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Permian and Mesozoic extensional faulting within the Caledonides of central south Norway

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Abstract: Palaeomagnetic data from fault rocks along major faults in the Lærdal–Gjende Fault System cutting the Caledonian structure in the Jotunheimen area of central south Norway reveals a multi-component remanence pattern. Sample and site-mean directions from the fault rocks obtained by thermal cleaning demonstrate a simple pattern of normal polarity low blocking components and reverse polarity high-blocking directions. The magnetic signature of the Lærdal–Gjende Fault System fault rocks is identical to that observed on breccias on late faults along the west coast of Norway. Based on available palaeomagnetic reference data, we assign ages of mid–late Permian and late Jurassic–early Cretaceous for important phases of faulting and breccia formation along the Lærdal–Gjende Fault System in central south Norway. Structural windows, partly exposing basement along the axis of the Caledonides in southern Norway were exhumed by footwall uplift on major faults in the Lærdal–Gjende Fault System. The consanguinity of fault rock data from the Lærdal–Gjende Fault System and fault rocks in western Norway, and comparison with displacement on the offshore continuation of the Lærdal–Gjende Fault System along the Hardangerfjorden Shear Zone, indicate that the main tectonic events responsible for the development of the North Sea basin also significantly affected the geology of central south Norway.

Keywords: Norway, Permian, Mesozoic, fault rocks, palaeomagnetism.

In the past decade the focus of the research on Norwegian mainland geology has shifted from the processes related to the Caledonian mountain building to those that are responsible for the post-Caledonian modification of the orogen and its structure. It has been shown that many fundamental structures within the Scandinavian Caledonides are of late- or post-Caledonian (Devonian) age, and that they are extensional rather than related to mountain-building processes (Norton 1986; Chauvet & Séranne 1989; Andersen & Jamtveit 1990; Fossen 1992; Milnes *et al.* 1997; Andersen 1998). The most important post-Caledonian structures are the large-scale extensional detachments (Fig. 1) controlling exhumation of the deep crust and formation of the Devonian basins in western Norway (see Norton 1987; Osmundsen *et al.* 1998*a*), and the widespread extensional reactivation of major thrusts in southern Norway (Andersen 1998; Fossen & Dunlap 1998). Several studies in western Norway have documented late- to post-Devonian rejuvenation of the detachments and faults truncating earlier extensional structures in their hanging- and footwalls respectively (Torsvik *et al.* 1987, 1997; Osmundsen & Andersen 1994; Osmundsen *et al.* 1998*a*).

Palaeomagnetic multi-component remanence patterns from fault breccias along reactivated Devonian faults have previously been identified in western Norway (Torsvik *et al.* 1992). Well-defined palaeomagnetic poles from these breccias (A2 at 205/-33 and A1 at 342/+58) were compared with the apparent polar wander path (APWP) for Baltica and Europe, suggesting Permian (A1) and late Mesozoic (A2) ages of re-activation of the faults. The conclusions based on the palaeomagnetic studies have recently been substantiated by $^{40}Ar/^{39}Ar$ thermochronological data from the fault breccias and surrounding rock units (Eide *et al.* 1997, in press). Although inaccurate in terms of precision, the palaeomagnetic 'dating' method has the advantage of being fast compared to traditional radiometric methods. The dating of fault-rocks in western Norway documents tectonic activity in western Norway, which previously was thought to be of negligible importance in the mainland. Evidence for young near-shore faulting is also available from sedimentary basins with confirmed or probable Jurassic sedimentary rocks in near shore areas along western Norway and Trøndelag (see Bøe & Bjerklie 1989; Bøe *et al.* 1992). Firm evidence of late Jurassic sediments (Oxfordian) and fault-rocks have recently been encountered in situ during construction of a submarine road tunnel west of Bergen (Fossen *et al.* 1997). Permian (*c.* 262 ± 6 Ma) and Triassic (223 ± 6 Ma) dykes occur in several localities between Haugesund and Møre (Færseth *et al.* 1976; Torsvik *et al.* 1997; Sturt *et al.* 1998). Thus, a considerable post-Caledonian tectonomagmatic and sedimentary activity has been documented in the coastal areas of western Norway and Trøndelag. Not surprisingly, this activity can be closely tied with the major Permo-Triassic and late Jurassic rifting events important for formation of the North Sea basin.

In the Jotunheimen area of central south Norway, a major normal fault, the Lærdal–Gjende Fault, cutting the Caledonian structure was identified by Milnes and co-workers (Milnes & Koestler 1985, Milnes *et al.* 1988). Recent mapping shows that the Lærdal–Gjende Fault is one of several faults in the area (see also Lutro & Tveten 1996). We informally refer to this system of faults as the Lærdal–Gjende Fault System. Our work show that fault rocks in the Lærdal–Gjende Fault System formed by multiple deformation events, and that the fault rocks are obviously late since they truncate ductile late to post-Caledonian extensional mylonites (Gathe & Andersen

