Vein architecture in the Devonian sandstones of the Hornelen basin, western Norway, and implications for the palaeostrain history

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Systems of veins in the Devonian sandstones of the Hornelen basin are described. These veins range from an early generation of anastomosing networks of thin veins and breccia zones with a fine-grained matrix to a later generation of veins with fibrous quartz fill. The presence of cataclasite fragments in the breccias suggests the existence of an earlier deformation phase still, possibly associated with shearing and grain size reduction of weakly consolidated sediments (deformation bands). The orientations, reactivation textures and cross-cutting relationships of these veins are interpreted as indicating a rotation of the extension direction from NW–SE to WSW–ENE with time. Correlation with other indications of the palaeostrain field orientation in western Norway from the literature suggests that this rotation took place between Middle Devonian and Late Permian times. The textures, mineralogy and morphology of the veins are used to interpret the history of brittle deformation, stress/strain system and fluid pressures in the Hornelen basin through these times.

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Introduction

Devonian age, low-grade sedimentary rocks crop out in a series of small basins in western Norway, known as the Hornelen, Håsteinen, Kvamshesten and Solund basins (Fig. 1). Of these, the Hornelen basin is the largest. The sedimentary structure and tectonic histories of these basins have been studied in some detail (Bryhni 1964; Steel 1976; Hossack 1984; Norton 1987; Torsvik et al. 1988; Seranne & Seguret 1987; Chauvet & Seranne 1989; Wilks and Cuthbert 1994; Osmundsen et al. 1998), but until recently the fracturing history has been largely neglected. These rocks, however, contain well-developed fracture systems and recently the geometry and scaling characteristics of the joint system in the Hornelen basin have been investigated through mapping at outcrop scale and low-level aerial photography (Odling 1997). In addition to joints and faults, the rocks have also been discovered to contain a variety of vein structures that reveal shifts in palaeostrain orientations during their formation. It is these vein structures that are the subject of this paper.

Regional setting of the Hornelen basin

The Caledonian orogeny in SW Norway was closely followed and perhaps overlapped by extensional tectonics that resulted in a crustal scale re-arrangement of the orogenic belt (Hossack, 1984; Norton 1986; 1987; Seranne & Seguret, 1987; Andersen & Jamtveit; 1990; Fossen, 1992; Milnes et al. 1997). Based on regional structural and kinematic analysis, two different styles of extension are recognized (Fossen 1992). Early stages of this extension involved ductile deformation and a NW to W directed reactivation of thrust zones. Later stages involved the formation of mylonitic, west-dipping detachment zones penetrating the whole tectono-stratigraphy. Down-to-the west, displacement on these detachment zones took place under progressively more brittle conditions and juxtaposed eclogite-bearing rocks in the foot-wall against low-grade and higher stratigraphic rocks in the hanging wall. The most significant of the detachment zones in western Norway is the 2–3 km wide, low-angle Nordfjord–Sogn Detachment (Norton 1987). It is generally accepted that displacement on this detachment zone and subsidiary faults was accompanied by the deposition of Middle Devonian sedimentary basins in the hanging wall (Fig. 1).

Similar detachments are found throughout western Norway (Fig. 1), including the Bergen Arc Shear Zone and the Hardangerfjord Shear Zone (Fossen 1992). The Bergen Arc Shear Zone also separates eclogite-bearing rocks in the foot-wall from Caledonian nappes and Devonian sediments in the hanging wall. It has recently been suggested that this shear zone represents a southward continuation of the Nordfjord–Sogn–Detachment (Fossen 1992; Wennberg & Milnes, 1994; Wennberg et al. 1998), indicating the probable regional significance of the structure. $^{40}Ar/^{39}Ar$ analyses indicate that rapid exhumation and cooling below blocking temperature of mica at around 390–400 Ma (Early Devonian) was associated with the later down-to-west displacement on the major detachments of western Norway (Chauvet & Dallmeyer 1992; Fossen & Dallmeyer 1998; Fossen & Dunlap, 1998, Andersen 1998 and references herein).

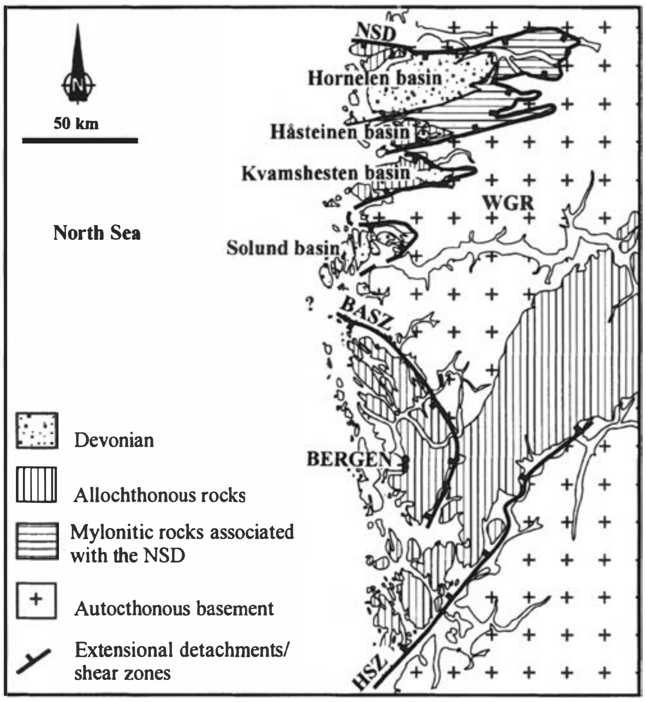

Fig. 1. Simplified geological map of SW Norway showing the main tectonic units and the location of the Devonian basins: Hornelen, Håsteinen, Kvamshesten and Solund. NSD = Nordfjord Sogn Detachment, BASZ = Bergen Arc Shear Zone, HSZ = Hardangerfjord Shear Zone, WGR = Western Gneiss Region.

