Journal of the Geological Society, *London*, Vol. **162**, 2005, pp. 675–687. Printed in Great Britain.

The Hardangerfjord Shear Zone in SW Norway and the North Sea: a large-scale low-angle shear zone in the Caledonian crust

HAAKON FOSSEN[1] & CHARLES A. HURICH[2]

[1]*Department of Earth Science, University of Bergen, Allégt. 41, 5007 Bergen (e-mail: haakon.fossen@geo.uib.no)*

[2]*Department of Earth Sciences, Memorial University, St. John's, Newfoundland A1B 3X5, Canada*

Abstract: The Hardangerfjord Shear Zone is a more than 600 km long low-angle extensional structure that affects the South Norway and North Sea Caledonides. The ductile shear zone, which shows total maximum onshore displacement of the order of 10–15 km, is primarily a basement structure with an associated passive, monoclinal fold structure of the overlying Caledonian nappes. Deep seismic data indicate that the shear zone continues down to the lower crust (20–25 km) at a dip of 22–23°, where it appears to flatten and merge with the general lower-crustal deformation fabric. Onshore, the Hardangerfjord Shear Zone consists of a system of hard-linked ductile shear-zone segments. Brittle faults (the Lærdal–Gjende fault system) occur in the folded Caledonian allochthons in the NE part of the Hardangerfjord Shear Zone, and reappear in the North Sea. These may represent a high-level brittle response to the Devonian development of the Hardangerfjord Shear Zone, but were reactivated during Permo-Triassic and late Jurassic extensional events. A *c.* 5 km thick package of seismic reflectors along the Hardangerfjord Shear Zone is presumed to represent a mylonite zone, which is too thick to be formed entirely by 10–15 km of Devonian displacement. Hence the Hardangerfjord Shear Zone is likely to be a Proterozoic shear zone, reactivated during Devonian extension.

Keywords: Caledonides, Hardangerfjord Shear Zone, deep seismic sections, extension, reactivation.

The post-Caledonian evolution of Baltoscandia has received growing attention during recent years, along with an interest in linking the offshore, North Sea framework with onshore structures (e.g. Séranne & Séguret 1987; Andersen & Jamtveit 1990; Fossen & Rykkelid 1992*a*; Milnes *et al*. 1997; Olesen *et al*. 2002; Skilbrei *et al*. 2002). One of the fundamental structures that can be seen to affect both southern Norway and the North Sea rift system is the Hardangerfjord Shear Zone. The zone has a total length of several hundred kilometres, with displacement up to 10–15 km. The NE–SW-trending monoclinal-style structural depression that runs more or less parallel to the shear zone has been known for at least a century, and is frequently referred to as the 'Faltungsgraben' (German for fold trench) (Goldschmidt 1912). Brittle faults along this trend have been known for some time (e.g. Battey 1965; Battey & McRitchie 1973), but the presence of a ductile shear zone along the Faltungsgraben was not appreciated until recent years (Hurich & Kristoffersen 1988; Fossen 1992, 1993). In spite of its great size and fundamental nature, the ductile Hardangerfjord Shear Zone has received surprisingly little attention in the literature. In this paper we describe the onshore expression of the shear zone together with reprocessed deep seismic data from its extension into the North Sea, and discuss its origin and history.

Regional setting

The Hardangerfjord Shear Zone is a NW–SE-trending ductile structure located in the Hardangerfjord–inner Sogn area of SW Norway (Fig. 1). The shear zone runs parallel to the Caledonian orogenic belt and more or less coincides with the transition from thin-skinned to thick-skinned Caledonian deformation.

The Caledonian basement is generally autochthonous and preserved from Caledonian deformation SE of the Hardangerfjord Shear Zone (Fig. 1), except for local reworking in the uppermost portion of the basement. In contrast, Caledonian reworking is present and locally pervasive in the NW (Western Gneiss Region). The autochthonous basement is of Proterozoic age, and is dominated by a large number of Sveconorwegian (Grenvillian) plutonic rocks that show intrusive relations to a 1200–1500 Ma supracrustal series and possibly older substratum of migmatitic gneisses (Gorbatschev 1985; Skår 1998). The Proterozoic evolution of the Western Gneiss Region is in broad terms similar to that of the autochthonous basement to the SE. However, the effect of the Palaeozoic reworking generally increases to the west or NW, thus masking its Proterozoic history (Milnes *et al*. 1997) (Fig. 1).

The Precambrian basement was peneplained during the late Proterozoic and covered by latest Proterozoic to Ordovician sediments (Bockelie & Nystuen 1985). These sediments are now found as intensely sheared phyllites and micaschists underlying the Caledonian nappes, and as psammitic units in the lowest nappes. The mechanically weak phyllitic layer acted as the basal thrust or décollement zone during the Caledonian orogeny (Fossen 1992; Milnes *et al*. 1997).

Remnants of the Caledonian orogenic wedge (thrust nappes) are found both in the hinterland and in the foreland, although the upper part of the wedge has been removed by erosion. The constituents of the orogenic wedge have been subdivided into the Lower, Middle and Upper Allochthon (Bryhni & Sturt 1985). The Lower Allochthon consists of units of Baltican basement and/or its upper Proterozoic to lower Palaeozoic cover that can be correlated with autochthonous units. Translations of these units are of the order of tens of kilometres in most cases. Allochthonous units of continental, crystalline Proterozoic rocks with late Proterozoic cover that do not correlate with the autochthonous basement belong to the Middle Allochthon. The Jotun Nappe is a conspicuous example, transported more than 300 km to the SE (Hossack & Cooper 1986). The Upper Allochthon comprises exotic nappes of outboard affinity, such as Ordovician–Silurian ophiolite and island-arc complexes. Some

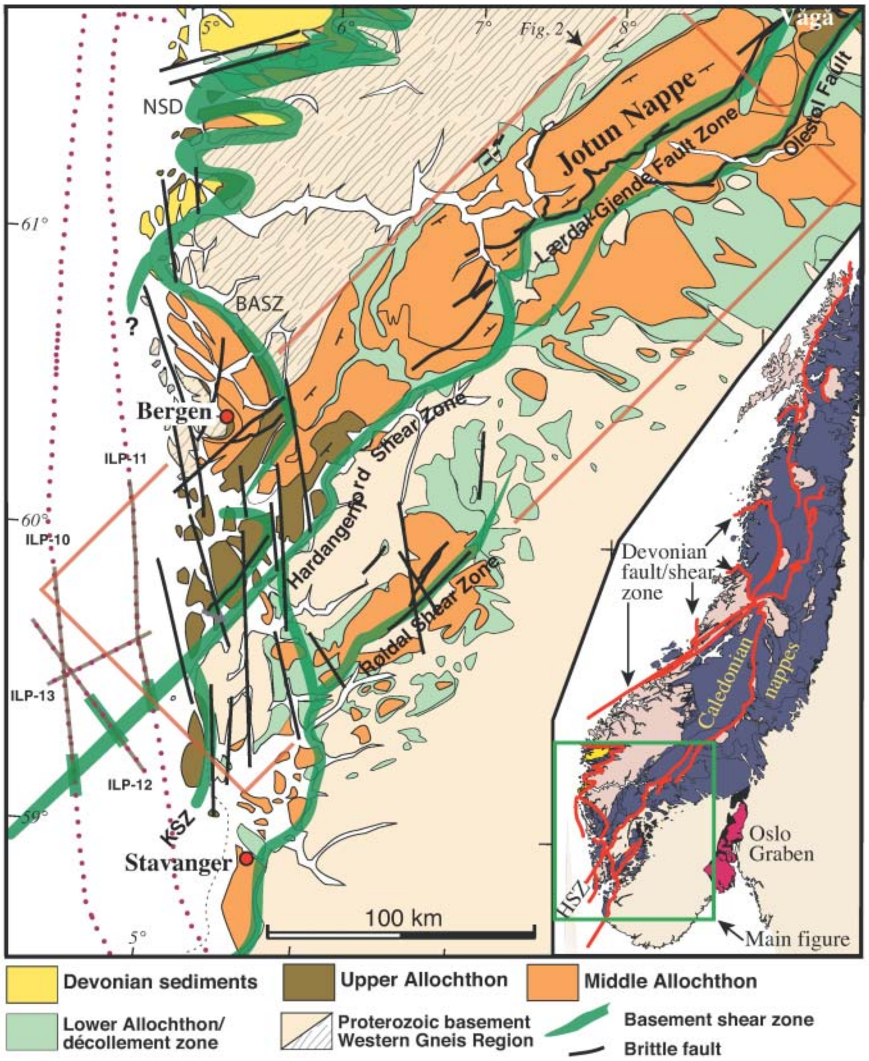

Fig. 1. Geological map of SW Norway, showing the Hardangerfjord Shear Zone in relation to other structures in the region. Major shear zones (Mode II extension) are shown as thick green lines. BASZ, Bergen Arc Shear Zone; NSD, Nordfjord–Sogn Detachment. The four deep seismic lines discussed later in the text (ILP sections) and the location and width of the dipping package of reflectors along these lines are indicated. Red lines (faults and shear zones) on inset map are based on Fossen & Rykkelid (1992*a*), Andersen *et al*. (1999), Fossen (2000) and Braathen *et al*. (2002).

of these outboard complexes or terranes may have originated on the Laurentian side of the pre-collisional ocean (Iapetus) and amalgamated onto the Baltican margin during the continent–continent collision (closure of Iapetus) (Pedersen *et al*. 1988). Rocks of the Upper Allochthon contain an outboard magmatic and tectonometamorphic history that predates the collisional phase. The Upper Allochthon is preserved mostly in the hanging wall of the Hardangerfjord Shear Zone.