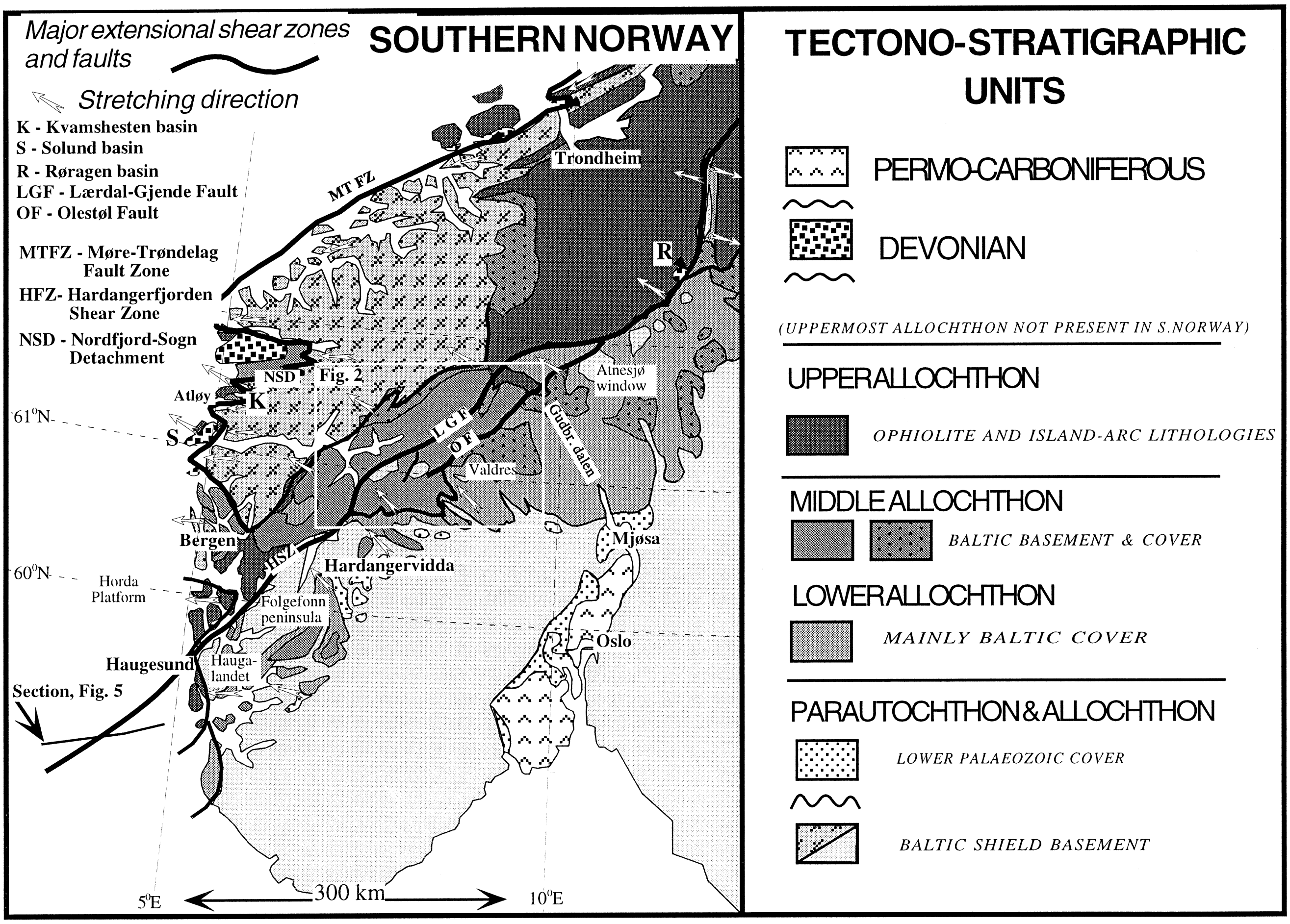

Fig. 1. Simplified geological map showing the main Caledonian tectono-stratigraphic units of southern Norway. Most tectonic contacts to the northwest of Hardangervidda are reactivated as top-to-west shear zones. Major extensional shear zones and faults are indicated. The location of Figs 2 and 5 are also shown.

1996; Andersen 1998). Based on the successful use of the palaeomagnetic 'dating' method in western Norway, we decided to analyse magnetic remanence of breccias of the Lærdal–Gjende Fault System in order to test whether the remanence could provide information regarding the age of brecciation. The main Lærdal–Gjende Fault and one of the subsiduary faults (Fig. 2) here named the Olestøl Fault, was targeted for further studies. Here we present data suggesting that tectonic activity related to 'North Sea rift events' previously recognized in the coastal regions in western Norway and along the Møre–Trøndelag fault zone (Fig. 1), also considerably affected the geology in the interior of central south Norway.

Geological setting

The Caledonides of the studied area in central south Norway comprise a tectonostratigraphy of variably autochthonous to allochthonous phyllites and schists of the Lower and Middle Allochthons and highly allochthonous basement and cover units of the Middle Allochthon. Higher units of the Upper Allochthon are preserved both to the northeast and southwest of the central Jotunheimen area (Figs 1 and 2). The nappes overlie the Fennoscandian basement, which in central south Norway is little affected by the Caledonian deformation. The Caledonian structure has been strongly modified by late to post-orogenic extension. Recent observations show that many Caledonian shear zones and rock units with low-shear-strength are overprinted by fabrics formed by extensional top-to-W movements (see recent reviews by Andersen 1998 and Fossen & Dunlap 1998). These fabrics include W-verging folds at various scales, S–C mylonites and extensional top-to-west shear bands accompanied by a NW–SE-trending stretching lineation (Figs 1 & 2). This is in contrast to the well-preserved thrust fabrics including contractional duplexes that are preserved further to the east in the Lower Allochthon, structurally below the Jotun–Valdres nappe complex (Nickelsen 1988).

The Caledonian superstructure in southern Norway is preserved in a NE-trending regional depression traditionally referred to as the 'Faltungsgraben' (Goldschmidt 1912). Fennoscandian basement crops out both to the NW and SE of the regional synformal structure (Fig. 1). The preserved maximum thickness of the nappes in the Jotunheimen area is approximately 10 km (Fig. 2). The nappes are thin and partly removed at the present level of erosion along the SE margin of the depression (see Fig. 2, cross-section). The Fennoscandian basement is exposed in structural windows positioned in the footwall of faults of the Lærdal–Gjende Fault System (Fig. 2). These faults have thus strongly modified the structural geometry in central south Norway, which traditionally is regarded as one of the classical thrust terrains in the Scandinavian Caledonides.