Geology of the Hornelen basin

In the Hornelen basin, sandstones and conglomerates of Middle Devonian age (Jarvik 1949) fill a fault-bounded basin, approximately 70 by 25 km in extent (Fig. 2). The basin sediments form laterally continuous cycles 100–200 m thick composed of beds 1–2 m thick. The basin fill is dominantly sandstone, but conglomerate fans are also found along the northern, southern and eastern margins of the basin (Bryhni 1964; Steel 1976). The sedimentary layering in the central portions of the basin dips approximate 20–25° eastwards and imposes a very strong control on topography, which consists of eastward facing slopes parallel to the tops of the cycles, separated by cliffs up to 300 m in height. The total summed thickness of these cycles is over 25 km (Bryhni 1964; Steel 1976). However, this is not interpreted as representing a true stratigraphic thickness, but rather as indicating that the deposition was controlled by tectonism where successive cycles overlapped to fill the space created by displacement on the underlying Nordfjord–Sogn Detachment and subsidiary faults. The rocks have suffered metamorphism bordering on greenschist grade (e.g. Seranne & Seguret 1987; Wilks & Cuthbert 1994) and are now of very low permeability (0.02 mD; Mæhle 1975). As a result, the sandstones are very resistant to weathering and form a mountainous region. Slopes on the tops of cycles are to a large extent free of vegetation, resulting in large areas of excellent exposure, ideal for study of the fracture and vein systems they contain.

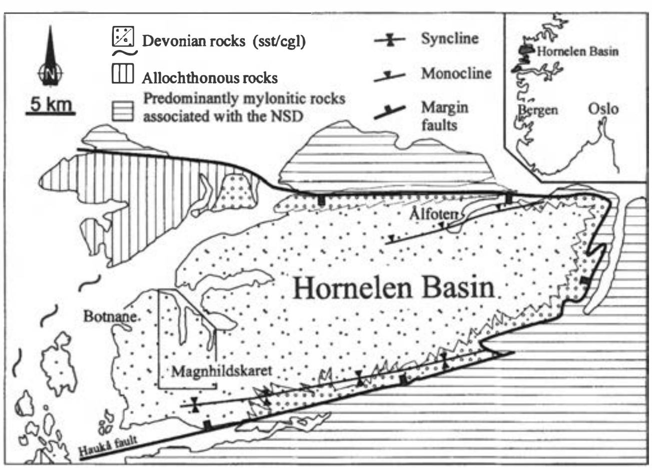

Fig. 2. Geological map of the Hornelen basin showing the bounding faults, location of major folds and the location of the main study area. NSD = Nordfjord–Sogn Detachment.

The present-day outcrop of the Hornelen basin is fault-bounded on all sides except to the west, where the sediments rest unconformably on older rocks (Fig. 2). The eastern margin of the Hornelen basin is defined by a low-angle brittle extensional fault representing high levels of the Nordfjord–Sogn Detachment (the Hornelen detachment; Dewey et al. 1993), which here dips around 15° westwards (Norton et al. 1990; Wilks & Cuthbert 1994). The northern and southern margins are defined by steep (50–60°) faults which dip toward the basin axis (Wilks & Cuthbert 1994). The southern boundary fault (Haukå fault) is seen to cross-cut the eastern low-angle fault indicating that the E–W striking faults were active at a later time (Bryhni & Lutro 1989; Torsvik et al. 1997; Braathen 1999). The presence of conglomerate fans at the margins, with sediment transport directions towards the basin centre, suggests that precursors to these faults were active at the time of sedimentation (Steel 1976; Wilks & Cuthbert 1994). However, based on palaeomagnetic and $^{40}Ar/^{39}Ar$ analysis of various fault rocks in western Norway, it seems likely that these faults have a complex and long-standing history, with periods of reactivation up to at least the Mesozoic (Torsvik et al. 1988, 1997; Eide et al. 1997; see also Braathen 1999).

The basin fill is relatively little deformed apart from E–W trending, upright to slightly overturned, open to close folds which are concentrated at the northern and southern margins (Fig. 2). The age of this folding has, and continues to be, a matter of some debate. Tighter folding of the same orientation in the underlying rocks (Krabbendam & Dewey 1998) and sedimentary features interpreted as unconformities in the Devonian rocks adjacent to bounding faults (Chauvet & Seranne, 1994) suggest that folding is partly syn-sedimentary in age. There is evidence, however, from the Kvamshesten basin (Osmundsen et al. 1998), and the Hornelen basin (Larsen in prep.), suggesting that folding post-dates sedimentation. Palaeomagnetic studies (Torsvik et al. 1988) and $^{40}Ar/^{39}Ar$ studies (Eide et al. 1999) suggest Late Devonian to Early Carboniferous age of folding. The

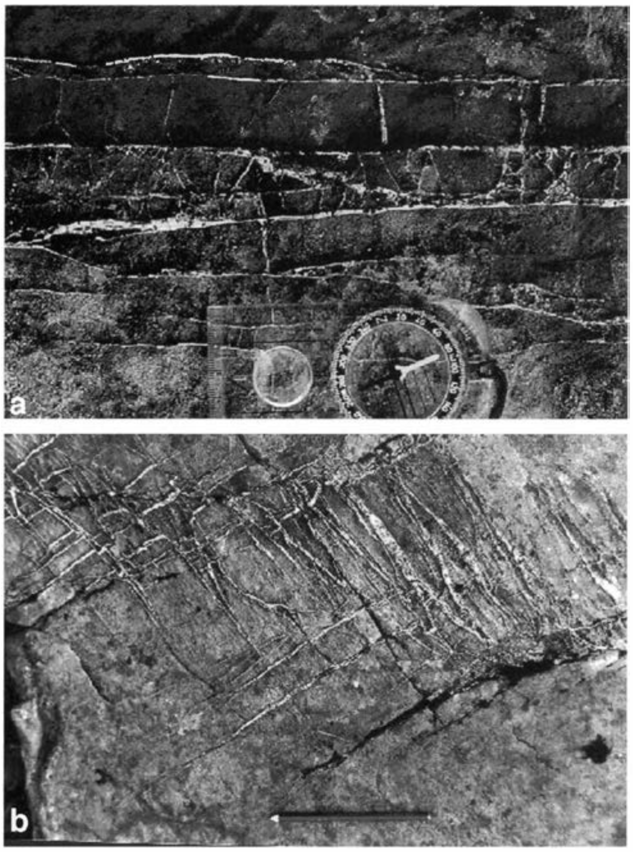

Fig. 3. (a) Photograph of early veins with fine-grained fill composed of quartz, calcite, chlorite and epidote showing a well-connected network geometry. (b) Photograph of an early vein zone showing orthogonal sets of anastomosing veins. The pencil is about 10 cm long.

