Absolute dating of brittle fault movements: Late Permian and late Jurassic extensional fault breccias in western Norway

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ABSTRACT
40Ar/39Ar geochronological and palaeomagnetic dating methods applied to fault breccias in western Norway have isolated two brittle reactivation episodes of the syn-post-Caledonian, extensional Nordfjord-Sogn Detachment. These events, of latest Permian and latest Jurassic–Early Cretaceous ages, demonstrate temporal relationships between development of chemical remanent magnetism and partial resetting of Ar isotopic systems during distinct breccia-forming episodes. A third event of Carboniferous age was also identified in the breccias with the 40Ar/39Ar technique and is a relict unroofing signature inherited from the fault wall-rocks. These brittle faults are significant time markers and become relevant to interpretations of offshore seismic data which attempt to place ages on faults that have undergone multiple reactivation episodes.

Introduction
The potential of fault rocks to delimit the timing of tectonic events has advanced significantly since the quintessential fault-rock classification schemes of Sibson (1977) and Wise et al. (1984). Various isotopic dating methods can be applied to fault rocks to generate absolute ages of fault genesis and have been used with some success on mylonitic rocks in ductile fault zones (Lee, 1991; House and Hodges, 1994) as well as on pseudotachylites (Kelley et al., 1994). Brittle fault rocks, because of their low-temperature nature and associated, ‘open system’ behaviour, are probably more difficult to date accurately with isotopic methods (Gibbons et al., 1996).

We have utilized two different dating techniques to constrain the ages of fault breccia genesis in a reactivated detachment zone in western Norway (Fig. 1). Brittle fault breccias are viable materials for palaeomagnetic determination of the age of a fault-rock matrix that acquired a low-temperature, chemical remanent magnetic (CRM) signature, or the age of breccia clasts from fault wall-rocks that have acquired a partial thermochemical remanent magnetic (TRM) resetting signature (Fig. 2). We have addressed the hypothesis that, with control provided by palaeomagnetic and regional geological data, the 40Ar/39Ar geochronological method can accurately identify ages of fault brecciation in this multiply reactivated fault zone.

The circumstances for dating these brittle fault rocks were ideal as we had excellent tectonostratigraphic control (Osmundsen and Andersen, 1994; Brekke and Solberg, 1987), a shallowly dipping fault breccia, clear cross-cutting relationships between the breccia and the extensional detachment, and K-feldspar-bearing units in both hanging wall and footwall. The rocks were previously dated palaeomagnetically (Torsvik et al., 1992), but the relatively large uncertainties associated palaeomagnetic ages (c. ± 10 Myr) encouraged us to reanalyse this earlier dataset and apply an independent dating technique (40Ar/39Ar) to the same rocks. The data illustrate complementary and supplementary powers of the two techniques when utilized in well-documented tectonostratigraphic settings.

Geological background
The Caledonian history of western Norway involved arc- and continental-collision and high-ultrahigh-pressure (HP-UHP) metamorphism as Baltican crust subducted beneath Laurentia from ≈ 450–410 Ma (Cuthbert et al., 1983; Smith, 1984; Eide and Torsvik, 1997).
Exhumation of deeply buried rocks by extensional collapse was accommodated by vertical shortening/horizontal stretching of the lower crust and large-scale, normal movement on a system of extensional detachments (Andersen and Jamtveit, 1990; Andersen et al., 1991, 1994). Extensional shearing along the main Nordfjord–Sogn Detachment (NSD) is manifested as 2–3 km-thick extensional mylonites that juxtapose ‘Lower Plate’, eclogitic basement and ‘Upper Plate’, allochthonous rocks plus Devonian sedimentary basins (Fig. 1).

The NSD and extensional mylonite are folded (Roberts, 1983) and intersected by brittle faults, the most spectacular of which outcrops on the island of Atløy where a nearly flat-lying, fault-breccia zone cuts the NSD (Figs 1 and 2). The fault-breccia zone comprises a green network breccia and a cross-cutting red breccia. The latter is a 15–35 cm-thick package dipping $\approx 10^\circ$ W and separates hanging wall (HW) from footwall (FW) green network breccias (Fig. 2) (Brekke and Solberg, 1987; Torsvik et al., 1992). The HW green breccia reworked rocks of the Upper Plate Dalsfjord mangerite suite while the FW green breccia reworked both Upper Plate rocks and Lower Plate mylonites.