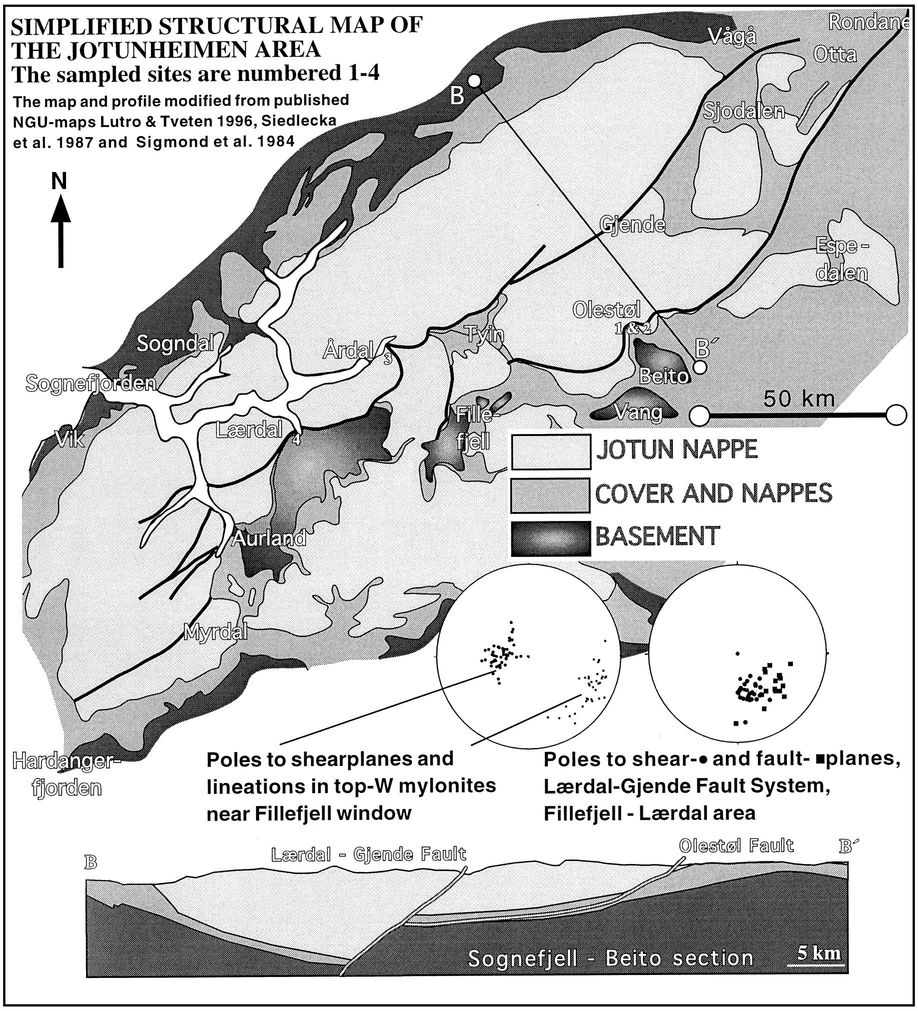

Fig. 2. Structural map and cross-section from the Jotunheimen area based mainly on published maps from NGU (see text and refs.). The map shows the distribution of basement and allochtonous units and the main faults in the Lærdal–Gjende Fault System in central South-Norway. Notice that structural windows of the lower tectono-stratigraphic units are located in the footwalls of the faults. Notice also location of sampled sites 1 to 4.

Lærdal-Gjende Fault System

The Lærdal–Gjende Fault System forms an array of NE–SW-trending fault strands and relay zones with considerable displacement gradients. The system is best defined in the area between the Aurland and Rondane (Fig. 2), but probably continues northeastwards into the Røragen detachment zone (Norton 1987; Andersen 1998). The brittle down-to-the-W normal faulting is particularly well displayed in cross-sections across the study area in Jotunheimen (Fig. 2). The by far most important structure in terms of throw within the study area is the Lærdal-Gjende Fault initially described by Milnes & Koestler (1985). Several faults with similar trends but with smaller displacements have been mapped (Lutro & Tveten 1996); however, little structural detail is yet available from the fault system. One of the faults from which we report new data, the Olestøl Fault, is the south-easternmost fault of the Lærdal–Gjende Fault System. The throw on the Olestøl Fault within the study area is unknown but it is relatively minor in comparison with the Lærdal–Gjende Fault (see cross-sections in Fig. 2). The Lærdal–Gjende Fault System is dominated by normal, down-to-the-W displacement. Local observations of fault-plane striations indicating sinistral strike slip has been made on the Lærdal–Gjende Fault near Lærdal. A detailed kinematic analysis is, however, not the object of the present contribution. Previous studies have suggested that the lineament is continuous into the Hardangerfjorden Shear Zone (Andersen *et al.* 1991). Seismic reflection data clearly show a major structural discontinuity projecting from the Hardangerfjorden area into the southern Horda Platform (Fig. 1), where substantial fault activity of several generations can be documented (see Fig. 5, see also Hurich & Kristoffersen 1988 and Færseth *et al.* 1995).

