Advances in understanding the post-Caledonian structural evolution of the Bergen area, West Norway

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The post-Caledonian development in the western Bergen Arc System and the nearby offshore area is characterized by a gradual transition from ductile through semi-ductile to brittle deformation. Interpretation of offshore seismic data shows a dominance of pre–late Jurassic faulting, with relatively minor late or post-Jurassic reactivation. This history is also seen in the Bjorøy tunnel in the Hjeltefjord fault zone, where most, but not all of the (semi)brittle faulting history is pre-Oxfordian (pre–late Jurassic). Pre-Oxfordian faults are typically cohesive fault rocks with striations on slip surfaces, whereas post-Oxfordian faults are identified as non-cohesive gouge zones without clear kinematic indicators. Slip analysis of the fault population with cohesive fault rocks in the Øygarden, Sotra, Løvstakken and Hjeltefjord area gives a relatively consistent NW–SE extension direction. Detailed investigation of Permian dikes in western Sotra and Permo-Jurassic dikes in Sunnhordland indicate a very precise E–W extension direction at about 260 Ma. These dikes intruded along pre-existing faults and fractures, and are mostly undeformed or weakly jointed. Much of the brittle or semi-brittle deformation in the region is therefore thought to be older than the Permian dikes. This suggests that a change in the orientation of the minimum principal stress axis happened at some time between the formation of the fault systems and intrusion of the Permian dikes. Since the NW extension direction is similar to the early to mid-Devonian stretching direction detected in the Caledonian nappe region, it is suggested that the main population of faults with well-developed slip indicators west of Bergen reflects the (late) Devonian stress field.

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Whereas the Precambrian and Caledonian development in the Bergen Arc region has been the subject of detailed studies for about one century (Reusch & Kolderup 1902; Kolderup & Kolderup 1940; Weiss 1977; Sturt & Thon 1978), the post-Caledonian evolution has been afforded almost no attention in the published literature. Exceptions are studies of ductile extensional tectonics of Devonian age (Rykkelid & Fossen 1992; Fossen 1993a; Wennberg & Milnes 1994) and paleomagnetic studies of Permian dikes in the western part of the area (Løvlie & Mitchell 1982) (see also Gabrielsen & Ramberg 1979).

The recent discovery of the Jurassic Bjorøy Formation in a subsea tunnel through a fault zone near Bergen has provided invaluable information about the age of the brittle deformation of the area and about its burial depth in Mesozoic and Cenozoic times (Fossen et al. 1995 and 1997). The finding has also generated renewed attention to the brittle deformation structures in the Bergen Arcs. Together with the proximity of the western Bergen area to the well-known North Sea rift system and the recent advances in understanding stress, faults and joints, a more systematic analysis of brittle structures in the area seems appropriate. This article summarizes post-Caledonian structural data collected during the past decade from the western part of the Bergen Arc System, and discusses their meaning in light of the new data from the Bjorøy tunnel and data that have been collected from seismic surveys immediately west of Sotra and Øygarden. It represents a synthesis of the available data, and forms a basis for continued work on the post-Caledonian development of the area.

Regional setting

The Bergen Arc System (Kolderup & Kolderup 1940) (Fig. 1) is composed of several arcuate tectonic units, named the Major and Minor Bergen Arcs (Færseth et al. 1977; Fossen 1989), the Lindås nappe (Bryhni & Sturt 1985) and the Ulriken Gneiss Complex/Rundemanen Formation (Fossen 1988), together with a western basement region called the Øygarden (gneiss) Complex. The Øygarden Complex is thought to represent parautochthonous basement (Sturt & Thon 1978) similar to the western part of the Western Gneiss Region to the northeast, and hence occupies the lowest tectonostratigraphic position in the region.

With the exception of the Rundemanen Formation and the Lower Paleozoic rocks in the Minor and Major Bergen Arcs, the rocks contain igneous and/or deformation structures of Precambrian age which are overprinted by Caledonian ductile deformation. The Caledonian foliation is mylonitic, and can generally be traced across lithological boundaries. In this sense, the Caledonian deformation caused a penetrative linear and planar fabric that formed prior to and during the juxtaposition of the different tectonic units (Fossen 1986).

The Caledonian deformation resulted in alternating domains of predominantly symmetric (coaxial deformation) and asymmetric structures (non-coaxial deformation), where the latter include S-C fabrics, asymmetric boudins, etc., that formed during thrusting. Subsequent reworking of these fabrics by ductile Devonian top-to-
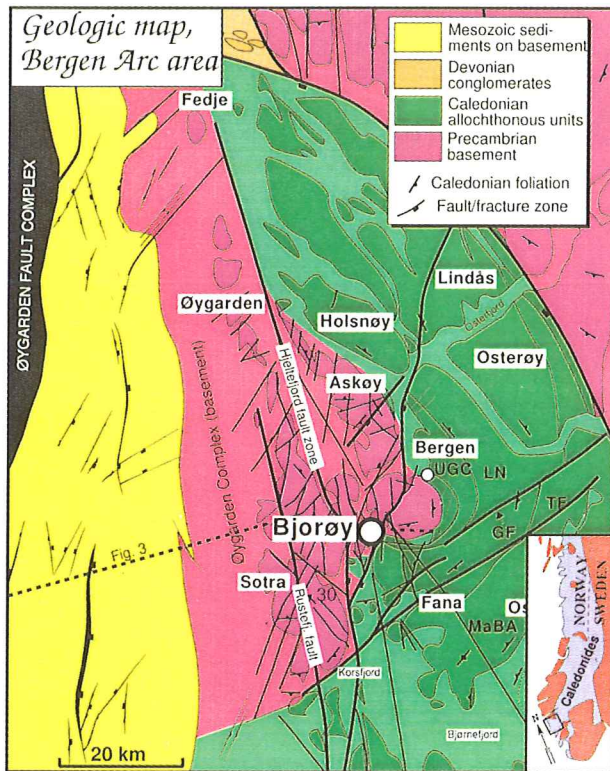
Fig. 1. Geologic map of the Bergen Arc System, including the pre-Quaternary geology to the west. GF = Grimevatn Fault, TF = Totland Fault.

the-(W)NW shear deformation is recognized in parts of the Major Bergen Arc and particularly in the western part of the Øygarden Complex, although the age relations are less obvious in the latter case (Fossen & Rykkelid 1990; Fossen 1993a).

The penetrative, ductile fabric is cut by a number of cataclastic zones, breccia zones, faults and joints which occur throughout the arc system (Figs. 1, 2). These include two substantial ENE–WSW-trending cataclastic zones that transect the arcs (the Grimevatnet and Tot-

Fig. 2. Mylonitic fabrics in gneisses of the Øygarden Complex showing trains or packages of asymmetric folds, small-scale thrusts and shear bands indicating (semi-)ductile top-to-the-WNW shearing. These structures are related to post-collisional extensional tectonics in Lower Devonian time, and are cut by a normal fault in the left-hand side of the photograph (black arrow). Looking NNE, Toftøy.

land faults in Fig. 1), cataclastic zones in the Fana area of various orientations (Fossen & Ingdahl 1987), NE–SW-trending faults in the Øygarden area, and N(NW)–S(SE)-trending fractures related to the Hjeltefjord fault zone, in addition to a number of smaller faults mapped in various parts of the Bergen Arc System (Færseth et al. 1977; Johns 1981; Austrheim 1978; Henriksen 1979; Bering 1984; Ingdahl 1985; Fossen 1986, 1989). In general, these structures have not been studied in great detail except for recent thesis work by students from the University of Bergen in parts of Øygarden. We here concentrate on the western part of the Bergen Arc System, which is very well exposed and also situated close to the area covered by North Sea commercial seismic data.

