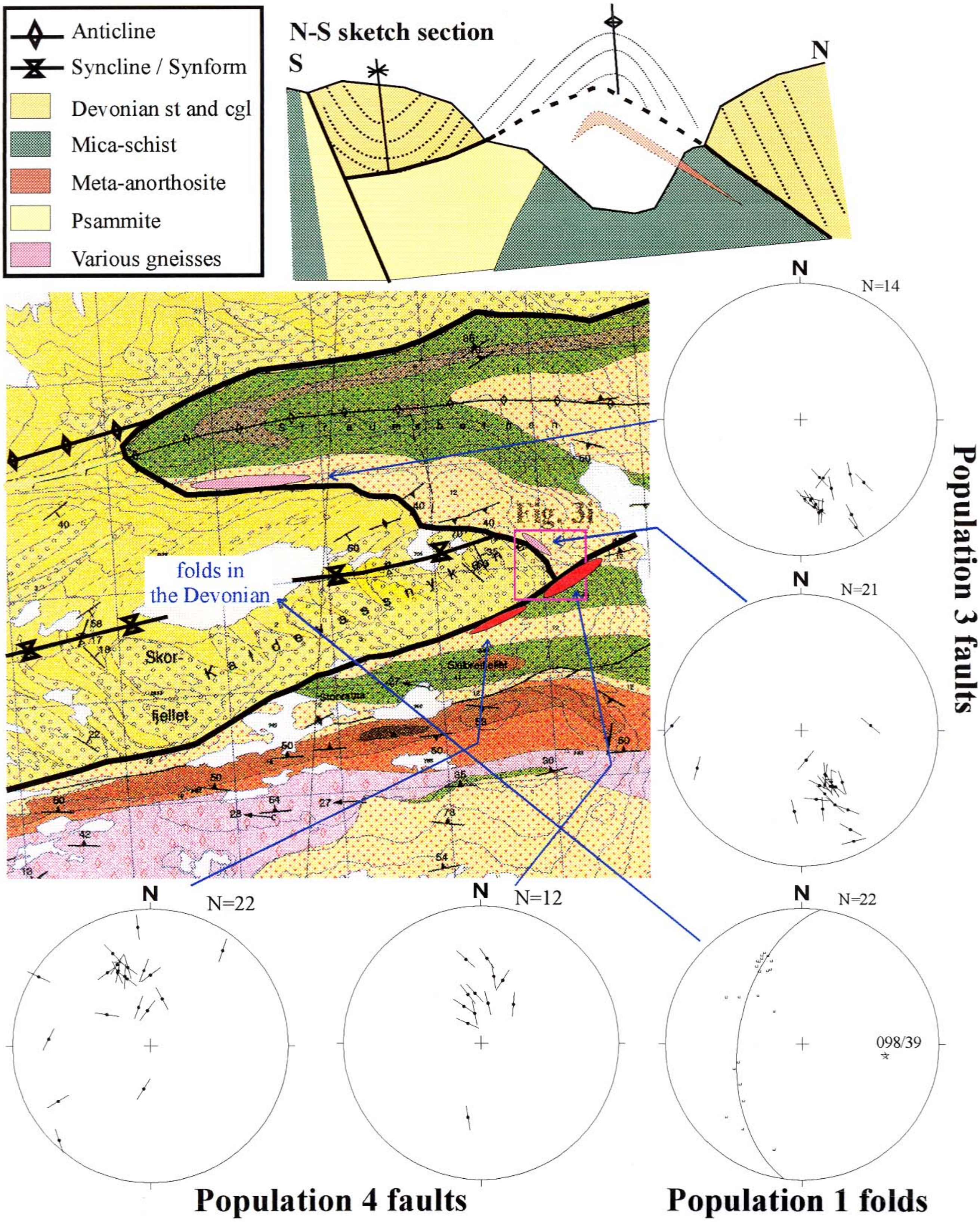


Fig. 5. Bedrock map of the southeast corner of the Hornelen basin and underlying metamorphic rocks, modified from Bryhni & Lutro (1991). Red and pink ellipses locate areas where meso-fault data, presented as slip-linear plots in the stereo-nets, have been recorded. Bedding orientations from the southeastern part of the Devonian basin are plotted as poles in the stereo-net.

4.4 Population 4

Map-scale features of population 4 affinity are evident as seven or more E-W to ENE-WSW-striking faults, which dip steeply to the north or south (Fig. 7). Commonly, these faults bound the northern and southern margin of the Devonian basins, whereas population 3 faults bound their eastern margins, as described in the section above. At several locations, fault movement has been found to exceed 500 m, and may be as much as 1000 m.

Population 4 meso-scale fault data have been collected at 17 sites along the major E-W faults (Fig. 7). Characteristically, they are cemented or coated with white or brown carbonate. Some of the sites are described above. Those sites, and the ones described here, all show a very consistent pattern. Recorded meso-faults strike WSW-ENE to WNW-ESE and dip steeply to the north or south. Slip-lines on the faults are generally subparallel to the dip-line, and, where visible, reveal normal fault movement. This coincides with the indicated down-to-the-north and -south displacement on the major faults, the latter of which bring Devonian rocks down in contact with Neoproterozoic to Lower Palaeozoic units.