Footwall uplift on the semi-ductile shear zones to brittle faults is responsible for excision of tectonostratigraphy and exhumation of Fennoscandian basement almost continuously from the Haugalandet near Haugesund to the Folgefonn peninsula on the SE side of Hardangerfjorden (Fig. 1). In the inner Sogn–Valdres area, footwall uplift on faults in the Lærdal–Gjende Fault System, explains the occurrence of tectonic windows that exhume the basement in the Lærdal, Fillefjell and Beito windows (Fig. 2). Windows of late Proterozoic to Palaeozoic metasediments occurring at Tyin, along Sjodalen and north of Espedalen (Fig. 2) are probably also controlled by footwall uplift in extensional shear zones and normal faults at or close to their NW margins. We tentatively suggest that the pronounced structural excision and exhumation of tectonic windows such as the Atnesjø window, shown on published maps (Nilsen & Wolff 1989; Siedlecka *et al.* 1987) are mostly related to footwall uplift on the same system of extensional shear zones and normal faults. The presence of these faults and extensional shear zones have therefore pronounced influence on the geological outcrop pattern along the axis of the Caledonides in central south Norway and probably also further north in the Scandinavian Caledonides (Hurich & Roberts 1997).

Sampling sites

In our pilot study of the fault rocks in the Lærdal–Gjende Fault System we have sampled four sites in well-exposed fault zones adjacent to the Lærdal–Gjende Fault and the Olestøl Fault (Fig. 2). All sites are from faults where previous mapping and reconnaissance have identified major zones of cataclasis, with multiple events of fault-rock formation (Ridley & Hossack 1986; Koestler 1989; Lutro & Tveten 1996; Gathe & Andersen 1996).

Olestøl Fault. The first two sites lie within the Olestøl Fault in Valdres (Figs 1 & 2). This previously unnamed fault was, however, identified as a zone of intense cataclasis and shown in a cross-section by Ridley & Hossack (1986). The strike-continuation can be traced on published maps (Siedlecka *et al.* 1987; Lutro & Tveten 1996) both westwards towards Fillefjell (Fig. 2) and eastwards to Rondane, a distance of some 120 km. The Olestøl Fault juxtaposes higher tectonostratigraphic units, mostly of the Jotun nappe with lower units in its footwall. Ophiolitic rocks of the Upper Allochthon are preserved in the hanging wall of the Olestøl Fault in the Otta area (Sturt *et al.* 1991). The field relationships and petrography of the fault rocks at both sites on the Olestøl Fault give clear evidence of multiple events on the fault. A single discrete main fault plane cannot be easily identified, and fault plane striations are not commonly observed. Systematic kinematic data are not presented here and detailed work is presently underway as a continuation of this study (K. Eig, work in progress).

Sampling site 1 (Fig. 2) is located in the fault zone, below the dam at the eastern end of Olefjorden (UTM-832 967). At this locality, Jotun nappe lithologies are present both in the hanging and footwall, but the footwall only preserves a very thin sliver (20–50 m) of Jotun nappe lithologies. These include orthogneisses of gabbro/amphibolite and syenitic to monzonitic composition (Ridley & Hossack 1986). Samples (J-1 to 19) were drilled across an 8.5 m structural section of the fault zone well exposed in the overflow channel below the dam. The protoliths of samples J-1 (top) to 19 (bottom) include foliated syenitic to monzonitic gneisses (J-1 to 7) and foliated amphibolite (J-8). Ultra-cataclastites and pseudotachylytes with indeterminable protoliths (J-9 to 19) were also sampled. The fault zone is commonly decorated by a network of pseudotachylyte veins. Previous descriptions of pseudotachylytes from the Jotunheimen area (Goldschmidt 1943; Dietrichson 1952) may well have been related to faults of the Lærdal–Gjende Fault System rather than to Caledonian thrusts. Epidote/chlorite veins are common both as small-scale networks and as well-defined, thicker veins. All samples are strongly reworked by semiductile to entirely brittle deformation mechanisms and are proto-catalasites to ultra-catalasites and pseudotachylytes. Recrystallization and recovery in the fault-rocks is negligible. In addition, the samples show variable jointing and brecciation with less cohesive breccia and more penetrative grain-size reduction. This superposed fabric reduced recovery of samples in the field and during preparation for palaeomagnetic measurements.

Sampling site 2 (Fig. 2) is located approximately 0.5 km to the east of site 1, where the fault line makes a marked physiographic feature (UTM-836 968). The fracture system along the 50–60 m thick fault zone shows good examples of outcrop-scale flat-ramp geometry. The samples (J-20 to 38) where collected (drilled) in a section, approximately 60 m along strike, at essentially the same structural level in the fault zone. The protoliths are the same syenitic to mozonitic gneisses as in site 1. The degree of grain size reduction is also similar to site 1, and variably brecciated and sheared pseudotachylytes are very common. Due to tight jointing and partly incohesive breccias related to reactivation of the fault, the recovery of material during sampling and lab-preparation from site 2 was problematic.

The Lærdal–Gjende Fault. This sharply cross-cuts the Caledonian nappes, cover and basement, making a prominent geological and partly physiographic feature (Fig. 3a). The fault can be traced approximately 180 km along strike from Aurlandsfjorden to Gudbrandsdalen where its continuity is, at present, less well-defined (Lutro & Tveten 1996). Between Aurlands- and Hardangerfjorden, the fault zone apparently steps southwestwards in a complex relay zone (Sigmond *et al.* 1984). The dominant displacement is normal, with a vertical separation in the order of 8 km in the inner Lærdal area. Autochthonous rocks in basement windows are exposed at a height of more than 1600 m above sea level (Fig. 2). Similar topographic heights of the Fennoscandian basement rocks along the axis of the Caledonides in Scandinavia are only achieved in the Folgefonn peninsula, in the footwall of the Hardangerfjorden Shear Zone (Fig. 1). A spectacular feature of the Lærdal–Gjende Fault is its thick development of cataclastic rocks, well illustrated on published maps from the Norwegian Geological Survey (Koestler 1989; Lutro & Tveten 1996). The positions of sampling sites 3 and 4 were selected because the displacement on the Lærdal–Gjende Fault here appears to be near its maximum, the outcrops of the fault rocks are excellent and the cross-cutting nature of the fault is obvious.