Ductile, post-Caledonian deformation in the Øygarden Complex

The strong top-to-the-(W)NW ductile to semi-ductile deformation in the western part of the Øygarden Complex described by Fossen & Rykkelid (1990) and Rykkelid & Fossen (1992) bears striking kinematic and geometric similarities with the D2 deformation (back-movement deformation) in the décollement zone/Bergsdalen Nappes east of the Bergen Arc System (Fossen 1993a). Characteristic structures include asymmetric boudins, S-C structures, development of asymmetric porphyroclasts, and formation of NW-verging folds with SE-dipping axial surfaces (Fig. 2). It is also very similar to the W(NW)-verging structures in the Western Gneiss Complex east of the Devonian Solund basin to the north (Milnes et al. 1988; Chauvet 1989; Chauvet & Séranne 1989). The top-to-the-(W)NW shearing is therefore ascribed to the Devonian extensional deformation that rapidly followed the well-known Caledonian contractional deformation in southern Norway (Fossen 1992, 1993a). Since this deformation has been described in detail before, we here focus on the subsequent, more brittle deformation of the western Bergen Arc System.

Onshore fault patterns

Information about the fracture patterns in the Bergen–Sotra area has been gained by interpretation of aerial photographs, general geologic mapping and field studies of fractures. The most pronounced fracture systems exhibit NNW–NE trends. Of particular interest in this context is the Hjeltefjord fault zone separating the Sotra–Øygarden area from the Askøy–Bergen area (Fig. 1).

The Hjeltefjord fault zone

Geologic mapping of the area, particularly in the Flesland–Sotra area, shows that anorthositic and man-
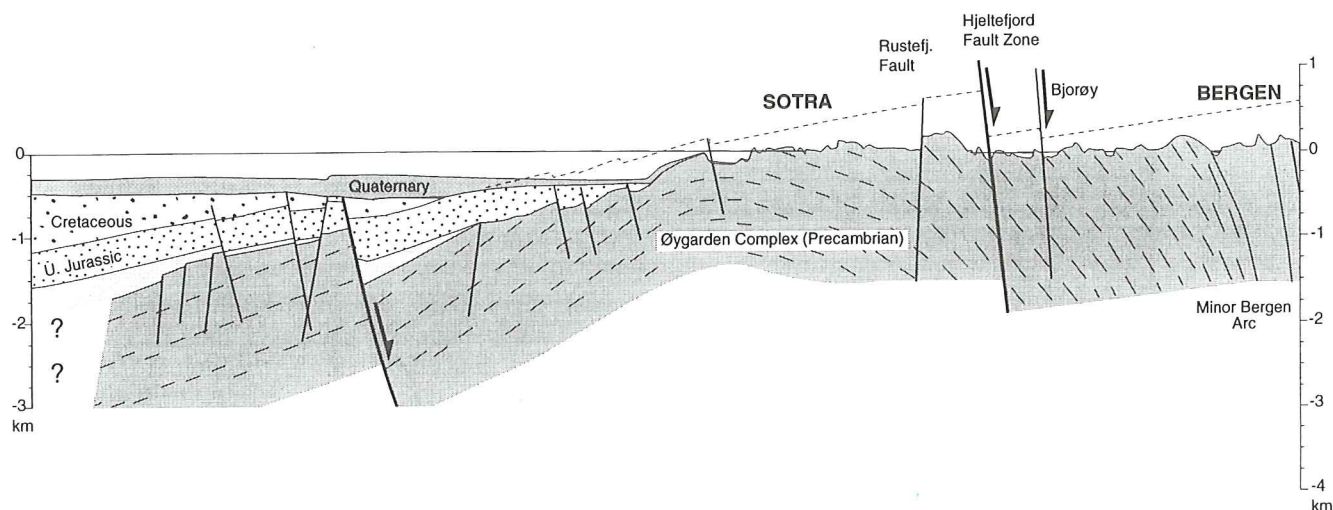
Fig. 3. Profile across the Hjeltefjord fault zone, using information from the Bjorøy tunnel (Fossen et al. 1997) and seismic line ST8125-250 (offshore). Extension of the Upper Jurassic strata over Sotra indicates a significant down-to-the-E throw of the Hjeltefjord fault zone. Vertical exaggeration = 4x. For location, see Fig. 1.

geritic lithologies of the Bergen Arc System occur on the eastern (Flesland) side of the fault zone, striking due east–west with a southerly dip of about 45° (Fig. 2 in Fossen et al. 1997). None of these characteristic lithologies occur on the western side of the fjord (Sotra), and a significant displacement must therefore be associated with the Hjeltefjord fault zone. Similarly, metagabbros, greenschists and mica schists of the Minor Bergen Arc do not appear on the western side of the Hjeltefjord fault zone. Considering the common interpretation that the allochthonous mangeritic/anorthositic rocks and the rocks of the Minor Bergen Arc occupy a tectonostratigraphically higher position than the Øygarden Complex, the Hjeltefjord fault zone appears to have a down-to-the-east component of displacement. This is also indicated by comparing the level of the westerly dipping Late Jurassic layers mapped on the seismic lines west of Sotra and Øygarden with the occurrence of chronologically equal sediments in the Bjorøy tunnel, where a post mid-Jurassic down-to-the-east displacement of several hundreds of meters is indicated (Fig. 3). However, striations on approximately N–S-oriented fault surfaces along the Hjeltefjord fault zone indicate dextral strike-slip or oblique slip movements. As argued below, these kinematic indicators are thought to be pre–late Jurassic, whereas the late or post-Jurassic faults or slip surfaces did not develop readily identifiable striations.

Although much of the Hjeltefjord fault zone is below sea level, breccias and microfaulted rocks are exposed on several of the islands in the Korsfjord–Hjeltefjord area. The largest of these islands (Lille Sotra) is more affected by faulting than rocks away from the Hjeltefjord area. The high frequency of brittle deformation structures in Lille Sotra reveals that the Hjeltefjord fault zone is a wide and significant fracture zone.

Many of the faults and fractures along the Hjeltefjord fault zone are filled with quartz, calcite, fluorite, epidote and sulphides, some of which exhibit ideomorphic crystals grown in open voids. Such mineral growth is typical for the near vicinity of the Hjeltefjord fault zone, and rapidly disappears or decreases in frequency to the east and west of this zone. One exception to this general observation is epidote-group minerals, which occur along many NE-trending faults outside of the Hjeltefjord fault zone.

Several episodes of movement along the Hjeltefjord fault zone have been demonstrated from the Bjorøy tunnel (Fossen et al. 1997). Here, a NNW–SSE-striking fault belonging to the Hjeltefjord fault zone contains old fault rocks formed at deeper depths (semi-brittle) which are overprinted by more brittle and partly open fractures both before and after deposition of the late Jurassic Bjorøy Formation.

The latest faults along the Hjeltefjord fault zone are identified as gouge zones with none-cohesive fault rocks that typically contain abundant clay minerals. These fault rocks thus appear to have formed at very shallow crustal levels. Such zones are easily eroded and therefore not well exposed. However, they are found in the Bjorøy tunnel, where they appear to be associated with deformation of the Late Jurassic (Oxfordian) sediments. A latest Jurassic or younger age is therefore assigned to these faults, which generally are reactivated structures. No distinct slip planes with associated slip indicators have been found in these faults with non-cohesive fault rock. They are therefore not included in the kinematic analysis presented below.

A large number of conspicuous and morphologically significant subplanar fractures occur along and in zones subparallel to the Hjeltefjord fault zone. Little or no slip is associated with the fractures, and they therefore classify as joints. These joints cross-cut many faults with striated slip surfaces, but are themselves never found to be affected by the faults. The joints therefore appear to be a relatively late development – at least later than the main faulting with associated cohesive fault rock formation.

Figure 4 shows that many of the joints in the study area are approximately N–S to NNW–SSE oriented, and the common NE–SW fault orientation is hardly reflected at all among the observed joint population. This may indicate that the joints formed as tension fractures by later reactivation of the Hjeltefjord fault zone. If this interpretation is correct, the jointing occurred as the minimum stress axis (σ_3) was oriented E–W to ENE–WSW. The age of this deformation is not clear, although it may well be contemporaneous with the down-faulting of the Jurassic Bjorøy Formation, i.e. latest or post-Jurassic in age.