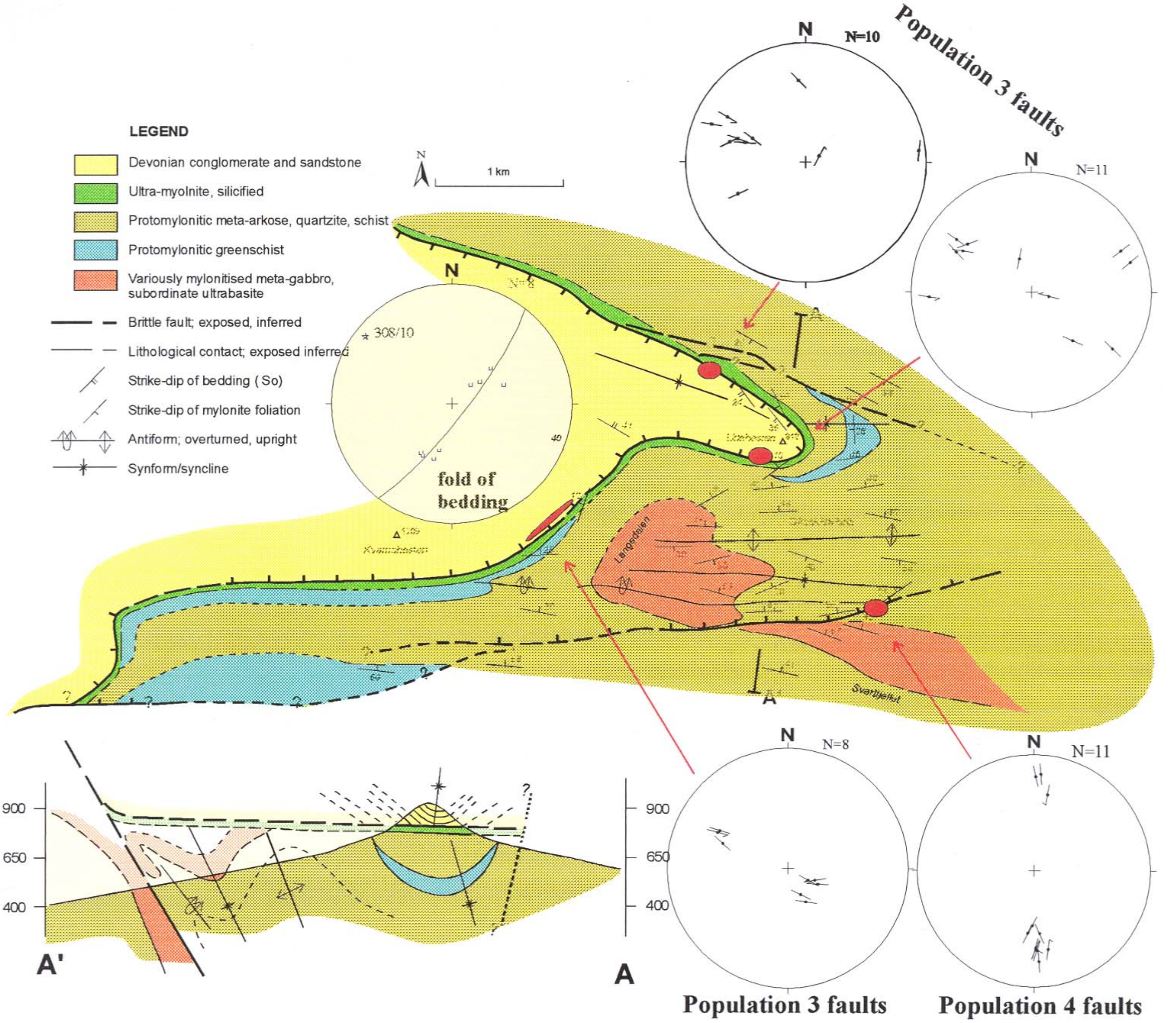


Fig. 6. Simplified bedrock map of the eastern part of the Kvamshesten Devonian basin and underlying Nordfjord-Sogn Detachment zone. Red circles and ellipses locate areas where meso-fault data, presented as slip-linear plots in the stereo-nets, have been recorded. Bedding orientations from the Devonian basin are plotted as poles in the stereo-net.

5. DISCUSSION

Comparison of the described map-scale structures, and the kinematics of meso-scale fault data (populations), reveal important information with respect to overprinting relationships of structural features, and allow recognition of chronologically different structural stages. A polyphase strain history (*in stages*) are deduced from the overprinting relationships of small- and large-scale faults and folds.

5.1 Strain chronology and kinematics

Stage 1 strain

Population 1 meso-faults are evident in association with the major reverse fault(s) of the NW Kvamshesten Devonian basin. In the west, this major fault dips moderately to the north, but further northeast, the orientation changes to subhorizontal attitudes, with local southerly dips. Since the reverse fault in the latter area occurs in the hangingwall next to one of the major E-W normal faults, it could be rotated southwards in a flexure related to the normal fault.

Kinematic data in the form of faults and folds have a consistent signature along the major thrust-fault. Fold axes established by plots of bedding in the footwall of the thrust(s) plunge moderately to the east (Fig. 2). Meso-faults have a thrust signature, with top-to-the-south and north transport, in some cases with a slight sinistral component. Thus, the bulk kinematic data support a N-S contractional setting with a horizontal N-S shortening (Z-) axis and a steeply west-plunging longest (X-) strain axis. The east-plunging folds (Y-axis), which indicate rotation of the stage 1 structural features around a N-S axis, may be due to listric normal faulting along faults bounding the basin to the east (see below). This interpretation could apply to the eastern Hornelen basin as well, where folds in the Devonian rocks have a similar eastward plunge (Fig. 5).

The contractional axis evident for structures in the Solund Devonian basin divert from the above established N-S shortening axis. On Utvær, tight SW-verging folds and a NE-dipping, penetrative axial plane cleavage (Sturt & Braathen in prep.) indicate NE-SW shortening. Further east in the basin, the recorded meso-faults are thrust-faults (Fig. 2), suggesting contraction along a NW-SE trend.

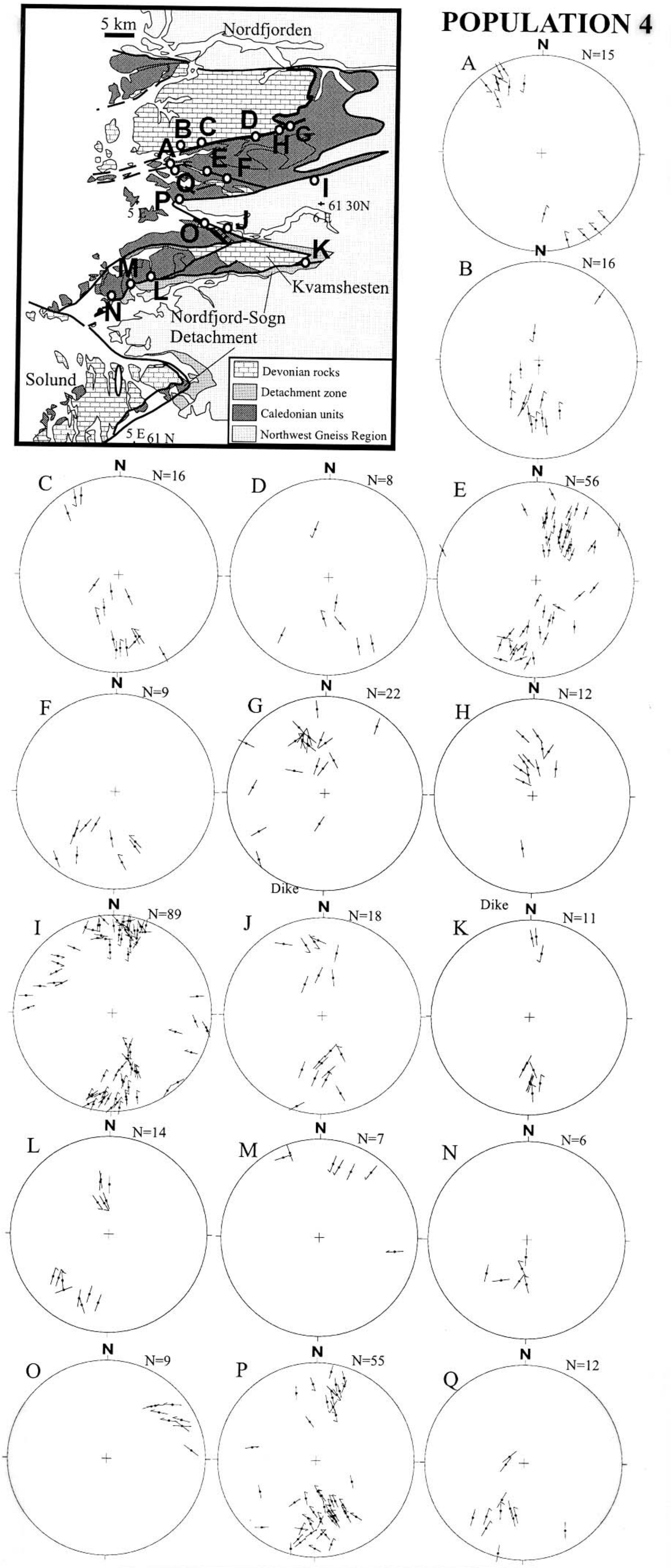


Fig. 7. Population 4 fault data from the Sunnfjord region. Dots locate sites for data recording. The meso-faults are plotted in slip-linear plots.

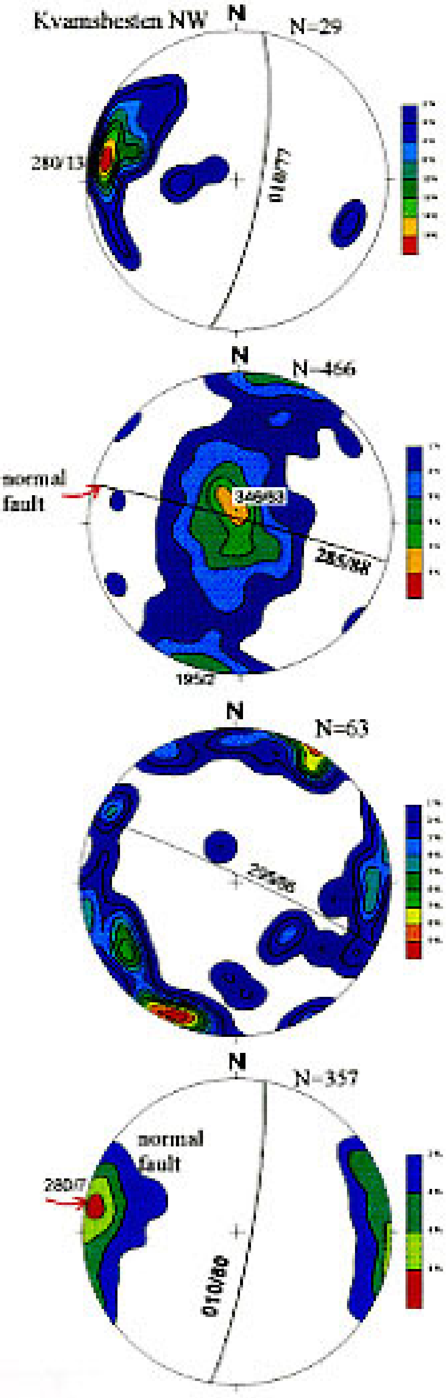
In summary, stage 1 structures are contractional in nature. The established strain axes vary but have a significant northerly component. This is clear for the major thrust and associated folds of the Kvamshesten basin, as well as for the folds in the Hornelen basin, both of which show N-S shortening. In the former area the meso-faults defines a 010°/70 ° oriented M-plane (Fig. 8) that reveals the direction of tectonic transport. In the case of the Solund area, the two locations with different strain axes have no simple explanation. One possibility is that one, or both, systems were rotated during later deformation, or alternatively, that the deformation there is more complex than hitherto appreciated.