Tectonic framework

Recent work has shown that the Caledonian contractional deformation, involving SE-directed nappe translations relative to the basement, was at some point replaced by extensional deformation that involved reversal of the shear sense in the décollement zone (Fossen 1992). This reversal of kinematics has been explained by a change from convergent to divergent motions across the orogenic zone (Fossen 1992, 2000; Wilks & Cuthbert 1994; Rey *et al*. 1997), dated to about 408–402 Ma (Fossen & Dunlap 1999). Millimetre- to kilometre-scale NW-verging folds and penetrative mylonitic fabrics developed within the basal Caledonian décollement zone as it was turned into a low-angle extensional detachment during this early (Mode I) stage of Devonian extension.

Continued extension caused the formation of several kilometre-thick extensional shear zones that affected the basement as well as the orogenic wedge, referred to as Mode II extension (Fossen 1992; Milnes *et al*. 1997). The Hardangerfjord Shear Zone has been considered as one such shear zone (Fossen 1992, 1993), along with other shear zones such as the Bergen Arc Shear Zone (Fossen 1992; Wennberg *et al*. 1998) and the Nordfjord–Sogn Detachment (Norton 1987). These are predominantly ductile structures that were overprinted by more brittle structures at later stages. Of these three, the Hardangerfjord Shear Zone is the least examined structure.

A later set of brittle faults, known as the Lærdal–Gjende fault system, follows the trend of the Hardangerfjord Shear Zone (Fig. 1). Although the two are related, we emphasize that they are defined as distinct zones with different length, width and depth of formation. The Hardangerfjord Shear Zone is entirely ductile, *c*. 5 km wide and in the NE covered by monoclinally folded Caledonian allochthonous units. In contrast, the Lærdal–Gjende fault system is brittle and marked by a much thinner zone of cataclastic fault rock. Furthermore, the latter zone is present only in the Lærdal–Gjende area, apparently dying out southwestward

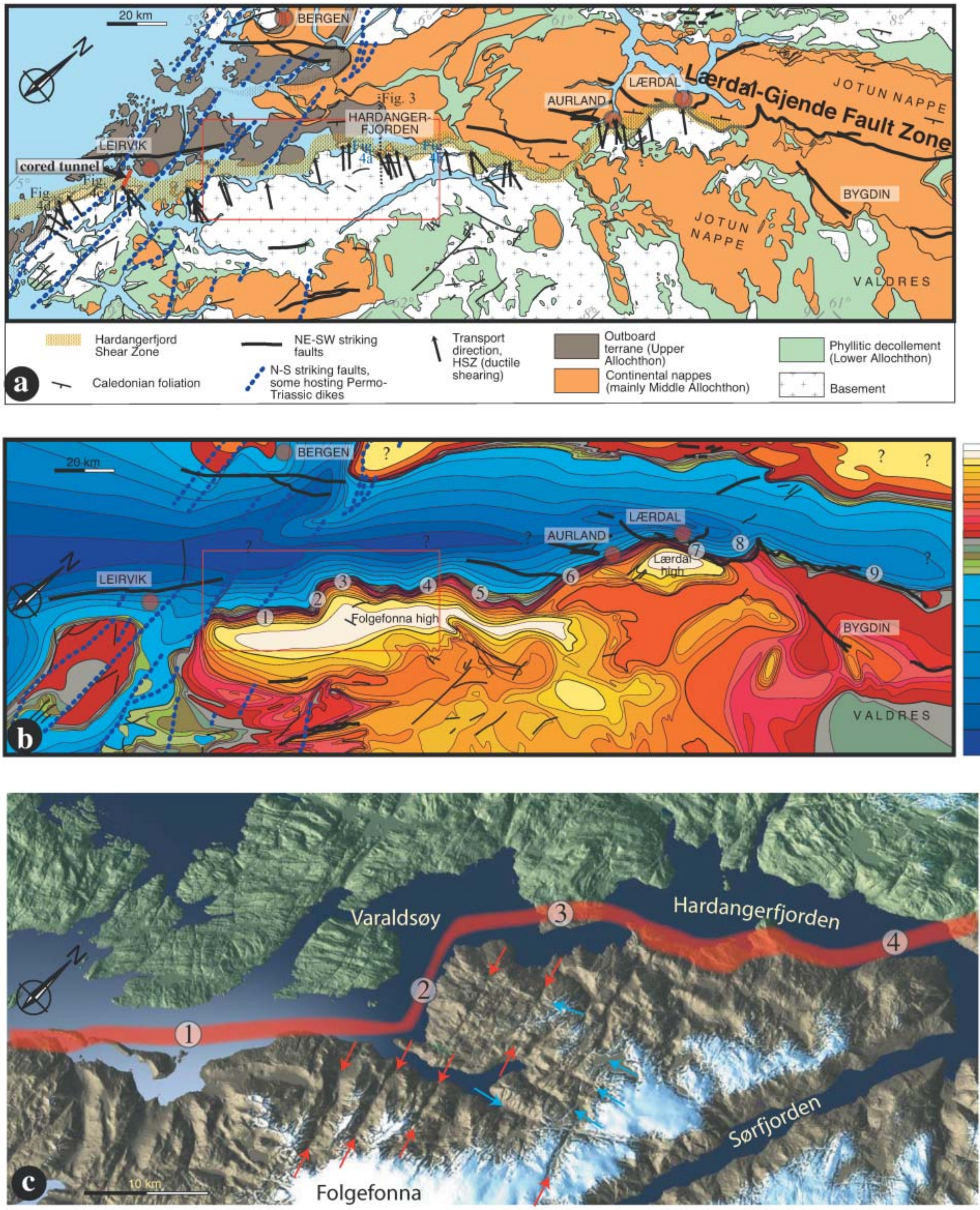

Fig. 2. (**a**) Geological map of the Hardangerfjord area, showing the Hardangerfjord Shear Zone, brittle faults and extensional transport directions along the shear zone. The NE extension of the Hardangerfjord Shear Zone is not indicated as it is covered by the Caledonian Jotun Nappe. (**b**) Contour map of the uppermost basement surface (sub-Cambrian peneplain). Numbers refer to segments of the Hardangerfjord Shear Zone as discussed in the text. (**c**) Shaded relief map showing the abrupt bend between segments 1 and 3 and its relationship to lineaments in the basement of the Folgefonna peninsula. The Hardangerfjord Shear Zone is indicated by a red line. Autochthonous units north of the shear zone are shown in a greenish tint. Basement rocks south of the Hardangerfjord Shear Zone are given a warmer tint. The location of (**c**) is indicated by the red rectangle in (**a**) and (**b**).

toward the Hardangerfjord area. The Hardangerfjord area is the area where the Hardangerfjord Shear Zone is best exposed, thus the following onshore description is largely based on observations from this area.

Onshore ductile expression of the Hardangerfjord Shear Zone

The Hardangerfjord Shear Zone is easily located onshore and can be traced for *c*. 350 km northeastward from the mouth of Hardangerfjorden (locally named Bømlafjorden) through Aurland to the Vågå area, where its extension is hidden under Caledonian nappe units. Several features characterize the shear zone: (1) the décollement zone and the underlying basement along the Hardangerfjord Shear Zone exhibit ductile NW-dipping mylonitic fabrics with down-to-NW sense of shear; (2) the basement–décollement interface and mylonitic foliation in the orogenic wedge display an abrupt change in altitude and orientation across the Hardangerfjord Shear Zone, from more or less horizontal in the footwall through NE-dipping in the shear zone to SE-dipping in the hanging wall; (3) the Jotun Nappe and the underlying décollement zone are folded or draped across the zone by predominantly plastic deformation mechanisms. This monoclinal fold structure, which in many ways resembles classic hanging-wall synclines related to major normal faults, or forced folds above reactivated basement faults, is easily detected from the map pattern of Figure 1. In general, basement rocks are exposed in the footwall block, whereas Caledonian nappe units are preserved in the hanging wall (Fig. 2). It is important to realize that the décollement zone is obliquely affected by the Hardangerfjord Shear Zone. The décollement zone occurs on both sides of the Hardangerfjord Shear Zone and it does not extend into the basement along the Hardangerfjord Shear Zone (Fossen 1993).

Folding of Caledonian nappes

The conspicuous monoclinal folding of Caledonian nappes in the half-graben above the Hardangerfjord Shear Zone is the most outstanding expression associated with the shear zone (Fig. 2). This feature was also the first to be noticed (Goldschmidt 1912), but was not attributed to an underlying shear zone. The Lower and Middle Allochthon (Jotun Nappe–Bergsdalen Nappes) take on a relatively simple monoclinal geometry in the hanging wall to the Hardangerfjord Shear Zone, where the lateral distance between the two hinge zones is of the order of 15 km and the opening angle is about 140–150°.

In the more anisotropic, multi-layered upper allochthonous nappes in the SW part of the Hardangerfjord Shear Zone, a more complex group of folds with shorter wavelengths is added to the 5–10 km wide monoclinal structure. Folding of the upper allochthon is very pronounced on the hanging-wall side of the Hardangerfjord Shear Zone. Folds that are related to the Hardangerfjord Shear Zone have subhorizontal axial surfaces and hinge lines parallel to the shear zone.

Ductile shearing of basement rocks

Precambrian fabrics and large-scale structures (folds) in the Folgefonna peninsula exhibit a change in orientation from horizontal to NW-plunging close to the Hardangerfjord Shear Zone (Torske 1982) (Fig. 3). Similarly, SE of the Hardangerfjord Shear Zone only Precambrian amphibolite-facies structures are identified, whereas greenschist-facies structures occur with increasing intensity into the Hardangerfjord Shear Zone. These hanging-wall fabrics include asymmetric, intrafolial folds, asymmetric boudins, and classical S–C structures of the type described by Berthé *et al*. (1979), all indicating down-to-NW sense of shear (Fig. 4).