Sampling site 3 (Figs 2 & 3a) is located at the tunnel entrance (old road) in the fault-line scarp at the SW outcrop of the fault by Årdalsvatn (UTM 336 929). Physiograpically the hanging wall of the fault makes a high near vertical cliff above the fault zone (Fig. 3a). All samples (J-39 to 51) where collected along a 26 m section at essentially the same level of the fault zone. Protoliths of the fault rocks are syenitic to monzonitic gneisses very similar to those described above at Olestøl (site 1 & 2). Intrusive relationships between felsic dykes and the gneisses are spectacularly exposed in the cliffs above the fault (Fig. 3a). The network of intrusive veins and dykes makes a good marker for identification of a number of minor faults in a zone 10–50 m above the main fault. The intensity of cataclasis varies along the main fault zone, hence protolith textures are commonly preserved. Epidote veins in hairline- to thicker veins are very common. Our samples from site 3 are mostly epidote veined proto-cataclasites and cataclasites, some of which are characterized by Fe-oxide staining of preserved K-feldspar grains from the igneous protolith.

Sampling site 4 at the entrance of the tunnel on the old road from Lærdal to Refsnes is probably the most spectacular and complete exposure of the Lærdal–Gjende Fault (Fig. 3b, UTM-168 775). The samples J-52 to 61 were collected in a 6 m structural section in the hanging wall, immediately above the main late fault plane with incohesive fault breccias and gouges (Fig. 3b). The analysed fault rocks are green feldspar-rich breccias to ultra-cataclasites with abundant epidote veins and without obvious recrystallization or annealing textures under the optical microscope. Superimposed on the cohesive fault

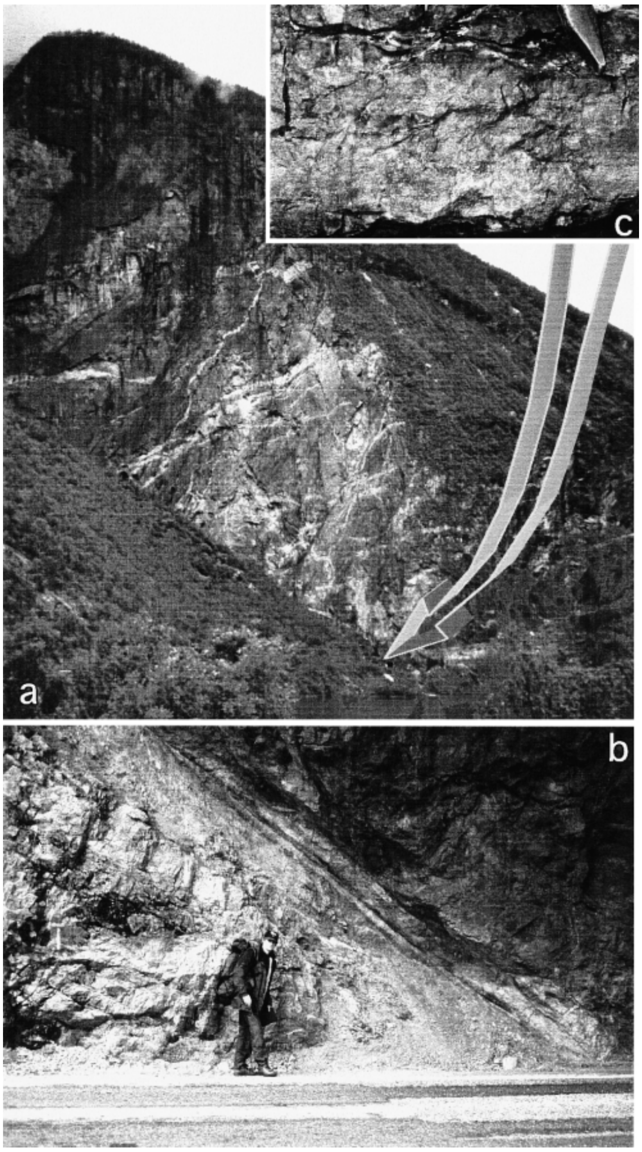

Fig. 3. (**a**) Overview of the Lærdal–Gjende Fault at Årdalsvatn (site 3). Notice that the fault line makes a major topographic feature in the hanging wall of the Jotun Nappe. Gently sloping forested surface to the left is the exposed fault plane and samples were collected at arrowed point near tunnel entrance of the old road. (**b**) Spectacular exposure of Lærdal–Gjende Fault plane with unconsolidated breccia and gouge at Lærdal. Footwall rocks are brecciated mylonites and ultra-mylonites whereas the sampled rocks in the hangingwall (site 4) are orthogneiss breccias. (**c**) Lærdal–Gjende Fault breccias and pseudotachylyte veins along the main fault plane. Hammer head for scale is *c*. 10 cm.

rocks are less cohesive breccias and gouges. Because of their incohesive nature, we do not yet have palaeomagnetic data from the youngest fault rocks decorating the fault plane at this site. The footwall of the Lærdal–Gjende Fault at Lærdal is formed by a 200–300 m thick succession of ultra-mylonites and mylonitic gneisses overlying the mica-schists and the gneisses of the Lærdal window (Gathe & Andersen 1996). The ductile extensional fabrics (top-NW) in the footwall are overprinted by zones of brecciation up to 30 m below the late discrete fault plane. Brecciation in the hanging wall is very common and intense and extends tens of metres above the late fault plane.