Rustefjord fault

Another NNW-striking lineament (Rustefjord fault in Fig. 5) is found in southern Sotra. This apparently very steep structure appears as a significant lineament on satellite and aerial photographs, and possibly crosscuts a set of NE-striking fracture zones in the area. Geologic mapping around the fault (Bering 1984) indicates that lithologies cannot be correlated across the structure (Fig. 6), and the lineament thus appears to be a fault (Rustefjord fault). The local geomorphology indicates that the Rustefjord fault downthrows to the west, although no conclusive evidence has yet been found for this interpretation. There are indications that this fault was reactivated several times. First, several post-Caledonian dikes of Permian age (see below) are associated with steep

fractures along the Rustefjord fault. Similar dikes have not been found elsewhere in the Øygarden Complex, but occur to the south (Færseth et al. 1976). The deep (mantle) source of similar Permo-Triassic dikes in the Sunnhordland area (the southernmost of the dikes marked on Fig. 5) (Færseth 1978) and their restricted occurrence in the study area along the Rustefjord fault indicate that this fault was a deep-rooted structure of significant importance in the Permian. Second, one of the Permian dikes shows sign of gentle brecciation where a fault parallels the dike margin. Finally, a completely non-cohesive fault rock (Fig. 7), which must have formed during faulting at very shallow crustal depths, has been observed along the same lineament. The alkaline dikes and their implications for the tectonic evolution of the area are discussed in more detail below.

Sotra-Øygarden area

NE-striking faults are widespread throughout the Sotra–Øygarden area, and occur mostly as dip-slip normal faults with well-polished fault surfaces. Many of these faults are NW-dipping, but SE-dipping faults are also common, and they show a wide range in dip. Epidote-group minerals accompany these fault zones, and the epidote infill is commonly deformed and locally shows polished and striated slip surfaces. In addition, a zone of alteration in the host rock is marked by anomalously reddish K-feldspar. Relative age relations indicate that these faults predate swarms of joints that are subparallel to the NNW-striking Hjeltefjord fault zone. This does not mean that the Hjeltefjord fault zone is entirely younger than the NE-striking faults, because the Hjeltefjord fault zone has a long history. Hence, the joints are interpreted to be the result of reactivation of the Hjeltefjord fault zone (see above).

Askøy–Bergen area

NNE-striking fracture zones in Askøy seem to correlate mineralogically and kinematically to the more NE-striking faults observed in the Sotra-Øygarden area (Figs. 1, 5). The same is the case with NE trending faults in the southernmost Askøy (Askvik 1971), whereas NE to ENE-striking faults in the central and southern part of Askøy, some of which have mappable offsets with normal components up to 50 m, are of unknown significance. Similar zones occur on the mainland to the south, and a significant fracture zone runs through the Løvstakken area in a SSW direction. Significant fracturing and fault rock development is seen along this zone.

East of Bergen the fracture frequency seems to decrease somewhat, except for two major ENE–WSW trending fault zones with mappable offsets and 100-m-wide cataclastic zones associated with them (Grimevatnet and Totland faults, Fig. 1). The zones have dextral apparent offset in map view, and observed subhorizontal
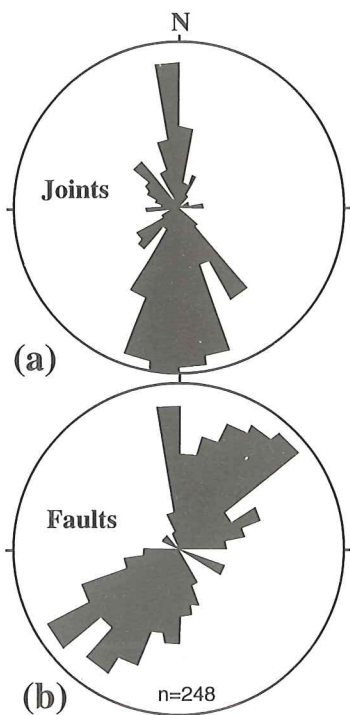

Fig. 4. (a) Orientation of fractures with no visible shear displacement and (b) faults with evidence of shear displacements in the Øygarden Complex west of Bergen (right-hand rule). Whereas faults typically exhibit N–S to NE–SW orientations, most joints are N(NW)–S(SE) oriented with a NW–SE oriented subpopulation.
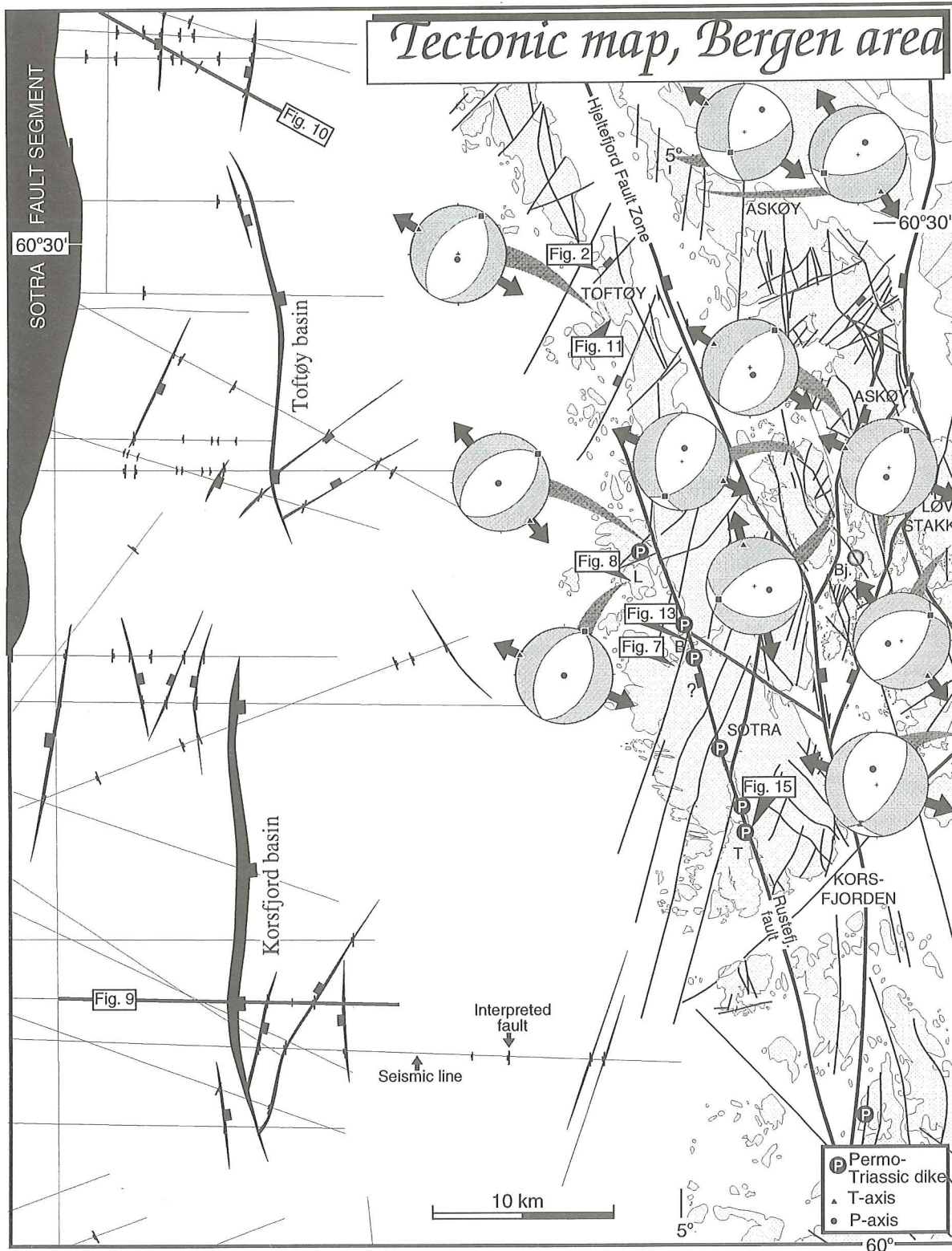
Fig. 5. Fault map of the area west of Bergen. Results of kinematic analysis of fault-slip data are shown as lower hemisphere stereoplots. Arrows indicate tension directions, and shaded areas of stereoplots indicate area of tension at the time of faulting. B = Brandsholmane dike locality, Bj. = Bjoroy locality.