The down-to-NW ductile fabrics observed in the basement along the Hardangerfjord Shear Zone are typical for middle greenschist-facies metamorphic conditions. Typically, hornblendes in altered magmatic basement rocks are partly altered to biotite and chlorite, and garnets and feldspars are found only as porphyroclasts in the NW-directed fabric (Fig. 4). In terms of metamorphism and kinematics, the fabrics are similar to the down-to-NW fabrics found in the overlying décollement zone within the Hardangerfjord Shear Zone (Fossen 1993).

The width of the shear zone is several kilometres, based on the rotation of pre-existing structures portrayed in Figure 3. The zone of mylonites in the basement with down-to-WNW shear in the southwestern part of the Hardangerfjord Shear Zone is estimated to be about 5 km from onshore mapping and cores collected under the fjord (Fig. 2). It should be noted that the basement is exposed only on the footwall side of the shear zone; the total thickness of the shear zone is thus not directly observable in the field. However, the distance between the hinge points of the monoclinal structure, which is 5–6 km at the uppermost basement level in Figure 3, can be taken to indicate the thickness of the shear zone.

Ductile shearing of allochthonous units

The Caledonian allochthonous rocks located directly above the basement are strongly influenced by down-to-NW shear indicators, including microfolds, shear bands, S–C structures, asymmetric boudins, etc. (Fig. 4) (Fossen 1992, 1993). Some of these structures must have formed during the NW movement of the nappes (Mode I extension) and rotated into the Hardangerfjord Shear Zone as the shear zone evolved, whereas others may have formed during movements along the Hardangerfjord Shear Zone as Mode II structures. Separating Mode I from Mode II structures in the allochthonous rocks is difficult, but examples of overprinted or folded S–C structures may indicate overprinting of Mode I by Mode II structures.

The geometry of the latest S–C structures and related

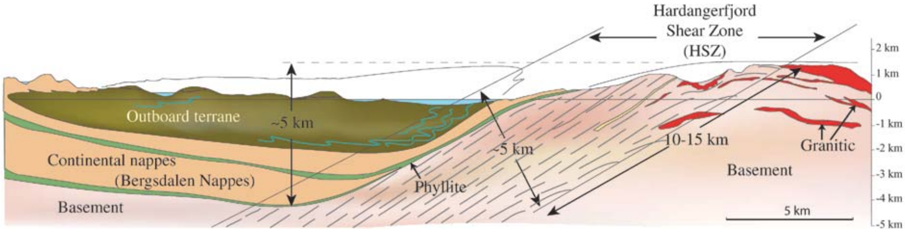

Fig. 3. Profile across the Hardangerfjord Shear Zone. (For location, see Fig. 2a.)

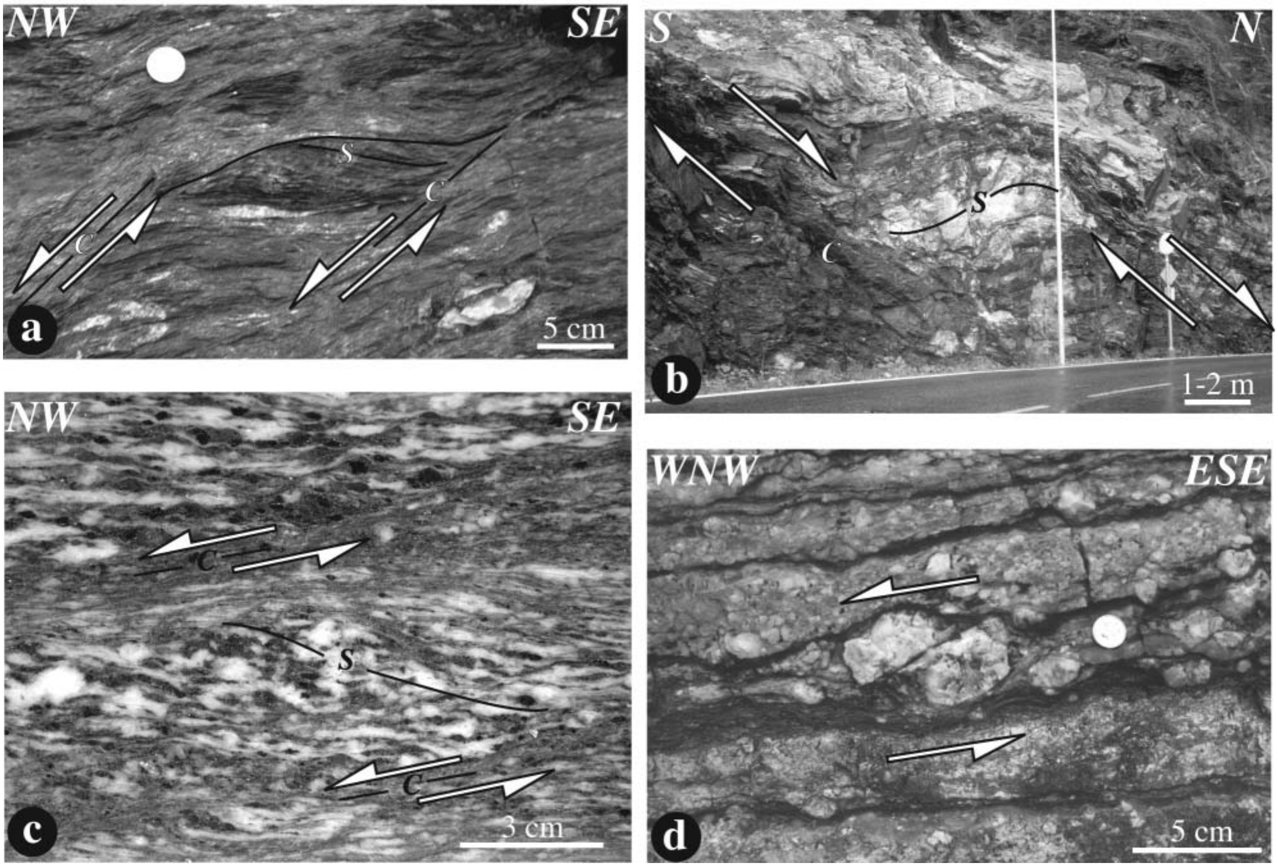

Fig. 4. Kinematic indicators from the Hardangerfjord Shear Zone showing top-to-NW sense of shear. (**a**) Shear bands in phyllite–micaschist near Aurland (west of Lærdal). (**b**) Shear zone structures in Precambrian basement near Bruravik. (**c**) S–C structures in mafic magmatic rock in the basement in the footwall of the Hardangerfjord Shear Zone (SW part of Fig. 2b). (**d**) Brittle deformation of feldspar porphyroclast in the basement in the SW onshore portion of the Hardangerfjord Shear Zone. Locations are shown in Figure 2a.

lineations observed in weak lithologies along the Hardangerfjord Shear Zone consistently indicates a down-dip (normal) sense of shear with a minor sinistral component, as shown in Figures 2a and 5. The dip of the décollement zone (i.e. dip of the contacts between the sheared phyllites and the overlying nappes and underlying basement in the Hardangerfjord Shear Zone) varies, with representative dips clustering around 22°. It is difficult to obtain an accurate onshore estimate of the dip of the shear zone itself, but it appears to be only slightly steeper than the rotated décollement zone.

Length of the Hardangerfjord Shear Zone

The Hardangerfjord Shear Zone can be traced from the coastal area along the Hardangerfjord through Aurland and along the NW side of Jotunheimen to the NE margin of the Jotun Nappe, a total distance of *c.* 350 km. The depression marked by the Caledonian nappes continues for at least 100 km to the NE, and a continuation of the Hardangerfjord Shear Zone or a related basement shear zone in this direction is likely. Its northeastward continuation is covered by upper allochthonous units and overprinted by brittle deformation (see below). The semi-brittle extensional faults continue far to the NE, possibly indicating the location of a buried system of ductile shear zones all the way to northern Norway (see Fig. 1, inset map).

Offshore, a regional lineament clearly lines up with the Hardangerfjord Shear Zone. This lineament is mapped as brittle faults in Permian–Jurassic rocks by seismic data and extends at least 250 km SW of the coastline (Fig. 6). The Ling depression is the main structural feature along this lineament (Færseth *et al.* 1995). The marked NE–SW orientation of faults along this trend strongly suggests that they represent reactivation along the Hardangerfjord Shear Zone, similar to the onshore Lærdal–Gjende fault zystem. A total length of at least 600 km is thereby indicated for the Hardangerfjord Shear Zone.

The NE–SW-trending faults that mark the offshore extension of the Hardangerfjord Shear Zone are overprinted and masked by the north–south-trending Viking Graben, which is considered to be a late Jurassic structure (e.g. Færseth *et al.* 1997). However, the NE–SW trend reappears to the SW along the trend of the onshore Highland Boundary Fault and the Devonian Midland Valley graben (Fig. 6). Gravity and magnetic data (Fig. 7) also portray the NE–SW-trending lineament outlined by the Mesozoic faults, suggesting a link between the Hardangerfjord Shear Zone and the Highland Boundary Fault. The fact that the Hardangerfjord Shear Zone and the Highland Boundary Fault throw in opposite directions and formed at different crustal depths implies that they cannot be directly correlated. Nevertheless, the NW–SE-trending lineament that crosses the North Sea indicates the presence of a >1000 km long and deep-rooted weak zone that has influenced the locations and orientations of faults since the early Devonian and probably also long before.

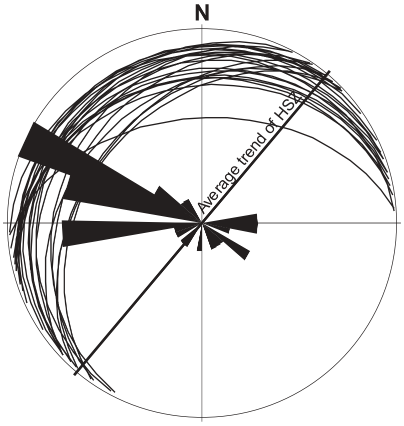

Fig. 5. Lineations related to down-to-NW shear from the Hardangerfjord Shear Zone (rose) and orientation of segments along the Hardangerfjord Shear Zone (great circles). The average trend of the Hardangerfjord Shear Zone is indicated. (See text for discussion.)