The nonbrecciated, Upper Plate, Dalsfjord mangerite-syenite contains microperthitic alkali feldspar, white mica, titanite, epidote, magnetite and ilmenite, orthopyroxene altered to chlorite, and minor calcite. The HW, green breccia comprises subangular feldspar clasts surrounded by veinlets with fine, feldspar fragments, chlorite, epidote, titanite, magnetite and fine, layer silicates (Fig. 2). The large clasts have subgrains and partially annealed fractures. The FW and HW green breccia are similar.

The red breccia comprises angular, mm- to cm-sized clasts in a fine-grained, brick-red matrix (Fig. 2). Rock clasts comprise greenish network-breccia fragments, calcite, minor layer silicates and oxides. Feldspar clasts occur either as masses of very fine, equigranular subgrains or coarse, twinned subgrain clusters, reminiscent of green-breccia clasts.

Summary of palaeomagnetic data

The magnetic mineralogies of both HW and FW green breccias comprise mainly magnetite, with accessory haematite and pyrrhotite. The FW breccia is dominated by high-temperature (HT) components with SSW declinations and negative inclinations (Fig. 2). This HT component, assigned a Late Permian age (250 Myr) by Torsvik et al. (1992), is sporadically overprinted by a younger, low-blocking (LB) component with NNW declinations and steep positive inclinations; the LB overprints are more pronounced in the HW than in the FW green breccia. The red-breccia fabric is almost isotropic and has a haematite- and goethite-stained matrix with abundant pyrrhotite and accessory magnetite. NNW declinations with steep positive inclinations prevail (Fig. 2), but along the upper contact of the red breccia we notice a polarity shift; hence, cementation and fluid fluxes in the red breccia appear to cover a reversal of the Earth’s magnetic field. The same LB (dual-polarity) component identified in the...
green breccias is the principal high-blocking (HB) magnetization component in the younger red breccia; this HB component (Fig. 2) was assigned a late Jurassic–Early Cretaceous age (150 Myr) (Torsvik et al., 1992). The stronger influence of LB components in the HW green breccia vs. the FW green breccia is attributed to expulsion of red-breccia fluids into the HW; the fluid infiltration is observed now as red patches in the upper green breccia close to the red-breccia contact. Analytical details, magnetic mineralogy and strain fabrics related to these palaeomagnetic data are presented in Torsvik et al. (1992).

**40Ar/39Ar data**

We used furnace step-heating to analyse a red-breccia whole rock, HW, and FW green-breccia whole rocks, K-feldspar clasts separated from the HW breccia, and white mica and K-feldspar separates from several Upper and Lower Plate units (Figs 1 and 2). Analyses were conducted at the Laboratoire de Géologie, Université Blaise Pascal et CNRS, Clermont-Ferrand, France with a protocol similar to Arnaud et al. (1993). Results and discussion of iso-thermal, cycled heating experiments and diffusion modelling of the K-feldspars will be presented elsewhere (Eide et al. in press). Ages are cited at the 1σ confidence interval, with J-value error. Complete data tables are available from the authors.

**Whole-rock fault-breccia data**

The first two steps of the HW green-breccia spectrum comprise 52.2% of total 39Ar gas and yield apparent ages of 129.5 ± 2.7 Myr and 253.2 ± 4.6 Myr, respectively (Fig. 2). The latter half of the spectrum gives a slightly disturbed group of semiconcordant steps with a weighted age of 296.2 ± 2.6 Ma (8 steps). Eleven steps from the FW green breccia define a pattern of ages which climb rapidly from 96.4 ± 2.5 Myr to a group of semiconcordant steps (steps 4 through 7; 58.4% of total 39Ar gas) with a weighted age of 296.4 ± 2.8 Myr. Ages in the final 25% of the FW breccia spectrum climb rapidly to unrealistically high values (Fig. 2). The red-breccia release spectrum is identical to that of the HW green breccia and is characterized by an imprecise age of 286.6 ± 3.3 Myr in the upper temperature portion of the experiment (48.6% of gas, excluding the last step which comprised only air) and significantly younger first and second steps (122.2 ± 3.0 Myr and 238.3 ± 5.7 Myr) (Fig. 2).