fault striations indicate that they may be true strike-slip faults. Similar zones of cataclastic rocks occur in the Lysefjord/Fana area (Fossen & Ingdahl 1987), many of which are NE–SW trending. As in the Sotra–Øygarden area, these zones are cut by younger NNW–SSE-trending fractures and minor faults. Again, it seems that NNW–SSE structures (Hjeltefjord fault zone) were active at a later stage than the NE–SW-trending faults.
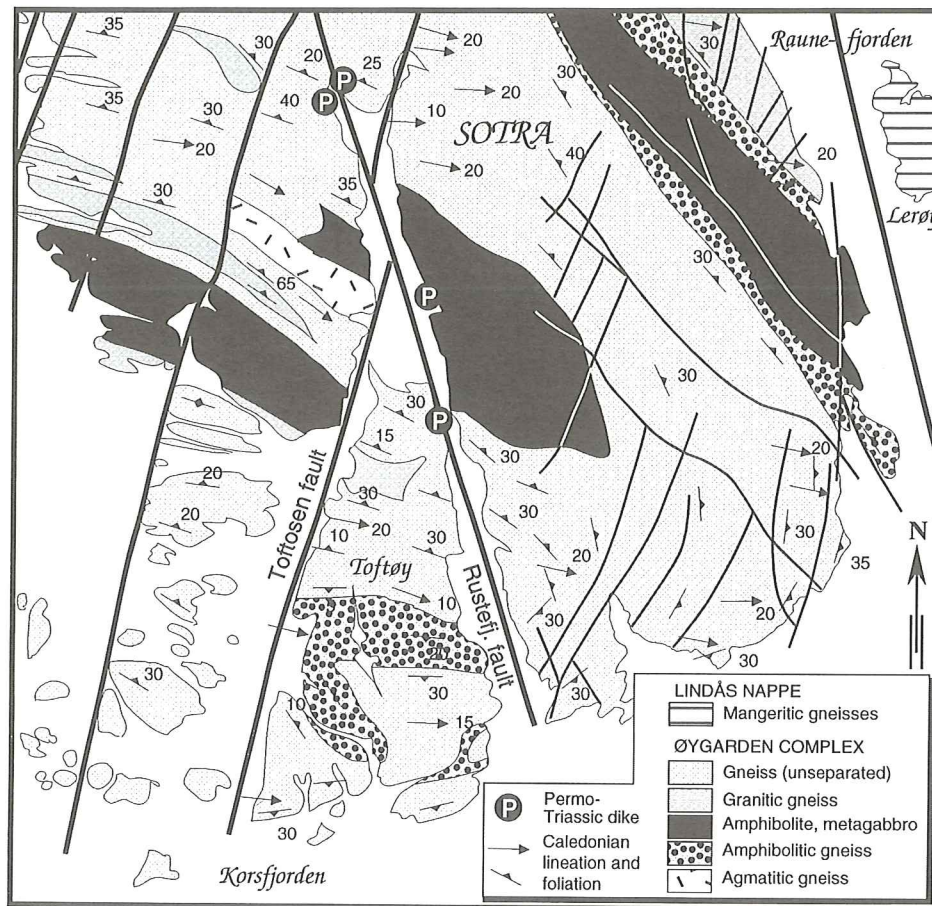
Fig. 6. Mapping in the southern part of the Øygarden Complex indicates the presence of faults with significant offset, particularly the Rustefjord fault. Modified from Bering et al. (1988).

Microfabrics

Microfabric studies of fault rocks in the Bergen area indicate that some deformation zones, particularly those with a NE–SW orientation, show a development from semi-ductile ultramylonitic fabrics via fractures with slightly recrystallized matrix or fracture fill to fractures with no sign of crystalloplastic deformation mechanisms (Fig. 8). The ultramylonitic fabrics occur in wide fault zones and exhibit a finer grain size than the those related to the Caledonian mylonitic deformation and the ductile, Devonian top-to-the-NW movement. It thus appears that the ultramylonites formed near the brittle-ductile transition in the crust. The fractures with less or no related recrystallization cut the ultramylonitic foliation, and clearly formed at higher crustal levels.

In contrast, the NNW–SSE-trending fractures generally lack the fine-grained ultramylonite stage, but as demonstrated from the fault zone between Bjorøy and the mainland (Fossen et al. 1997), evidence of recrystallized quartz in quartz-filled fractures cut by later, brittle fractures without related recrystallization is observed.

Offshore fault patterns

Several commercial seismic lines have been shot close to the coast of Sotra, and contain valuable information about the fault population of the area. The seismic data that have been applied in this study are the eastern parts of the regional surveys ST84201, ST8301, ST8201, ST8125, NNST84-03, TLGS-78, GSB-85, NE, NVGT-88, 805, NSDP84, and SG8403, and the locations of the seismic lines are indicated in Fig. 5.

The Øygarden Fault Complex

The dominating structure in the off-shore area is the Øygarden Fault Complex, which separates kilometer-thick sequences of Jurassic, Triassic and possibly older sediments in the hanging wall from basement and onlapping Jurassic sediments in the footwall (Horda Platform). The geometry of the Øygarden Fault Complex is that of a large-scale segmented fault system where each of the segments are linked with complex relay or accommodation zones.

A major segment of the Øygarden Fault Complex (here termed the Sotra fault) is situated about 30 km west of Sotra and Øygarden. The central portion of this fault has a N–S trend, but bends to the west toward its northern tip, where it enters an accommodation zone (Scott & Rosendahl 1989). North of this accommodation zone the Permo-Triassic fault polarity is reversed from W-dipping to E-dipping (Gabrielsen et al. 1990; Færseth et al. 1995). To the south, the Sotra fault shows a rapid decrease in

Fig. 7. Subvertical fault in granitic gneiss, Sotra. The completely non-cohesive fault rock consists of rounded fragments in a sandy matrix of similar composition as the side rock, indicating that the fault rock formed by grinding at a shallow crustal level. See Fig. 5 for location. UTM 808904.

displacement at the latitude of southern Sotra, typical for regions of linked fault segments (e.g. Childs et al. 1995). In this area, the Sotra fault segment is linked to the marginal fault of the Stord Basin through another accommodation zone. Onlapping Jurassic strata indicate

Fig. 8. Microphotograph of ultramylonite from a fault zone on Lokøy, W of Sotra, cut by more brittle microfaults. The fabrics seen in this photograph are cut by a Permian dike (not shown), and are therefore pre-Permian in age. This sort of textural relationship is common in the Bergen Arc System. UTM 778949.

that this structure was established prior to the main late-Jurassic rifting event in the North Sea.

The area immediately west of Sotra

The footwall of the Sotra fault is internally faulted (Fig. 1), although to a lesser extent than the area to the west. Figure 5 displays an interpretation of the fault pattern of the area east of the Sotra fault, as well as the position of the available seismic lines. These faults are well defined on the seismic sections where Jurassic sediments are present, but near land, where the Mesozoic sediments are removed by erosion, only basement (sea bottom) scarps indicate possible fault locations. The possibility and reliability of fault correlation depend mainly on the local distribution of seismic data (shown in Fig. 5), and the geometric characteristics or seismic expression of the faults on each seismic line.

A characteristic feature of the area between Sotra and the Sotra fault is several N–S trending half-grabens bound by east-dipping normal faults. The two most pronounced half-grabens form basins filled with mid-Jurassic sediments, and are informally named the Korsfjord and the Toftøy basins, respectively (Fig. 5). The fault planes dip about 65° to the east, and the maximum displacement of the top basement surface along these east-dipping faults is almost 1 km. Smaller faults are predominantly N–S to NE–SW striking, although correlation between the scattered lines may be difficult or impossible in some areas.