Segmentation and growth

The average NE trend of the Hardangerfjord Shear Zone corresponds to NW–SE extension, roughly consistent with regional and local kinematic indicators (see Fossen 1992, 1993). A closer inspection of the onshore geological map of the Hardangerfjord Shear Zone (Fig. 2b) reveals an irregular geometry, where several more or less straight segments are connected by shorter and differently oriented segments. The most prominent shifts are located in the Varaldsøy region, where two NE-trending segments (segments 1 and 3 in Fig. 2b and c) are connected through a short NNW-trending segment (segment 2). The changes in trend are remarkably abrupt, and there is no sign of the NNW-trending structure in the footwall to the Hardangerfjord Shear Zone.

Continuing NE, the Hardangerfjord Shear Zone continues as a non-planar structure, where individual straight segments have E(NE) to NNE trends (e.g. segments 4 and 5 in Fig. 2b). The average trend is NE until a pronounced NNE-trending segment (segment 6) results in the the zone having a more northerly direction. Reaching the Lærdal–Gjende fault system, the trend returns to a NE direction (segment 7), with an additional step to the left (segment 8). On a 10 km scale, the Hardangerfjord Shear Zone thus appears to consist of a large number of connected segments. However, at a somewhat larger (100 km) scale, the Hardangerfjord Shear Zone appears to consist of two main segments: one is the part that runs along the Hardangerfjord itself (segments 1–5); the other is the one running along the Lærdal–Gjende fault (segments 7–9). These two first-order segments are linked by segment 6, which connects two portions of the footwall (basement) that both exceed 1600 m in elevation (Folgefonna and Lærdal highs in Fig. 2b). At this scale, segment 6 links two high-displacement areas along the Hardangerfjord Shear Zone.

A likely interpretation of the described pattern would be that the entire shear zone evolved through coalescence or linkage of individual segments, similar to the way most brittle fault systems evolve (e.g. Cartwright *et al*. 1995; Childs *et al*. 1995). The segmented pattern described above is best explained as the result of deformation of an already mechanically heterogeneous basement. The location and geometry of an extensional shear zone such as the Hardangerfjord Shear Zone is likely to be influenced by pre-existing faults and shear zones. The highly oblique NNW-trending segments reflect a well-known basement trend in the Proterozoic of southern Norway, as does the NNE trend (Sigmond *et al*. 1984; Gabrielsen *et al*. 2002). More locally, faults and fracture zones that are parallel to the variously oriented segments of the Hardangerfjord Shear Zone are found in the basement in the footwall, marked with arrows in Figure 2c. As discussed below, there is thus a possibility that these fault populations represent Proterozoic faults that have caused the segmented structure of the Hardangerfjord Shear Zone.

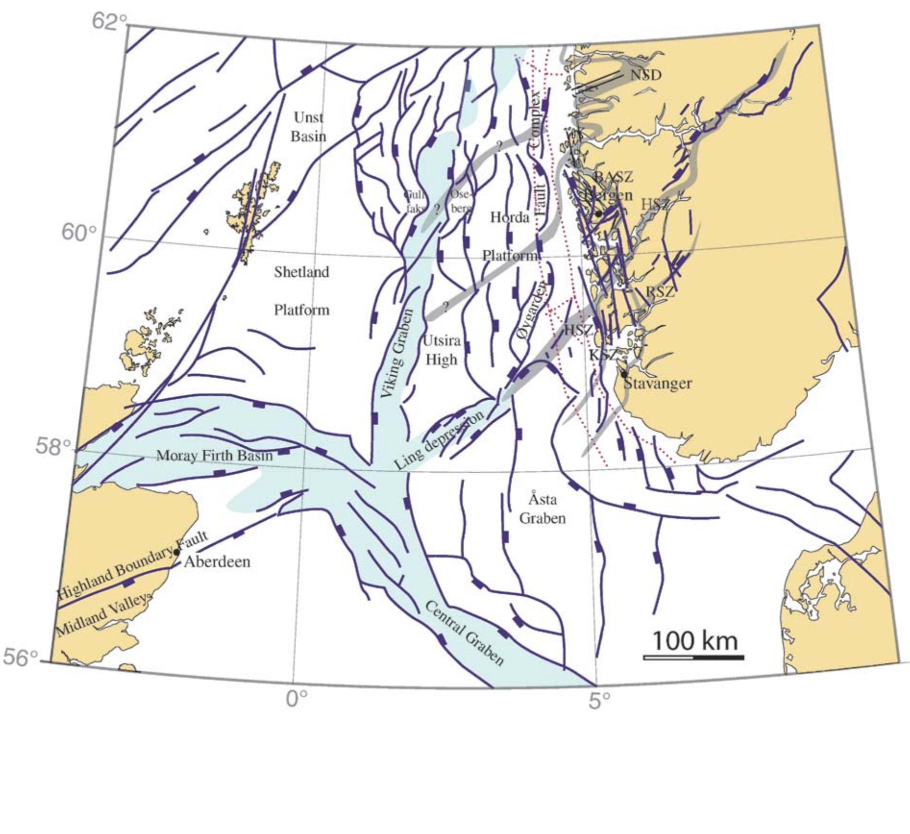

Fig. 6. Regional map of the North Sea region, showing the main fault trends and the location of the Hardangerfjord Shear Zone and related shear zones. (Note how the Hardangerfjord Shear Zone lines up with the Ling depression and the Highland Boundary Fault–Midland Valley.) HFZ, Hardangerfjord Shear Zone; BASZ, Bergen Arcs Shear Zone; NSD, Nordfjord–Sogn Detachment; KSZ, Karmøy Shear Zone; RSZ, Røldal Shear Zone. Based in part on Ziegler (1990) and Færseth (1996).

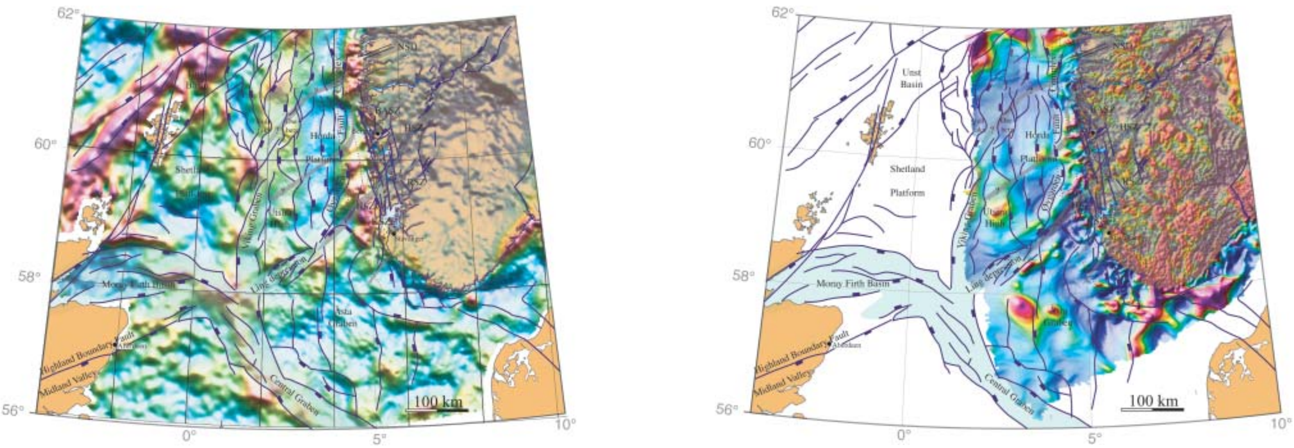

Fig. 7. Gravity (left) and magnetic (right) map showing the likely extension of the Hardangerfjord Shear Zone into the Ling Graben, across the Viking Graben and possibly to the Highland Boundary Fault. Data from Skilbrei *et al*. (2000).

Offset and footwall uplift

Geological profiles constructed across the Hardangerfjord Shear Zone in the Hardangerfjord region (e.g. Fig. 3) indicate that a total vertical offset (throw) of the order of 5 km (displacement estimated at 10–15 km). A throw of 6–7 km was indicated by Milnes *et al*. (1997) on a section farther NE (Lærdal area). Uncertainties associated with these estimates are related to the depth of the uppermost basement surface in the hanging wall.

Large-scale extensional faulting generally results in uplift of the footwall block (Jackson & McKenzie 1983), and the pattern of exhumed basement rocks (windows) in the footwalls to extensional faults at many places in the Caledonian orogen indicates that this is a common feature in the Caledonides (e.g. Andersen *et al*. 1999). The map of the sub-Cambrian basement unconformity (peneplain) shown in Figure 8 indicates positive elevation anomalies on the footwall side of the Hardangerfjord Shear Zone. The sub-Cambrian peneplain has a dome-shaped geometry on a regional scale, and the general structure is attributed to Tertiary differential uplift (Rohrman *et al*. 1995; Riis 1996). The peneplain has a gentle regional dip to the NW toward the Hardangerfjord area (Fig. 8). This trend is perturbed along the SE side of the Hardangerfjord Shear Zone where the peneplain is taken up from *c*. 1000 m above sea level (a.s.l.) SE of the Hardangerfjord Shear Zone to *c*. 1600 m a.s.l. close to the shear zone. Extrapolating this dip into the Hardangerfjord Shear Zone yields a footwall uplift of 800–1000 m (Fig. 8, profile) and a related half-wavelength of 25–30 km. The contour map (Fig. 8) also reveals a linear trend that runs parallel to the Hardangerfjord Shear Zone but some 40–50 km to the SE. This is a zone consisting of several extensional shear zones and faults that are closely related to the Hardangerfjord Shear Zone and the Lærdal–Gjende fault system.