Palaeomagnetic measurements and interpretation

The natural remanent magnetization (NRM) was measured with a JR5A spinner magnetometer at the Norwegian Geological Survey laboratory facility in Trondheim. The NRM stability was tested with progressive stepwise thermal demagnetization undertaken in a MMTD60 furnace. Characteristic remanence components were calculated with the least square regression analysis implemented in the SIAPD computer program (for details and download of the program, see http://www.ngu.no/geophysics). Thermal demagnetization experiments commonly revealed a clear-cut multi-component pattern of low-unblocking (LB) temperature components with northerly declinations and steep positive inclinations (347.7/+58.4), followed by identification of reverse polarity SSW directed high unblocking (HB) temperature components with negative inclinations (206.0/ − 33.2, Fig. 4a–c and Table 1).

From sites 1, 2 and 3, the HB component is identified above 425–475°C, 275–475°C and 275–425°C respectively. Maximum unblocking temperatures of 570–580°C suggest almost pure magnetite as the dominant HB temperature remanence carrier. Site 4 is dominated by the LB temperature component. No HB temperatures components were isolated from this site (Fig. 4c); HB components are present, but irregular directional behaviour above 525°C prevented the exact identification.

Distribution of sample and site-mean directions (Fig. 4b–c) from the Lærdal–Gjende Fault System fault rocks demonstrate a simple pattern of normal polarity LB temperature components and reverse polarity HB temperature directions. This magnetic signature is identical to that observed from fault rocks along a reactivated segment of the Nordfjord–Sogn Detachment (Fig. 1) at Atløy of western Norway, shown in Fig. 4d (Torsvik *et al.* 1992). In Fig. 4e, the palaeomagnetic poles of the HB and LB temperature components of the Lærdal–Gjende Fault System are compared with the poles from the fault rocks in western Norway and high-quality palaeomagnetic reference data. The data from the Lærdal–Gjende Fault System plot on the smoth APWP curve for Europe (Fig. 4e; see also Torsvik *et al.* 1997 and Torsvik & Eide 1998). Based on comparison with the APWP, and the palaeomagnetic and radiometric data from the fault rocks in western Norway, we assign ages of mid- to late Permian for the HB temperature component and late Jurassic to early Cretaceous for the LB component respectively. We suggest that the two stages of remanence acquisition were related to important phases of faulting and breccia formation in the Lærdal–Gjende Fault System.

The Permian HB magnetizations are most likely related to brecciation and metasomatism as the breccias are characterized by common epidote veins. The Mesozoic LB components were probably the result of lower temperature thermochemical magnetization (TCRM) of the fault zone. The mode of remanence acquisition and some aspects of demagnetization in fault rocks are discussed in Torsvik *et al.* (1992) and Eide *et al.* (1997).

Summary and conclusions

Recent work in western Norway documents a complex tectonic history following the Caledonian orogeny. Based on a number of integrated studies and using a variety of techniques, the post-Caledonian tectonic phases are well defined and can, in many cases, be directly correlated to offshore structural features and tectonics. Our data from the Lærdal–Gjende Fault

