Devonian-Triassic brittle deformation based on dyke geometry and fault kinematics in the Sunnhordland region, SW Norway

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The coastal area south of Bergen exhibits fracture systems and lineaments that can be grouped into N-S to NNW-SSE, NW-SE and NE-SW trends. Faults and Permo-Triassic Alkaline dykes along N-S to NNW-SSE lineaments in Sunnhordland have been subjected to kinematic analysis and used as absolute and relative age markers in this study. Observations suggest early, semi-brittle dip-slip movements associated chiefly with NE-SW striking faults, and later (re-) opening of N-S to NNW-SSE striking fractures associated with dyke intrusion. Kinematic analysis of faults and fractures gave a sub-horizontal extension axis trending 130°-310° for the early (pre-dyke) faults. Comparison of field observations with regional information indicates that this extensional episode is likely to have been Devonian.
Dyke geometry has been utilized to estimate extension direction in the Permo-Triassic stress field. The study indicates a fairly consistent extension direction, and a horizontal minimum principal stress σ_3 of the regional Permo-Triassic stress field is found to trend 079°-259°. Hence, the regional stretching (and σ_3) direction has rotated from a NW-SE orientation in pre-dyke (?Devonian) time to E(NE)-W(SW) in the Permo-Triassic.
Dyke intrusion is connected to the contemporaneous crustal stretching and basin formation in the northern North Sea. Thus, the 079°-259° Permo-Triassic stretching direction calculated for the Sunnhordland area is considered to be a good estimate also for the North Sea basin west of the study area.

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Introduction

In this work we focus on post-Caledonian deformation of the Sunnhordland area in southwestern Norway (Fig. 1). We use fracture and dyke observations to determine the direction of the deforming stress field in time and space that acted on the post-Caledonian crust. The fracture sets under consideration are parallel to prominent N-S to NNW-SSE, NW-SE and NE-SW striking trends that can be observed from satellite images, aerial photos and topographic data (Gabrielsen & Ramberg 1979; Karpuz et al. 1989) (Fig. 2). The dykes are Permo-Triassic and are all associated with these lineaments (Færseth et al. 1976). Hence these fracture systems were important in accommodating post-Caledonian strain. Given the closeness to the northern North Sea the Permo-Triassic stretching direction estimated in this study might also reflect the stretching direction during the important Permo-Triassic rift episode in the northern North Sea.

Regional setting

The study area is located within the southwestern Caledonides south of Bergen and includes the islands of Bømlo, Stord, Halsnøy and Tysnes (Fig. 3). The Caledonian orogen formed as a result of convergent plate motions between Laurentia and Baltica during the Early Paleozoic (Bryni & Sturt 1985). The continent-continent collision took place during the Late Silurian and earliest Devonian, and caused transportation of enormous allocthonous units several hundred kilometres towards the southeast (e.g. Andresen & Færseth 1982; Bryni & Sturt 1985; Hossack & Cooper 1986). During the Early Devonian the southwestern parts of the Caledonides underwent a transition from contraction to extension (Fossen 1992; Fossen & Rykkelid 1992; Fossen & Dunlap 1999), associated with a collapse of the thickened crust in the hinterland and uplift of the orogenic root (Andersen & Jamtveit 1990, Millnes et al. 1997). Due to the gradual uplift the extension was accommodated both by ductile, semi-brittle and

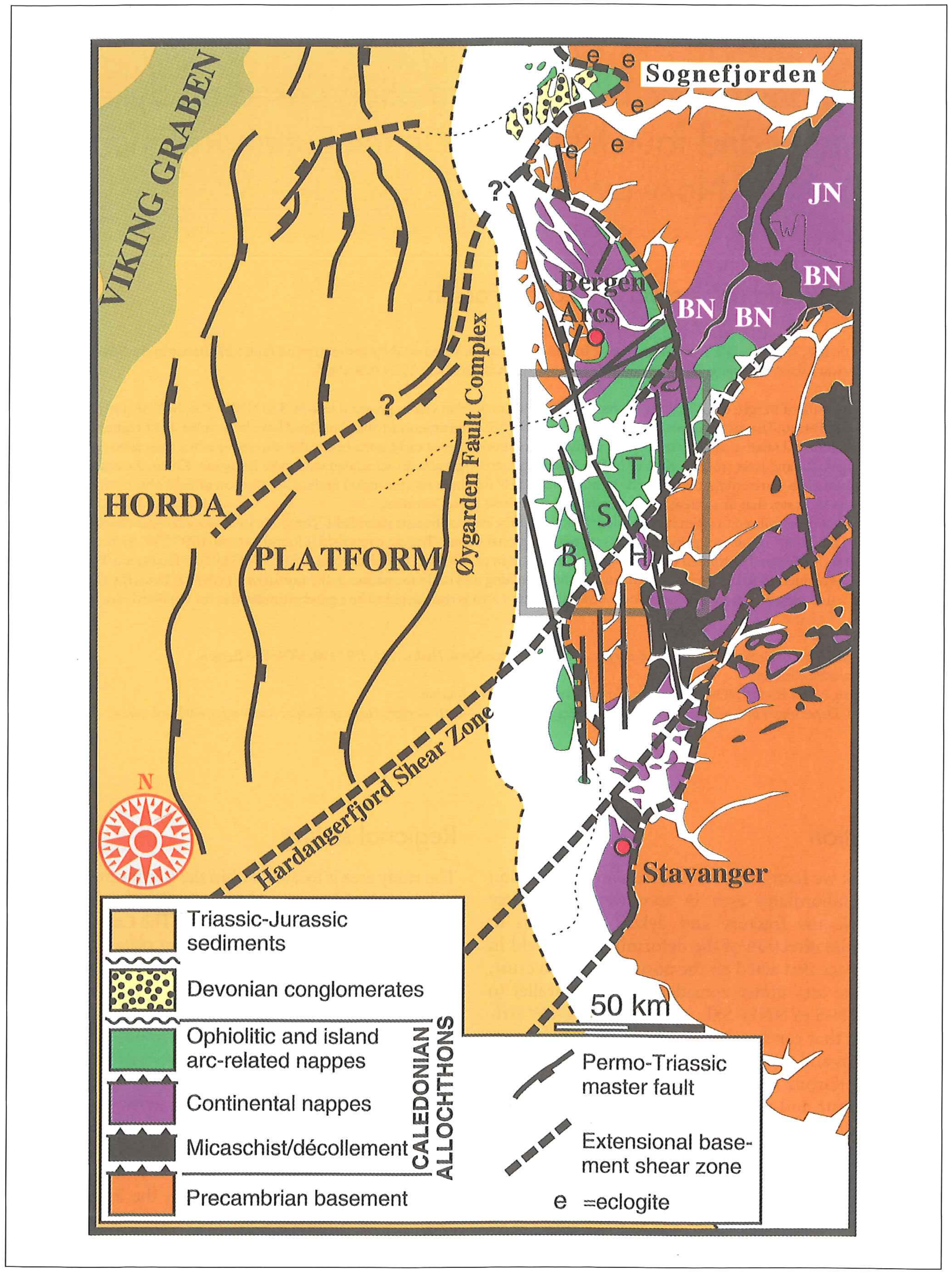

Fig. 1 Geological map showing the main tectonic units of SW Norway and main structures of the Horda Platform (North Sea). Bømlo (B), Stord (S), Tysnes (T) and Halsnøy (H).

brittle deformation processes (Fossen 1998, 2000). Brittle extension occurred repeatedly from Devonian faulting through Permo-Triassic dyke intrusion (Færseth et al. 1976), faulting of Late Jurassic sediments (Fossen et al. 1997) and also current seismic activity along N(NW)-S(SE) fracture trends (Gabrielsen 1988).