The amplitude of footwall uplift depends on several factors, particularly the nature of the fill in the hanging-wall basin. Sediment loading effectively pushes the structure down and counteracts footwall uplift. Loading by water allows for more pronounced uplift of the footwall. In the present case, thick accumulations of Devonian clastic sediments are well known from the contemporaneous Nordfjord Sogn Detachment (Steel *et al*. 1985), from the Devonian Røragen detachment to the NE (Norton 1987; Gee *et al*. 1994), and are also interpreted from the hanging wall to the Hardangerfjord Shear Zone (Færseth *et al*. 1995). The Devonian basin fill was deposited during rapid sedimentation and short transport to the evolving half-graben above extensional detachments (e.g. Séranne & Séguret 1987). Thus sediment loading of the hanging wall can be assumed, in which case footwall uplift is roughly of the order of 10%

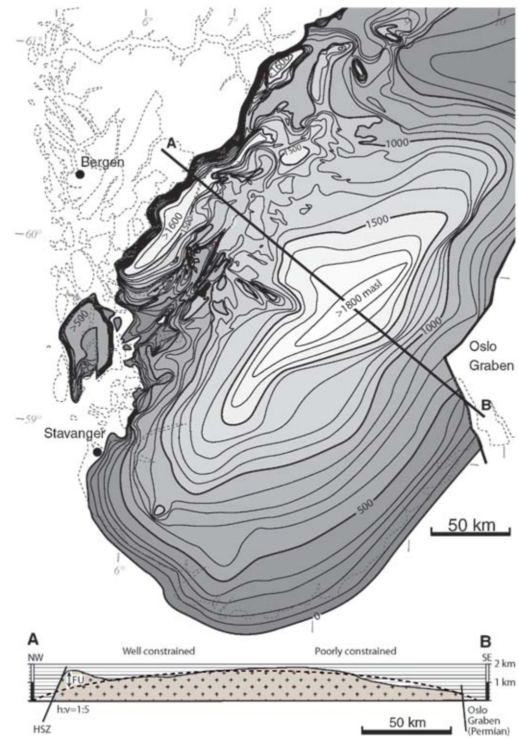

Fig. 8. Regional map of the uppermost basement surface, constructed from 1:250 000 scale bedrock maps of southern Norway. The surface, which generally equals the sub-Cambrian peneplain, reaches heights in excess of 1800 m a.s.l. in the central part of the mapped area. (Note local elongated highs along the SE side of the Hardangerfjord Shear Zone.) A profile is shown, indicating the deviation from the general dome trend near the Hardangerfjord Shear Zone. FU, footwall uplift (see text for discussion).

(Jackson & McKenzie 1983) or 5–25% (Yielding & Roberts 1992) of the total throw. These considerations are consistent with the 5–7 km of vertical offset indicated from the constructed profiles. Furthermore, the large wavelength of the footwall uplift seen in this case points to a thick early to mid-Devonian elastic crust.

Onshore brittle structures along the Hardangerfjord Shear Zone

Brittle faults with NE–SW trends occur along the trend of the Hardangerfjord Shear Zone. These faults are found in the Caledonian nappes and have received more attention in the literature than the Hardangerfjord Shear Zone itself (Battey 1965; Battey & McRitchie 1973; Milnes & Koestler 1985; Andersen *et al*. 1999). They are either simultaneous structures formed at a shallower level and/or later structures not directly related to the ductile shearing. An important but hitherto overlooked feature is their absence in the southwestern part of the Hardangerfjord Shear Zone and their abundance in the NE (the Lærdal–Gjende fault system).

The Lærdal–Gjende fault system

The ductile structures along the onshore section of the Hardangerfjord Shear Zone are overprinted by a system of brittle faults in the NE part of the Hardangerfjord Shear Zone that run parallel to the ductile shear zone and appear to represent deformation at shallower crustal levels (lower temperatures). The faults form a linked system that is well developed in the Aurland–Årdal–Tyin area (Battey & McRitchie 1973), informally named the Lærdal–Gjende fault system (Andersen *et al*. 1999). The largest fault has been referred to as the Lærdal–Gjende fault in previous studies (Milnes & Koestler 1985; Lutro & Tveten 1996). This fault has a characteristic zone of greenish and very cohesive cataclastic and hydrothermally altered rock that reaches a maximum thickness of about 200 m in the Årdal–Tyin area. Additional minor faults and fractures outside this zone may also be considered part of the damage zone of the Lærdal–Gjende fault, although the exact width of the total damage zone has not been established. Regardless, the damage zone thickness appears to be consistent with kilometre-scale brittle offset in this area, based on empirical data from other faults (Hull 1988; Evans 1990).

A palaeomagnetic study of the cataclastic fault rock along the Lærdal–Gjende fault by Andersen *et al*. (1999) indicated an episode of Permian faulting, and local, non-cohesive fault gouge bears signs of some late Jurassic–Cretaceous reactivation. The fact that late slip surfaces in the cataclasites along the Lærdal–Gjende fault indicate sinistral strike-slip can be attributed to Permian reactivation. The Permian strain field was one of east–west extension (Færseth *et al*. 1995; Fossen 1998; Valle *et al*. 2002), and sinistral strike-slip motion along the Hardangerfjord Shear Zone fits kinematically with (Permian) east–west extension. It should be noted, however, that the strike-slip movement is likely to have been small compared with the total vertical offset. Fault surface irregularities would otherwise have caused local transpressional–transtensional structures, for which there is little current evidence.

The possibility that the Lærdal–Gjende fault system is older than Permian in origin should be considered likely for several reasons. Rb/Sr isochrons of 367 Ma were obtained for minerals in brittle fractures in the area (Schärer 1980). This age is similar to ages obtained from minerals in early fractures from the coastal area near Bergen (Larsen *et al*. 2003). Both areas contain epidote-filled fractures and epidote-bearing cataclasite and cohesive microbreccia (Fossen 1998; Larsen *et al*. 2003). The cohesive epidote-bearing cataclasites are consistent with a deep (close to 10 km) position within the brittle crust during formation. Although the exact depth of burial during the Permian period is not known, thermochronological data indicate that the rocks were closer to 10 km depth in the Devonian than during the Permian period (Dunlap & Fossen 1998). The fact that epidote-bearing faults elsewhere in SW Norway are kinematically consistent with NW–SE Devonian extension (Fossen 1998, 2000; Valle *et al*. 2002; Larsen *et al*. 2003), rather than the Permian east–west extension direction adds to the general impression that the Lærdal–Gjende fault system may have initiated in the Devonian. A reasonable interpretation is that the fault system initiated within the Caledonian orogenic wedge as a brittle response to the growth of the underlying ductile Hardangerfjord Shear Zone.

Brittle deformation in the Hardangerfjord area

Whereas the Lærdal–Gjende fault system occurs as a significant brittle structure along and above the Hardangerfjord Shear Zone in the NE, no sign of similar NE–SE-oriented major fault structures is found in the Hardangerfjord area (area covered by Fig. 2a). Nor have the characteristic green cataclasites of the kind exposed in the Tyin–Årdal area been observed to any significant extent, and information from continuous cores along the tunnel that was recently constructed under the southwestern part of the fjord (the Bømlafjord tunnel; see Fig. 2a) also indicate that the Hardangerfjord Shear Zone is a ductile shear zone in this area. Geological mapping indicates that the brittle Lærdal–Gjende fault system dies out between Aurland and the Hardangerfjord. The strain accommodated by the Lærdal–Gjende fault system to the NE may have been accommodated by other NE–SW-trending faults away from the Hardangerfjord Shear Zone (Fig. 2a), such as the Røldal shear zone (Fig. 1) (Naterstad *et al*. 1973).

Most faults and fracture zones in the Hardangerfjord area belong to a system of north–south- to NNW–SSE-trending faults that are independent of, and clearly postdate movements on the Hardangerfjord Shear Zone. These faults are locally intruded by Permian and Triassic basaltic dykes (Færseth *et al*. 1976; Fossen & Dunlap 1999), and many are associated with calcite mineralization. On a regional scale, the north–south- to NNW–SSE-trending faults also postdate NE–SW-trending faults. This age relationship is based on crosscutting relations and dating of dykes and fault mineralization (Fossen 1998; Valle *et al*. 2002; Larsen *et al*. 2003). The north–south- to NNW–SSE-trending faults are well represented in the Lower Palaeozoic rocks in the hanging wall of the Hardangerfjord Shear Zone (Fig. 2c), and are thus entirely of Palaeozoic (Permian) or later origin in this area. However, the basement in the Folgefonna peninsula SE of the Hardangerfjord Shear Zone is generally unaffected by Caledonian deformation. Thus, it is possible that the north–south to NNW–SSE basement faults represent a Proterozoic (although later rejuvenated) fault system in this area, and that they caused the irregular and segmented geometry of the Hardangerfjord Shear Zone portrayed in Figure 2.

Offshore expression of the Hardangerfjord Shear Zone

Commercial seismic sections from the North Sea do not image intra-basement reflectors very well. Thus, recognition and mapping of the Hardangerfjord Shear Zone in the North Sea requires deep seismic data. Commercial seismic data do, however, clearly indicate a fundamental linear trend defined by NE–SW-oriented faults that contrast with the general north–south fault orientation in this part of the North Sea (Fig. 6). These faults affect the Jurassic sequence, but some also show evidence for earlier (Permo-Triassic) activation. Pre-Triassic faulting is difficult to identify on commercial seismic lines, but cannot be precluded.

In this work we have revisited the deep seismic lines ILP 10, 11, 12 and 13 (Hurich & Kristoffersen 1988; Færseth *et al.* 1995). These deep seismic lines have been reprocessed for a closer evaluation. The seismic reflection data were originally acquired in 1988 as part of a joint programme between the Norwegian Lithosphere Project and the Mobil Search programme. The data recently underwent post-stack reprocessing at Memorial University (Newfoundland) to enhance middle- and lower-crustal reflectivity. Reprocessing included time-migration, coherency filtering, tuning of bandpass filters and depth conversion. Velocity information for the migration and depth conversion was derived from co-located wide-angle data, as discussed by Deemer & Hurich (1991).

