We use 3D seismic data to image a series of enigmatic, SW-dipping reflection packets within pre-Mesozoic crystalline basement offshore western Norway. Based on their low-angle dip and complex reflection wave-train our preferred interpretation is that the reflection packets are the seismic expression of mylonitic zones generated by nappe emplacement during the Caledonian orogeny. Late Jurassic faults truncate and offset these reflection packets by several hundred metres, suggesting that these faults did not exploit pre-existing basement weaknesses. Our observations suggest that older basement fabrics may not always play a significant role in determining the geometry of later fault systems.

Supplementary materials: Details of the time-depth relationships from wells that have been used to depth-convert interpretations (S1), a supplementary figure showing an uninterpreted version of the seismic profile presented in Fig. 2 (S2) and a throw v. distance plot for fault F1 at the structural levels of the basement reflection and intra-basement reflection 1 are available at www.geolsoc.org.uk/SUP18683.

The reactivation of basement fabrics can control the location and structure of rifts, even when the extension direction is at a comparatively high angle to the primary basement structural trends (e.g. Morley 1995). In many cases, thrust faults, which are associated with earlier periods of contraction, are reactivated as normal faults during subsequent extension; the geometry and size of the associated rift basins are, therefore, at least partly determined by the geometry of the precursor thrust array (e.g. Bartholomew et al. 1993; Doré et al. 1997).

Several researchers have suggested that this style of reactivation occurred along the NE margin of the North Sea (Fig. 1a) during Devonian, Permian–Triassic, Jurassic and Cretaceous rifting (Bartholomew et al. 1993; Ferseth et al. 1995; Doré et al. 1997). Convergence of Laurentia and Baltica during the Caledonian orogeny resulted in the formation of a range of predominantly contractual structures, such as low-angle thrusts and folds (Gee et al. 2008). The structures associated with this major tectonic event are particularly well developed in onshore Norway (e.g. Andersen et al. 1990), although the offshore continuation of these structures, beneath the North Sea Basin, and their relationship to extensional structures associated with Permo-Triassic and Late Jurassic rifting, has been debated (e.g. Doré et al. 1997). This uncertainty reflects the fact that pre-Mesozoic basement rocks are typically buried beneath a thick sedimentary cover and are, therefore, poorly imaged on seismic reflection or potential field data (Fichler & Hospers 1990; Platt & Cartwright 1998). Very few seismic reflection-based studies have identified and mapped, in three dimensions, intra-basement reflections at shallow depths, although the work of Hedin et al. (2012), which was based on 2D seismic reflection data only, highlighted the insights that can be gained from these geophysical tools. In this study we use high-resolution 3D seismic reflection data to image a series of enigmatic reflections within pre-Mesozoic, crystalline basement beneath the Måløy Slope, offshore western Norway (Fig. 1b). Relatively shallow burial of the basement, combined with a relatively thin (<2.5 km), stratigraphically simple sedimentary cover, means that intra-basement structures are well imaged and allow, for the first time, direct 3D analysis of the interaction between Late Jurassic faults and structures in underlying crystalline basement.

Geological setting. The Måløy Slope is located along the NE margin of the North Viking Graben and is underlain by crystalline basement that is penetrated by four boreholes (Fig. 1b; Slagstad et al. 2008). Boreholes 35/9-2 and 36/7-1 penetrate schistose basement (Basset, 2003), whereas borehole 36/1-1 penetrates foliated, granitic gneiss (Fig. 1a and b; Johnston et al. 2007). Onshore, gneisses that have experienced Caledonian-age eclogite-facies metamorphism in the Western Gneiss region are overlain by a series of Caledonian-age nappes, which are interpreted in some cases as having been transported up to 300 km (Fig. 1a; Andersen 1998; Gee et al. 2008). Nappe emplacement occurred during the collision of Baltic and Laurentia, and progressively more distal components were emplaced at structurally higher levels within the nappe stack; the complex composition of these nappe stacks reflects the varied composition of the deformed rift margins (Fossen & Rykkveld 1992; Osmundsen & Andersen 1994; Gee et al. 2008). Kinematic indicators within Caledonian rocks in southern Norway yield a dominantly SE direction for initial nappe translation (Fossen 1992).

After the Caledonian orogeny, the nappe stack experienced Devonian extensional deformation, which resulted in reactivation of basal thrusts as low-angle, normal faults (e.g. ‘backsloping’ or ‘extensional collapse’; e.g. Fossen 1992; Fossen & Rykkveld 1992; Andersen 1998), in addition to the development of low-angle, normal-sense shear zones, such as the Nordfjord–Sogn detachment (e.g. Johnston et al. 2007; Vetti & Fossen 2012; Fig. 1). Shearing and the development of mylonite zones accompanied this phase of extensional faulting (Roberts & Sturt 1980). The cumulative effects of these tectonic events imparted a Caledonian ‘grain’ to onshore and offshore Norway, which may have subsequently influenced later structural trends (Doré et al. 1997).