Stage 2 strain

Abundant population 2 meso-faults associated with N-S lineaments (master-joints), and the subordinate sets of NE-SW and NW-SE lineaments, reveal a systematic strain pattern. Faults subparallel to the major N-S structures show normal movements, whereas faults with a higher angle to the lineament are oblique or strike-slip faults. Dextral separation dominates on NW-SE structures, whereas sinistral offset characterises NE-SW structures (Fig. 4). The overall geometry is that of conjugate strike-slip faults and bisecting normal faults, with structures symmetrically distributed around the first-order lineament. This fault pattern can be explained in the context of constrictional strain, with a horizontal NNE-SSW shortening (Z-) and a WNW-ESE extension (X-) axis, as indicated by the distribution of the poles to M-planes for the entire data-set. The poles plot along a NNE-SSW girdle and the average M-plane for the normal faults has a 285°/88° orientation (Fig. 8). Similar fault and strain patterns are found in the western Hornelen basin (Hartz & Andresen 1997).

The stage 2 structures occur in all rocks of the region and probably formed by reactivation of pre-existing fracture systems in the Precambrian basement that led to propagation of structures into the overlying rocks. However, two rock-types are without population 2 structures: fault breccias of populations 3 and 4 affinity. Absence of population 2 structures indicates that stage 2 structures predated the formation of these fault breccias. In the Kvamshesten Devonian basin, strike-slip faults, with kinematic patterns similar to the population 2 meso-faults interact with the major thrust-faults, indicating that they formed in close association (Osmundsen 1996, 1997). In the western Hornelen basin, as well as in the Kvamshesten basin, the population 2 structures post-dated syn-sedimentary faulting, but locally rejuvenated older faults (Osmundsen 1996; Hartz & Andresen 1997; Osmundsen et al. in press). Whereas the older deposition-related faults are folded, population 2 faults are not.

MOVEMENT-PLANE OBSERVATIONS



Population 1

- reverse faults
- fault breccia, secondary chert + epidote
- folds: synclines and anticlines
- cleavage/foliation in the Devonian rocks

Population 2

- conjugate strike-slip faults
- bisecting normal faults subparallel to N-S lineaments
- secondary chert + epidote

Population 3

- oblique-normal faults
- down-to-the-WNW (?)
- breccia
- secondary green chert

Population 4

- normal faults
- down-to-the-N and S
- breccia
- secondary carbonate

Fig. 8. Diagram presenting a resume of observations related to the four structural populations. The M-plane plot of each population presents contoured poles to M-planes, and the average M-plane for the data-set.

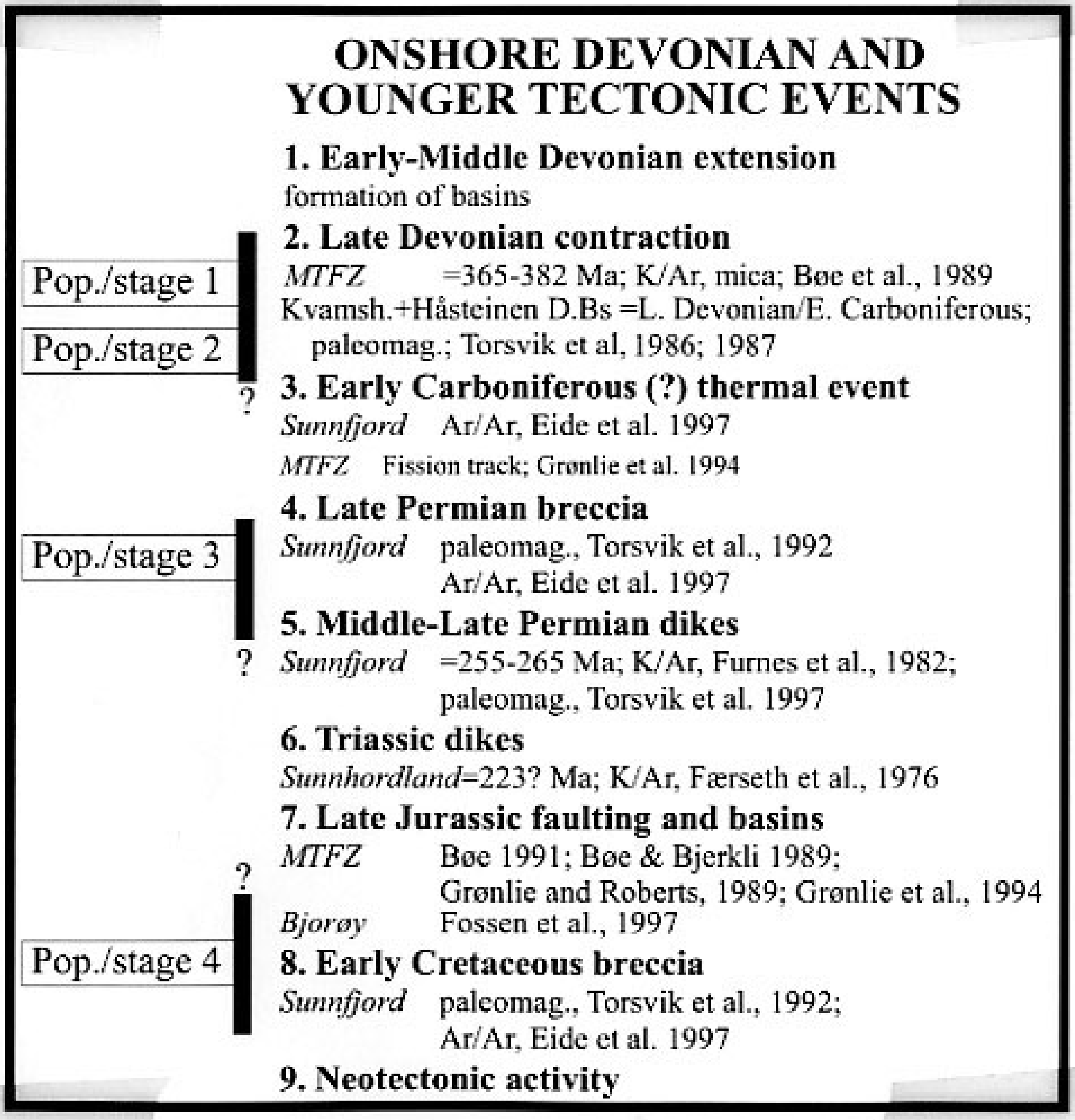
Stage 3 strain

Stage 3 structures are restricted to the low-angle faults along the eastern margin of the Kvamshesten and Hornelen Devonian basins (Figs. 5 and 6). Associated meso-faults in the Hornelen area show strike-perpendicular movements along a NNW-SSE trend, with a minor sinistral component. In a few cases, normal separation on the structures can be deduced. The dataset is dominated by faults with a high angle to the associated major low-angle fault; these high angles, in combination with the lack of slip-predictions, undermine reliable kinematic estimates. A crude estimate from the kinematic data is that the hangingwall to the low-angle fault moved in a SSE direction. However, the NE dip of the low-angle fault further north which, with such kinematics, would be a reverse fault, opposes this interpretation. A more plausible explanation for the SSE fault-movement direction is that the southern segment of the low-angle fault was reactivated during stage 4 faulting (see below).