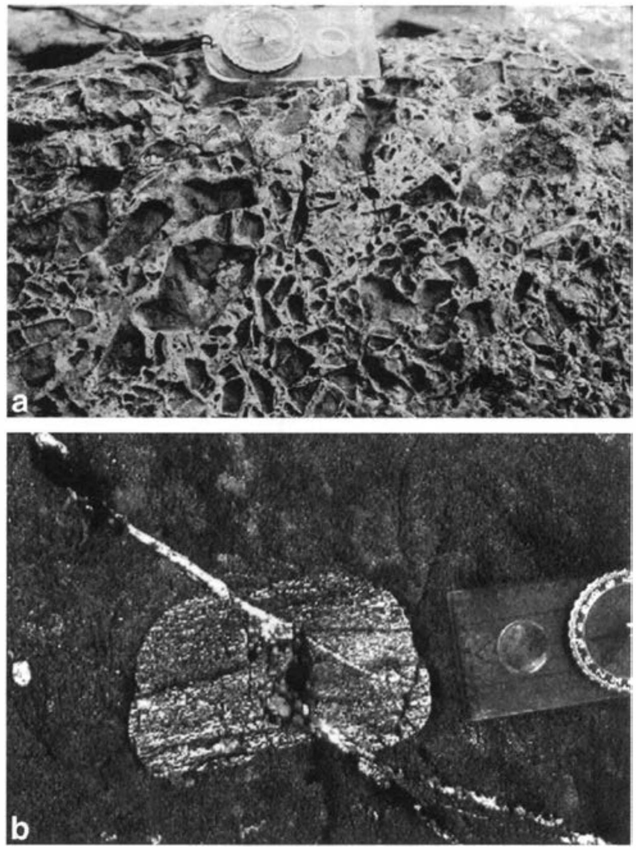

Fig. 4. (a) Photograph of an early vein showing breccia structure composed of disoriented sandstone fragments within a fine-grained matrix, composed largely of quartz with calcite, chlorite and epidote. (b) Photograph of an early vein cutting both a gneiss pebble and sandstone matrix alike, indicating that the sandstones were well lithified at the time of vein formation.

folds are cut by the eastern low-angle margin fault thought to be Late Permian in age (Braathen 1999 and references herein), providing a lower time limit. The data on veins presented in this paper come from the little-deformed central part of the Hornelen basin far from major influence of folding, and thus the conclusions drawn here are independent of the age of folding. The relationship between the vein structures and folding in the Hornelen basin will be the subject of another paper (Larsen in prep.) and will not be discussed further here.

In addition to the folding, the basin sediments display a range of brittle structures. The earliest of these are veins of varying morphology, which form the subject of this paper. These are post-dated by a pervasive system of sub-vertical joints showing four major trends and a power law length distribution over at least three orders of magnitude (Odling 1997). The range of brittle structures present in the basin fill suggests a history of fracturing that took place over a considerable time period and range of pressure and temperature conditions.

Vein morphology in the Devonian sandstones of the Hornelen basin

Veins represent the earliest brittle structures observed in the sandstones of the Hornelen basin. These veins can be broadly divided into two categories, termed here "early" and "late" veins, based on morphology, texture and age relations. The major distinguishing features are that the early veins are dominated by a very fine-grained mineral fill (dominated by quartz) and breccia structures, while the late veins are characterized by fibrous quartz fill. Each of these categories is described below.

(a) Early veins

The earliest veins comprise a variety of structures from networks of thin veins and breccias to straight-sided veins. There is a complete gradation between well-connected networks of thin (1 mm or less), irregular veins (Fig. 3) to pods and veins of breccia up to 1 m across composed of sandstone fragments "floating" in a mineral matrix (Fig. 4a). Vein fill and breccia matrix are composed of a fine-grained (around 25–100 μm), white to green mineral mass of quartz, calcite, chlorite and epidote. In the breccias, textures range from "jig-saw" type, where the fragments fit closely with a minimum of matrix, to a few disoriented sandstone fragments "floating" in the mineral matrix. Veins are observed to cut gneiss pebbles and sandstone

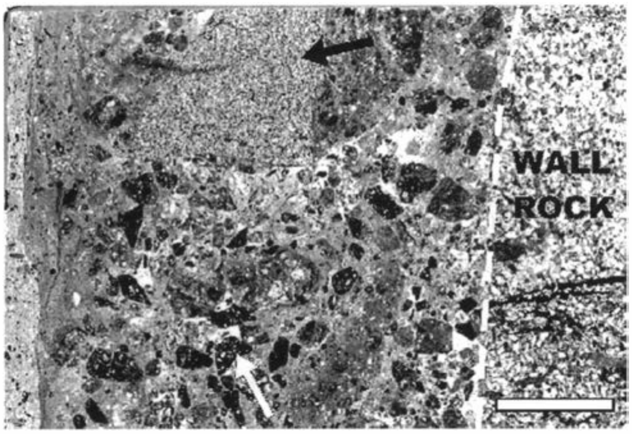

Fig. 5. Microphotograph of early vein showing fragments of cataclastic material from an earlier deformation phase (white arrow) and an angular sandstone fragment (black arrow). The matrix is composed of very fine-grained quartz. The scale bar is 0.5 mm.

matrix alike, indicating that the host sandstone was already well lithified at the time of vein formation (Fig. 4b).

Although good markers for detecting displacement are not common in the sandstones, some breccias and veins show evidence of fault movements up to some tens of centimetres. Some pods have irregular boundaries, while others are clearly formed by displacement of the fracture walls to form voids at jogs in the fracture trend. Breccia vein terminations are sometimes marked by dense networks of contemporaneous near orthogonal sets of fine veins which are symmetrically arranged about the main vein trend (Fig. 3b). Many veins show evidence of multiple phases of mineral deposition, with cross-cutting relationships and new layers of mineralization at vein margins, indicating a history of repeated reactivation. Associated with these breccias and fine network of veins are straight-sided veins with a coarse-grained, white quartz fill up to 50 cm wide. These quartz veins can be many tens of metres in length and from cross-cutting relationships it can be concluded that they generally post-date the fine-grained veins but share a common trend.

The fine-grained veins and breccias and later quartz veins form large-scale N–S trending zones of vein development some 3–4 m broad that can be traced for a kilometre or more. Within these zones, individual veins of all early types are commonly arranged *en echelon*, where veins are right-stepping with respect to the zone trend. These early vein zones and breccia pods seem to be particularly well developed in the Magnhildskaret area. However, small veins with the same morphology, mineralogy and texture are found throughout the basin.

The irregular network geometry of early veins seen on outcrop scale can also be observed in thin section. On this scale, the breccias can be seen to contain fragments of both sandstone and cataclasite in a fine-grained matrix (Fig. 5). The presence of fragments composed of cataclastic material indicates that the breccia veins reactivated earlier structures, suggesting that at least two episodes of deformation have occurred during breccia development. The earliest of these episodes (preserved in the cataclasite fragments) are characterized by angular and disoriented grains (0.3 mm or less) in a brown, cloudy matrix of fine-grained quartz, calcite, epidote and iron oxides which comprises 50% or more of the rock. The textures within these fragments resemble textures found in breccia veins with greenish-coloured matrix. These greenish breccias can be seen, from intersection relationships, to pre-date the breccia veins with white mineral matrix.