Well data indicate that Palaeozoic sediments are absent on the Måløy Slope area and Early Jurassic rocks directly overlie basement (Fig. 2). The absence of Permo-Triassic strata suggests that the Måløy Slope did not experience significant extension during the Permo-Triassic rift phase, in contrast to the Horda Platform area to the south (e.g. Roberts et al. 1995).

Data and methods. We use a zero-phase, pre-stack time-migrated 3D seismic reflection dataset that covers 1200 km². The dataset has an inline and crossline spacing of 12.5 m and a vertical record length of 5000 ms two-way time (ms TWT). The seismic data are displayed with SEG reverse polarity; that is, a negative
or trough event corresponds to a red reflection on seismic profiles and reflects a downward increase in acoustic impedance. No direct velocity information was available for the pre-Mesozoic crystalline basement, thus an interval velocity of 6000 m s⁻¹, which we consider to be appropriate for gneissic crystalline basement, was used to constrain the depth and dip of the intra-basement reflections (Goff & Holliger 1999). Within crystalline basement the dominant frequency is c. 15 Hz, suggesting that these seismic data have a vertical resolution of c. 100 m in the interval of interest. The age of strata in the Mesozoic to Cenozoic sedimentary cover is constrained by four boreholes, all of which penetrate the pre-Mesozoic crystalline basement (see above, Fig. 1b). Checkshot data from these wells were used to convert measurements in ms TWT to metres.

**Intra-basement reflections.** Crystalline basement beneath the Måløy Slope is generally characterized by relatively low-amplitude, chaotic reflections (Figs 2 and 3a). Locally, however, three laterally continuous, mappable packets of high-amplitude reflections are identified within the upper 4 km of the crystalline basement; these packets consist of a peak–trough–peak–trough–peak wave-train with a duration of 0.2 s (Figs 2 and 3b–d). The lowermost reflection packet is the most areally extensive (c. 83 km²) and is observed between depths of 2.6 and 6.4 km (intra-basement reflection packet 1; Figs 2a, b and 3b). To the NE, the reflection packet terminates or is truncated at top basement, at a depth of c. 2.6 km (Figs 2a and 3b). The reflection packet dips to the south–SSW or west (Fig. 3b), and dips range from 15° in the south to 25° in the north. The middle reflection packet is the most poorly imaged and covers c. 11 km² (intra-basement reflection packet 2; Figs 2 and 3c). It dips relatively steeply (30–45°) and consistently to the west, terminates against the top basement at a depth of 2.7 km, and is observed down to a depth of 5 km (Fig. 2a and b). Intra-basement reflection packet 2 potentially links to the intra-basement reflection packet 1 downdip towards the NW (Fig. 2c). The upper reflection packet covers 20 km² and terminates toward the north against top basement at a depth of 2.8 km (intra-basement reflection packet 3; Fig. 2b) and is observed down to 4.5 km depth (Fig. 3d). The reflection packet dips 25–30°, predominantly towards the SW (Fig. 2). The western part of the intra-basement reflection packet 3 dips towards the west; the dip in this area is shallower (<10°) than elsewhere (Fig. 3d).

**Relationship between Late Jurassic faults and intra-basement reflections.** A 29 km long, north–south–to NNE–SSW-striking, steeply (60°) west-dipping, normal fault system is developed on the eastern part of the Måløy Slope (Figs 1b and 2). F1 is composed of two main segments, which are physically linked along the central part of the fault system and which tip out upward in the Upper Jurassic interval (Fig. 2a and b). After depth conversion, the fault segments are broadly planar within the Mesozoic sedimentary cover and the underlying crystalline basement (Fig. 2a and b). It should be noted that the fault system offsets both the top Middle Jurassic and
top basement horizons, in addition to the intra-basement reflection packet 1; the fault system has the same strike and dip direction at all structural levels (Fig. 2b).

To investigate the evolution of this fault system, throw–distance (T–x) plots were constructed for the top basement reflection and intra-basement reflection packet 1 by measuring throw on a succession of fault-perpendicular seismic lines spaced every 250 m along an 8 km length of the fault system (see supplementary material). Our analysis indicates that, at top basement level, maximum throw of 300 m is developed 8 km along the fault; two local maxima of c. 300 m are also developed 4.75 and 6.0 km along the fault. These two throw maxima are separated by a local throw minimum in the area of fault overlap and linkage; this throw minimum is c. 100 m less than the values (i.e. >200 m) observed on the adjacent fault segments. A key observation is that there is a strong correspondence between the overall pattern of throw observed at the structural level of the top basement and intra-basement reflection packet 1. At the intra-basement reflection packet 1 level two discrete throw maxima are observed; the first (c. 520 m) is developed 3–4 km and the second (c. 650 m) is developed 8 km along the fault; these maxima spatially correspond to those observed at the top basement level.

Although intra-basement reflection packet 1 is offset by F1, other Mesozoic faults appear to potentially link with the steeper intra-basement reflection packet 2 (Fig. 2a). In other areas, however, intra-basement reflection packet 2 also appears to be truncated by Mesozoic faults (Fig. 2c).