The Sunnhordland region is located near the eastern margin of the North Sea basin (Fig. 1) and the basin is related to a prolonged extensional history. The composite fault pattern within the northern North Sea results mainly from Late Permian-Early Triassic and Jurassic extensional episodes (see Færseth 1996 for references). The eastern margin of the sedimentary basin is largely associated with the Øygarden Fault Complex of Permo-Triassic origin (Færseth et al. 1995; Færseth 1996), which runs N-S along a major part of the SW Norwegian coast and downthrows up to 5 km towards the west (Fig. 1). This fault complex also marks a sharp transition in pre-Mesozoic crustal thickness from the mainland to the adjacent sedimentary basin. Færseth et al. (1995) demonstrated that major basement units and fracture systems similar to those seen today in southwest Norway can be identified in the offshore basin substrate west of the Øygarden Fault Complex. On a regional scale, the dominant fault orientations in the northern North Sea are N-S and NE-SW. At the Horda Platform, which was the area of maximum Permo-Triassic extension (Roberts et al. 1993; 1995; Færseth 1996), faults with maximum throws of some 4-5 km at basement level typically appear with 10-20 km horizontal spacing. They have an overall N-S strike, although locally they curve to parallel NNW-SSE oriented basement fractures (Færseth et al. 1995) (Fig. 1). Accordingly, it seems that Permo-Triassic masterfaults west of the Øygarden Fault Complex have an orientation and spacing comparable to the intruded onshore lineaments (c.f. Fig.3). It is thus likely that the stress field information that can be obtained from the onshore lineaments may also apply to the offshore areas.

As illustrated in Table 1, ages from dykes along the west coast of Norway as well as additional ages from faultrock material, tend to fall in groups of Permian (246-270 Ma), Triassic (220-241 Ma) and Middle Jurassic (162-179 Ma) (Færseth et al. 1976; Løvlie & Mitchell 1982; Eide et al. 1997; Eide & Torsvik 1997; Fossen & Dunlap 1999). However, it seems clear that the main dyke intrusion in the Sunnhordland region occurred between ~260-220 Ma (Eide & Torsvik 1997; Fossen & Dunlap 1999). The Permian-Early Triassic and Middle Jurassic periods correlate with episodes of regional extension in the North Sea basin.

In the offshore area the recorded magmatic material is basically Jurassic (Tab. 1), and mainly associated with the extensive Rattray Formation volcanics in the Piper-Forties area and is aged in the range 190-150 Ma (Woodhall & Knox 1979; Fall et al. 1982; Latin et al. 1990; Smith & Ritchie 1993).

Table 1. Summary of ages from dyke and fault rock material from onshore (left) and offshore (right) western Norway

Onshore				Offshore (North Sea)			
Locality	Source	Daiting method	Age (Ma)	Locality	Source	Daiting method	Age (Ma)
Nordfjord Sogn Detatchment	Eide et al. 1997	Ar-Ar	260 and 144-98	Mid North Sea High	Dixon et al. 1981	Ar-Ar	138±4
Sunnfjord dykes	Furnes et al. 1982a	K-Ar	261±6 to 256±6	Wich Ground Graben	Woodhall & Knox 1979	Strat.	Jurasssic to early Cret.
	Torsvik et al. 1997	Pal. mag	270-250				
Sotra dykes	Løvlie & Mitchell 1982	Pal. mag	271±4 to 228±5		Ritchie et al. 1988	Ar-Ar	153±4
					Latin 1990	Ar-	170±2
Sunnhordland dykes	Færseth et al. 1976	K-Ar	221±4 to 219±4 and 164±3		Latin et al. 1990	Ar K-Ar	188±10
	Fossen & Dunlap 1999	Ar-Ar 219±0.7	223±0.8 to	Egersund Sub Basin	Furnes et al. 1982b	K-Ar	180-178

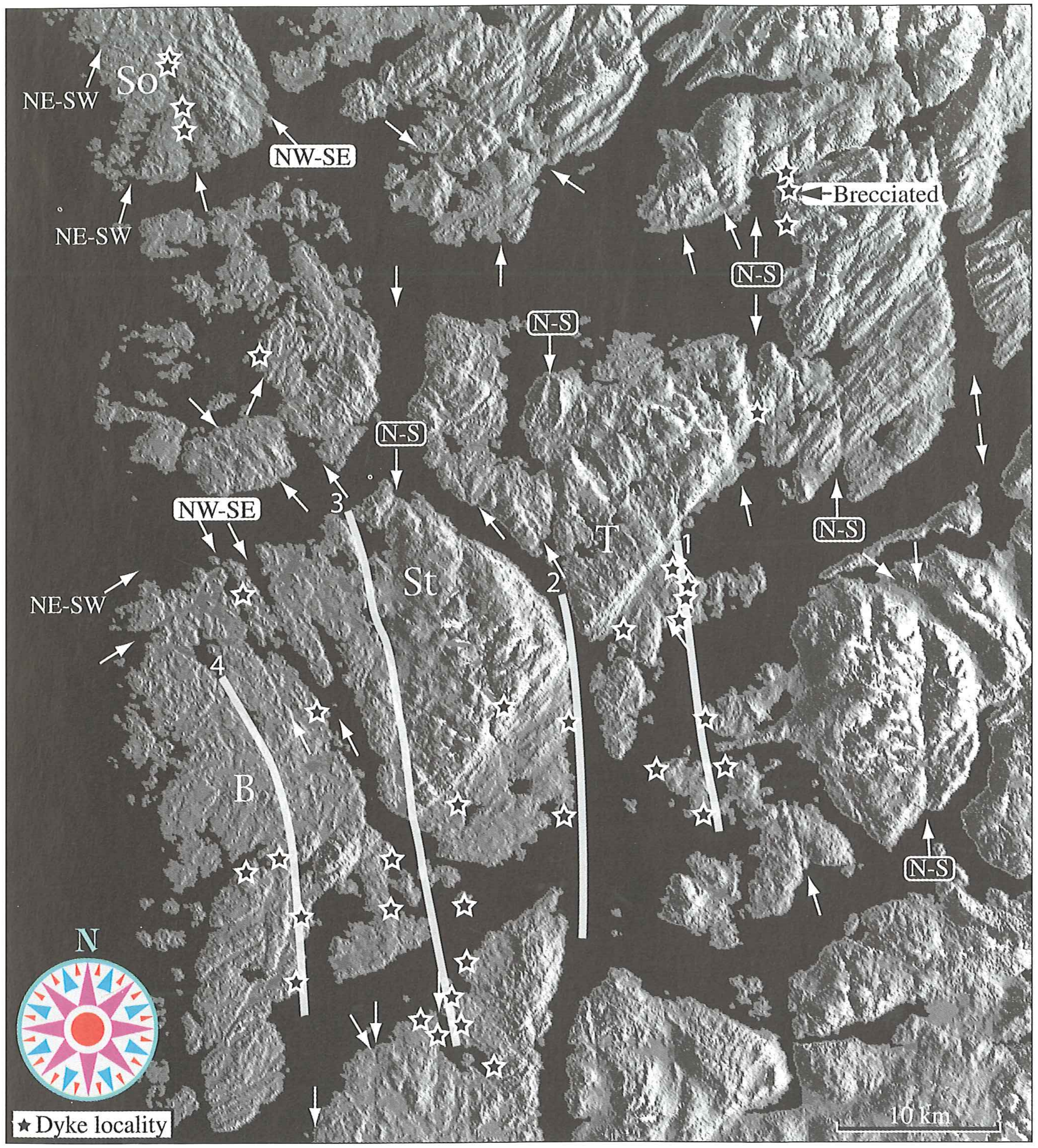

Fig. 2 Digital elevation model of the Sunnhordland area, illustrating the variety of lineament directions in the bedrock (see rectangle in Fig. 1 for regional location of the elevation model). Examples of the N-S, NW-SE and NE-SW main trend are indicated, and the main lineaments are denoted L1-4. B = Bømlo, St = Stord, T = Tysnes, So = Sotra. The dykes on Sotra are studied by Løvlie & Mitchell (1982) and Fossen (1998).

Description of fractures and dykes

The study area was previously investigated with respect to lineaments (Grabrielsen & Ramberg 1979; Karpuz 1990; Karpuz et al. 1991). Karpuz (1990) produced a lineament map based on LANDSAT-TM in additon to panchromatic SPOT pictures, and the lineaments presented in Figs. 2 and 3 are consistent with this work.