The later deformation episode in breccia development is characterised by fragments of the cataclasite described above and sandstone in a white matrix of quartz with less epidote and iron oxides than the matrix of cataclasite fragments and greenish breccias. Fragments of the later white breccias are larger and grain-size reduction is less pronounced (Fig. 5). The texture of the mineral matrix shows some signs of shear. This is consistent with the observed evidence of fault displacements and repeated reactivation in outcrop. The sandstone fragments within breccia veins and in the surrounding country rock show no significant differences in porosity. It might be expected that if the sandstone had high porosity at the time of breccia development, it would be preserved in the mineralized breccia veins. This is thus consistent with the earlier conclusion that the sandstones were already well lithified at this stage of breccia vein development.

The texture of the earliest deformation recorded by the cataclasite fragments in breccias resembles that found in deformation bands in porous sandstones (e.g. Aydin 1978; Aydin & Johnson 1983; Underhill & Woodcock 1987; Antonellini et al. 1994). Also, some of the fine networks of early veins show an irregular, anastomosing geometry similar to that shown by deformation band swarms. It is therefore possible that the breccia vein development was preceded by minor faulting of deformation band style, perhaps before the rocks were fully lithified. These early zones of deformation seem to have been repeatedly reactivated and overprinted by later stages of vein and breccia formation, suggesting that they formed zones of weakness to be exploited by later deformation.

(2) Late veins

The early structures described above are cross-cut by veins that are easily distinguished from the early veins by the fibrous textures and coarser grain size of their mineral fill (Figs 6a and 8), straight vein walls, and lesser thicknesses (2 cm or less). These veins tend to be most abundant in the vicinity of the large-scale zones of early vein development, although they also occur spread throughout the basin. *En echelon* geometries are common where N–S trending main veins terminate in arrays of right-stepping veins trending NNW–SSE (Fig. 7a). The vein-array angle is about 20°. The main N–S trending veins also form *en echelon* geometries but with a smaller vein-array angle of around 5°.

Fibrous quartz dominate the vein fill, but veins locally also contain calcite. Chlorite occurs as clusters of

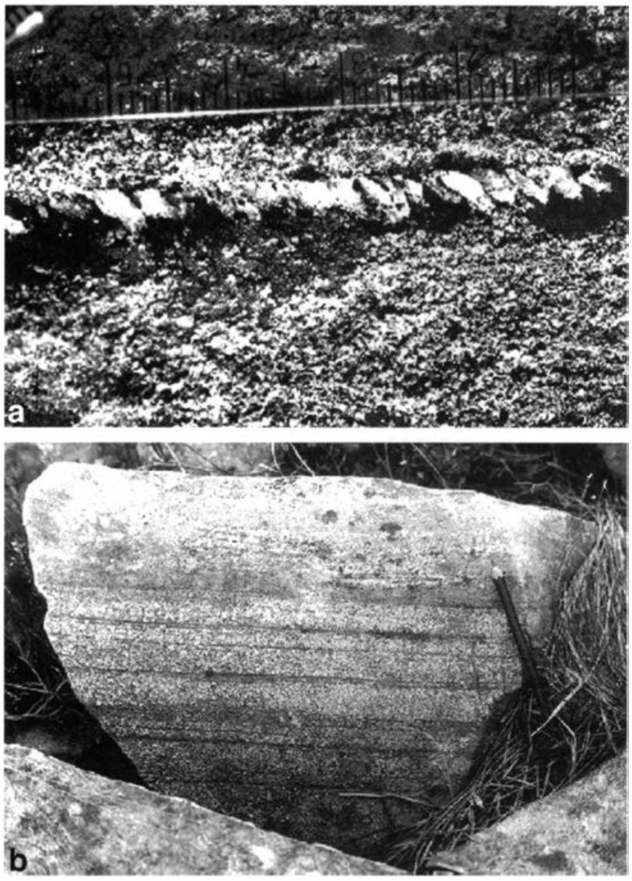

Fig. 6. (a) Close-up photograph of a late vein with fibrous quartz fill. The fibre trend is rotated counter-clockwise with respect to the direction normal to the vein wall. The photograph is approximately 5 cm across. (b) Photograph of the surface of a partially mineralized late vein. The mineralization picks out the sedimentary layering in the sandstone and mineralization is most complete where the sandstone grain size is coarsest. The pencil is approximately 10 cm long.

wormicular grains within some quartz crystals, and characterizes low-grade metamorphic systems. Vein fill ranges from solid to partial filling of the fracture space. Good exposures of partially filled vein surfaces show that the most complete mineralization is associated with the coarsest grain size in the sandstone (Fig. 6b). These mineralization patterns may therefore reflect the rate at which fluid could reach different parts of the fracture, suggesting that grain size may have been correlated with permeability.

In thin sections, it can be seen that some fibres are in optical continuity with grains in the country rock (Fig. 8). This is consistent with syntaxial growth, i.e., successive splitting of internal part of the vein and growth toward the vein centre (Durney & Ramsay 1973). However, other veins with curved fibres imply antitaxial growth and it is therefore likely that both growth mechanisms have occurred. Thicker veins often contain coarse-grained, blocky quartz (~1–5 mm) in their central parts, with fibrous fill on one or both vein margins, while fibrous growth fills the vein tips. The change from fibrous to euhedral or subhedral, blocky quartz suggests different conditions during vein development. The fibrous crystals are thought to be the result of mineral growth during many