The K/Ca ratios for the green HW and red breccias are similarly characterized by high initial values that drop and then climb in the higher-temperature portions of the experiments. K/Ca values drop again as the samples approach fusion (Fig. 3). The FW breccia exhibits a broadly similar pattern in the high-temperature, high-age steps, with a slightly lower initial K/Ca ratio compared to the other breccias. The CI/K ratios for all three breccias are fairly low and exhibit a gradual increase through the high-age, high-temperature steps (Fig. 3).

Inverse isochron analysis of the red and HW green breccia data was not useful due to their highly radiogenic nature. Isochron analysis of the FW green breccia data clearly indicates excess Ar in the final four, high-temperature steps that yielded anomalously high ages.

**White mica and K-feldspar**

The spectrum for white mica from the Upper Plate Høyvik Group, overlying the mangerite, gives a plateau age of 448 ± 8 Myr (77% of 39Ar released; sample AS2; Figs 1 and 2; Eide et al., 1996). This age is within uncertainty of cooling ages from the same unit on Atloy and several other Upper Plate white micas (Andersen et al., in press). The spectra from isothermal, cycled heating experiments of K-feldspar separates from Upper and Lower Plate rocks (AS1, AS2, AS3, and AS6; Fig. 1) have identical release patterns, albeit with some intersample age differences related to partial, late Permian resetting (Eide et al., 1996; Eide et al. in prep.). An example spectrum (AS3), from immediately above the Atloy Fault defines three domains: a low-temperature domain of rapidly climbing ages (86.5–265.9 Myr), an intermediate-retentivity domain of semiconcordant-to-slightly increasing steps (292.6 ± 2.3 Myr, weighted age), and a high-temperature domain of concordant steps (379.1 ± 9.6 Myr, weighted age) (Fig. 2).

**Discussion of 40Ar/39Ar data**

The whole-rock spectra define three different age groups (ranges A, B and C, Fig. 2) corresponding to separate thermal episodes. Large volumes of Ar gas released in the whole-rock experiments resided in the K-feldspar clasts and distinguished inherited (reflect, wall-rock) and new (brecciation-related) ages. Age range (A) (from ∼287 and 310 Ma) comprises the central group of semiconcordant ages in the FW breccia, the highest temperature portions of the HW green and red breccia spectra, and the intermediate domain in the K-feldspar (AS3). Age range (B) (from 238 to 253 Ma) represents a minimum resetting age and incorporates the second step in each of the red and HW green breccias, the concordant step from the FW breccia, and the downward cusp in the K-feldspar spectrum. Age range (C) (from 96 to 162 Ma) represents a maximum age range for the youngest resetting episode(s).

These three age groups document resetting of <300 Myr old rocks (inherited age A) during one pervasive event older than 253 ± 5 Myr (the maximum of range B, Fig. 2). A less thorough resetting event, or events, occurred in sub-late-Jurassic times (range C, Fig. 2). The ages within (C) are indicative of partial Ar loss during at least two events: one more recent than 96 ± 3 Ma (perhaps associated with genesis of clay-rich fault gouge; see Fig. 2) and one event at least younger than 238 Ma and, most likely, younger than 163 ± 4 Ma (the maximum limit of range C). The latter event can be linked to the younger of two palaeomagnetic ages and probably dates the genesis of the red breccia (see ‘Data comparison’).
The higher, relative initial K/Ca ratios and low apparent ages in the first step of each whole-rock spectrum are attributable to outgassing of high-K phases with low Ar retentivity (Figs 2 and 3). The likely sources are fine-grained layer silicates in the rock matrices and low-retentivity, fine-grained portions of the K-feldspar clasts with some Cl-contribution from matrix chlorite. Genesis of the low-temperature layer silicates is linked to partial replacement of K-feldspar breccia clasts by quartz via the reaction:

$$6KAlSi3O8 + 4H2O = 12SiO2 + K2Al4(Si6Al2O20)[OH]4 + 4KOH.$$ 

Thermal and diffusion modelling of the cycled, isothermal K-feldspar heating experiments from Upper and Lower Plates suggests that the Late Carboniferous age ($\approx 287–310$ Ma) of range (B) represents partial resetting of an early Carboniferous (350 Ma), rapid cooling event (Eide et al., 1996). The high-retentivity portion ($\approx 379$ Ma) of the single-grain, K-feldspar experiment (Fig. 2) is neither present in the whole-rock experimental data nor in an analysed separate of K-feldspar HW clasts; the HT feldspar domain was destroyed during younger, grain-size reduction/brecciation events.

**Data comparison and synopsis**

Figure 4 synthesizes the $^{40}$Ar/$^{39}$Ar and palaeomagnetic fault-rock ages in the context of an annotated Mid-Palaeozoic to Cretaceous apparent polar wander path (APWP) for Baltica/Europe. Group (B), whole-rock $^{40}$Ar/$^{39}$Ar ages corroborate Late Permian, green-brecchia palaeomagnetic ages of Torsvik et al. (1992) and fit closely to the APWP age of 260 Myr. The Late Permian palaeomagnetic age is interpreted as the time of CRM remanence acquisition during green-brecchia formation at temperatures $< 250$ °C (Torsvik et al., 1992) (Figs 2 and 4); the group (B) $^{40}$Ar/$^{39}$Ar data document a strong resetting event older than 253 ± 5 Ma. The green-brecchia forming event is thus constrained between $\approx 248$ and 260 Ma. Regionally, extension-related dykes in western and southwestern Norway overlap in time with green brecchia formation (Fig. 4; see also Torsvik et al., in press).

Similarly, the palaeomagnetic data from the red breccia fall near the 98–144 Ma pole for Europe and overlap with data from extension-related dykes (Hinlopen) from Svalbard (Fig. 4). Torsvik et al. (1992) suggested the red-brecchia data documented genesis of a late Jurassic, HB component, related to CRM acquisition during low-temperature haematite precipitation and red-brecchia formation. Confidence in the red-brecchia palaeomagnetic pole position is imparted by the dual-polarity nature of the HB component in the rock (LB component in the green breccia). The Group (C), whole-rock $^{40}$Ar/$^{39}$Ar data constrain red-brecchia genesis to be more recent than 162 Ma, with unique definition of the red-brecchia phase complicated by fault-gouge genesis after 96 Ma. The late Jurassic–Early Cretaceous age for red-brecchia formation is likewise coincident with regional rifting and basin formation in the northern North Sea (Torsvik et al., 1992; Færseth, 1996).

The fact that the HB component is only weakly developed in the HW green breccia (extracted as the LB component from the rock; see Fig. 2), and is nearly undeveloped in the FW green breccia, is due to the nearly horizontal orientation of the Dalsfjord Fault: warm fluids flowing through a fracture with this orientation would probably have percolated preferentially upwards, leaving very little haematite precipitate in the FW breccia. This implies that the Dalsfjord Fault orientation has not changed (rotated) significantly since the Early Cretaceous and again, reinforces the position of the red-breccia pole in Fig. 4.

Of the two brittle faulting events, the latest Permian, green-brecchia-forming episode was dominant. The magnetic component is unblocked only at high temperatures in both HW and FWs, and the most dramatic impact on the Ar-systematics of the whole-rock systems was effected during the green-breciation activity. The magnitude of this latest Permian event takes on regional significance not only from broad inferences to early rifting events along the Baltica–Laurentia suture (e.g. Færseth, 1996), but even more directly from the numerous Late Permian mafic dykes exposed along the coast of western Norway (Fig. 4; Torsvik et al., in press). The common denominator in the brittle fault activity was infiltration of low-temperature fluids and cataclastic activity, manifested both as CRM signatures and Ar-resetting ages. We cannot state with absolute certainty that the Ar ages accurately date the time of CRM acquisition, given the fact that these two age-dating techniques are dependent upon very different properties of mineral systems; however, we emphasize that the palaeomagnetic and Ar data are remarkably consistent with one another and also with constraints provided by regional geology.
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