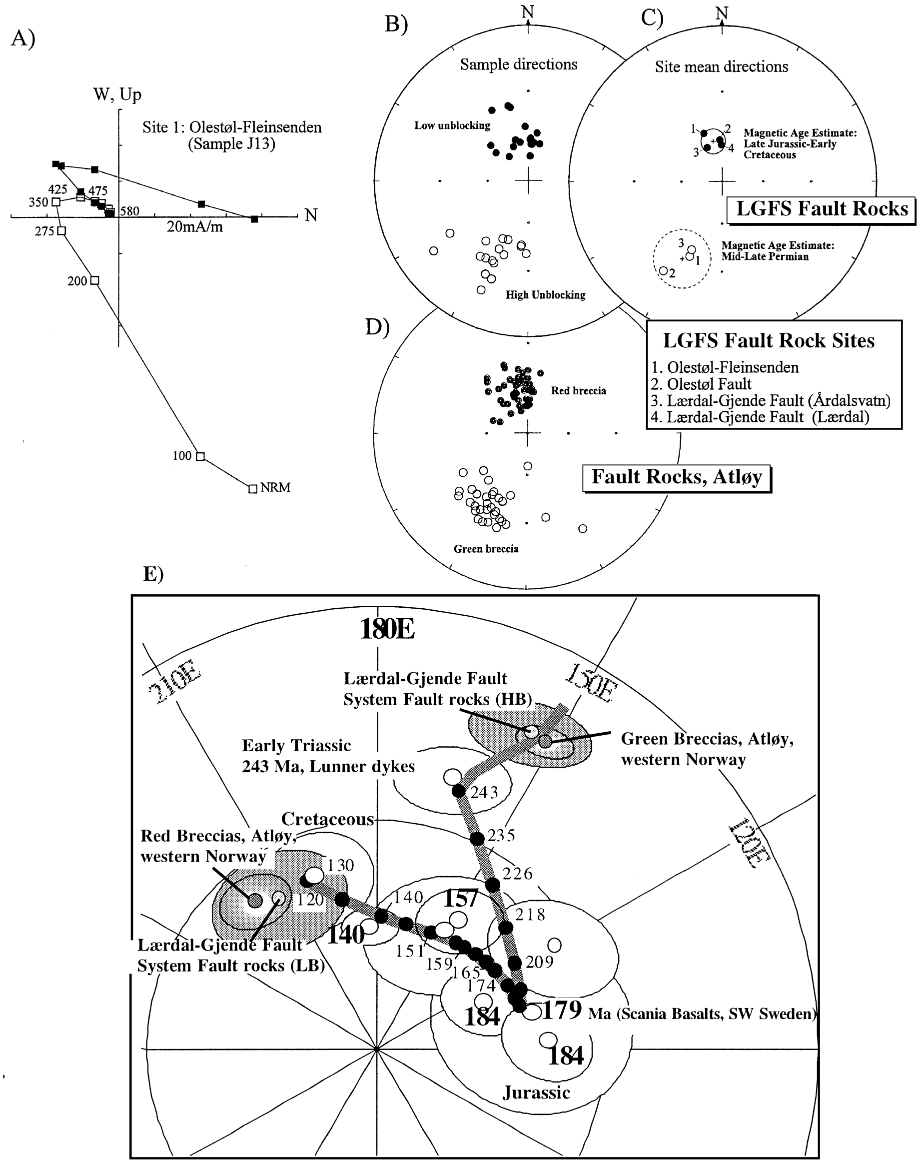

Fig. 4. (**a**) Example of thermal demagnetization of site 1 sample J-13. In the Zijderveld diagram, solid (open) symbols denote projections in the horizontal (vertical) plane. Temperatures in centigrade. (**b**) Equal-area stereographic projection of individual sample directions after thermal demagnetization (characteristic remanence components). (**c**) Equal-area stereographic projection of mean site directions and overall mean directions of low unblocking temperature (LB) and high unblocking temperature (HB) components shown with 95% confidence circles. (**d**) Sample directions obtained from the fault rocks in the Atløy region of western Norway. In stereographic projections, closed (open) symbols denote positive (negative) inclinations respectively. Comparison of the fault rocks from the Lærdal–Gjende Fault System shown in (c), reveals identical magnetization directions for the fault rocks in central south- and western Norway. (**e**) High-quality and well-dated palaeomagnetic north poles (with 95% confidence ellipses) from Scandinavia/stable Europe and a smooth apparent polar wander path (APWP) in million years (solid circles) which has been fitted to the input poles (Torsvik & Eide 1998). Large numbers refer to some selected input poles. Poles from the Atlyø (Torsvik *et al.* 1992) and the Lærdal–Gjende Fault System fault rocks (this study) rocks are shown for comparison with shaded 95% confidence ellipses. Equal area polar projection. The smooth path was calculated with the spline analysis implemented in the GMAP computer program (http://www.ngu.no/geophysics).

System show that these events have affected a much wider region in southern Norway than previously recognized. The following post-Caledonian stages have been documented.

(1) The extensional collapse of the orogen was associated with extreme crustal thinning, exhumation of high-pressure rocks (Andersen 1998) and Devonian sedimentary basins were formed in the hanging walls of low-angle extensional detachments (Osmundsen *et al.* 1998*a*). Large-scale folding of probable mid-Devonian to earliest Carboniferous age affected the entire crustal sequence of western Norway (Torsvik *et al.* 1986; Osmundsen *et al.* 1998*b*). The folding was probably related to orogen-parallel sinistral transtension (Chauvet & Séranne 1994; Krabbendam & Dewey 1998; Osmundsen *et al.* 1998*a*). Offshore structural continuation of the extensional detachments have been suggested previously (cf. Færseth *et al.* 1995; Færseth 1996). Recent work by Osmundsen *et al.* (pers. comm. 1998 and work in progress) shows that offshore counterparts of the detachments and folds mapped in western Norway, had significant control on the structure and basin geometries in the North Sea at approximately 61°N.

Table 1. *Palaeomagnetic results from fault rocks of the Lærdal–Gjende Fault System*

Site	Component	Dec°	Inc°	N	α_{95}°	k
1	P	204.0	− 34.8	12	8.2	28.9
	J–C	338.8	53.2	8	11.2	25.5
2	P	214.0	− 20.9	3	29.2	18.9
	J–C	356.7	60.0	6	11.3	36.1
3	P	204.7	− 38.8	3	13.3	86.4
	J–C	335.8	63.0	1	—	—
4	J–C	359.0	63.5	4	7.8	140.3
Sample means:						
	P	206.0	− 33.2	18	6.7	27.3
	VGP: 42.9°N, 154.3°E, dp/dm = 4.3°/7.6°					
	J–C	347.7	58.4	19	6.0	18.4
	VGP: 66.4°N, 213.2°E, dp/dm = 6.6°/8.9°					

N, Number of samples; Component: P, Permian, J–C, late Jurassic–early Cretaceous; Dec°/Inc°, mean declination/inclination; α_{95}, cone of 95% percent confidence about the mean; VGP, virtual geomagnetic pole; dp/dm, semi-axes of the cone of 95% confidence about the pole.