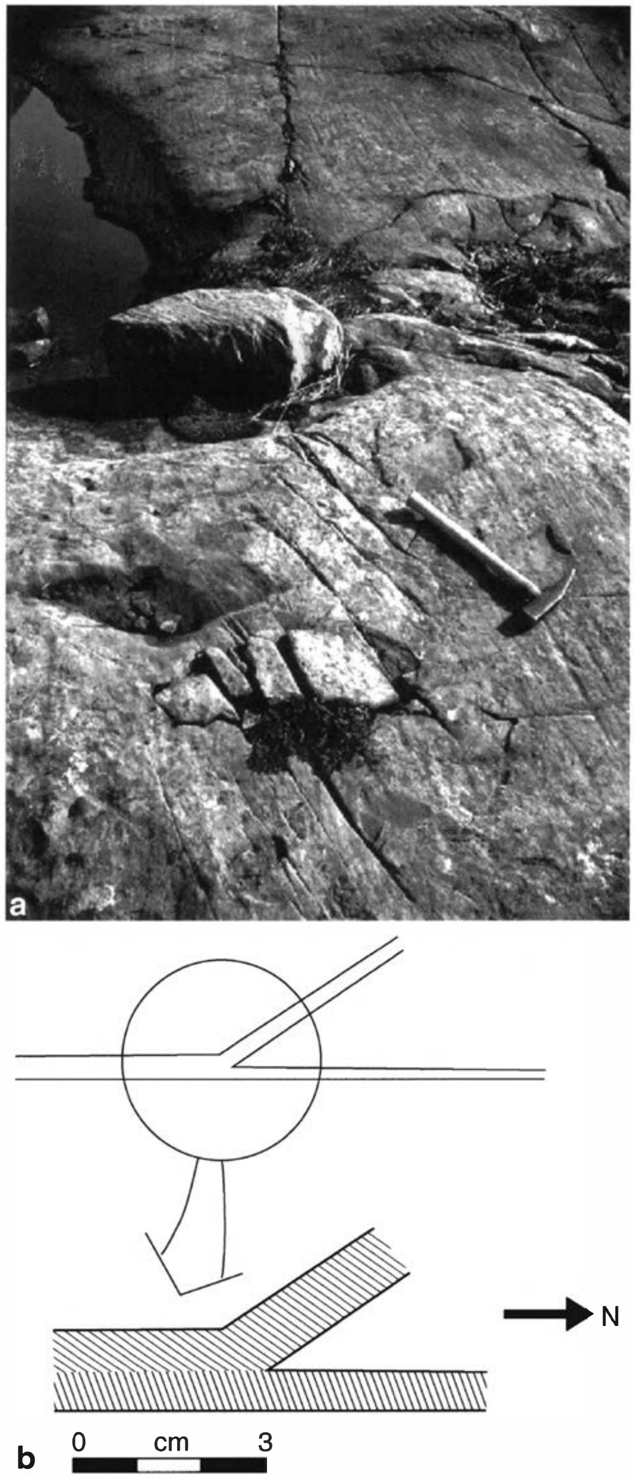

Fig. 7. (a) Photograph of a N–S trending late vein terminating in right-stepping *en echelon* veins, looking toward the south. (b) Sketch showing relationships between different quartz fibre generations in reactivated late veins.

crack-sealing cycles (Ramsay 1980), whereas the coarse-grained, blocky quartz formed during a single crack opening episode that created enough space for euhedral crystal growth.

The fibrous veins show a range of orientations and younger fibrous veins can be observed to cut older ones. However, the most common geometry is that the younger

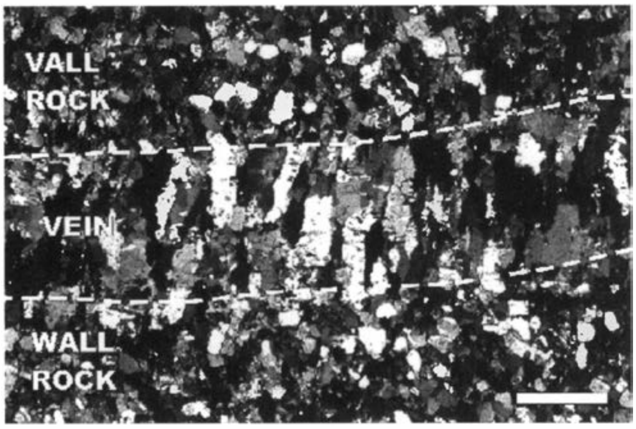

Fig. 8. Microphotograph of late vein showing syntaxial quartz fibres. The quartz fibres are in optical continuity with the quartz grains of the walls, which are indicated by the dashed lines. The scale bar is 1 mm.

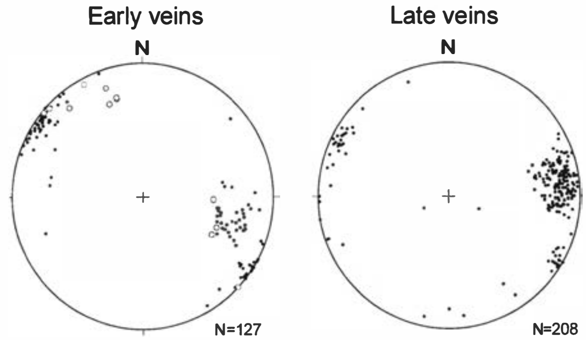

Fig. 9. Stereoplots (equal area lower hemisphere projection) of early and late vein orientations in the study area (see Fig. 2). The open circles in the plot of early vein orientations indicate veins with significant shear displacement. See text for details.

veins abut onto earlier veins that are reactivated along one margin where a new fringe of fibres is formed. The orientation of fibres in the younger veins and reactivated fringes of older veins is the same, and commonly oblique to fibre orientation in the older vein (Fig. 7b). These features indicate a history of multiple opening and mineral fill events.

The quartz grains in late veins show signs of intracrystalline deformation (undulose extinction), recrystallization and recovery. Depending on strain rate, differential stress and the presence of fluids, these processes usually require temperatures of about 300° or more (Passchier & Trouw 1996), giving an estimate of the temperature at the time of late vein formation. This is within the range of temperature estimates derived from fluid inclusion analysis in the Devonian basins of western Norway (Svensen & Jamtveit 1999).

Vein and fibre trends and their meaning for extension directions

The veins and their textures can be used to infer the history of tectonic conditions over the time period of vein formation. The gradation from irregular, well-connected networks of thin veins, through "jig-saw" breccias to breccias with disoriented fragments, suggests that these veins were formed by hydraulic fracturing (e.g. Long et al. 1996). This implies that at this stage in the basin's history fluid pressures exceeded the tensile strength of the rock. Hydraulic fractures form with trends perpendicular to the local least compressive stress direction. Since shear across the breccia veins is minimal in most cases, the directions normal to these veins are likely to indicate the opening direction at the time of vein initiation.