The low-angle stage 3 fault beneath the eastern part of the Kvamshesten basin reveals meso-faults with very consistent patterns. These faults show mainly top-to-the-WNW normal displacement, suggesting that the hangingwall of the main fault was transported towards WNW. This is also supported by the established M-plane for the entire population 3 data-set. Including data from Hornelen, the plot reveals some scatter of poles to the M-planes (Fig. 8), but a well defined M-plane oriented $295^{o}/86^{o}$ can be constructed on the basis of the consistent dataset from the eastern Kvamshesten basin. Similar kinematics have been suggested for late, steep faulting in western parts of the Hornelen basin (Hartz & Andresen 1997).

The low-angle normal faults have been suggested to have acted as basin-bounding, listric, normal faults during the deposition in the Devonian basins (e.g., Seranne & Seguret 1987; Chauvet & Seranne 1994). Such a syn-depositional origin is unlikely, since the Devonian basin and underlying mylonites were folded and then truncated by the planar fault. The changing plunges of major folds in the Kvamshesten Devonian basin, from moderate east plunges to a subhorizontal west plunge near the eastern margin, may be explained by a flat-ramp geometry of the eastern margin fault. In this case the low-angle fault, overlain by a subhorizontal fold near the eastern nose of the basin, constitutes a flat-geometry, whereas parts of the fault under the moderately plunging folds further west would be ramp-faults.

There are clear cross-cutting relationships between the stage 3 and stage 4 faults. The best example is revealed from the SE corner of the Hornelen Devonian basin (Fig. 5i), where the low-angle stage 3 fault is truncated by the steep stage 4 fault (Torsvik et al. 1997). A similar cross-cutting relationship is indicated for the SE termination of the Kvamshesten basin (Fig. 6; Kildal 1970).



ONSHORE DEVONIAN AND YOUNGER TECTONIC EVENTS

1. Early-Middle Devonian extension
formation of basins

2. Late Devonian contraction
MTFZ =365-382 Ma; K/Ar, mica; Bøe et al., 1989
Kvamsh.+Håsteinen D.Bs =L. Devonian/E. Carboniferous; paleomag.; Torsvik et al, 1986; 1987

3. Early Carboniferous (?) thermal event
Sunnfjord Ar/Ar, Eide et al. 1997
MTFZ Fission track; Grønlie et al. 1994

4. Late Permian breccia
Sunnfjord paleomag., Torsvik et al., 1992
Ar/Ar, Eide et al. 1997

5. Middle-Late Permian dikes
Sunnfjord =255-265 Ma; K/Ar, Furnes et al., 1982;
paleomag., Torsvik et al. 1997

6. Triassic dikes
Sunnhordland=223? Ma; K/Ar, Færseth et al., 1976

7. Late Jurassic faulting and basins
MTFZ Bøe 1991; Bøe & Bjerkli 1989;
Grønlie and Roberts, 1989; Grønlie et al., 1994
Bjorøy Fossen et al., 1997

8. Early Cretaceous breccia
Sunnfjord paleomag., Torsvik et al., 1992;
Ar/Ar, Eide et al. 1997

9. Neotectonic activity

Fig. 9. Diagram of documented tectonic events in western and northwestern South Norway. Timing of tectonic events are linked with the four populations/stages, as discussed in the text.

Stage 4 strain

The major E-W faults of stage 4 affinity are normal in character. This is supported by the kinematics of the population 4 meso-faults, having a similar orientation as the first-order structure, and revealing slip-indicators consistent with normal faulting. The entire population 4 dataset reveals a well defined average M-plane oriented at 010^o /80^o (Fig. 8).

Indications for drag-folding related to the stage 4 faulting exist in places where the major stage 4 normal faults are seen to truncate, or be in the proximity of older structures. The low-angle stage 3 fault of the eastern Hornelen basin, for example, is curved towards the steep, E-W stage 4 fault (Figs. 3i and 5). This is seen as a successive change from SW dips to more westerly dips of the former proximal to the stage 4 fault, and the low-angle fault may have been reactivated at this stage. Another example is the subhorizontal orientation of the stage 1 thrust in the northern cliff-face of the Kvamshesten basin (Fig. 3b). This thrust, initially climbing towards the south, is rotated to a position where it is locally dipping to the south, showing down-dip fault offset. This is certainly inconsistent with the contractional nature of the fault-propagation folds. In combination, drag-related folding controlled by the movement on the major stage 4 normal fault is a reasonable explanation for the discussed structures.

5.2 Timing of tectonic events

Absolute dating of brittle fault movements (Fig. 9) has isolated two brittle reactivation episodes in the Sunnfjord region (Torsvik et al. 1992; Eide et al. 1997). On Atløy, along one of the stage 4 E-W faults, breccia-forming episodes are demonstrated to be of Late Permian (green, chert-cemented breccia) and latest Jurassic - Early Cretaceous ages (red, carbonate-cemented breccia), based on ^{40}Ar-^{39}Ar-dating and paleomagnetic analyses. The younger red breccia truncates the green breccia, and the latter also hosts population 4 meso-faults. There seems to be a systematic regional pattern with respect to introduced secondary minerals - carbonate cement is typical for population 4 faults, whereas green chert is commonly associated with population 3 faults.

A third event, of Early Carboniferous age, is documented as a rapid cooling (unroofing) episode via ^{40}Ar-^{39}Ar thermochronolgy; the cooling event is manifested in both the hanging- and footwall (Eide et al. 1997, Eide & Torsvik 1998). Other time-markers in western Norway are those of dolerite dykes, commonly intruded along N-S lineaments. Their ages range from Permian to Triassic (e.g., Færseth et al. 1976); however, in Sunnfjord, a mid-Late Permian age has been detected by remanent magnetism (Torsvik et al. 1997) and K-Ar dating (Furnes et al. 1982). The latter age suggests that the dolerite dykes are contemporaneous with the Permian brittle faulting, whereas metamorphic alteration to a lower greenschist-facies mineralogy in proximity to E-W shear/fault zones indicates tectonic rejuvenation post-dating dyke intrusion (Torsvik et al. 1997). Paleomagnetism has also been used to indicate an age for formation of the lower greenschist-facies axial plane cleavage related to E-W folds (population/stage 1) in the Kvamshesten and Håsteinen Devonian basins (Torsvik et al. 1986, 1987, 1988). These fabrics yielded a Late Devonian/Early Carboniferous magnetisation age that are contemporaneous with the mentioned rapid cooling event.

The absolute ages presented above may well relate to the established tectonic stages (Fig. 9). Stage 1 thrusting, with associated folding and formation of cleavage, probably occurred in Late Devonian - Early Carboniferous times. This is further supported by K-Ar-dating of a phengite-bearing axial plane cleavage in Devonian rocks on Hitra (Møre-Trøndelag Fault Zone), which yielded an age of 365-282 Ma (Bøe et al. 1989).

The stage 2, conjugate strike/oblique-slip faults and bisecting normal faults post-date deposition in the Devonian basins, and besides, have been suggested to have interacted with stage 1 thrust faults (Osmundsen 1996). Thus, the stage 2 faults probably formed contemporaneously with, or followed the thrusting and folding. A progressive strain sequence from stage 1 to stage 2 is most likely since the stage 2 faults truncate folds without showing evidence of participation in the major folding. In summary, it is reasonable to assume that stage 2 faults followed stage 1 shortening, thereby recording continuous N-S shortening and a shift from stage 1 contractional to stage 2 constrictional strain.

The later, stage 3 west-directed normal faults are characteristically cemented by green chert. Fault rocks on Atløy, with a similar cement, have yielded a Late Permian age, which is the most reasonable age-assumption for the stage 3 faulting. Indirect evidence for such an age - stage 3 faults truncate the stage 1 E-W folds and the stage 2 faults, and are truncated by stage 4 faults - fit this postulate.