Fractures

All the lineament trends observed by the remote sensing are identified in the field, where they appear as fracture zones composed of extension- and shear fractures developed under semi-brittle to brittle deformation conditions. The NE-SW striking fractures have dips in the range 20-80°, but the majority of the dip measurements fall within the range of 50 to 70° (c.f. Fig. 5a). A relatively large number of the fractures have greenish surfaces due to chlorite mineralization, and these surfaces often contain striations indicating that they have been created or re-activated as shear fractures. When studied under the microscope it can be seen that the polished surfaces are composed of a ~1mm thick micro-breccia (Fig. 4).

The poles of all the striated fractures (faults) are plotted in stereograms in Fig. 5. The majority (85) of the totally 161 striation observations are connected to the NE-SW striking fracture population (Fig. 5a). The remaining striations are associated with the N-S striking fractures (41 observations, Fig. 5b), the E-W striking fractures (26 observations, Fig. 5c) and finally the NW-SE fracture population (Fig. 5d) with only 9 striation observations. On the NE-SW, N-S and NW-SE striking faults the striae indicate oblique slip to pure dip-slip movements (rakes in the range 50°-90°), while the striations on the E-W striking fractures indicate oblique slip movements (rakes in the range 20°-50°). The sparse appearance of stratigraphic markers in the study area has in most cases made it necessary to rely on slickenside and fault surface morphology to decide the relative movement on the fault surfaces. Where observed, the slickensides give a general impression of oblique to pure normal dip-slip movement on the NE-SW, N-S and the NW-SE striking fractures. 70 % of the striae observations in the NE-SW striking fractures indicates down-to-E(NE) movement, while 60 % of the striae observations in the NW-SE striking fractures indicate down-to-E(SE) movement. For the E-W striking fractures 75 % of the striae observations show down-to E oblique slip movement, while 90 % of the striac observations on the N-S striking fractures indicates down-to S movement.

Dykes

The dykes are located along or in the vicinity of four NNW- SSE striking lineaments that are annotated L 1-4 from the east towards the west in Figs. 2 and 3. The dykes are rather unevenly distributed among these lineaments, with 55 per cent (weighted by length of dykes) associated with the easternmost lineament. The dykes exist as single features (Fig. 6a) or, less commonly, as swarms (Fig. 6b).

The dykes normally consist of several rectilinear parallel-sided segments with a slightly diverging strike that gives the dykes a step-like or "zigzag" appearance in the horizontal plane (Fig. 6c). A total of 385 dyke segments from 90 dykes were recorded. Diverging strikes for single dyke segments are normally associated with the presence of differently striking fracture sets (c.f. Fig. 6c), indicating that the dykes, at least partly, are exploiting pre-existing fractures. Fig. 7 summarizes the recorded dyke parameters (strike, opening direction and width) for each of the four main lineaments shown in Fig. 3. An overall N-S strike of the dykes can be seen from Fig. 7. The only observations that deviate significantly from this trend are those from lineament 2 which define a predominant NNW-SSE (331°±014°) strike. The average of all opening direction observations are 079°± 005°. Both the observations from lineaments 2 and 4 show deviations (068°± 008° and 094°± 023° respectively) but the data remain within the confidence interval of the overall trend. As can be seen from the histograms to the right in Fig. 7, about half of the dyke segments have widths less than 0.5 m, and the widest dyke segment (shown in Fig. 6a) is observed in lineament 4.

Timing of activity on the different fracture populations

The available field data was used to evaluate the age of at least some of the different fracture populations relative to dyke injection. The only deformation event constrained with absolute dating methods is the opening of the N-S to NNW-SSE striking fracture population during dyke intrusion. Fig. 8a demonstrates the relative age relationship between dykes and NE-SW and NW-SE striking fractures. At Espevik on Tysnes (c.f. Fig. 3) one of the late Triassic dykes (220Ma, Færseth et al. 1976; Fossen & Dunlap 1999) cross-cuts a NE-SW striking fault plane (Fig. 8a). Semi-brittle breccia (c.f. Fig. 4) is developed on this fault plane and the striations indicate down-to-the NE dip-slip movement. Hence slip along this normal fault is post-dated by the dyke, and gives a late Triassic minimum age for the faulting. Fig. 8b shows a corresponding example from Straumøy in Sveio (see Fig. 3 for location), where the NE-SW striking fractures clearly terminate against the dyke margin, and are interpreted to pre-date the dyke intrusion. Fig. 8c demonstrates the relative age relationship between a dyke and NW-SE striking fractures (locality Espevik, c.f. Fig. 3). Here the NW-SE striking fractures are cross cut by the N-S striking dyke, which gives a Triassic minimum age also for the activity on NW-SE striking fracture population in the Espevik area. We speculate if this activity might be coeval to the development of semi-brittle fault rock on some of the NW-SE striking faults observed both in the present study area and to the north of the present study area (Fossen et al. 1997).

At Jektevik on Stord (c.f. Fig. 3) a cross-cutting relationship was observed between NE-SW and NW-SE fractures. Here NE-SW striking fault planes covered by microbreccia (c.f. Fig. 4) terminate against a NW-SE striking fracture zone, which at this locality contains a calcite cemented fault breccia (Fig. 8d). The age of the breccia (younger or older than the dykes) is however unknown, although calcite-cemented breccias are found to post-date dyke intrusion elsewhere (Færseth et al. 1976; Fossen et al. 1997).