**Interpretation and discussion.** The geometry and extent of the intra-basement reflection packets does not mimic any shallower reflections (i.e. seabed, top crystalline basement, etc.; compare Fig. 3a with b, c and d), implying that they do not represent multiples generated by major acoustic boundaries in the overburden; we therefore interpret that they represent rock volumes that define some lithological or structural discontinuity within crystalline basement.

Based on the fact that the intra-basement reflections are observed within demonstrable crystalline basement, and by consideration of the structure, composition and geological history of onshore western Norway, our preferred interpretation is that the reflection packets are the seismic expression of mylonite zones. These zones may have been initially generated by nappe emplacement during the Caledonian orogeny; subsequent to this, they may or may not have been reactivated as extensional faults during Devonian extension. An alternative interpretation is that these structures represent low-angle, normal-sense shear zones that developed in the Devonian, such as the Nordfjord–Sogn detachment (e.g. Johnston et al. 2007). Fountain et al. (1984) indicated that mylonite zones can be seismically imaged within unmylonitized bodies of crystalline rock owing to their distinct composition and orientation of their constituent minerals. Although the acoustic impedance contrast between mylonitized and unmylonitized bodies may be small, reflections from the top and base of thin mylonitized zones can be amplified by constructive interference. To test this hypothesis we generate normal-incidence synthetic seismograms by convolving a 15 Hz Ricker wavelet with various mylonite zone geometries, assuming a negative reflection coefficient at the top of the mylonite zone and a positive reflection coefficient at the base. The 0.2 s duration multicyclical nature of the intra-basement reflection wave-trains can be reproduced by the presence of two 90 m thick mylonite zones separated by c. 150 m of unmylonitized rock, although we note that this solution in non-unique (Fig. 2e). In this simple experiment no attempt has been made to model absolute amplitude and we have assumed that there has been no attenuation of the input wavelet with depth (see Fountain et al. 1984). These potential c. 90 m thick mylonitized zones are similar in scale to those reported for some areas of the Moine Thrust, Scotland (e.g. Holdsworth et al. 2006) and the Linville Falls Fault, USA (Newman & Mitra 1993), and the scale of the complex, multilayered mylonite geometry is similar to that of Lewisian mylonite zones (Fountain et al. 1984). The lack of imaging of the reflection packets towards the north, in locations where their absence cannot be attributed to truncation at top basement level, may correspond to a decrease in the thickness of the mylonite zones, such that they fall below the vertical resolution of the seismic data.

Although the general SW dip direction of the reflection packets does not directly correspond to the suspected SE transport direction of the Caledonian nappes (Fossen 1992), studies onshore Norway, at the latitude of the Måløy Slope, have shown that the
region experienced significant NE–SW to north–south shortening in the Late Devonian to earliest Carboniferous, which resulted in the formation of NW–SE- and east–west-trending, Western Gneisscored anticlines and synclines that preserve Devonian sediments and Caledonian terranes (e.g. Torsvik et al. 1986; Osmundsen & Andersen 2001; Fig. 1). The intra-basement reflection packets identified in this study are at a similar latitude to the southward-dipping limb of the Solund Basin syncline, and are due west of the island of Værlandet, where the unconformity between Caledonian nappes and Devonian sediments dips 40° to the south owing to later folding (Osmundsen & Andersen 2001). If this fold extends directly offshore, the Måloy Slope study area would be located on this south-dipping limb, which may account for the southward dip of the intra-basement reflection packets that we interpret as Caledonian mylonite zones. We suggest that the intra-basement reflections lie in the hanging wall of the Nordfjord–Sogn detachment, within the allochthonous Caledonian sequence.

Our second key observation is the discrepancy between the strike and dip of the intra-basin Caledonide (or Devonian) structures and the Late Jurassic faults (Fig. 3), with the former clearly offset, by several hundred metres, across the latter. This observation suggests that the Late Jurassic faults did not simply exploit pre-existing basement weaknesses (Morley 1995), but that east–west-oriented Late Jurassic extension resulted in the formation of new, north–south-striking fault systems that were oriented perpendicular to the extension direction (Færseth et al. 1995). In this case it appears that the Caledonian or Devonian fabric has not played a significant role in determining the geometry of the later Mesozoic normal fault systems or therefore the associated rift basin.

For the first time, mylonite zones beneath northern North Sea Mesozoic sedimentary basins have been mapped in three dimensions, revealing that, at least at this location and structural level, Mesozoic faults have truncated these zones rather than exploiting them as structural weaknesses. This study has highlighted the importance of 3D seismic data as a tool to investigate upper crustal structure and its interaction with later faulting in regions of relatively shallow basement and thin sedimentary cover. The detailed observations that we make between basement fabric and later rift-structure and its interaction with later faulting in regions of relative importance of 3D seismic data as a tool to investigate upper crustal structures or therefore the associated rift basin.

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