The stage 4 E-W faults are the youngest established structures in the region (except for neotectonism). This late relative age, the regional introduction of carbonate along the faults, and indications for Permian dykes being affected by E-W faults, all point to a common age in accordance with the red fault breccia on Atløy. A Late Jurassic - Early Cretaceous age is therefore reasonable for the stage 4 faulting.

5.3 Neotectonics

There are several indications of neotectonic reactivation in the Sunnfjord region. However, the lack of Quaternary sediments or markers preclude the establishment of definite ages. The only valid information that exists is the relatively high frequency of near-shore and offshore faulting (e.g., Lindholm et al. 1995), pointing towards neotectonic reactivation in the onshore areas.

Several of the major E-W faults have 0.2-1 m-thick zones of fault gouge, indicating that these structures have probably been reactivated in recent times (latest 100,000 years). The best example is found on Atløy, where the red and green fault breccias are reactivated and partly truncated by a non-lithified 20-60 cm zone (Fig. 3g). The fault gouge consists of gravel-size fragments of the older breccias set in a matrix of very fine-grained, dark rock flour and clay(?) minerals. In places, groundwater seeps from the fault. Similar observations exist for the E-W Standal fault, which recently was excavated in a road tunnel and immediately cemented during construction work. This fault contained an unlithified part as well (T.B. Andersen, pers. comm. 1995). Another example is the steep fault bounding the northern side of the Hornelen basin, also excavated in a road tunnel. This structure leaks water along what is probably a non-lithified part of the fault zone. When these observations are summarised, they show that at every location where the E-W faults have been excavated, there are apparently young non-lithifed parts. Therefore, young/neotectonic reactivation of E-W faults seams to be ubiquitous.

Detailed studies on the fracture patterns and occurrences of fault rocks in the centre of N-S, NW-SE and NE-SW lineaments indicate that parts of the major structures may be reactivated and therefore, are important groundwater conduits (Gabrielsen et al. 1997; Braathen et al. 1997b, 1998; Berg et al. 1997). In places, this fracture permeability appears to have been markedly reduced by the growth of secondary zeolite (Fig. 3j) and clay minerals. Such minerals commonly occur along distinct, young fractures cross-cutting older fractures, indicating reactivation of the lineaments.

Predictions in regional rock stress models, based on earthquake and drillhole breakout data (Bungum et al. 1991; Lindholm et al. 1995, Fejerskov et al. 1995), have recently been confirmed by onshore in-situ stress recordings in the Sunnfjord region. The latter data-set consists of hydro-fracturing assessments in shallow vertical drillholes (Hansen 1996) and overcoring results from inside tunnels (Myrvang 1993; Fejerskov et al. 1995; Midtbø 1996). The model shows a regional maximum horizontal rock stress with a WNW-ESE to E-W axis in southern parts of Sunnfjord, rotating slightly clockwise northwards. However, in areas with rough topography, gravity-induced stress interacts with the regional stress, causing local deviations. Very high horizontal stresses, occasionally exceeding 30 MPa, have been detected. One consequence of these high stresses, in combination with high, steep valley sides, is the formation of surface-parallel fractures (Glasser 1997), which are common features in the Sunnfjord region. Such fractures occur in areas where the regional stress acts parallel to the valley sides (Midtbø 1996), and probably represent areas with an increased risk for rock avalanches. Another aspect of the high stresses is the potential for reactivation of pre-existing structures.

High shear stress along inherited structures is essential in this respect (e.g., Morris et al. 1996); high shear stress theoretically favours reactivation of structures with an approximately 30^o angle to the maximum regional stress. A crude estimate for the Sunnfjord region indicates: (i) a high potential for reactivation of the E-W faults, especially where they have a gentle dip; (ii) low potential for reactivation of N-S lineaments; and (iii) moderate potential for reactivation of NE-SW and NW-SE lineaments. The young fault gouges present along the E-W faults fit these predictions.

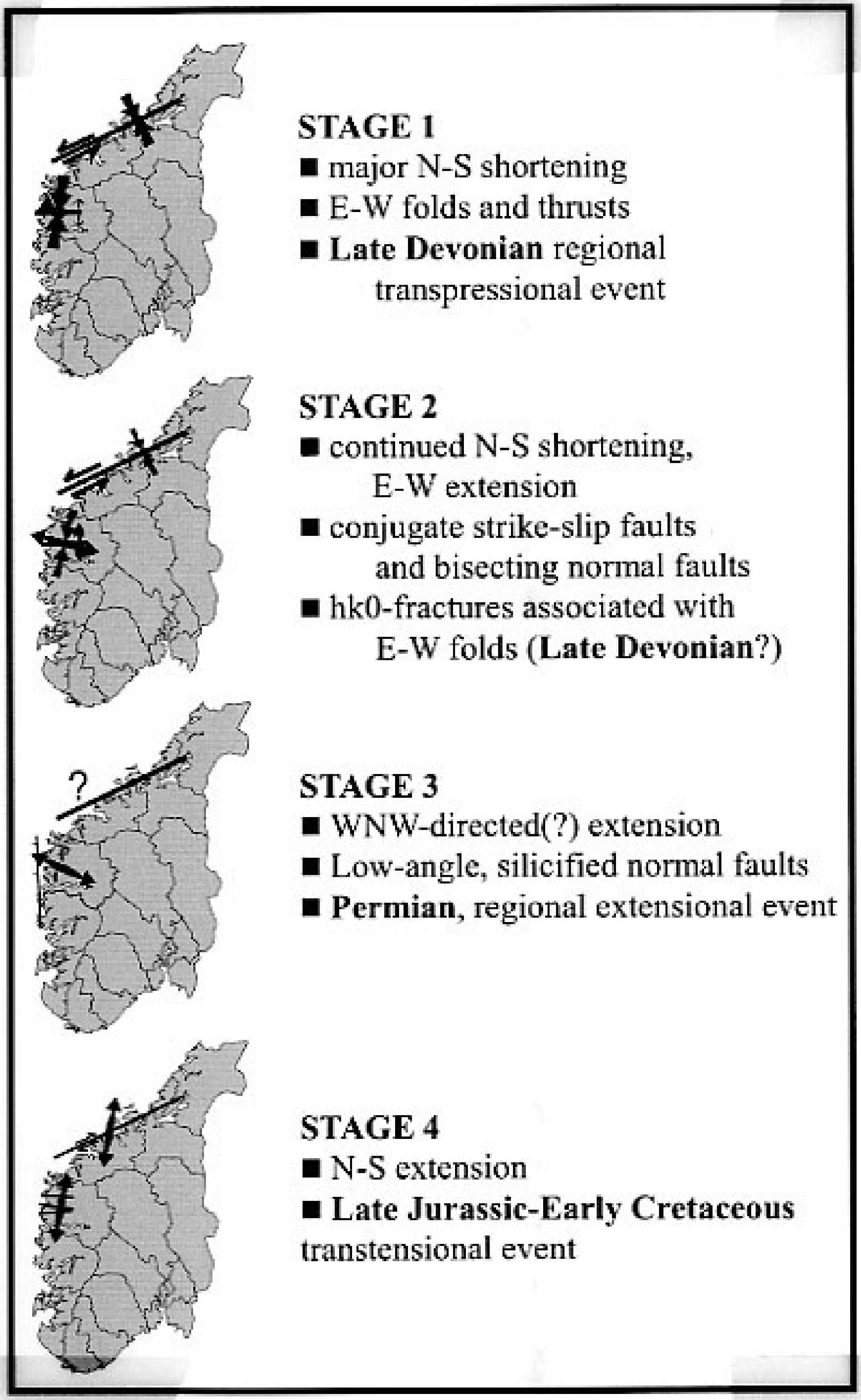
6. REGIONAL CONSIDERATIONS

All of the four established stages of brittle faulting in the Sunnfjord region post-date the creation of the Caledonian thrust-welt and the late Caledonian hinterland-directed extension. Faults related to the formation of the Devonian basins are documented inside some of the basins and along their western margins (Bryhni & Skjerlie 1975; Steel et al. 1985; Hartz et al. 1995; Osmundsen 1996, 1997; Hartz & Andresen 1997). According to Osmundsen (1996) and Hartz & Andresen (1997), these faults are arranged in an orthorhombic pattern, reflecting N-S and E-W extension. They were subsequently folded together with the Devonian and underlying rocks into regional E-W trending flexures. Thus, stage 1 folding and thrusting followed west-directed extension of the orogen and basin-related faulting.