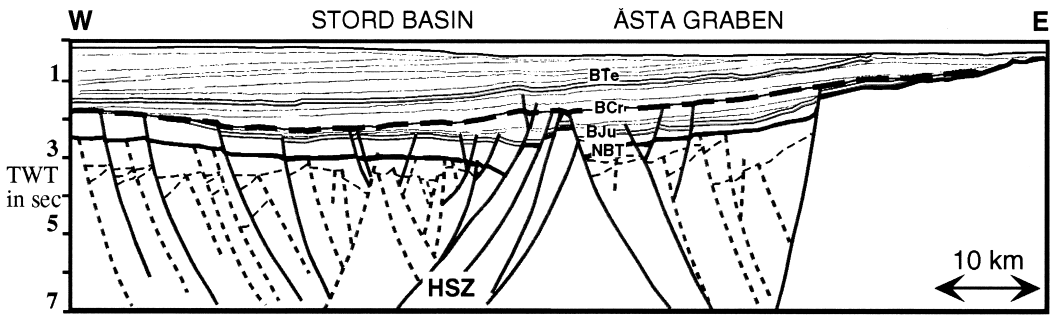

Fig. 5. Interpreted seismic section from the southern Horda Platform, crossing the offshore continuation of the Hardangerfjorden Shear Zone (HSZ) lineament. Line interpretation is redrawn after Ditcha (1998) and shows widespread Permo-Triassic (dotted) and Late Jurassic (solid) faults. Notice also reactivation of main west-dipping fault along the HSZ lineament affecting Cretaceous and Tertiary reflectors. The stratigraphically controlled displacement on faults in the offshore continuation of the HSZ lineament shows a good correlation with the Permian and late Jurassic to early Cretaceous Lærdal–Gjende Fault System-rock magnetization documented in this paper. The late undated breccias and gouges (see Fig. 3b and text) on the Lærdal–Gjende Fault may correlate with Tertiary reactivation seen in the profile. The abbreviations on major reflectors: NBT, Near Base Triassic; BJu, Base Jurassic; BCr, Base Cretaceous; BTe, Base Tertiary.

(2) The Devonian events (see above) were succeeded by rapid cooling ($\geq 15°C\ Ma^{-1}$) in the Early Carboniferous at 360–340 Ma (Eide *et al.* in press). This cooling event has presently only been identified in the coastal areas of western Norway where the syn- to post-depositional folding of the Devonian basins is most intense. Eide *et al.* (in press) suggest that the rapid cooling was related to enhanced erosional unroofing succeeding the important stage of folding.

(3) A very significant stage in formation and rejuvenation of faults in the mainland apparently took place in the late Permian (Torsvik *et al.* 1992, 1997; Eide *et al.* 1997). In this study we show that this event also affected the interior of the mainland southern Norway. The Permo-Triassic phase is a major extensional event forming half grabens in a wide area across the northern North Sea (see Færseth 1996). Recent mapping in the offshore area to the west of the Devonian basin in Solund (Fig. 1) indicates that major low-angle detachment faults, inherited from stage 1 (see above) were substantially reactivated during the Permo-Triassic as well as the Jurassic (Osmundsen *et al.* work in progress). The late Permian to Triassic extension in western Norway was associated with significant magmatic activity (see summary of geochemistry and ages in Torsvik *et al.* 1997). The basaltic to alkaline magmatism in western Norway continued into the Triassic, succeeding the peak-activity of the main Oslo Rift magmatism (Ramberg & Larsen 1978; Sundvoll 1995). In this study we have demonstrated that magnetic remanences of fault breccias along the Lærdal–Gjende Fault System in the central Jotunheimen area (Fig. 4a–d) are identical, within error, to those of Atløy (Torsvik *et al.* 1992). Both areas contain high-unblocking temperature components which plot close to the late Permian pole (250–260 Ma) when compared with the APWP for Europe (Fig. 4e). $^{40}Ar/^{39}Ar$ dating of the Atløy breccia gave ages between 260 and 248 Ma in the late Permian to earliest Triassic (Eide *et al.* 1997). Coincidence of the palaeomagnetic data, supported by radiometric ages from Atløy, is taken as reasonably good evidence that the Permo-Triassic faulting was of regional importance.

The Lærdal–Gjende Fault System is associated with spectacular and continuous zones of intensely deformed fault-rocks, some of which have been discerned as mappable units (Lutro & Tveten 1996). The Lærdal–Gjende Fault System has significant control on the outcrop pattern, particularly the distribution of basement culminations and structural windows in southern Norway (Figs 1 and 2). Translation on the faults in the Lærdal–Gjende Fault System can be correlated with movement on major faults in the North Sea through its continuation along the Hardangerfjorden Shear Zone (Fig. 5). A stratigraphically well-constrained seismic section (Fig. 5) across the continuation of the Hardangerfjorden Shear Zone reveals major Permo-Triassic and Jurassic normal faulting as well as a phase of inversion (Ditcha 1998).

The identification of Permian fault breccias in central south Norway shows that at the dawn of the Mesozoic, a wide region across central parts of northern Pangea was characterized by lithospheric extension. The extension was associated with emplacement of magma in the main rifts and along their shoulders such as along the coast of western Norway. The present work shows that the Precambrian–Caledonian platform in southern Norway, which previously has been regarded as a stable area between the main rift segments (North Sea and Oslo Rifts), was significantly affected by extension.

(4) The final event identified in our study of magnetic remanence of breccias in the Lærdal–Gjende Fault System is a low-blocking temperature (LB) temperature component, which thermochemically overprints the Permian HB temperature component. The LB component is identical, within error, to the late Jurassic pole obtained from breccias of Atløy. The Jurassic rift-event controlling the economically most important system of basins and structures in the North Sea, has previously been recognized in the coastal areas of western Norway and in Møre–Trøndelag (see above and Grønlie & Roberts 1989; Bøe *et al.* 1992). Our data suggest that the Mesozoic rifting event also reactivated faults in central south Norway. This is in accordance with stages of major faulting identified along the Hardangerfjorden Shear Zone lineament offshore (Fig. 5). Younger activity can be identified in the unconsolidated and less-cohesive fault-rocks such as at site 4 (see above Fig. 3b). The age(s) of these events have, however, not yet been determined.

In summary, field relationships of the faults in the Lærdal–Gjende Fault System clearly point to their post-Caledonian origin. The magnetic remanences of the fault-rocks suggest breccia formation of Permo-Triassic and late Jurassic to early Cretaceous age. Such young deformational events have previously not been recognized in central south Norway. These ages correlate with major stages of rifting in north-central Pangaea and can be correlated directly with the main rift events in the North Sea.

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