The fault displacement of the top basement surface is everywhere considerably larger than of the late Jurassic strata (Fig. 9). This indicates that most of the fault movement took place in pre–late Jurassic (pre-Brent Fm.) time, i.e. prior to deposition of the Bjorøy Formation. This is more clearly seen further west, for example along the Sotra fault, where the pre–late Jurassic/post-lower Devonian fault displacement is one to two orders of magnitude larger than the displacement of the late Jurassic strata (Fig. 10). Some of this faulting is clearly Permo-Triassic (Badley et al. 1984; Gabrielsen et al. 1990; Steel & Ryseth 1990; Færseth et al. 1995), although the possibility that the fault may be older cannot be excluded. These observations show that the late or post-Jurassic fault activity is of relatively minor importance and only represents a mild rejuvenation of a pre-existing fault array in the study area.

Slip directions and extension directions

Linear structures are locally developed on mineralized fault surfaces, primarily as striations on mechanically polished surfaces in the microbreccias in the faults (Fig. 11). A number of fault planes with fault striae have been measured in the basement west of Bergen, and the method and program described by Marret & Allmendinger (1990) have been used to analyze the data.
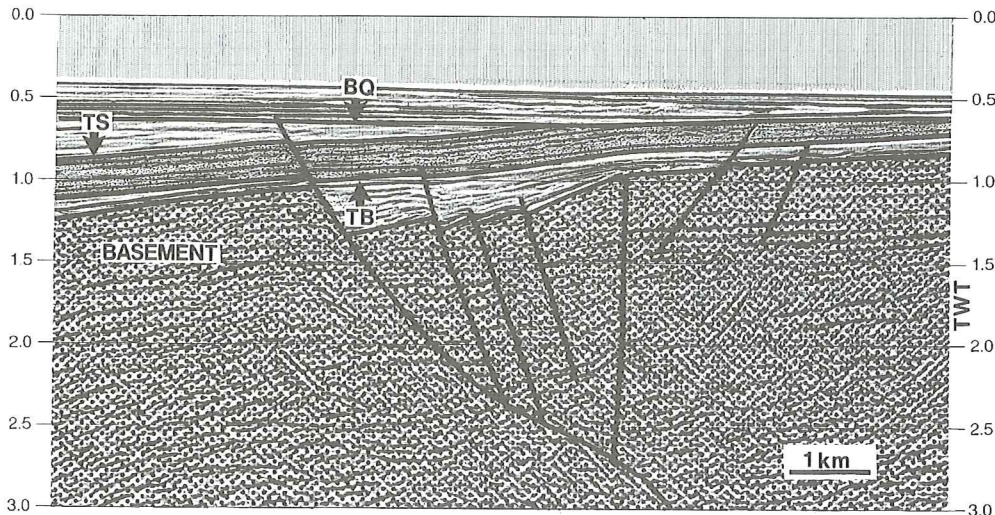
Fig. 9. Seismic profile across the Korsfjord Basin showing pre–late Jurassic faults with evidence of some Jurassic reactivation. TS = top Sognefjord Formation, TB = top Brent Formation. See Fig. 5 for location.

The application of stress inversion programs (e.g. Etchecopar et al. 1981; Angelier 1984) gives similar results to the kinematic approach applied in this article. The kinematic data exclude the latest faults of post-Middle Jurassic age with non-cohesive fault gouge, and thus represent pre–late Jurassic faulting events during which the extension direction remained more or less unchanged.

Analysis of the slip surfaces should be done with care, since we know that the faults were active at different depths and therefore at different times and possibly during shifting stress conditions. Nevertheless, if the slip data extracted from each locality are analyzed kinematically as a single data set, it is found that the vast majority of the data fit a simple deformation with vertical shortening and horizontal extension (Fig. 5). The exact extension direction is seen to vary somewhat from locality to locality, but the general trend is NW–SE. A compilation of data from all localities in the Øygarden Complex (Fig. 12) shows a single, well-defined extension

direction which is horizontal and trending N128E. Correspondingly, NE–SW trending faults are mostly dip-slip, whereas N–S to NNW–SSE trending faults (e.g. the Hjeltefjord fault zone, Fig. 1) show clear evidence of a dextral strike-slip component. This is the same stretching direction and deformation style as reported from the Devonian Solund basin (Séranne & Seguret 1987; Séranne et al. 1989), and preliminary data indicate a similar stretching direction for faults in the Sunnhordland area south of Bergen and in the Jotun Nappe to the east. Because the majority of the data are both internally and geographically consistent, the results indicate that most of the striated slip surfaces formed or were reactivated in a regional stress system that caused vertical shortening and NW–SE extension.

The kinematic approach applied here calculates the deformation that fits all the fault data as well as possible. Because the majority (but not all) of the fault slip data conform to the calculated deformation type, it is reason-
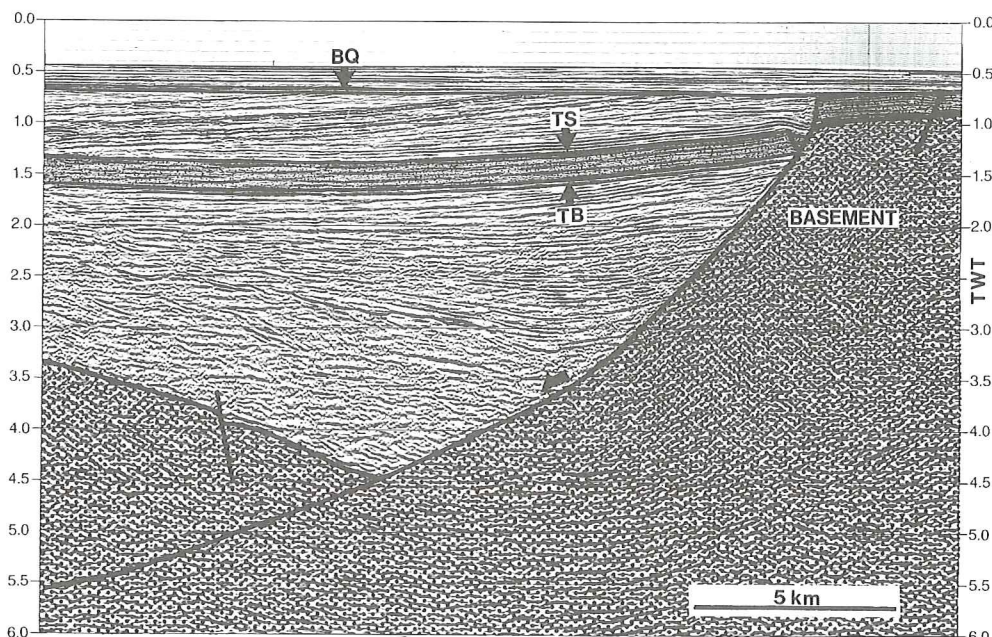