The regional distribution of stage 1 shortening is illustrated by the extent of E-W folds in western Norway, and the related NE-SW folds along the Møre-Trøndelag Fault Zone (or Complex; Blystad et al. 1995). Major E-W folds are also evident in inland parts of the Caledonides of southern Norway (Strand 1951; Roberts 1974; Sturt & Ramsay 1997). The assembled observations lend support to the suggestion that a Late Devonian, regional contractional or transpressional event, post-dating Devonian extension (e.g., Roberts 1983; Sturt 1983), affected southern Norway; Sturt (1983) have referred to this folding event as the *Solundian* phase. The significance of stage 1 N-S contractional strain in the Sunnfjord region may also be viewed in the light of movements along the Møre-Trøndelag Fault Zone (Aanstad et al. 1981; Roberts 1983; Grønlie & Roberts 1989, Seranne 1992). In such a model (Fig. 10), N-S shortening rejuvenated the NE-SW structural grain along the Møre-Trøndelag Fault Zone, leading to sinistral transpression there, whereas areas without such inherited structural control suffered pure contraction (Sturt 1983). The close temporal relationship between stage 1 and stage 2 structures suggests that continued stage 1 shortening and crustal thickening in the Sunnfjord region resulted in a shift from pure N-S contraction to shortening and additional horizontal WNW-ESE extension, the latter of stage 2 affinity. Likewise, sinistral simple shear along the Møre-Trøndelag Fault Zone could create a WNW-ESE stretching field in addition to NNE-SSW shortening. Such sinistral shearing has actually been suggested for the Møre-Trøndelag Fault Zone (Grønlie & Roberts 1989; Seranne 1992), contradicting older work that have argued for dextral movements (Aanstad et al. 1981; Roberts 1983). The Carboniferous cooling phase recognised in Sunnfjord (Eide et al. 1997), and a similar Early Palaeozoic uplift/cooling in the Trøndelag region (Grønlie et al. 1994), may well be explained as an effect of this regional event.

E-W extension in Permian time is well established on the Norwegian continental shelf (e.g., Dore & Gage 1987; Nødtvedt et al. 1995; Færseth et al. 1995; Færseth 1996). The wide extent of this tectonism, supported by the abundant onshore Permian dykes and the dated fault rock of Sunnfjord, is an argument in favour of Permian faulting in the Sunnfjord region. There, kinematic indicators on the low-angle stage 3 faults along the eastern margin of the Devonian basins suggest WNW-directed extension (Fig. 10), which coincides with the kinematics on steep NNE-SSW-striking normal faults on the coast (Hartz & Andresen 1997). The major, approximately N-S oriented, Øygarden Fault Complex, located some kilometres offshore from the Sunnfjord region, probably acted as a master fault at this stage (Færseth et al. 1995), triggering steep, normal faults in its vicinity, and partial reactivation of the low-angle Nordfjord-Sogn Detachment further east.

The Jurassic - Early Cretaceous period was another important stretching event in the evolution of the North Sea, as manifested by the formation of the narrow Viking Graben (e.g., Færseth 1996). Outside the graben, minor reactivation is documented, e.g., along the Øygarden Fault Complex (Færseth et al. 1995), as well as onshore in the Sunnfjord (Torsvik et al. 1992; Eide et al. 1997) and Bergen areas (Fossen et al. 1997a). A NW-SE stretching in offshore areas has been advocated for the NNE-SSW oriented Jurassic faults (Dore & Gage 1987; Færseth 1996), and may well apply to the faulting in the Bergen area (Reemst et al. 1997; Fossen et al. 1997b). In contrast, kinematics of stage 4 normal faults in the Sunnfjord region reveal a NNE-SSW stretching axis, which is not easily accommodated in the regional strain patterns. One possible explanation includes dextral transtension along the Møre-Trøndelag Fault Zone in accordance with a NW-SE regional stretching field. This is supported by Jurassic basin formation (Bøe & Bjerkli 1989; Bøe 1991) in association with suggested dextral reactivation of this fault zone (Grønlie & Roberts 1989). Such dextral transtension there could have caused clockwise rotation towards a more N-S-oriented stretching axis. If valid, the stage 4 normal faulting in the Sunnfjord region is here explained by the imposition of a more local NNE-SSW stretching field, where the reactivation of an E-W inherited structural grain probably played a role.



STAGE 1
- major N-S shortening
- E-W folds and thrusts
- **Late Devonian** regional transpressional event

STAGE 2
- continued N-S shortening, E-W extension
- conjugate strike-slip faults and bisecting normal faults
- hk0-fractures associated with E-W folds (**Late Devonian**?)

STAGE 3
- WNW-directed(?) extension
- Low-angle, silicified normal faults
- **Permian**, regional extensional event

STAGE 4
- N-S extension
- **Late Jurassic-Early Cretaceous** transtensional event

Fig. 10. Diagram presenting the shortening and extension directions, and suggested timing, for the four stages of brittle deformation in the Sunnfjord region. Possible regional implications and kinematics are indicated on the maps, and are further discussed in the text.

7. ACKNOWLEDGEMENTS

The author thanks Torgeir Andersen, Per Terje Osmundsen, Ann Kathrine Svendby, Ebbe Hartz, Arild Andresen, Helge Henriksen, Roy Gabrielsen, Elisabeth Eide, Rune Larsen, David Roberts, Brian Sturt and Trond Torsvik for many fruitful discussions bearing on the progress of this work. The project has been financed by the Geological Survey of Norway and associated industrial partners.

8. REFERENCES

Allmendinger, R.W., 1982. Analysis of microstructures in the Meade plate of the Idaho-Wyoming foreland thrust belt, USA. *Tectonophysics, 85,* 221-251.

Aleksandrowski, P., 1985. Graphical determination of principal stress direction for slikenside lineation populations: An attempt to modify Arthaud's methode. *J. Struct. Geol., 7,* 73-82.

Andersen, T.B., & Jamtveit, B., 1990. Uplift of deep crust during orogenic extensional collapse: A mode based on field studies in the Sogn-Sunnfjord region of western Norway. *Tectonics 9*, 1097-1111.

Andersen, T.B. & Andresen, A. 1994. Stratigraphy, tectonostratigraphy and accretion of outboard terranes in the Caledonides of Sunnhordland, W. Norway. *Tectonophysics 231*, 71-84.

Andersen, T-B., Skjerlie, K.P. & Furnes, H. 1990. The Sunnfjord Melange, evidence of Silurian ophiolite accretion in the West Norwegian Caledonides. *J. Geol. Soc. Lond., 147*, 59-68.

Andersen, T.B., Jamtveit, B., Dewey, J.F. & Swensson, E., 1991. Subduction and eduction of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova, 3,* 303-310.

Angelier, J., 1984. Tectonic analysis of fault slip data sets. *Journal of Geophysical Reserch, 89*, 5835-5848.

Angelier, J. 1994. Fault slip analysis and paleostress reconstruction. In Hancock, P.L. (ed.): *Continental deformation*. Oxford Pergamon Press, 421 p.

Berg, S., Braathen, A., Gabrielsen. R.H., Lothe, A. and Henriksen, H., 1997. Lineaments and systematic fracture distribution in the Sunnfjord region, western Norway. TSGS-meeting, Stavanger, November 1997.

Blystad, P., Brekke, H., Færseth R.B., Larsen B.T., Skogseid, J. & Trørudbakken, B. 1995. Structural elements of the Norwgian continental shelf. Part II: The Norwegian Sea region. *Norwegian Petroleum Directorate Bulletin no. 8*, 42 p.

Bryhni, I. & Lutro, O. 1991. Naustdal, berggrunnsgeologisk kart 1218 III, M 1:50000, *Norges geologiske undersøkelse*.