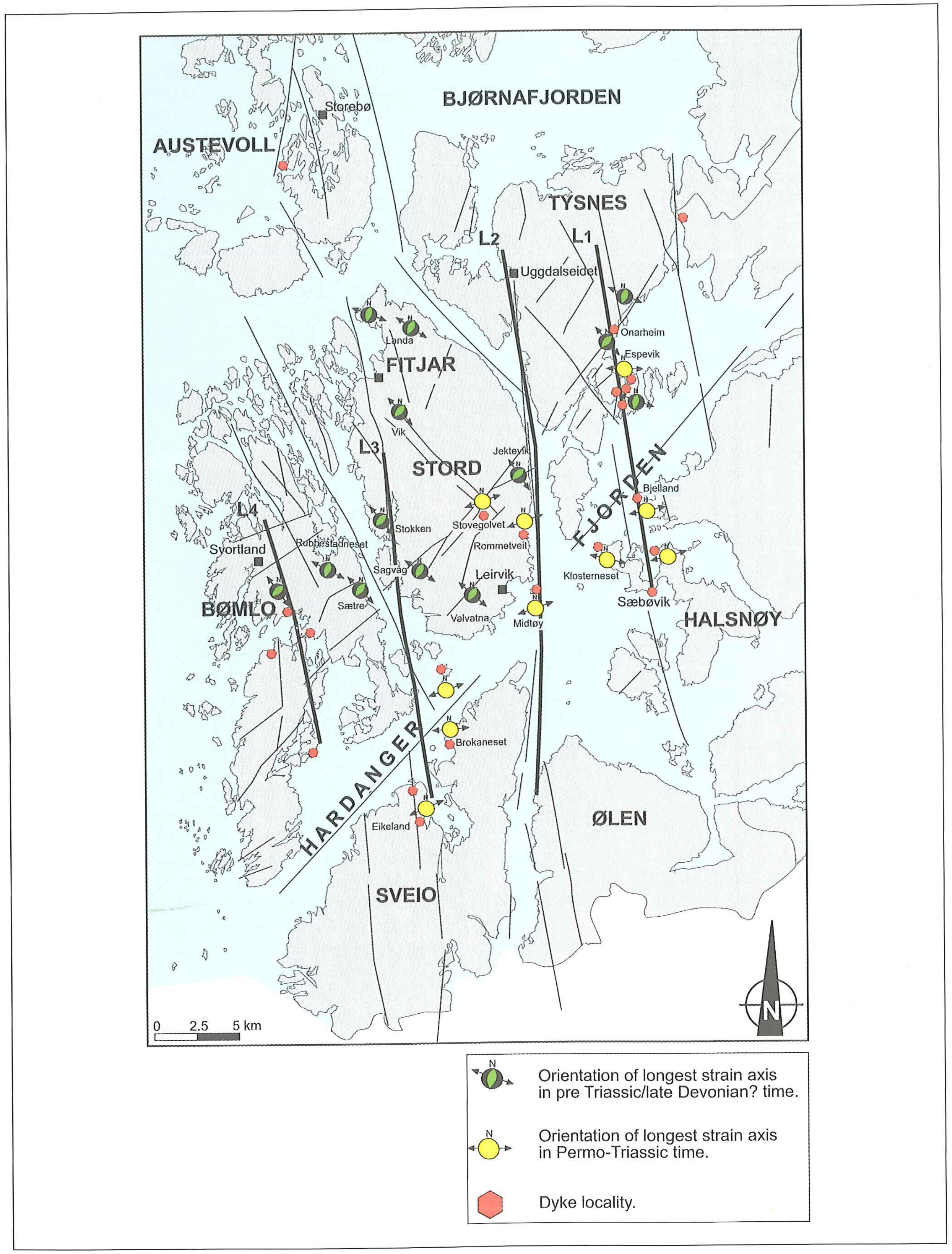

Fig. 3 Map summarizing the paleo-stress observations presented in this study. Circles with green and red arrows represent the pre-Permo-Triassic (Devonian?) and the Permo-Triassic extension direction, respectively. The lineament interpretation is simplified from Karpuz (1989) and Karputz et al. (1991). The main lineaments are annotated (L 1-4)

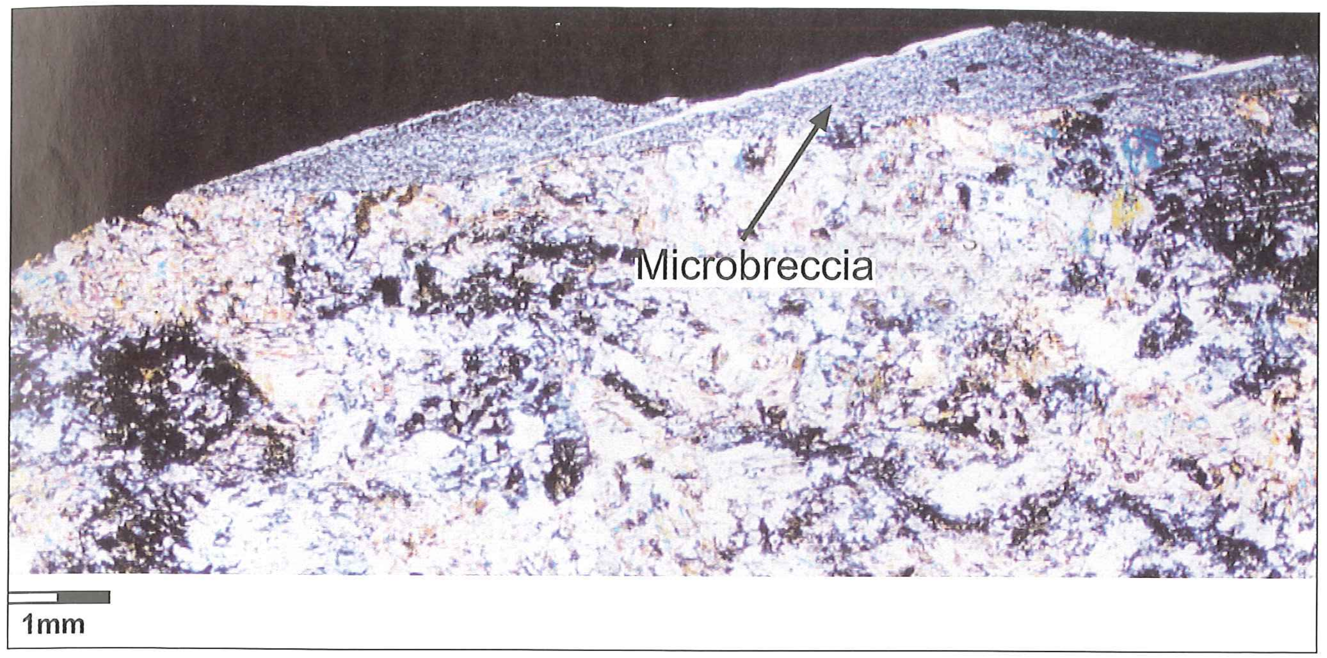

Fig. 4 Photomicrograph of striated NE-striking fault plane that conforms with NW-SE stretching. Note microbreccia with plastic deformation of quartz in the upper part of the section. UTM: 1214 IV, LM, 1260 4725.

Paleo-stress from dykes: methodology and results

A rock body that is located in the brittle crust and subjected to a stress field of sufficient magnitude will deform due to the formation of new fractures or by re-activation of pre-existing fractures. For pure mode I fractures, the pole to the fractures will give the direction of the longest horizontal strain axes, which in this case is parallel to the least principal stress axis (σ_3) (Anderson 1951). In the case of shear fractures the picture becomes more complicated, since the longest strain axis (e_1) and the least principal stress axes are not longer necessarily parallel. Fractures have considerable re-activation potential, and it can be energetically favourable for a stress system to exploit pre-existing fractures with 'non-ideal' orientation instead of generating new fractures with ideal orientation reflecting the prevailing stress axes (Handin 1969; Twiss & Moores 1992).

Dykes often show geometries that make it possible to decide the opening direction during intrusion (Escher et al. 1976; Delaney et al. 1986; Baer et al. 1994; Jolly & Sanderson 1995). In these cases the direction of the local e_1 can be determined, since it is identical to the opening direction of the intruded fracture. Under certain conditions (discussed below) strain vectors defined by opening directions can be used to determine orientation of paleostress (σ_3), even if the intrusion represented re-activation of older fractures (Delaney et al. 1986; Jolly & Sanderson 1995). When combined with radiometric and/or paleo-magnetic dating, the dykes then can be used as a tool to determine paleo-stress both in time and space.

For a fracture with no tensile strength to dilate and fill with magma the following condition must be met:

$$P_m \geq \sigma_n \qquad (1)$$

where P_m = magma pressure and σ_n = stress normal to the dyke margin (Delaney et al. 1986). By expressing σ_n in terms of the maximum and minimum principal stress (S_H and S_h respectively) and the angle θ between S_H and S_n (Fig. 9) the latter authors derived the *R-ratio*:

$$R = \frac{(P_m - S_H) + (P_m - S_h)}{(S_H - S_h)} \geq \cos 2\theta \qquad (2)$$

From (2) we see that the R-ratio describes the interaction between varying magma pressure and the contemporaneous remote stress field. The relationship between R and θ is illustrated graphically in Fig. 10.

The R-ratio is equal to 1 when $P_m = S_H$. This means that vertical fractures of all directions are able to dilate (c.f. Fig. 10), since P_m now is resisting all horizontal stresses and consequently no shear forces arise along the fracture margins. In this situation the e_1 and S_h are parallel features. However, this implies strong restrictions in "translating" strain (represented by different dyke parameters) to stress axes in the remote stress field, since such a translation demands a R-ratio in the vicinity of ± 1 (c.f. Fig. 10). In the following we argue that the R-ratio probably was approximately equal to 1 when the Sunnhordland dykes were intruded. Consequently the e_1 observations (opening directions) referred in Fig. 7 are valid as σ_3 indicators resulting in an E(NE)-W(SW) (079°-259°) striking extension vector in the Permo-Triassic stress field for the Sunnhordland region:

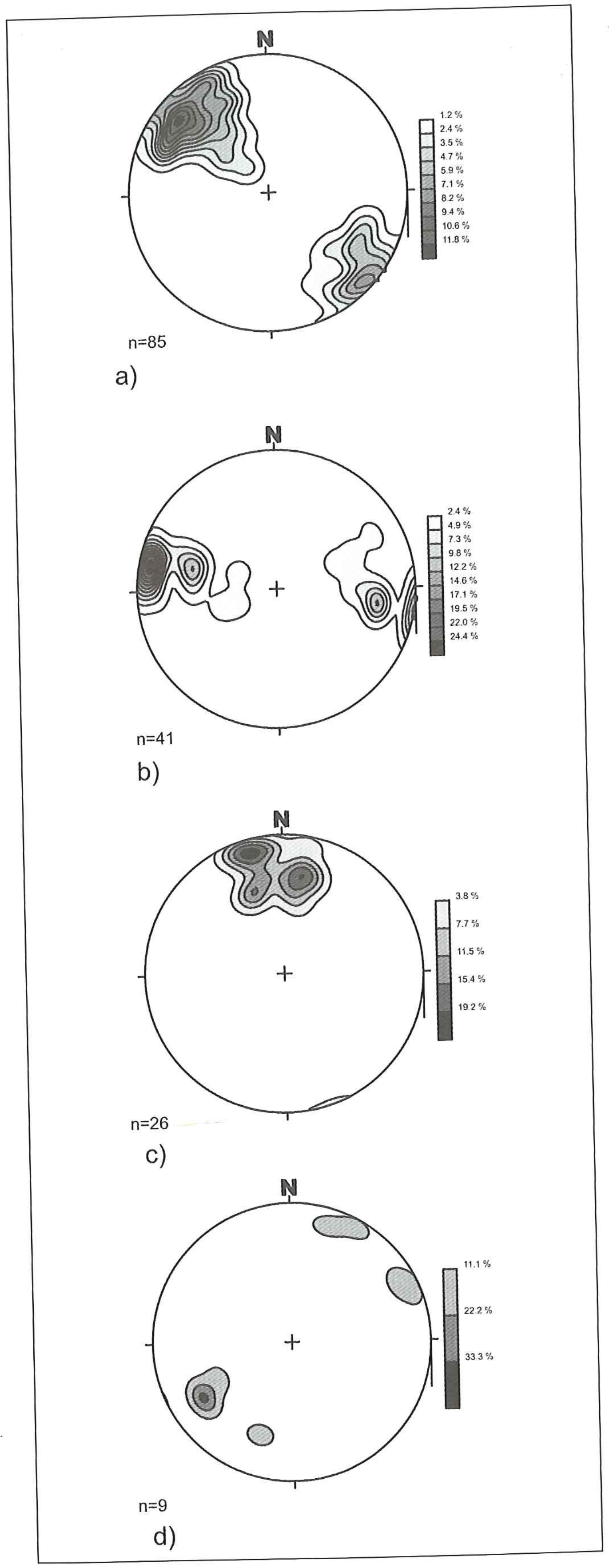

Fig. 5 Poles of the striated fault planes plotted in stereograms. a) NE-SW striking fractures, b) N-S striking fractures, c) E-W striking fractures, d) NW-SE striking fractures.

Wide range of intruded fractures

As discussed above e_1 will parallel the least compressive stress axis (σ_3) and leave the opening direction of dykes as an unambiguous σ_3 indicator when P_m equals S_H. Under this condition fractures of many directions are able to dilate (c.f. Fig. 10), and the far-field (regional) stress field becomes the controlling factor. Thus the direction of the minimum horizontal principal stress can be deduced from the distribution of dilated fractures.

In the present case, a wide range of intruded fractures (Fig. 11) cover a sector of approximately 290 degrees, suggesting that that P_m was close to S_H when the dykes intruded. If true, the preferred strike direction of ~NNW of the dykes in Fig. 7 (left column) alone is sufficient to estimate σ_3 (~ESE).

Extremely consistent opening directions

Except for the observations in lineament 4 (which are only based on three measurements), the opening direction observations must be characterized as consistent with very low deviation from the mean value (079° ± 005°) (Fig. 7). If the R-ratio deviated significantly from 1 when the dykes intruded, we should expect a wider range of opening directions. Hence, the 079° ± 005° orientation is considered a good estimate for the extension and σ_3 direction.

Paleo-strain from striated fault planes

The striated fault planes are investigated with respect to kinematics, and the method and program ("Fault Kinematics") described by Marret & Allmendinger (1990) have been used to analyse the data. The goal of this analysis was to evaluate the orientations of the axes in the regional strain field responsible for the fault movements.

Again the reactivation problem must be taken into account, since the different faults may have been active in several periods and subjected to different stress conditions. Analysing the full fault population could then lead to an artificial, "averaged" stress system that never existed. However, separate analysis of the different fault localities (Fig. 3) all show a quite consistent deformation picture with vertical shortening and horizontal extension. Consistency with other kinematic fault analyses from SW Norway (Séranne & Séguret 1987; Fossen 2000) further indicates that most of the recorded fault movements reflect a common regional tectonic stress field. The extensional direction is seen to vary somewhat from locality to locality, but the general trend is NW-SE. The NE-SW striking faults all show a more or less pure dip-slip movement, while the striations on the E-W striking fault planes indicate oblique to strike-slip move-

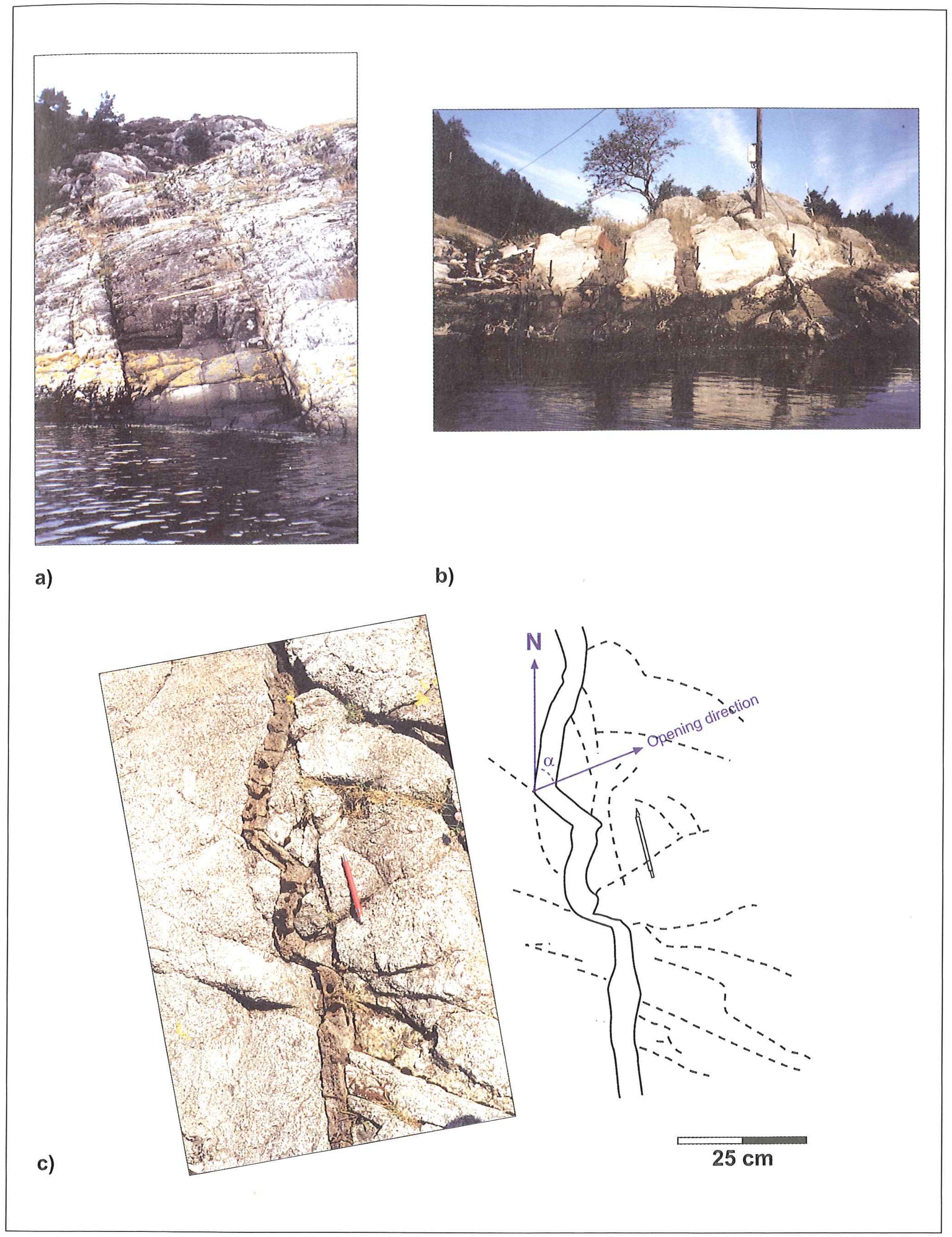

Fig. 6 a) Single dyke from the island of Bømlo (c.f. Fig. 2). Folding ruler in the centre of the picture is 1m long. View to the south. UTM: 1114 I, KM, 8770 2940, b) dyke swarm at Espevik (c.f. Fig. 3) where six dykes (black arrows) have intruded within less than 20 m of horizontal distance. UTM: 1214 IV, LM, 1260 4720, c) N-S striking dyke with horizontal 'steps'. Pencil for scale. The line drawing shows how the steps can be exploited in deciding the opening direction of the intruded fractures. UTM: 1214 IV, LM, 1280 4625.