Fibre trends in veins have often been used to infer opening direction (e.g. Ramsay & Huber 1987). More recently, Urai et al. (1991) have suggested that fibres in obliquely opening veins may grow in any direction from perpendicular to the vein walls to parallel to the actual opening direction. In the Hornelen basin, a number of features suggest that the fibres in the late veins do at least approximately track the opening direction. In thin section, fibres can be occasionally seen to link markers in the form of distinctive grains on opposite vein walls. The sense of rotation in fibre orientation in reactivated veins is consistent throughout the basin and also with cross-cutting relationships between veins. It is also consistent with the sense of curvature of fibres in syntaxial veins. The manner in which changes of opening direction with time are interpreted from curved fibres depends on whether veins are syntaxial or antitaxial, both of which are thought to be present in Hornelen. However, most veins in fact show only one major fibre orientation generally oblique to the vein walls. The evolution of the opening direction is inferred from vein fibre-wall geometries, cross-cutting relationships between veins and reactivated vein textures, and is therefore independent of the vein growth mechanism.

Vein orientations are plotted on stereo-plots in Fig. 9. These data were collected principally from the area around Magnhildskaret and along the road to Botnane in the west (Fig. 2). Since data were collected in areas distant from the margins of the basin, where folding is tightest, their orientation is not significantly affected by this folding. The early veins show two major orientations. The principal set is sub-vertical to steeply SE dipping (NE–SW trending) and is composed largely of breccia veins with white mineral matrix. The second, subordinate set is steeply (70–80°) WNW dipping (NNE–SSW trending) and is composed of the earlier veins with green coloured matrix (Fig. 9). A few of the NE–SW trending white veins show significant fault displacement (Fig. 9) and later reactivation as breccia veins. In the few cases where marker horizons are present, displacement is down to the SE. The most abundant set of NE–SW trending breccia veins indicates NW–SE directed extension. The earlier green veins may indicate an earlier extension direction of WNW–ESE, but there are too few of them to form a statistically representative sample, so that no firm conclu-

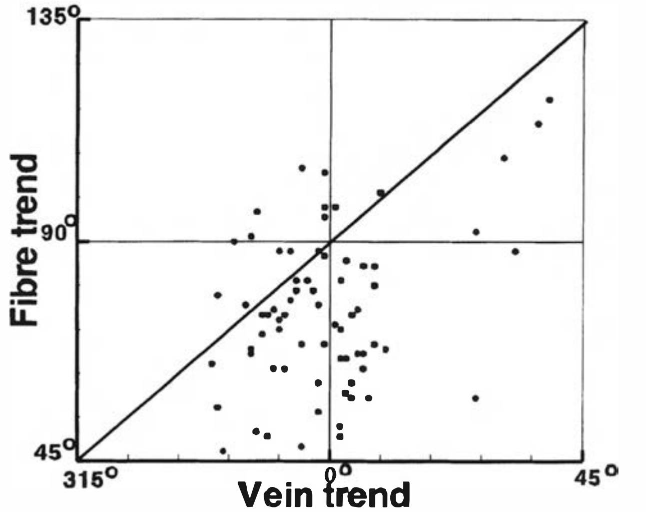

Fig. 10. Plot of vein trend versus fibre trend for late veins. The trend for veins where fibres are perpendicular to the vein walls is shown by the dashed line. Most of the points lie below this line, showing that fibre trend is consistently rotated counter-clockwise.

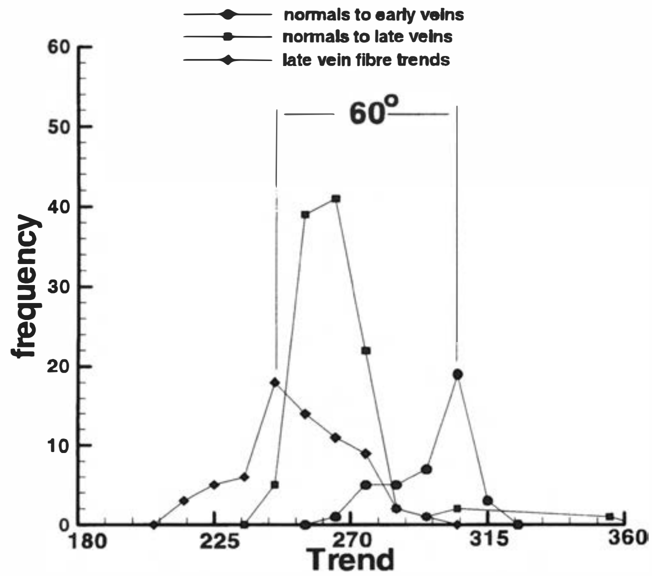

Fig. 11. Frequency plot of directions normal to early and late vein trends and late vein fibre trends. The modes of each distribution indicate a minimum rotation of 60° in the extension direction, from close to NW–SE to WSW–ENE.

sions about the extension direction during their development can be made.

Later fibrous veins show two main orientations (Fig. 9), one dipping vertically, trending NNE–SSW, and a second dipping steeply W to WSW, trending N–S to NNW–SSE. The orientations of the first set of later veins overlap with the range of orientation for the early veins. Cross-cutting relationships indicate that the N–S to NNW–SSE trend is younger than the NE–SW trend. These orientations of early and late veins indicate a systematic rotation of vein trend from NE–SW to NNW–SSE with time. This westward rotation in vein trend with time is corroborated by the relationship between vein fibres and vein walls. The fibres themselves show a range in trend from NE–SW to ESE–WNW and, within individual veins, fibres are consistently rotated to the west with respect to the vein walls (Fig. 10).

The more westerly trend of vein fibres compared to directions normal to vein walls (Fig. 10) suggests that, although a vein orientation ceased with time to be perpendicular to the principal direction of extension, it still represented a plane of weakness in the rock so that fracturing along the vein wall continued, resulting in oblique vein fibres. This reactivation of pre-existing fractures oblique to the extension direction is also clearly shown where younger veins abut onto and reactivate older veins forming a fringe of more oblique younger fibres at the older vein edge, as seen in Fig. 7b.

This rotation of the strain field is consistent with the sense of *en echelon* vein geometries within late vein arrays and at late vein terminations. The small angle between vein trend and array trend (5–20°) and the lack of any significant internal deformation within the sandstones suggest that the veins do not represent tension gashes within a shear zone, where the angle should be around 45°. Pollard et al. (1982) discuss how a rotation of the minimum stress direction about an axis parallel to the propagation direction can result in the formation of *en echelon* arrays. Such a stress rotation causes a component of shear on the fracture plane resulting in mixed mode loading. The result may be a breakdown of the propagating fracture to a series of *en echelon* segments at the fracture tip, where the geometry of these segments (right-or left-stepping) reflects the sense, although not necessarily the full magnitude, of the stress rotation. Such *en echelon* geometries are common in the late veins (Fig. 7a) and consistently suggest a counter-clockwise rotation of the extension direction at the time of vein formation. This rotation is also consistent with the sense of displacement inferred by thick vein segments formed at dilational jogs in pre-existing early veins.