Bryhni, I. & Skjerlie, F.J. 1975. Syndepositional tectonism in the Kvamshesten district (Old Red Sandstone), western Norway. *Geological Magazine 112*, 593-600.

Braathen, A., 1997a. Post-devonske forkastningssystemer i Sunnfjord, Vest-Norge. *Geonytt 1-97*, p. 27.

Braathen, A. 1997b. Post-Caledonian fault systems in the Sunnfjord region of western Norway. TSGS meeting, Stavanger, November 1997.

Braathen, A., Gabrielsen, R.H. & Henriksen, H. 1997. Lineamenter, sprekkefordeling og grunnvann i krystalline bergarter i Sunnfjord. Hydrogeologisk Seminar, *NGU Report 97.150*, p.11.

Braathen, A. & Bergh, S.G. 1995: Kinematics of Tertiary deformation in the basement-involved fold-thrust belt, western Nordenskiøld Land, Svalbard; Tectonic implications based on fault slip data analysis. *Tectonophysics, 249,* 1-29.

Braathen, A., Gabrielsen, R.H. & Henriksen, H. 1998. Lineament architecture and fracture systems: frequency and orientation of fractures in crystalline rocks of Norway. *Norges geologiske undersøkelse report 98.043.*

Braathen, A. And Henriksen, H., 1997. Post-Devonian fracture systems in the Sunnfjord region, onshore western Norway. *Norges geologiske undersøkelseBulletin 433,* p. 16-17.

Bungum, H., Alsaker, A., Kvamme, L.B. & Hansen, R.A. 1991. Seismicity and seismotectonics of Norway and nearby continental shelf. *Journal of Geophysical Research 96*, 2249-2265.

Bøe, R., 1991. Structure and seismic stratigraphy of the innermost mid-Norwegian continental shelf: an example from the Frohavet area. *Mar. Pet. Geol., 8*, 140-151.

Bøe, R., and Bjerkli, K., 1989. Mesozoic sedimentary rocks in Edøyfjorden and Beistadfjorden, central Norway. implications for the structural history of the Møre-Trøndelag Fault Zone. *Mar. Geol., 87*, 287-299.

Bøe, R., Atakan, K. & Sturt, B.A. 1989. The style of deformation of the Devonian rocks on Hitra and Smøla, Central Norway. *Norges geologiske undersøkelse Bulletin 414*, p. 1-20.

Chauvet, A. & Seranne, M., 1989. Microtectonic evidence of Devonian extensional westward shearing in Southwest Norway. In R.A. Gayer (Ed.), *The Caledonide Geology of Scandinavia*. Graham & Trotman.

Cuthbert, S., 1991. Evolution of the Hornelen Basin, west Norway: new constraints from petrological studies of metamorphic clasts. In A. Morton, S.P. Todd & P.D.W. Haughton (eds.) *Developments in sedimentary Provenence Studies*. Geol. Soc. Lond. Special Publ., 57, 343-360.

Dore, A.G., and Gage, M.S., 1987. Crustal alignements and sedimentary domains in the evolution of the North Sea, Northeast Atlantic Margin and Barents Shelf. In: Broos, J., and Glennie, K. (eds.), *Petroleim geology of North West Europe*, p. 1131-1148. Graham and Trotman.

Eide, E.A., Torsvik, T.H. & Andersen, T.B. 1997. Absolute dating of brittle fault movements: Late Permian and late Jurassic extensional fault breccias in western Norway. *Terra Nova*, *9*, 135-139.

Eide, E.A. & Torsvik, T.H. 1998. Onshore dating of Late Palaeozoic activities on the eastern and western proto-North Atlantic margins. *Norges geologiske undersøkelse Report 98.004*.

Etchopar, A., Vasseus, G., & Daigniers, M., 1981. An inverse problem in microtectonics for the determination of stress tensor from fault striation analysis. *J. Struct. Geol., 3,* 51-65.

Fejerskov, M., Myrvang, A.M., Lindholm, C. & Bungum, H. 1995. In-situ rock stress pattern on the Norwegian continental shelf and mainland. In Fejerskov, M. & Myrvang, A.M. (eds.), *Proceeding from Workshop on rock stresses in the north Sea*, Trondheim, Norway, 13-14 February 1995.

Fossen, H. 1992. The role of extensional tectonics in the Caledonides of southern Norway. *Journal of Structural Geology 14,* 1033-1046.

Fossen, H., Mangerud, G., Hesthammer, J., Bugge, T. & Gabrielsen R.H. 1997a. The Bjorøy Formation: a newly discovered occurrence of Jurassic sediments in the Bergen Arc system. *Norsk geologisk tidsskift 4*, 269-288.

Fossen, H, Gabrielsen, R.H. & Reemst, P.1997b. Assessment of the post-Caledonian history of SW Norway through integrated studies. Abstract, TSGS-meeting, Stavanger.

Furnes, H., Mitchell, J.G., Ryan, P. & Skjerlie, F.J., 1982. Petrography and geochemistry of peralkaline, ultrapotassic syenite dykes of Middle Permian age, Sunnfjord, West Norway. *Nor. Geol. Tidsskr., 62*, 147-159.

Furnes, H., Skjerlie, K.P., Pedersen, R.B., Andesren, T.B., Stillman, C.J., Suthren, R., Tysseland, M. & Garmann, L.B., 1990. The Solund-Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: Geology, geochemistry and tectonic environment. *Geol. Mag., 28,* 209-224.

Færseth, R.B., Gabrielsen, R.H. & Hurich, C.A., 1995. Influence of basement in structuring of the North Sea basin, offshore southwest Norway. *Nor. Geol. Tidsskr. 75*, 105-119.

Færseth, R.B.1996. Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea. *Journal of the Geological Society, London, 153*, 931-944.

Færseth, R.B., Macintyre, R.M., & Naterstad, J., 1976. Meszoic alkaline dykes in the Sunnhordaland region, western Norway: ages, geochemistry and regional significance. Lithos 9, 332-343.

Goldstein, A., & Marshak, S., 1988. Analysis of fracture array geometry. In *Basic Methodes of Structural Geology*, p. 249-268, edited by Marshak, S. and Mitra, G.,. Prentice-Hall, Eaglewood Cliffs, New Jersey.

Gabrielsen, R.H., Braathen, A., E. Alsaker, L. Aamodt, S.S. Berg, H. Henriksen & A. Lothe, 1997. The architecture of lineaments. Abstract, TSGS meeting, Stavanger, November.

Gabrielsen, R. & Ramberg, I.B., 1978. Fracture patterns in Norway from LANDSAT imagery: results and potential use. Nor. Pet. Soc. 23, 1-28.

Glasser, N.F. 1997. The origin and significance of sheet joints in the Cairngorm granite. *Scottish Journal of Geology 33,* 125-131.

Grønnlie, A., Naeser, C.W., Naeser, N.D., Mitchell, J.G., Sturt, B.A., and Ineson, P.R., 1994. Fission-track and K-Ar dating of tectonic activity in a transect across the Møre-Trøndelag Fault Zone, central Norway. *Norsk Geologisk Tidsskrift 74,* 24-34.

Grønnlie, A., and Roberts, D., 1989. Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Fautls, Møre-Trøndelag Fault Zone, Central Norway. *Journal of Structural Geology, 11,* 295-305.

Hancock, P.L.,1985. Brittle microtectonics: principles and practice. *Journal of Structural Geology, 7,* 437-457.

Hansen, S.E. 1996. Spenningsmåling ved hydraulisk splitting, Hestad og Atløy i Sogn og Fjordane. *Sintef Report STF22 F96090,* 11 p.

Hartz, E. & Andresen, A. 1997. From collision to collapse: Complex strain permutations in the hinterland of the Scandinavian Caledonides. *Journal of geophysical Research 103,* 24697-24711.

Hartz, E., Andresen, A. & Andersen, T.B. 1995. Structural observations adjacent to a large-scale extensional detachment zone in the hinterland of the Norwegian Caledonides. *Tectonophysics 231*, 123-137.