Dipping reflectors on ILP lines

Four deep seismic lines (ILP 10–13; Fig. 9) cross the extrapolated location of the Hardangerfjord Shear Zone SW of the mouth of the Hardangerfjord. Two of the sections (ILP 12 and 13) were designed especially to image the Hardangerfjord Shear Zone, whereas the other two (ILP 10 and 11) are more regional, coast-parallel lines. Only the parts of the sections that display the Hardangerfjord Shear Zone are shown in this work.

Section ILP 12 is oriented more or less perpendicular to the strike of the Hardangerfjord Shear Zone and is also the line that images the shear zone best (Fig. 1). A package of strong, dipping reflectors appears between 4 and 25 km depth. The package is remarkably thick (about 5–10 km, possibly even more) and dips 23–24° to the NW.

ILP 13 runs ENE–WSW (at a low angle to the Hardangerfjord Shear Zone) and shows a distinct zone of reflectors with apparent dips of 12–13° to the NNW to depths of almost 20 km (Fig. 9). The reflectors look very similar to those of ILP 12, and the zone appears to be about 7 km thick.

ILP 11 is the section closest to the Norwegian mainland. Dipping reflectors (*c.* 12°) occur in the position of the extrapolated HFZ (Fig. 9), although they are not as pronounced as in the previous sections. A bend in the reflectors at about 10 km depth may be real, but could also be due to incomplete 2D migration. The zone of dipping reflectors is at least 5 km thick and can be traced down to about 20 km.

ILP 10 also shows a package of dipping, parallel reflectors down to about 20–25 km, with thickness comparable with that of the other lines. The reflectors dip about 16°.

The accuracy of the dip estimate is dependent on the velocity function used for depth conversion (Fig. 9). Because of limited velocity control, we depth converted using a velocity function derived from the wide-angle data based on velocities derived from the wide-angle data that are most appropriate for the nearshore area. The major potential source of velocity error in the depth conversion of ILP-12 (the dip line) is the thickening of the Mesozoic wedge in the offshore direction. Not accounting for the wedge of the lower-velocity sediments may result in an underestimation of dip in the depth-converted seismic data. If, in the worst case, our velocity function is 50% too high for the northern portion of ILP-12, our depth conversion could lead to an underestimation of the dip of the Hardangerfjord Shear Zone by up to 4°.

The approximate positions of the reflectors at uppermost basement level (illustrated in Fig. 1) show that the reflectors line up with the onshore trend of the Hardangerfjord Shear Zone. Furthermore, if the apparent dips and dip directions of the reflectors on each line are plotted together in a stereoplot, they closely fit the plane 211/23, which is reasonably close to the average onshore orientation of the Hardangerfjord Shear Zone in the Hardangerfjord area (steep limbs of deflected layers indicate an average orientation of 223/22). Hence, the position and dip direction of the reflectors identified on the four lines clearly suggest that they are related to the Hardangerfjord Shear Zone.

Dipping energy of the strength portrayed by the ILP lines must represent parallel layers of contrasting acoustic impedance. Many examples show that mylonite zones or zones of transposed layering are imaged as packages of subparallel reflections similar to those seen on the present lines (Jones & Nur 1984; Hurich *et al.* 1985). As the orientation of these reflections is different from the known onshore basement structuring, and as it penetrates from the top of the basement to middle and possibly lower crust, the energy is likely to represent a fundamental crustal-scale shear zone. The reflectors consistently show that the shear zone cuts down to present depths of at least 25 km, where it possibly flattens and dissipates into the lower crust.

Discussion

The observations and data from the Hardangerfjord Shear Zone presented above support the interpretation of the Hardangerfjord Shear Zone as a ductile shear zone that affects the basement. However, the data give room for at least two kinematic interpretations, namely a simple NW-dipping shear zone transecting the basement–allochthon contact, or a simultaneous combination of shearing along such a zone with subhorizontal shear along the décollement (late Mode I and early Mode II extension of Fossen (1992)).

Simple shear zone model

The simplest model is that of a simple, NW-dipping shear zone cutting through both the basement and the overlying allochthonous décollement zone–nappes. In this model, the monoclinal fold geometry of the allochthonous units near the Hardangerfjord Shear Zone is a direct result of simple shear along the Hardangerfjord Shear Zone. This model has similarities to the formation of forced folds at the Colorado Plateau and elsewhere, where reactivation of faults has caused monoclinal folding of the overlying sedimentary sequence (e.g. Jamison & Stearns 1982; Hardy & McClay 1999). The mechanical decoupling and, in particular, the difference in mechanical properties between the basement and the cover are considered to be important in the Colorado Plateau examples, which have been successfully modelled using the trishear method (e.g. Allmendinger 1998). In the Hardangerfjord Shear Zone example, the weak, micaceous décollement zone decoupled the basement from the overlying Caledonian nappes. In this model, the shear zone is a (preexisting?) basement structure that grew into the orogenic wedge. The (at the time) subhorizontal or gently NW-dipping stratification of the nappe stack would rotate during the shearing to form the monoclinal structure ('Faltungsgraben'). Hence, knowing the dip of the shear zone, it is possible from this model to calculate the shear strain from the dip of the layers across the zone.

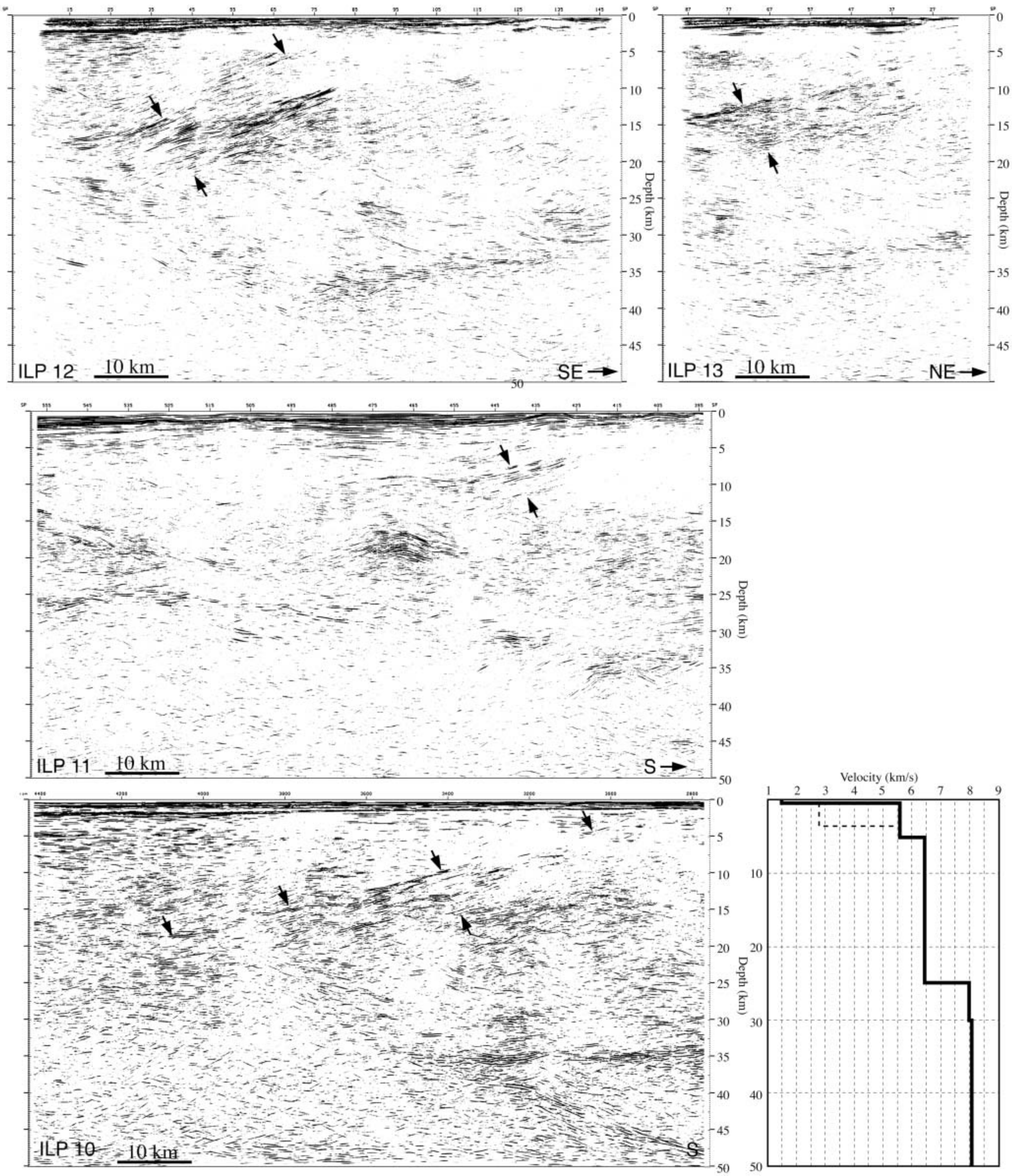

Fig. 9. The Hardangerfjord Shear Zone imaged on four depth-converted deep seismic lines. The package of reflectors (indicated by arrows) is aligned with the onshore trend of the Hardangerfjord Shear Zone. The velocity profile used for depth conversion is shown. Dashed line represents replacement of the shallow velocity function with a velocity 50% lower than that used for the depth conversion. The thickness of the lower-velocity layer is dictated by the thickness of the Mesozoic(?) package on the NW end of ILP-12.