The normal directions to early vein trends, normal directions to late fibrous vein trends and fibre trends, which are interpreted as representing the opening directions during vein formation, are plotted in Fig. 11. This shows a progressive, counter-clockwise rotation from 305° for the mode of normal directions to early veins, through 270° for the mode of normal directions to later fibrous veins, to 250° for the mode of fibre trends. Since the early veins represent the earliest identifiable brittle structures in the rocks, these changes in trend record a change in extension direction of some 60° from the time of onset of brittle fracture until temperatures and pressures fell to a level where mineralization no longer occurred.

The change in the geometry of the veins may also provide insight into changes of the relative magnitudes of the principal stresses. The earliest veins show highly irregular network of veins and irregular pods of breccia, while the later phase of quartz veining and the late fibrous veins show straight sides. It has been suggested (Olson & Pollard 1989; Thomas & Pollard 1993) that straight-sided fractures, where fracture trends show little or no deviation in response to nearby fractures, indicate high levels of differential stress at the time of fracture formation, while irregular fracture trends or fractures that show rotation of trend along their traces indicate low levels of differential stress. This would suggest that levels of differential stress were low when the early veins and breccias formed, but had increased at later stages of early veining and continued at a higher level through the development of the late fibrous veins. Thus there seem to have been significant changes in the relative magnitudes of the principal stresses in addition to a rotation of the extension directions.

Overview of the strain history in western Norway

The following section presents a synthesis of previous work concerning the palaeostrain, kinematics and timing of the late/post-Caledonian extension in western Norway. Several phases, partly involving reactivation of older structures, have been recognized. These are grouped into (1) Early to Middle Devonian extension closely related to the collapse of the Caledonides and (2) Late Devonian to Mesozoic extension related to rifting in offshore Norway.

(a) Early to Middle Devonian

Kinematic indicators at different levels in the Caledonian tectono-stratigraphy of western Norway show that most structures related to SE-directed nappe transport are overprinted by NW–W directed transport during ductile extension (Chauvet & Seranne 1989; Andersen & Jamtveit 1990; Fossen 1992, 1993; Wilks & Cuthbert 1994; Hartz et al. 1994). This transport direction is consistent with the extension direction inferred from the sedimentation patterns and syn-depositional structures in the Devonian basins (Fig. 1). In the Solund basin, the orientation of elongated conglomerate pebbles, tension gashes in the pebbles and striated minor faults all indicate NW–SE directed extension (Chauvet & Seranne 1989). In the Kvamshesten basin, NW–SE directed extension during early basin formation has been inferred from basin geometry and stratigraphy (Osmundsen et al. 1998), while syn-sedimentary faults indicate a counter-clockwise rotation to more westerly trends of the extension direction during the later stages of basin formation.

In the Bergen area, kinematic analyses of brittle fracture populations also suggest that NW–SE extension (Fossen 1998) followed ductile to semi-ductile displacement on the Bergen Arc Shear Zone. Estimates of the age of this brittle deformation are given by biotite $^{40}Ar/^{39}Ar$ cooling ages at around 400 Ma (Boundy et al. 1996; Fossen & Dunlap 1998) and from U/Pb isotope dates from sphene from fracture mineralisation at 395 ± 5 Ma (Pedersen et al. 1999). This infers an Early Devonian age for the onset of regional brittle extension in western Norway.

(b) Late Devonian–Mesozoic

Early stages of this period (Late Devonian to Early Carboniferous) have been suggested to involve N–S shortening and E–W extension (Hartz & Andresen 1997; Osmundsen et al. 1998; Braathen 1999). The E–W folds in the Hornelen basin are thought to be related to this stage and appear to be cut by the eastern margin fault (Krabbendam & Dewey 1998; Braathen 1999). This fault is assumed to be of Late Permian age (248–260 Ma) by Braathen (1999) based on $^{40}Ar/^{39}Ar$ dating on a similar fault segment below the Kvamshesten basin (Eide et al. 1997). Another episode of brittle reactivation of the Nordfjord–Sogn Detachment (below the Kvamshesten basin) is dated at 92–162 Ma (Late Jurassic–Early Cretaceous) (Eide et al. 1997). Both episodes are consistent with the major rift phases known from the North Sea (e.g. Færseth 1996). In addition, $^{40}Ar/^{39}Ar$ analyses of Eide at al. (1997, 1999) suggest a period of rapid exhumation at 340–360 Ma during the Early Carboniferous.

The mineralized fractures of Devonian age in the Bergen area predate N–S to NNW–SSE trending dykes which have yielded K-Ar ages of around 260 Ma (Løvlie & Mitchell 1982; Fossen 1998). Intrusion of dykes controlled by N–S to NNW–SSE trending fractures has also been reported from the Sunnhordland region (between Bergen and the Hardangerfjord Shear Zone; Fig. 1) where K-Ar and $^{40}Ar/^{39}Ar$ isotope analyses indicate two episodes of intrusion at around 260 and 220 Ma (Færseth et al. 1976; Fossen & Dunlap 1999). In coastal areas west of the Devonian basins, palaeomagnetic data indicate that approximately N–S trending dolerite dykes have ages around 250–270 Ma (Torsvik et al. 1997). These data also suggest a later metamorphic and magnetic overprinting related to reactivation of the fault defining the southern margin of the Hornelen basin (Haukå fault; Fig. 2). These observations indicate that the extension direction throughout western Norway changed from NW–SE to E–W at some time between Early to Middle Devonian and the dyke intrusion in the Late Permian.

Brittle deformation history of the Hornelen basin: a discussion

The change in the extension direction from NW–SE through W–E to WSW–ENE recorded by the vein systems in the Hornelen basin corresponds well with that inferred from other parts of western Norway (see above).

1. The NW–SE direction of extension inferred from early breccia veins corresponds to the direction of movement on the Nordfjord–Sogn Detachment during deposition of the Devonian sediments (Chauvet & Seranne 1989; Wilks & Cuthbert 1994), as well as in other parts of western Norway (Fossen 1992, 1993). The same direction

of extension is also inferred from tension gashes in Solund basin (Chauvet & Seranne 1989), basin geometry and stratigraphy in Kvamshesten basin (Osmundsen et al. 1998) and mineralized fractures giving Early to Middle Devonian ages in the Bergen area (Fossen 1998; Pedersen et al. 1999). Thus, the onset of vein development in the Hornelen basin probably began in Middle to Late Devonian times.