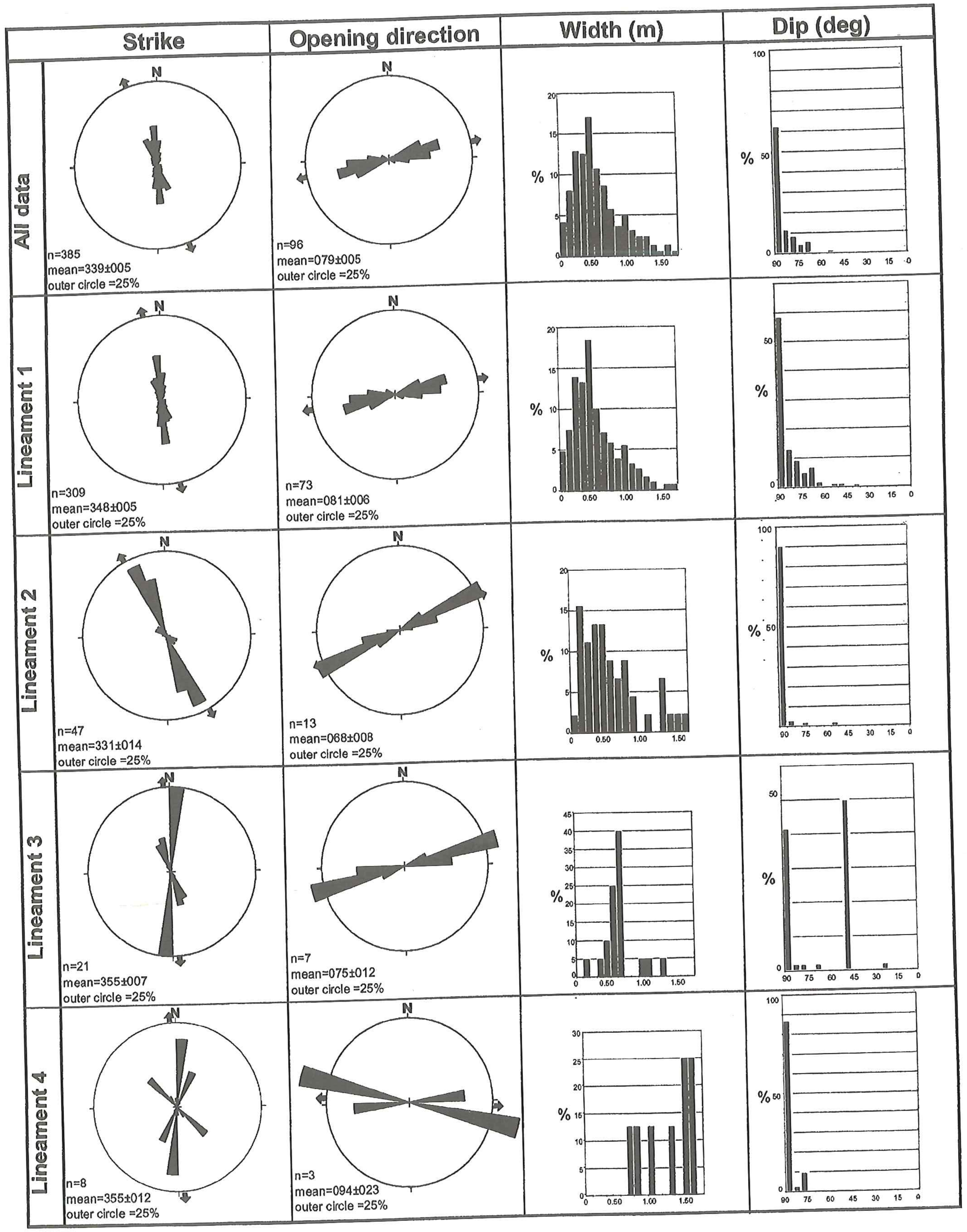

Fig. 7 Summary of dyke parameters as observed in the different lineaments (row 2-5). In row 1 all data are merged. Column 1: Strike of dyke segments, column 2: observed opening directions, column 3: width of dyke segments and column 4: dip of dyke segments.