Kildal, E.S., 1970. Geological map of Norway, bedrock Måløy, map-sheet 20, 1:250 000. Geological Surv. Norway.

Lindholm, C.D., Bungum, H., Bratli, R.K., Aadnøy, B.S., Dahl., N., Tørudbakken, B., & Atakan, K., 1995. Crustal stress in the northern North Sea as inferred from borehole breakouts and earthquake focal mechanisms. Terra Nova 7, 51-59.

Marret, R., & Allmendinger, R.W., 1990. Kinematic analysis of fault slip data. *J. Struct. Geol., 12* (8), 973-986.

Marshak, S., Geiser, P.A., Alvarez, W. and Engelder, T., 1982. Mesoscopic fault array of the northern Umbrian Apennine fold belt, Italy: Geometry of conjugate shear by pressure solution slip. *GSA Bull., 93*, 1013-1022.

Midtbø, E. 1996. *Sammenheng mellom in-situ spenninger og grunnvannstrøm i berg*. Diplomogave, 61 p., Norges teknisk-naturvitenskaplig universitet.

Milnes, A.G., Wennberg, O.P., Skår, Ø & Koestler, A.G. 1997. Contraction, extension and timing in the Southern Norwegian Caledonides: the Sognefjorden transect. In Burg, J-p. & Ford, M. (eds): Orogeny through time. *Geological Society Special Publication 121,* 123-148.

Morris, A., Ferrill, D.A. & Henderseon D.B. 1996. Slip-tendency analysis and fault reactivation. *Geology 24,* 275-278.

Myrvang, A.M. 1993. Rock stress and rock stress problems in Norway. In Hudson, J.A. (ed.), *Comprehensive rock engineering, vol. 3*. Pergamon Press, p. 461-471.

Nilsen, T.H., 1968. The relationship of sedimentation to tectonics in the Solund Devonian district of southwestern Norway. *Nor. Geol. Unders. 259*, 108 pp.

Norton, M., 1986. Late Caledonian extension in western Norway: A response to extreme crustal thickening. Tectonics, 5, 195-204.

Nøttvedt, A., Gabrielsen, R.H. and Steel, R.J.1995. Tectonostratigraphy and sedimentary architecture of rift basins, with reference to the northern North Sea. *Marine and Petroleum Geology 12*, 881-901.

Osmundsen, P-T., 1996. *Late-orogenic structural geology and Devonian basin formation in Western Norway: A study from the hanging wall of the Nordfjord-Sogn Detachment in the Sunnfjord Region*. Unpublished Dr. Scient thesis, University of Oslo.

Osmundsen, P.T., Andersen, T.B., Markusen, S., Svendby, K. & Bakke, B.A. 1997. Structural geology and facies architecture in a supra-detachment basin: the Kvamshesten Devonian basin. *Geonytt 1-97*, 74-75.

Osmundsen, P.T. & Andersen, T.B., 1994. Caledonian compressional and late-orogenic extensional deformation in the Stavenest area, Sunnfjord, Western Norway. *J. Struct. Geol. 16*, 1385-1401.

Osmundsen, P.T., Andersen, T.B, Markussen, S. & Svendby, A.K in press: Tectonics and sedimentation in the hanging wall of a major extensional detachment: The Devonian Kvamshesten basin, western Norway". *Basin Research.*

Petit, J.P., 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. *J. Struct. Geol., 9*, 597-608.

Ramberg, I.R., Gabrielsen, R., Larsen, B.T. & Solli, A., 1977. Analysis of frature patterns in southern Norway. *Geologie en Mijnbouw 56*, 295-310.

Reemst, P.1997. Stress history of the Bergen area from lineament and fault analysis: an analogue of northern North Sea rift evolution? Abstract, TSGS-meeting, Stavanger.

Roberts, D. 1974. Sedimentary, tectonic and metamorphic features of the Devonian of Røragen, Sør-Trøndelag. *Norges geologiske undersøkelse 311*, p. 89-108.

Roberts, D. 1983. Devonian tectonic deformation in the Norwegian Caledonides and its regional perspective. *Norges geologiske undersøkelse 380*, p. 85-96.

Roberts, D. & Gee, D.G. 1985. An introduction to the Scandinavian Caledonides. In Gee, D.G & Sturt, B.A. (eds.), *The Caledonian Orogeny - Scandinavia and related areas*. John Wiley & Sons, p. 55-68.

Seranne, M. 1992. Late Palaeozoic kinematics of the Møre-Trøndelag Fault Zone and adjacent areas, central Norway. *Norsk Geologisk Tidsskrift 72*, 141-158.

Seranne, M. & Seguret, M., 1987. The Devonian basins of western Norway:tectonics and kinematics of an extending crust: In *Contintal extensional tectonics* (eds. M.P. Coward, J.F. Dewey & P.L. Hancock) Spec. Publ. Geol. Soc. Lond., 28, 537-548.

Steel, R., Siedlecka, A. & Roberts, D. 1985. The Old Red Sandstone basins of Norway and their deformation: a review. In *The Caledonian Orogeny - Scandinavia and related areas,* by Gee, D.G. & Sturt, B.A. (eds). John Wiley & Sons

Sturt, B.A. 1983.Late Caledonian and possible Variscan stages in the orogenic evolution of the Scandinavian Caledonides. Abstract, *The Caledonian Orogen - IGCP Project 27,* symposium de rabat, Morocco 1983.

Sturt, BA. & Ramsay, D.M. 1997. The Gubrandsdalen Antiform - a major late Caledonian structure. *Norges geologiske undersøkelse Bulletin 433*, p. 12-13.

Strand, T. 1951. The Sel and Vågå map areas. *Norges geologiske undersøkelse 178,* 1-116.

Torsvik, T.H., Sturt, B.A., Swensson, E., Andersen, T.B., and Dewey, J.F., 1992. Paleomagnetic dating of fault rocks: evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjorden Fault, western Norway. *Geophys. J. Int. 109*, 565-580.

Torsvik T.H., Andersen, T.B., Eide E.A. & Walderhaug, H.J. 1997. The age and tectonic significance of dolerite dykes in western Norway. *Journal of the Geological Society, London, 154,* 961-973.

Torsvik, T.H., Sturt, B.A., Ramsay, D.M., Bering, D. & Fluge, P.R., 1988. Palaeomagnetism, magnetic fabrics and the structural style of the Hornelen Old Red Sandstone, Western Norway. J. Geol. Soc. Lond., 145, 413-430.

Torsvik, T.H., Sturt, B.A., Ramsay, D.M., Kisch, H.J. & Bering, D. 1986. The tectonic implications of Solundian (Upper Devonian) magnetization of the Devonian rocks of Kvamshesten, western Norway. *Earth and Planetary Science Letters 80,* 337-347.

Torsvik, T.H., Sturt, B.A., Ramsay, D.M. & Vetti, V. 1987. The tectono-magnetic signature of the Old Red Sandstone and pre-Devonian strata in the Håsteinen area, western Norway, and implications for the later stages of the Caledonian Orogeny. *Tectonics 6,* 305-322.

Wennberg, O.P. 1996. Superimposed fabrics due to reversal of shear sense: an example from the Bergen Arc Shear Zone, western Norway. *Journal of Structural geology 18,* 871-889.

Wennberg, O.P. & Milnes, A.G. 1994. Interpretation of kinematic indicators along the northern margin of the Bergen Arc system: a preliminary field study. *Norsk Geologisk Tidsskrift 74,* 166-173.

Wilks, W.J. & Cutbert, S.J., 1994. The evolution of the Hornelen Basin detachment system, western Norway: implications for the style of late orogenic extension in the southern Scandinavian Caledonides. Tectonophysics, 238, 1-30.

Wojtal, S., 1986. Deformation within foreland thrust sheets by population of minor faults. *J. Struct. Geol., 8,* 341-360.

Aanstad, K.M., Gabrielsen R.H., Hagevang, T., Ramberg, I.B. & Torvanger, O. 1981. Correlation of offshore and onshore structural features between 62oN and 68oN, Norway. *Proceeding Norwegian Symposium Exploration, Bergen,* 11, 25.