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 consistency of fault rock data from the Lærdal–Gjende Fault System along the Hardangerfjorden Shear Zone, indicates 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 1987; 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. 1998a), 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. 1998a).

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 ⁴⁰Ar/³⁹Ar 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 nearshore 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 More (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 1992).
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 subsidiary 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 ‘Faltungssgranen’ (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.
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. E. 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-cataclasites and pseudotachylytes with indeterminable protoliths (J-9 to 19) were also sampled. The fault zone 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-cataclasites to ultra-cataclasites 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 physio-
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 Lerdal–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 Lerdal–Gjende Fault System are compared with the poles from the fault rocks in western Norway and high-quality palaeomagnetic data. The data from the Lerdal–Gjende Fault System plot on the smooth 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 Lerdal–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 Lerdal–Gjende Fault...
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. 1998a). 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. 1998b). The folding was probably related to orogen-parallel sinistral transtension (Chauvet & Séranne 1994; Krabbendam & Dewey 1998; Osmundsen et al. 1998a).

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 Lardal–Gjende Fault System

<table>
<thead>
<tr>
<th>Site</th>
<th>Component</th>
<th>Dec°</th>
<th>Inc°</th>
<th>N</th>
<th>α95°</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P</td>
<td>204.0</td>
<td>−34.8</td>
<td>12</td>
<td>8.2</td>
<td>28.9</td>
</tr>
<tr>
<td>2</td>
<td>J–C</td>
<td>338.8</td>
<td>53.2</td>
<td>8</td>
<td>11.2</td>
<td>25.5</td>
</tr>
<tr>
<td>3</td>
<td>J–C</td>
<td>356.7</td>
<td>60.0</td>
<td>6</td>
<td>11.3</td>
<td>36.1</td>
</tr>
<tr>
<td>4</td>
<td>J–C</td>
<td>359.0</td>
<td>63.5</td>
<td>4</td>
<td>7.8</td>
<td>140.3</td>
</tr>
<tr>
<td>Sample means:</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

VGP: 42.9°N, 154.3°E, dp/dm = 4.3°/7.6°

N: Number of samples; Component: P, Permian; J–C, late Jurassic–early Cretaceous; Dec°/Inc°, mean declination/inclination; α95°, 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.
(2) The Devonian events (see above) were succeeded by rapid cooling (≥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 (Fænseth 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 Atøy (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). ⁴⁰Ar/³⁹Ar dating of the Atøy 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 Atøy, 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 Riffs), 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 Atøy. 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-Trondelag (van der Voo 1980; Groenli & Roberts 1989; Boe et al. 1992). Our data suggest that the Mesozoic rift 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 Pangea and can be correlated directly with the main rift events in the North Sea.