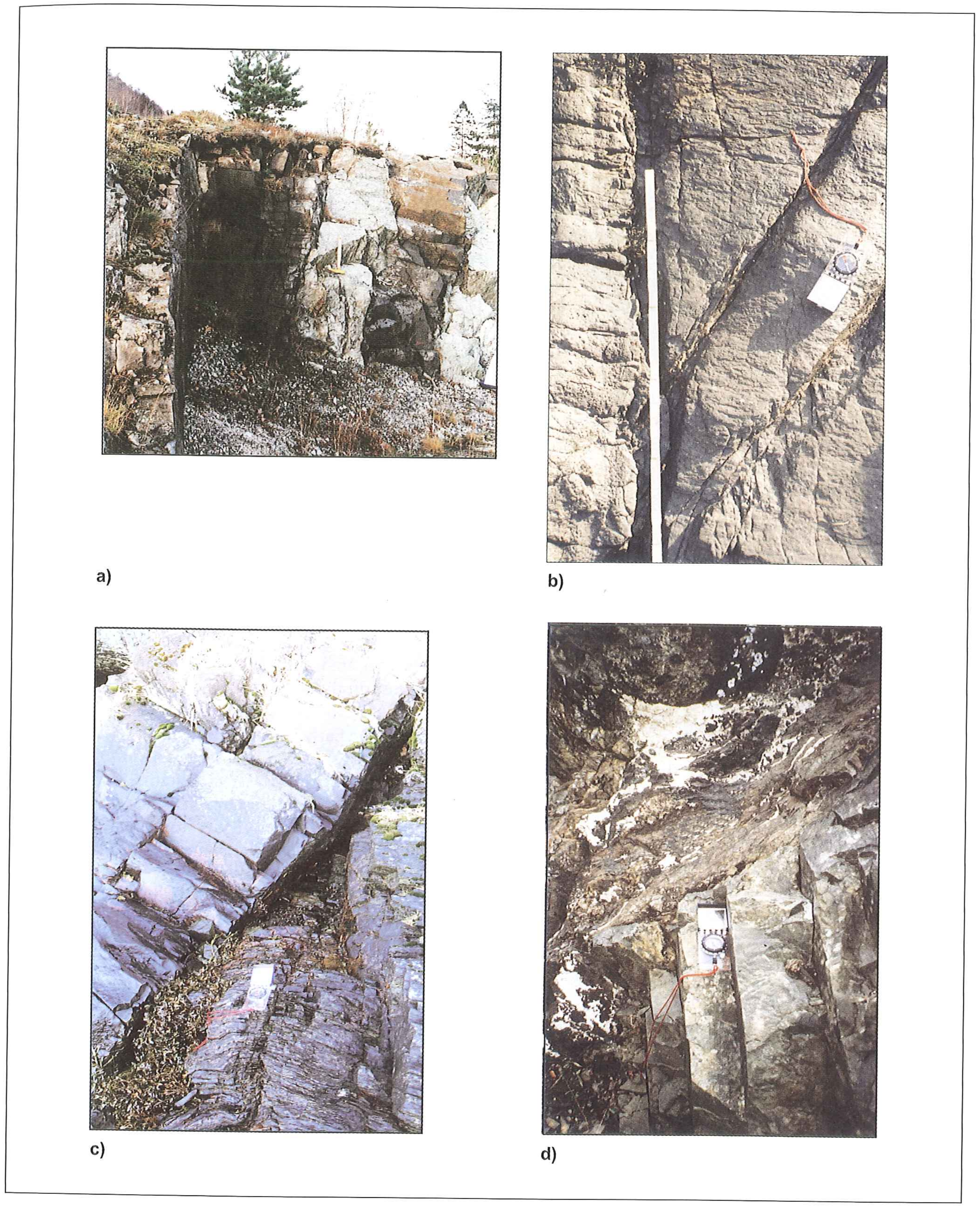

Fig. 8 a) cross cutting relationship between N-S striking Triassic (220Ma) dykes and NE-SW striking fault plane (hammer rests on fault plane) where the fault plane is covered with semi-brittle fault rock (c.f. Fig. 4). View towards the north, hammer as scale. UTM: 1214 IV, LM, 1260 4725, b) cross cutting relationship between N-S striking dyke and NE-SW striking fracture at Straumøy north of Eikeland (c.f. map Fig. 3) where the NE-SW striking fracture terminates against the dyke. Compass for scale and orientation of picture. UTM: 9920 1750, c) cross cutting relationship between N-S striking dyke and NW-SE striking fracture at Espevik (c.f. Fig. 3) where the NW-SE striking fracture terminates against the dyke. Compass for scale and orientation of picture. UTM: 1214 IV, LM, 1265 4810, d) NE-SW striking fractures that terminate against NW-SE striking calcite cemented fractures. View towards the NE, compass for scale. UTM: 1214 IV, LM, 0540 4420.

ments. The analysis of the full data set is presented in Fig. 12, where the data describe a well-defined sub-horizontal 130°-310° trending extension axis.

Discussion

The striated and chlorite-mineralized fault surfaces demonstrate a relatively consistent pattern of vertical shortening and NW-SE trending extension axis throughout the study area. The age of this faulting is uncertain, but the observation of Triassic dykes cutting through such striated fault planes gives a minimum age for the fault activity. Similar faults occur throughout western Norway, and most of them conform to vertical shortening and NW-SE extension (Millnes et al. 1997; Fossen 1998, 2000). They are the first structures to follow ductile NW-SE directed Devonian extension, and the coaxiality of the strain pattern indicates that they formed in broadly the same regional (Devonian) stress regime as the extending Caledonian crust passed the brittle-ductile transition (Fossen 1998, 2000).

The faults consistent with NW-SE stretching have a predominantly NE-SW trend, but include a range of other orientations. Likewise, the wide range of fracture orientations filled with dyke material suggests that fractures with a range of orientations existed prior to Permo-Triassic dyke intrusion. This may indicate that stress fields additional to that causing the NW-SE extension existed prior to dyke intrusion. These stress fields are neither reflected in the current kinematic data, nor were they apparent from the previous work by Fossen (1998). It is not known whether this is because these stress fields only generated extension fractures rather than faults, or if their structures were overprinted during the dominating NW-SE extension.

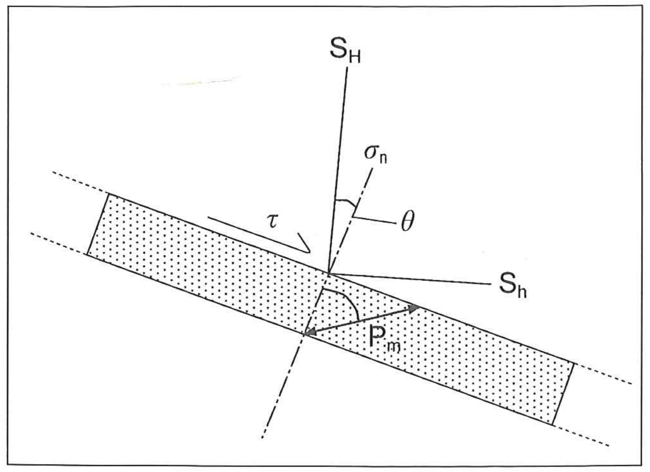

Fig. 9 Notation used in the analysis of stress and opening direction of dykes. Compressive stress regarded as positive; the solid arrow indicates the opening direction of the dyke walls. S_H = maximum horizontal stress, S_h = minimum horizontal stress, σ_n = normal stress, θ = angle between S_H and the normal to the fracture, τ = shear stress, P_m = magma pressure (redrawn from Jolly & Sanderson 1995).

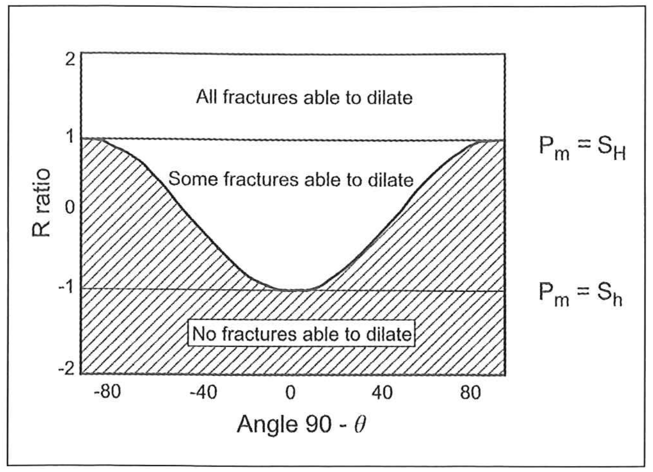

Fig. 10 Plot of the R-ratio against 90-θ (see Fig. 9 for definition of θ), indicating the conditions under which fractures are able to open (non-shaded area) (redrawn from Delaney et al. 1986).

Despite some local variations, the Permo-Triassic dykes in the Sunnhordland region exhibit a fairly consistent picture with respect to opening directions. The calculated opening direction of 079° ± 005° differs from the pure ~ E-W direction estimated for Permian dykes in the Sotra area west of Bergen (Fossen 1998). The extension direction from the latter area was based on a significant lower number of observations, and all observations were from dykes located along one single lineament (c.f. Fig. 2). Further east on the Norwegian mainland, kinematic fault analyses within the Oslo Rift reveal an ENE-WSW extension during the Early Permian (Heeremans et al. 1996).

Based on onshore fault observations on the western margin of the North Sea (Great Britain), several groups of workers have recently interpreted the Permo-Triassic extension to be directed NE-SW to ENE-WSW. Chadwick and Evans (1995) estimated an ENE-WSW (060°-240°) strike for the Late Permian-Early Triassic extensional axis for basins in southern Britain. Anderson et al. (1995) stated that Permo-Triassic basins in the northwest British Isles formed in response to contemporary ENE-WSW stretching. Also halfgraben development across the NW-SE striking Watchet-Cothelstone-Hatch Fault, traceable for at least 60 km from Bristol Channel into the western Wessex Basin, is claimed to result from Late Permian-Early Triassic NE-SW extension (Milioriozos & Ruffel 1998). Hence, observations from the margins of the North Sea basin indicate that the Permo-Triassic extension direction on a regional scale deviates from a pure E-W extension and a majority of the observations suggests an ENE-WSW oriented extension.