Fig. 10. Seismic profile across the Sotra fault segment of the Øygarden Fault Complex. The pre–late Jurassic throw component for this fault is much larger than the late or post-Jurassic component. Note that basement in the hanging wall may or may not include Devonian sediments. BQ = base Quaternary, TS = top Sognefjord Formation, TB = top Brent Formation. See Fig. 5 for location.
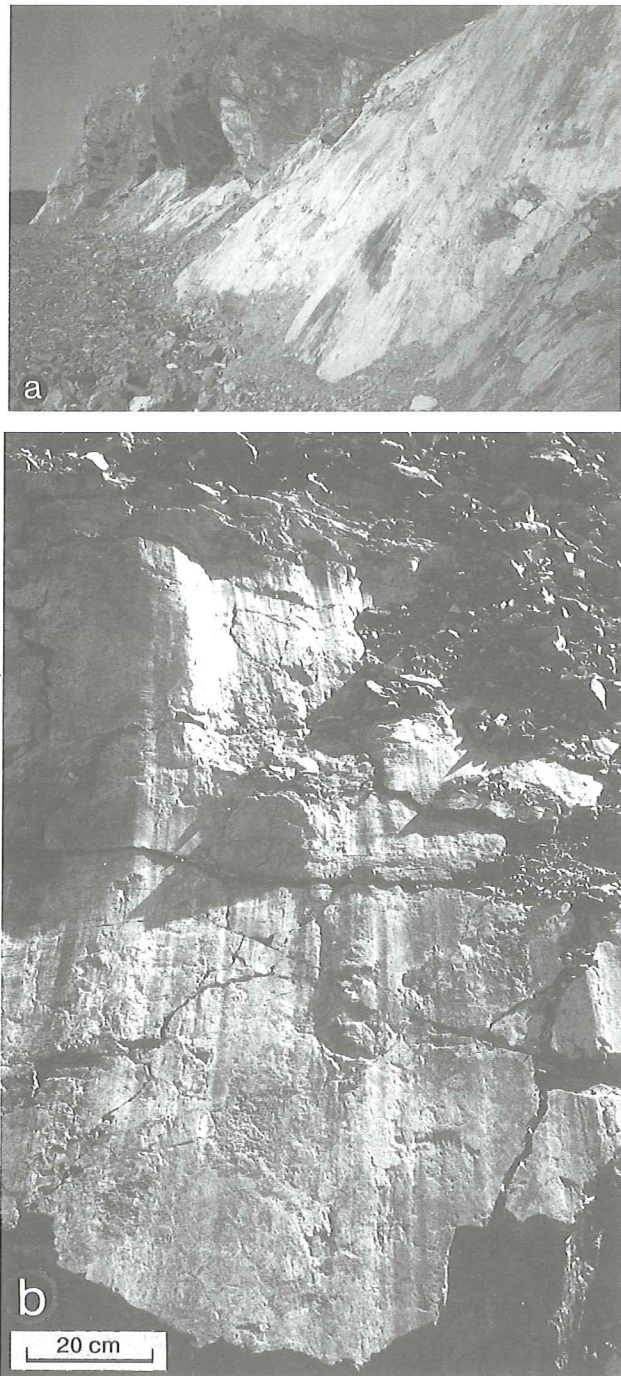
Fig. 11. Photograph of (a) NW-dipping fault (about 5 m high cliff) and (b) striae on the fault surface in gneisses of the Øygarden Complex at Balsneset, Toftøy (UTM 766096).

Fig. 12. (a) Kinematic data from all faults measured in the Øygarden Complex west of Bergen. Great circles indicate fault planes and arrows indicate associated slip directions. A variety of fault orientations and slip directions (dip-slip to strike-slip) are recorded. (b) Extensional (shaded) and compressional fields as calculated from the kinematic field data. The contractional (P) and extensional (T) axes for the data set are indicated. The many filled circles and open squares indicate orientations of calculated P-axes and T-axes, respectively. (c) The contoured T-axes distribution shows a single, well-defined NW–SE-oriented extension direction for the entire data set.

able to conclude that this deformation is responsible for most of the faulting. The analysis does not indicate whether there were one or several deformation episodes of similar character. Furthermore, it is very possible that the subset of the fault population that does not fit with the calculated deformation type formed under different stress conditions (i.e. at different times), and more detailed analyses are currently being carried out to investigate this issue.
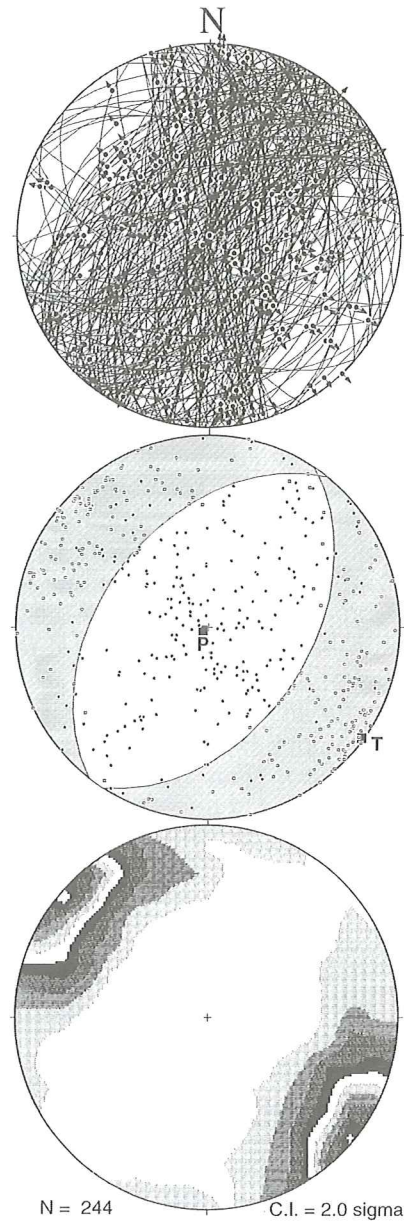
Alkaline dikes and the Permo-Triassic stress field

A number of unaltered and generally undeformed dikes occur along the Rustefjord fault (Fig. 5). The dikes are best exposed along the shore, where they normally occur with widths of less than 50 cm, although local widths of up to 4 m occur. The dikes are intruded along steep fracture systems, but the dikes themselves are generally undeformed or weakly jointed. They usually occur as

parallel dike segments varying from some tens of cen-
timeters up to some hundreds of meters in length. Their
length is to some extent proportional to their thickness,
i.e. thick dike segments tend to be longer than thin ones.

Individual segments may be linked by a bend in the
dike orientation if the segments are close enough, or may
be indirectly linked by fractures running from one dike
tip to the other (Fig. 13). In three dimensions the widely
applied model that dikes (fractures) are continuous at
depth and split into a series of fringes seems to fit these
observations very well (e.g. Anderson 1951) (Fig. 14).
The same geometry is seen in many of the approximately
N–S-trending fracture systems in the Øygarden Com-
plex. It has been proposed that such dike geometries
reflect a change in the orientation of the least principal
stress toward the surface (Anderson 1951; Delaney &
Pollard 1981). Alternatively, the en echelon patterns can
form as a result of combined extension and shear along
the dike (Delaney & Pollard 1981). Field evidence sug-
gests that the latter explanation can be ruled out. If the
formation of dike-filled fractures is related to dike intru-
sion, this indicates near-surface conditions during intru-
sion. However, the en echelon fracture pattern may well
have been formed long before dike intrusion, influenced
by a shear component along the fractures.

Several of these dikes have been dated by the K-Ar
method to ca. 260 Ma (Løvlie & Mitchell 1982), and thus
correspond to the older generation of dikes described
from the Sunnhordland region (Færseth et al. 1976).
However, the southernmost dike shown in Fig. 5 was
reported to yield a Triassic age by Færseth et al. (1976).
Based on paleomagnetic considerations, Løvlie &
Mitchell (1982) suggested a minimum temperature of the
host rock during intrusion of ca. 150 °C, i.e. the dikes
intruded at depths in excess of ca. 5 km. However, the
amphibole and whole rock results of their K/Ar analyses
are generally indistinguishable, suggesting that no signifi-
cant reheating above about 150 °C has taken place since
emplacement. Hence, the intrusion temperature in the
host rock is not likely to have been in excess of 150 °C.