2. The later E–W to ENE–WSW direction of extension indicated by late veins and their fibre orientations corresponds to extension directions inferred from Middle to Late Permian, N–S trending dykes found west of the Devonian basins (Torsvik et al. 1997) and Middle Permian to Late Triassic, N–S to NNW–SSE trending dykes in the Sunnhordland (Færseth et al. 1976; Fossen & Dunlap 1999) and Bergen areas (Løvlie & Mitchell 1982; Fossen 1998). The stage of late veining therefore probably ended by Late Permian times.

The consistency of the extension direction indicated by the two types of veins and indications of extension directions over the rest of western Norway suggest that they also indicate the direction of regional principal stresses. This would imply that the regional minimum stress direction rotated some 60° from NW–SE to W–E with time, probably within the interval from Middle to Late Devonian and Late Permian.

The earliest signs of brittle deformation are fragments of cataclasite within the breccias. Signs of shear and grain-size reduction suggest that these originated from structures similar to deformation bands described from weakly consolidated sandstones. These structures are likely to have formed before the sandstone was as well lithified as it is today, and may be contemporaneous with sedimentation. It is possible that the occasional NE–SW trending minor faults belong to this generation of deformation. These structures have been largely overprinted by later breccia veins, suggesting that they either formed zones of weakness or acted to focus stress resulting in the exploitation by later deformation.

The early veins and breccias are thought to be hydraulic in origin, suggesting that fluid pressures exceeded the tensile strength of the rock at the time of their formation (Long et al. 1996). This phase of fracturing occurred when the rocks were already close to their present state of compaction and lithification and had therefore most likely been buried to their maximum depth. Metamorphic conditions are therefore likely to have been at a peak (lower greenschist facies). A likely cause of hydraulic fracturing is a reduction of the minimum tectonic stress so that the difference between the minimum rock stress and the fluid pressure exceeded the tensile strength of the rock. This could have been caused either by an increase in extension rate or by uplift and erosion relieving over-burden pressure. The rapid exhumation in the Early Carboniferous (Eide et al. 1999) would have caused a rapid decrease in overburden pressure and a decrease of all the principal stresses while maintaining the direction of minimum stress (NW–SE). If this reduction in stress occurred too fast for fluids to escape, large fluid over-pressures resulting in hydraulic fracturing could have occurred. The irregular style of fractures associated with breccia suggests that the differential stress was low, which favours exhumation rather than an increased extension rate, which would tend to increase differential stress as the cause of high fluid pressures. In these early veins and breccias, the mineral matrix is dense and can compose more than 50% of the rock. During hydraulic fracturing, large drops in fluid pressure can occur, resulting in very rapid deposition of minerals (e.g. Knipe 1992) which could explain the formation of breccias where disoriented fragments "float" in a mineral matrix. This suggests a ready supply of large volumes of fluid with the chemical species in solution necessary to form the vein fill. However, the rocks themselves were probably of low permeability at the time of vein formation, as they are today, and thus movement of fluid through the rock matrix itself was probably somewhat restricted. The early veins are observed to form linear zones on the scale of kilometres, which suggests a source of fluid from below, perhaps from an underlying fault in the basement.

The later veins have a different texture dominated by quartz fibres suggesting a more stable tensile fracture propagation and mineral deposition in the generated space, rather than high-energy breccia development. This suggests that if fluid over-pressures were present they were not as extreme as during the formation of the early breccia veins. This could reflect a slowing of the exhumation rate or that excess fluid pressures had by this time been relieved through earlier hydraulic fracturing. The change in vein morphology from irregular to straight-sided suggests an increase in the differential stress that could be related to increased extension rates, possibly in relation to Late Palaeozoic rifting in the North Sea. In the fibrous veins, the mineral fill is often partial. This suggests that the source of fluids that fed the breccia vein system had dwindled, although the concentration of fibrous veins around early breccia vein zones suggests that it was to some extent still active. Later joints are completely unmineralized, suggesting that, by that time, the rock was of very low permeability and that fluid supply to the fractures, and thus mineral precipitation, was very limited.

There are few indicators of temperature and pressure in the mineral assemblage of the veins, but signs of recrystallization and recovery of strained quartz suggests temperatures in the region of 300°C at the time of the deposition of the later vein fill (Passchier & Trouw 1996). The geothermal gradient in sedimentary basins varies between 15 and 50°C/km, with an average around 30°C/km (North 1985). However, fluid inclusion analysis suggests that the thermal gradient may have been as low as 20°C/km in the Devonian basins in western Norway (H. Svensen, pers. comm). Thus, a rough estimate of the basin thickness at the time of the formation of the later veins is around 15 km. Since it is thought that later fibrous veins formed after some exhumation had already taken place, this figure may be a minimum.

Conclusions

From the evidence provided by the veins described above, combined with information from the literature, the following deformation history of the Hornelen basin can be constructed:

1. Sediment deposition in the Middle Devonian in a tectonically controlled setting contemporaneous with down-to-west movement on the underlying Nordfjord–Sogn Detachment. Precursors to the present-day northern and southern margin faults of the Hornelen basin probably played a role in controlling sedimentation.
2. Development of deformation band style faulting with formation of cataclasite before the rocks were lithified to today's state and probably before the basin achieved its maximum sediment thickness.
3. Rapid exhumation in the Early Carboniferous generated high fluid pressures and hydraulic fracturing with the formation of the early veins and breccias along pre-existing weakness zones. At this time the basin had already achieved its maximum thickness of 15 km or more and the rocks were lithified to their present-day state. The extension direction was NW–SE and differential stress was probably low. This extension direction probably also reflects the direction of minimum stress at Early Carboniferous times. Faults in the basement underlying the Devonian sediments are a possible source of fluid with temperatures in excess of 300°C.
4. By the Late Permian–Triassic, the stress field has rotated some 60° from NW–SE to WSW–ENE and fibrous veins were formed. The morphology and textures of the late veins suggest a lower energy environment with lower fluid pressures and fluid availability, and fluid temperatures around 300°C. This suggests that the rate of exhumation had slowed. However, the concentration of these veins around zones of early veins suggests that earlier sources of fluid were present though at a reduced level. The differential stress had increased probably related to rifting activity in the North Sea.
5. Continued exhumation to the present day resulted in a complex system of joints which are largely unmineralized, suggesting that fluid flow had become restricted or that fluid temperatures had fallen too low for quartz deposition. There was some reactivation of the faults bounding the present-day basin in the Late Jurassic to Early Cretaceous probably reflecting rifting activity in the basins to the west.

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