Double shear model

The Hardangerfjord Shear Zone was activated after a period of northwestward transport of the Caledonian orogenic wedge (Mode I extension). The tectonic and chronological data indicate that the extensional development occurred quickly in the Early Devonian, and the change from Mode I to Mode II extension was rapid (Fossen & Dallmeyer 1998; Fossen & Dunlap 1998). Hence, as Mode I extension was gradually being replaced by Mode II extension, a period of simultaneous NW transport of the orogenic wedge and shearing along the Hardangerfjord Shear Zone is expected (Fig. 10a). This situation has been modelled experimentally by Fossen & Rykkelid (1992*b*), who showed that folds develop in the hanging-wall position above the dipping shear zone (Fig. 11). Numerous folds with metre- to kilometre-scale wavelengths are widespread in the hanging wall of the Hardangerfjord Shear Zone, and it is possible that some are related to a period of overlapping Mode I and II extension (Fig. 11). Hence, a model is envisioned where a double shear zone model (Fig. 10a) is gradually replaced by a simple shear model (Fig. 10b).

Role of the Lærdal–Gjende fault system

The brittle faulting along the Hardangerfjord Shear Zone (Lærdal–Gjende fault system) may be considered as a shallow-level expression of the Hardangerfjord Shear Zone at a late stage of its history (Fig. 10c). Ductile shearing in the basement may have caused brittle faulting in the Jotun Nappe because of the difference in crustal depth and perhaps also because of the lower quartz content in many rocks of the Jotun Nappe. A location close to the brittle–plastic transition is likely from the greenschist-facies mineral parageneses found in the basement shear zone and from radiometric age constraints. Ar/Ar data indicate that cooling through *c*. 350 °C occurred at *c*. 400 Ma along the Hardangerfjord Shear Zone (Fossen & Dallmeyer 1998; Fossen & Dunlap 1998). At this time the NW-directed nappe translation (Mode I extension) was still continuing. During the subsequent Mode II extension, during which the Hardangerfjord Shear Zone acted as a simple shear zone, the now exposed section must have moved into or close to the brittle–plastic transition (*c*. 300 °C). This is confirmed by dating of early brittle deformation in the basement west of Bergen, which yielded U/Pb ages around 396 Ma for sphene in early fractures and Rb/Sr ages of 363–371 Ma based on epidote and hydrothermally altered alkali-feldspar (Larsen *et al*. 2003). The Rb/Sr ages are basically identical to the Rb/Sr data reported by Schärer (1980), who obtained a Rb/Sr isochron of *c*. 367 Ma from minerals in fractures in the Lærdal–Gjende fault system, supporting the view that the Lærdal–Gjende fault system formed during the Devonian extensional phase and that Permian and later deformation was by reactivation.

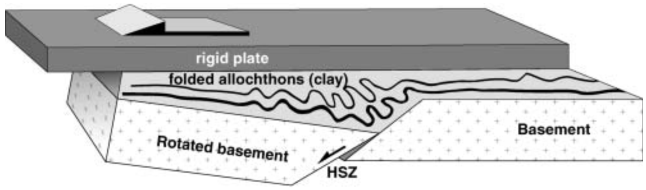

Fig. 11. Experiment performed by Fossen & Rykkelid (1992*b*), showing how folds develop above the hanging wall of a basement fault (corresponding to the Hardangerfjord Shear Zone) if shearing of the overlying section (décollement and Caledonian nappes) is still continuing.

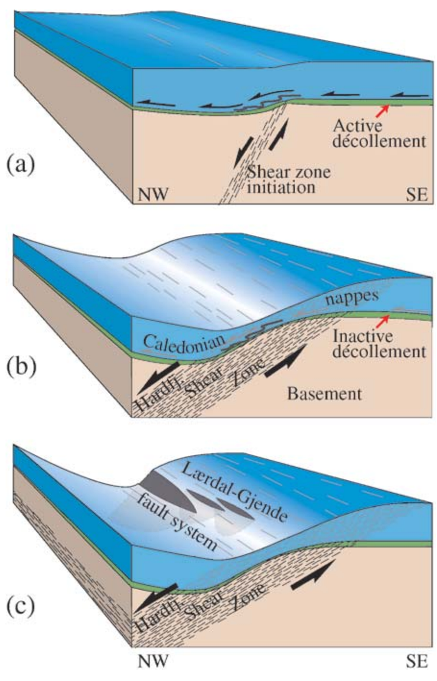

Fig. 10. Schematic evolution of the Hardangerfjord Shear Zone and related brittle faults. (**a**) The Hardangerfjord Shear Zone initiates as the top-to-NW shearing (Mode I extension) affects the décollement. (**b**) Accumulated offset on the Hardangerfjord Shear Zone inactivates the décollement, which is monoclinally folded together with overlying Caledonian nappes. (**c**) At some point, the brittle Lærdal–Gjende fault system develops, probably as a result of falling temperature (decreasing depth) in the Devonian.

The problem with a >5 km thick mylonite zone

The basement is exposed only in the hanging-wall side of the shear zone, and it is not possible from onshore observations alone to predict the geometry of the Hardangerfjord Shear Zone or the Lærdal–Gjende fault system at depth. It has earlier been suggested that the fault system has a listric geometry and flattens to merge with the phyllitic décollement zone at shallow (present) depths (Milnes *et al*. 1997). The reprocessed seismic data presented here give, however, strong indications that the shear zone continues to depths of 20–25 km, where the zone probably flattens to merge with the subhorizontal fabrics of the lower crust.

The seismic data indicate a 5–10 km thick package of reflections. If these reflections represent a mylonite zone, the total accumulated displacement across the zone must be considerably larger than the 10–15 km estimated from the onshore offset of Caledonian units. If the mylonite zone is taken to be *c*. 5 km wide and the displacement is 10 km, then the shear strain would be 2–3. To generate mylonites, shear strains around 10 or more are required (e.g. Skjernaa 1980; Fossen & Rykkelid 1990; Swanson 1992).

A likely explanation for this discrepancy is that the Hardangerfjord Shear Zone developed on a pre-existing mylonite zone. The zone could be one of several Sveconorwegian (Grenvillan) shear zones in the Sveconorwegian basement, or it could be a Caledonian contractional shear zone (thrust). Restoring the section across the Hardangerfjord Shear Zone shows that the uppermost basement surface restores to a planar surface if the effect of the Hardangerfjord Shear Zone is removed (e.g. Fossen 1992; Milnes *et al*. 1997). Any significant Caledonian reverse movement along the Hardangerfjord Shear Zone must therefore have been removed during the Mode II extensional deformation. It is also difficult to see how Caledonian shearing responsible for more than 5 km of mylonites could be more than reversed during the extensional phase. In this perspective we favour an explanation where the Hardangerfjord Shear Zone formed along an already existing Proterozoic shear zone.

Thanks go to J. R. Skilbrei for providing us with digital grav-mag image files, and to R. Færseth, O. P. Wennberg and editor T. Needham for many useful comments during the review process.

References

Allmendinger, R.W. 1998. Inverse and forward numerical modeling of trishear fault-propagation folds. *Tectonics*, **17**, 640–656.

Andersen, T.B. & Jamtveit, B. 1990. Uplift of deep crust during orogenic extensional collapse: a model based on field studies in the Sogn–Sunnfjord region of western Norway. *Tectonics*, **9**, 1097–1112.

Andersen, T.B., Torsvik, T.H., Eide, E.A., Osmundsen, P.T. & Faleide, J.I. 1999. Permian and Mesozoic extensional faulting within the Caledonides of central Norway. *Journal of the Geological Society, London*, **156**, 1073–1080.

Battey, M.H. 1965. Layered structure in rocks of the Jotunheimen complex. *Mineralogical Magazine*, **34**, 35–51.

Battey, M.H. & McRitchie, W.D. 1973. A geological traverse across the pyroxene-granulites of Jotunheimen in the Norwegian Caledonides. *Norsk Geologisk Tidsskrift*, **53**, 237–265.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican Shear Zone. *Journal of Structural Geology*, **1**, 31–42.

Bockelie, J.F. & Nystuen, J.P. 1985. The southeastern part of the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. Wiley, Chichester, 69–88.

Braathen, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D. & Meyer, G.B. 2002. Orogen-parallel extension of the Caledonides in northern Central Norway. *Norwegian Journal of Geology*, **82**, 225–241.

Bryhni, I. & Sturt, B.A. 1985. Caledonides of southwestern Norway. *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. Wiley, Chichester, 89–107.

Cartwright, J.A., Trudgill, B.D. & Mansfield, C.S. 1995. Fault growth by segment linkage: an explanation for scatter in maximum displacement and trace length data from the Canyonlands Grabens of SE Utah. *Journal of Structural Geology*, **17**, 1319–1326.

Childs, C., Watterson, J. & Walsh, J.J. 1995. Fault overlap zones within developing normal fault systems. *Journal of the Geological Society, London*, **152**, 535–549.

Deemer, S.J. & Hurich, C.A. 1991. Comparison of coincident high-resolution wide-aperture and CDP profiling along the southwest coast of Norway. *In:* Meissner, R., Brown, L., Dürbaur, H., Franke, W., Fuchs, K. & Seifert, F. (eds) *Continental Lithosphere: Deep Seismic Reflections*. American Geophysical Union, Geodynamics Series, **22**, 435–442.

Dunlap, W.J. & Fossen, H. 1998. Early Paleozoic orogenic collapse, tectonic stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, southern Norway. *Tectonics*, **17**, 604–620.

Evans, J.P. 1990. Thickness–displacement relationships for fault zones. *Journal of Structural Geology*, **12**, 1061–1065.

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

Færseth, R.B., Gabrielsen, R.H. & Hurich, C.A. 1995. Influence of basement in structuring of the North Sea basin, offshore southwest Norway. *Norsk Geologisk Tidsskrift*, **75**, 105–119.

Færseth, R.B., Knudsen, B.-E., Liljedahl, T., Midbøe, P.S. & Søderstrøm, B. 1997. Oblique rifting and sequential faulting in the Jurassic development of the northern North Sea. *Journal of Structural Geology*, **19**, 1285–1302.