The fractures along which the Permo-Triassic dikes
occur show little evidence of vertical movements, and the
dikes therefore seem to have been emplaced as the frac-
tures acted in a tensile mode. Because most Permo-Trias-
sic dikes along the coast of western Norway have a N–S
to NNW–SSE orientation, it has been assumed that the
dikes intruded during approximately E–W extension
(Færseth et al. 1995). However, if the dikes intruded
along *pre-existing* fracture zones, their orientation would
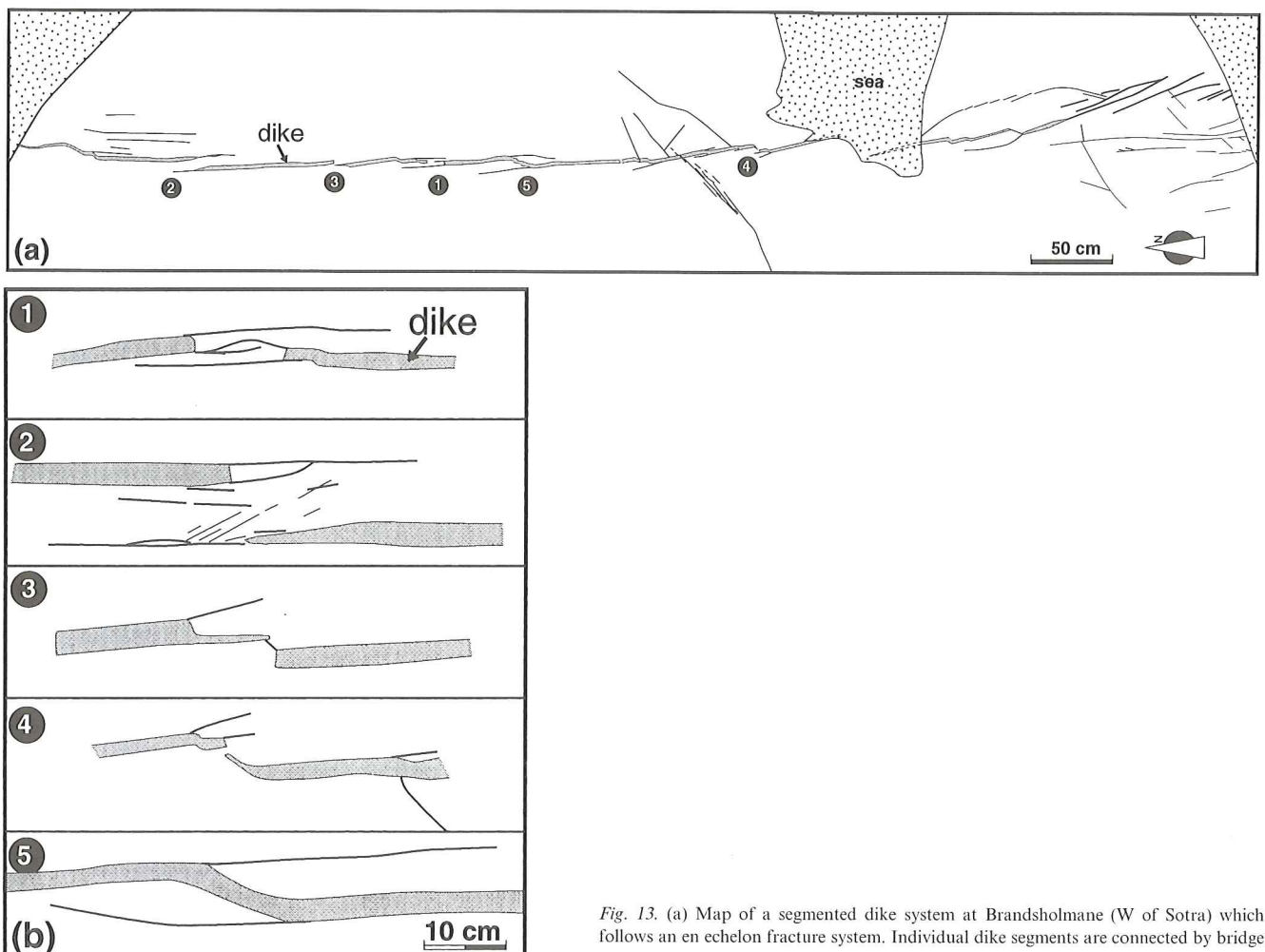be controlled not only by the existing stress field, but

Fig. 13. (a) Map of a segmented dike system at Brandsholmane (W of Sotra) which
follows an en echelon fracture system. Individual dike segments are connected by bridge
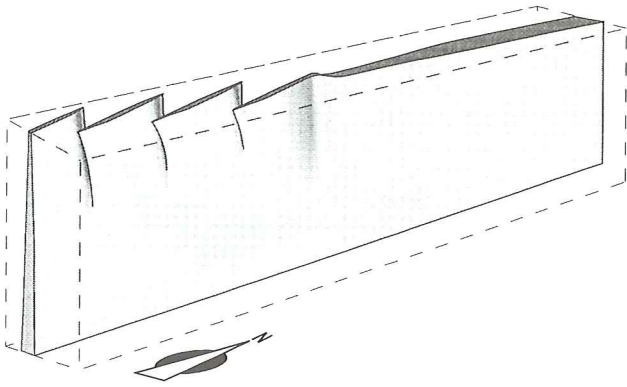systems as shown in (b). See Fig. 5 for location.

Fig. 14. Three-dimensional interpretation of the fracture system mapped in Fig. 13.

also by the orientation of such fractures. Hence, a more rigorous analysis is required before making assumptions about the extension direction during intrusion.

Most of the dikes along the Rustefjord fault show irregular contacts with the country rock, and in many cases it is possible to identify points (in plan view) on each side of the dike that were in contact prior to dike intrusion. Such points may be corners where locally the dike has followed a fracture of a different orientation, or where gneissic layering or quartz veins meet the dike wall at each side of the dike (Figs. 15 and 16). The straight line between two such points is the horizontal component of the local displacement vector related to the dike intrusion. For this method to be accurate, one must choose surfaces that contain or are close to the extension vector. In the common case where the width of the dike is larger than the vertical displacement by an order of magnitude or more, horizontal outcrop surfaces are suitable.

The results of this method (Fig. 17) show that the extension associated with the Permo-Triassic dike intrusions is almost due E–W. Preliminary analysis indicates similar extension directions for both Permian, Triassic and Jurassic dikes in the Stord–Tysnes area to the south. This extension direction is different from the one determined from the fault slip analyses (Figs. 5, 12), and if we make the assumption that the extension associated with dike intrusion is related to the concurrent regional stress field, it thus appears that dike intrusion occurred not only at a different time, but also in a different stress field than the one at the time of faulting. Because almost all the dikes are undeformed or only weakly jointed even where they intrude complex fault zones in the gneiss (as seen in road cut in Lokøy, Fig. 5), it is concluded that most of the faulting that resulted in striated fault surfaces along the Rustefjord fault is older than the dikes. Based on correlations of fault rock microfabrics and kinematics with other faults in the study area, it is reasonable to assume that the majority of the fault population presented in Figs. 5 and 12 are also of early or pre Permo-Triassic age. In addition, the differences in extension direction indicate a change in the minimum
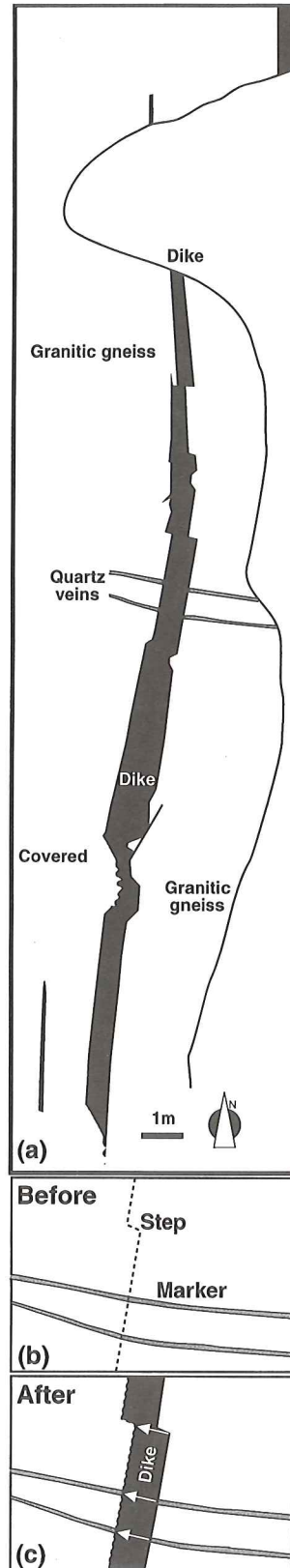

Fig. 15. Map of Permian dike, Tuftarøy, southern part of the Øygarden Complex (dated by Løvlie & Mitchell 1982). Irregularities or markers along the dike can in some cases be matched on each side, allowing for reconstruction of the rock prior to intrusion. The horizontal extension direction can be found from such reconstructions.