In the offshore area, normal faults are generally considered to have propagated along the rift zone perpendicular to the least principal stress (σ_3). As the general trend of Permo-Triassic faults is N-S, most workers have assumed that the Permo-Triassic faults and basin development resulted from a regional E-W extension direction (e.g. Doré & Gage 1987; Roberts et al. 1990; Ziegler

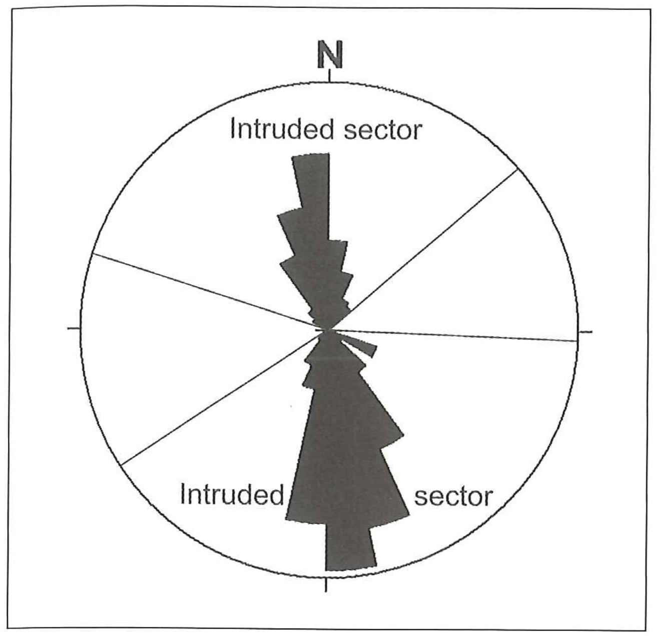

Fig. 11 Rose diagram showing that the intruded fractures covers a range of 290 degrees (equal area, n = 385, outer circle = 13 %).

1990; Færseth et al. 1995). However, the strike of the faults alone cannot be used to determine the exact extension direction, as they are likely influenced by pre-existing basement heterogeneity. Hence, we consider it very likely that the 079-259° direction estimated from dyke geometries also was the Permo-Triassic extension direction in the North Sea basin.

Clearly, the Permo-Triassic direction is different from that related to the earlier, possibly Devonian faults (NW-SE). This is also reflected in the selection of reactivated fault sets at different times. Whereas activation or formation of NE-SW trending faults were most common during the ?Devonian faulting, N-S to NNW-SSE fractures were activated during the Permo-Triassic dyke intrusion pulses, and during more or less contemporaneous North Sea faulting. NE-SW trending basement fractures were generally not activated during the Permo-Triassic in the offshore area (Færseth et al. 1997). In contrast, the NE-SW oriented basement fractures were re-mobilized during the late Jurassic structural development when regional extension directions were reoriented to a more NW-SE to WNW-ESE direction (Færseth et al. 1997).

Conclusions

The post-Caledonian deformation of southwestern Norway is closely connected to prominent lineament trends, where the three main trends strike N-S to NNW-SSE, NW-SE and NE-SW. Based on the present field data, it is evident that the Sunnhordland region has experienced at least two significant episodes of Devonian-Triassic extension.

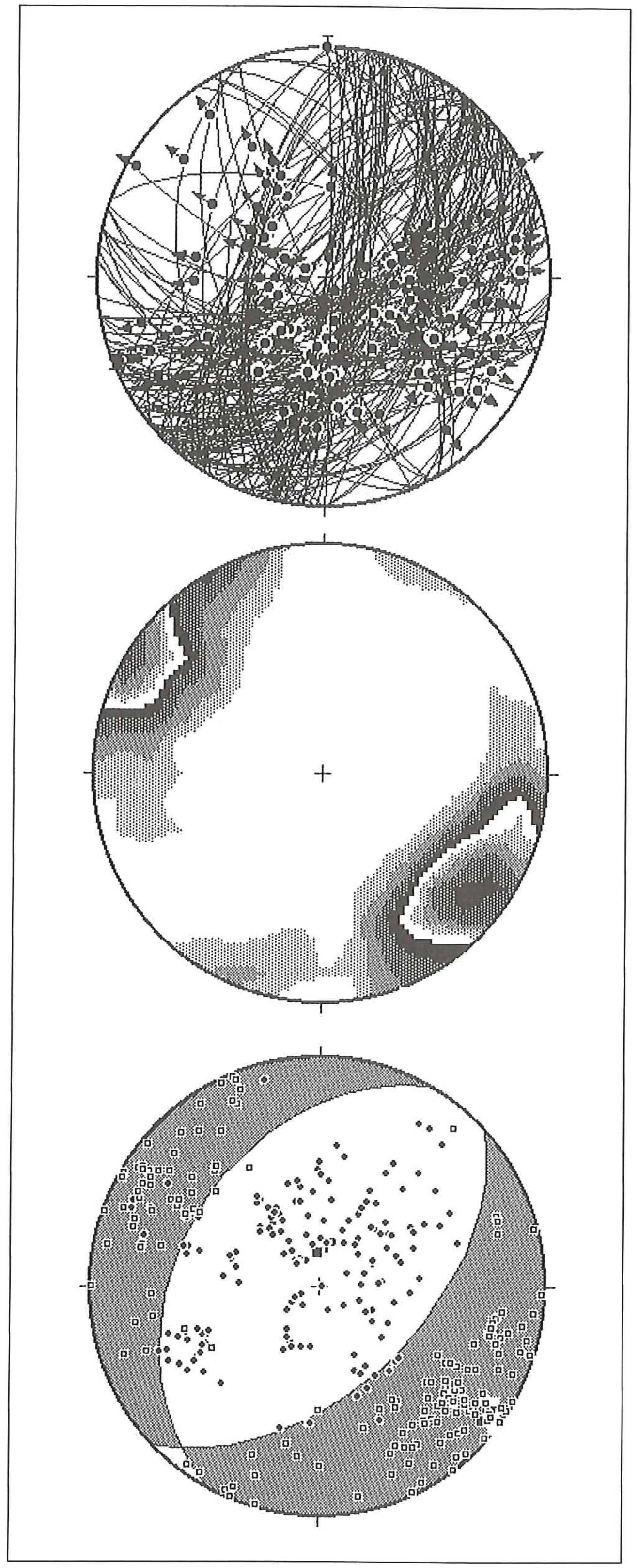

Fig. 12 Plots for the full fault fault/striation data set (n = 161). Upper: Stereoplot (equal area) showing faults and striations. Here faults are indicated by great circles, while the arrows are indicating the associated trend and plunge for the striations. Middle: Contoured T-axes showing a well-defined near flat lying NW-SE striking extensional axis. Lower: Fault plane solution together with calculated P-axes (filled dots) and T-axes (open squares) in addition to averaged P- and T-axes (large filled squares).

- Extension associated with alkaline dyke intrusion is concentrated along four NNW-SSE striking lineaments. Most or all of the dykes appear to be aged Permian to Triassic, and the intrusion (stretching) events are related to the contemporaneous crustal stretching and basin development in the northern North Sea.
- Investigation of dyke geometry shows that the regional extension direction was between E-W and ESE-WNW (079°-259°). The orientations of the dykes are governed by pre-existing fractures, and the strike of dyke segments varies between NW-SE and NE-SW. Inferring that dyke geometry is closely connected to the stress field responsible for the intrusion, this direction (079°-259°) represents the most reliable estimate of the regional Permo-Triassic extension axis for both the Sunnhordland area and the Horda Platform.
- Pre-dyke faulting is extensional, and kinematic analysis of striated fault planes show that most of the recorded fault movements conform well with a near-vertical compression and sub-horizontal NW-SE oriented extension. Various lines of evidence indicate a Devonian age for this extension.
- The minimum principal stress (σ_3) in the regional stress field has rotated from a NW-SE orientation in pre-dyke (?Devonian) time to become ENE-WSW oriented in the Permo-Triassic. Additional pre-Permian stress fields may have existed, but may not have generated a significant amount of shear fractures. Observations of cross-cutting relations in the Sunnhordland region suggest the following succession of activity on post-Caledonian fracture populations related to the prevailing regional stress fields: 1. Semi-brittle dip-slip movements associated with NE-SW striking fractures, 2. Re-opening of N-S to NNW-SSE striking fractures associated with dyke intrusion. 3. Repeated brittle movements associated with NW-SE to N-S striking fractures. However, the NW-SE striking faults are also occasionally associated with semi-brittle fault rocks and are observed to be cross cut by Permo-Triassic dykes, suggesting at least two phases of fault movement associated with the NW-SE striking fracture population within the study area.

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