Færseth, R.B., Macintyre, R.M. & Naterstad, J. 1976. Mesozoic alkaline dykes in the Sunnhordland region, western Norway: ages, geochemistry and regional significance. *Lithos*, **9**, 331–345.

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

Fossen, H. 1993. Structural evolution of the Bergsdalen Nappes, Southwest Norway. *Norges Geologiske Undersøkelse Bulletin*, **424**, 23–50.

Fossen, H. 1998. Advances in understanding the post-Caledonian structural evolution of the Bergen area, West Norway. *Norsk Geologisk Tidsskrift*, **78**, 33–46.

Fossen, H. 2000. Extensional tectonics in the Caledonides: synorogenic or postorogenic? *Tectonics*, **19**, 213–224.

Fossen, H. & Dallmeyer, R.D. 1998. $^{40}Ar/^{39}Ar$ muscovite dates from the nappe region of southwestern Norway: dating extensional deformation in the Scandinavian Caledonides. *Tectonophysics*, **285**, 119–133.

Fossen, H. & Dunlap, W.J. 1998. Timing and kinematics of Caledonian thrusting and extensional collapse, southern Norway: evidence from $^{40}Ar/^{39}Ar$ thermochronology. *Journal of Structural Geology*, **20**, 765–781.

Fossen, H. & Dunlap, W.J. 1999. On the age and tectonic significance of Permo-Triassic dikes in the Bergen–Sunnhordland region, southwestern Norway. *Norsk Geologisk Tidsskrift*, **79**, 169–178.

Fossen, H. & Rykkelid, E. 1990. Shear zone structures in the Øygarden Complex, western Norway. *Tectonophysics*, **174**, 385–397.

Fossen, H. & Rykkelid, E. 1992a. Post-collisional extension of the Caledonide orogen in Scandinavia: structural expressions and tectonic significance. *Geology*, **20**, 737–740.

Fossen, H. & Rykkelid, E. 1992b. The interaction between oblique and layer-parallel shear in high-strain zones: observations and experiments. *Tectonophysics*, **207**, 331–343.

Gabrielsen, R.H., Braathen, A., Dehls, J. & Roberts, D. 2002. Tectonic lineaments of Norway. *Norwegian Journal of Geology*, **82**, 153–174.

Gee, D.G., Lobkowicz, M. & Singh, S. 1994. Late Caledonian extension in the Scandinavian Caledonides—the Røragen detachment revisited. *Tectonophysics*, **231**, 139–155.

Goldschmidt, V.M. 1912. *Die kaledonische Deformation der südnorwegischen Urgebirgstafel*. Skr. Vidensk. Selsk. Christiania, **19**.

Gorbatschev, R. 1985. Precambrian basement of the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. Wiley, Chichester, 197–212.

Hardy, S. & McClay, K. 1999. Kinematic modelling of extensional fault-propagation folding. *Journal of Structural Geology*, **21**, 695–702.

Hossack, J.R. & Cooper, M.A. 1986. Collision tectonics in the Scandinavian Caledonides. *In:* Coward, M.P. & Ries, A.C. (eds) *Collision Tectonics*. Geological Society, London, Special Publications, **19**, 287–304.

Hull, J. 1988. Thickness–displacement relationships for deformation zones. *Journal of Structural Geology*, **4**, 431–435.

Hurich, C.A. & Kristoffersen, Y. 1988. Deep structure of the Caledonide orogen in southern Norway: new evidence from marine seismic reflection profiling. *In:* Kristoffersen, Y. (ed.) *Progress in the Studies of the Lithosphere in Norway*. Norges Geologiske Undersøkelse Special Publications, **3**, 96–101.

Hurich, C.A., Smithson, S.B., Fountin, D.M. & Humphreys, M.C. 1985. Mylonite reflectivity: evidence from the Kettle dome, Washington. *Geology*, **13**, 577–580.

Jackson, J. & McKenzie, D. 1983. The geometrical evolution of normal fault systems. *Journal of Structural Geology*, **5**, 472–483.

Jamison, W.R. & Stearns, D.W. 1982. Tectonic deformation of Wingate Sandstone, Colorado National Monument. *AAPG Bulletin*, **66**, 2584–2608.

Jones, T. & Nur, A. 1984. The nature of reflections from deep crustal fault zones. *Journal of Geophysical Research*, **89**, 3153–3171.

Larsen, Ø., Fossen, H., Langeland, K. & Pedersen, R.B. 2003. Kinematics and timing of polyphase post-Caledonian deformation in the Bergen area, SW Norway. *Norwegian Journal of Geology*, **83**, 149–165.

Lutro, O. & Tveten, E. 1996. *Årdal, geological bedrock map 1:250 000*. Norges Geologiske Undersøkelse, Trondheim.

Milnes, A.G. & Koestler, A.G. 1985. Geological structure of Jotunheimen, southern Norway (Sognefjell–Valdres cross-section). *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. Wiley, Chichester, 457–474.

Milnes, A.G., Wennberg, O.P., Skår, Ø. & Koestler, A.G. 1997. Contraction, extension and timing in the South Norwegian Caledonides: the Sognefjord transect. *In:* Burg, J.-P. & Ford, M. (eds) *Orogeny through Time*. Geological Society, London, Special Publications, **121**, 123–148.

Naterstad, J., Andresen, A. & Jorde, K. 1973. Tectonic succession of the Caledonian nappe front in the Haukeli–Røldal area, southwest Norway. *Norges Geologiske Undersøkelse Bulletin*, **292**, 1–20.

Norton, M. 1987. The Nordfjord–Sogn Detachment, W. Norway. *Norsk Geologisk Tidsskrift*, **67**, 93–106.

Olesen, O., Lundin, E. & Nordgulen, Ø. et al. 2002. Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology*, **82**, 243–262.

Pedersen, R.B., Furnes, H. & Dunning, G. 1988. Some Norwegian ophiolite complexes reconsidered: progress in studies of the lithosphere in Norway. *In:* Kristoffersen, Y. (ed.) *Progress in the Studies of the Lithosphere in*

Norway. Norges Geologiske Undersøkelse Special Publications, **3**, 80–85.

Rey, P., Burg, J.-P. & Casey, M. 1997. The Scandinavian Caledonides and their relationship to the Variscan belt. *In:* Burg, J.-P. & Ford, M. (eds) Geological Society, London, Special Publications, **121**, 179–200.

Riis, F. 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global Change*, **12**, 331–357.

Rohrman, M., van der Beek, P., Andriessen, P. & Cloetingh, S. 1995. Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. *Tectonics*, **14**, 704–718.

Schärer, U. 1980. *Geologie und U–Pb/Sr–Sr Geochronologie der kaledonischen Jotundecke im Tyingebiet, Südnorwegen*. Dissertation, ETH Zürich.

Séranne, M. & Séguret, M. 1987. The Devonian basins of western Norway: tectonics and kinematics of an extending crust. *In:* Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 537–548.

Sigmond, E., Gustavson, M. & Roberts, D. 1984. *Bedrock map of Norway 1:1 million*. Norges Geologiske Undersøkelse, Trondheim.

Skilbrei, J.R., Kihle, O., Olesen, O., Gellein, J., Sindre, A., Solheim, D. & Nyland, B. 2000. *Tyngdeanomalikart, Norge med havområder. 1:3 000 000*. Norges Geologiske Undersøkelse, Trondheim.

Skilbrei, J.R., Olesen, O., Osmundsen, P.T., Kihle, O., Aaro, S. & Fjellanger, E. 2002. A study of basement structures and onshore–offshore correlations in Central Norway. *Norwegian Journal of Geology*, **82**, 263–279.

Skår, Ø. 1998. *The Proterozoic and Early Paleozoic evolution of the southern parts of the Western Gneiss Complex, Norway*. Dr.scient. thesis, University of Bergen.

Skjernaa, L. 1980. Rotation and deformation of randomly oriented planar and linear structures in progressive simple shear. *Journal of Structural Geology*, **2**, 101–109.

Steel, R., Siedlecka, A. & Roberts, D. 1985. The Old Red Sandstone basins of Norway and their deformation: a review. *In:* Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*. Wiley, Chichester, 293–315.

Swanson, M.T. 1992. Late Acadian–Alleghenian transpressional deformation: evidence from asymmetric boudinage in the Casco Bay area, coastal Maine. *Journal of Structural Geology*, **14**, 323–341.

Torske, T. 1982. Structural effects on the Proterozoic Ullensvang Group (West Norway) relatable to forceful emplacement of expanding plutons. *Geologische Rundschau*, **71**, 104–119.

Valle, P., Færseth, R.B. & Fossen, H. 2002. Devonian–Triassic brittle deformation based on dyke geometry and fault kinematics in the Sunnhordland region, SW Norway. *Norsk Geologisk Tidsskrift*, **82**, 3–17.

Wennberg, O.P., Milnes, A.G. & Winsvold, I. 1998. The northern Bergen Arc Shear Zone—a oblique-lateral ramp in the Devonian extensional detachment system of western Norway. *Norsk Geologisk Tidsskrift*, **78**, 169–184.

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

Yielding, G. & Roberts, A. 1992. Footwall uplift during normal faulting—implications for structural geometries in the North Sea. *In:* Larsen, R.M., Brekke, H., Larsen, B.T. & Talleraas, E. (eds) *Structural and Tectonic Modelling and its Application to Petroleum Geology*. Norsk Petroleumsforening Special Publication, **1**, 289–304.

Ziegler, P.A. 1990. Tectonic and palaeogeographic development of the North Sea rift system. *In:* Blundell, D.J. & Gibbs, A.D. (eds) *Tectonic Evolution of the North Sea Rifts*. Clarendon Press, Oxford, 1–36.

Received 1 January 2004; revised typescript accepted 2 February 2004.
Scientific editing by Tim Needham