Fig. 16. One of the steps along the dike displayed in Fig. 15.

Fig. 17. Extension directions and orientations of dikes along the Rustefjord fault, Sotra (a) and of Permian-Jurassic dikes from Espevik and Tysnes south of Bergen, currently studied by P. Valle, R.B. Færseth and the present author. Fractures within the field of dike orientations opened during dike intrusion. The extension direction must therefore be located within the white sectors of the stereonets.

stress axis (σ_3) at some point between the main faulting and the time of dike intrusion.

Discussion

The extension direction during early–middle Devonian ductile deformation is indicated by the fairly consistent top-to-the-(W)NW transport direction, as determined by fabric analysis in the décollement zone in southern Norway (Fossen 1992, 1993a, b). In addition, the NE–SW trending Hardangerfjord Shear Zone and similarly oriented semi-brittle faults formed or were reactivated as extensional shear zones in the Devonian. This extension direction is practically identical to the one extracted from the fault kinematic data (Fig. 12). Hence, the ductile Devonian extension and the more brittle faulting appear to have formed in the same or similar stress field(s), different from the Permian stress field at the time of dike intrusion.

In this context, it is interesting that the fault systems of the Bergen Arc System contain evidence of a temporal transition from semi-ductile (ultramylonites) through semi-brittle to purely brittle fabrics. From the dating o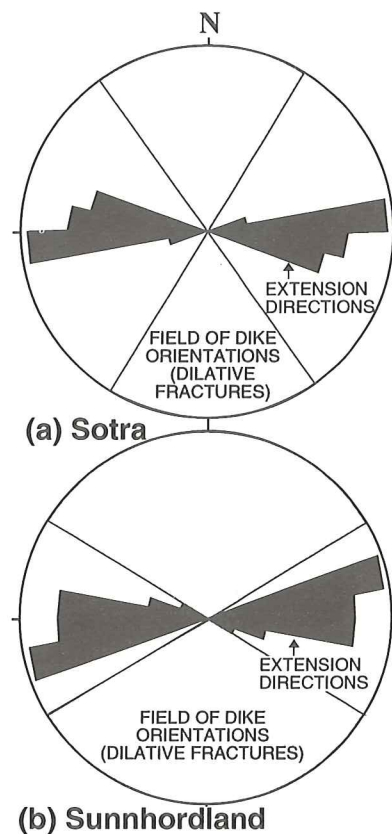f the Permo-Triassic dikes and the relative age relation between the dikes and the faults, and from the stress regime recorded by the Permian dikes, it appears that a large portion of this faulting and uplift history occurred before ca. 260 Ma. The rapid lower–middle Devonian cooling of western Norway that has been demonstrated by several recent Ar/Ar dating projects (Lux 1985; Chauvet & Dallmeyer 1992; Boundy et al. 1996; Fossen & Dunlap 1997) appears to have continued into the Upper Devonian as rocks were passing through the brittle-ductile transition zone. This development corresponds with the model of Séranne et al. (1989), who interpreted brittle deformation in the Solund area as an expression of Devonian extensional deformation towards the end of a continuous post-collisional uplift history.

Seismic data from the offshore Bergen area show a dominance of pre-Jurassic fault deformation and are thus in agreement with the onshore data, although the Jurassic sediments are also affected by some faulting. This is similar to what is seen in the Bjorøy tunnel, where most, but not all of the (semi)brittle faulting history is pre-Oxfordian. The Permo-Triassic ?E–W extension recorded west of the Øygarden Fault Complex (Steel & Ryseth 1990; Færseth et al. 1995) appears to be less pronounced in the onshore area west of Bergen, according to the discussion above. Later (post-Oxfordian) fault

movements are, however, recorded in the Bjorøy tunnel as non-cohesive gauge zones, and it is not known how common this type of faulting is in the area because of the rapid erosion and cover of these zones. The N–S faults associated with the Toftøy and Korsfjord basins show evidence of post-Oxfordian reactivation, and the downthrow of the Bjorøy Formation and other lithologies to the east across the Hjeltefjord fault zone indicates that post-Oxfordian faulting may be significant. Brecciation of a Permo-Triassic dike SE of Bergen is reported by Færseth et al. (1976) to give a Jurassic age, and may be another expression of late deformation in the area.

Conclusions

The results presented in this article indicate that the rocks in the western Bergen Arc System were subjected to stresses that resulted in extensional deformation during several phases since the Devonian. The successive overprinting of ductile structures by semi-ductile, semi-brittle and eventually purely brittle ones is evidence for tectonic activity during gradual uplift from at least mid-crustal levels (ductile regime in the lower–middle Devonian) to the surface (at the time of deposition of the Late Jurassic Bjorøy Formation). Much of the faulting produced fault rocks that show evidence of a ductile component (several kilometers of burial), and locally 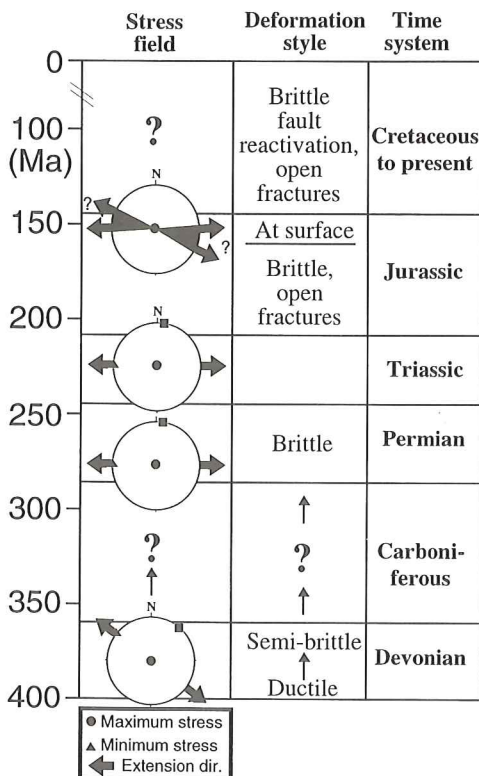is postdated by Permian dikes. It is therefore assumed that much of the faulting in the area is after the Lower–Middle Devonian ductile extension, but pre-Permian.

The majority of the (pre-Permian) faults with striated surfaces formed in a regional stress field where the least principal compressive stress (σ_3) was oriented approximately NW–SE. This orientation is consistent with the nature of the ductile extension in the Lower–Middle Devonian. Analysis of the geometries of Permian dikes reveals a more E–W orientation of σ_3, implying a change in σ_3 from Devonian to Permian times (Table 1). This orientation corresponds well with the approximately E–W extension direction inferred in the North Sea during the Permo-Triassic and late Jurassic rifting phases (e.g. Roberts et al. 1990; Rouby et al. 1996), and also with estimates of extension from Permo-Triassic and Jurassic dikes from Sunnhordland south of Bergen (Fig. 17b). Permo-Triassic and/or later phases are represented by fault reactivation in the Bergen Arc System, particularly along the Hjeltefjord fault zone where post-Oxfordian joints and faults with non-cohesive, clay-rich fault gouge typical for very shallow crustal depths postdate faults with striated surfaces.

Table 1. Schematic presentation of the main variations in the regional stress field and deformation style based on the observations presented in this article.

Stress field	Deformation style	Time system
?	Brittle fault reactivation, open fractures	Cretaceous to present
	At surface	Jurassic
	Brittle, open fractures	
		Triassic
	Brittle	Permian
?	**?**	Carboniferous
	Semi-brittle / Ductile	Devonian

(y-axis: 0, 100 (Ma), 150, 200, 250, 300, 350, 400)

● Maximum stress
▲ Minimum stress
◀ Extension dir.

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