Journal of the Geological Society, London. doi: 10.1144/jgs2012-067
Published *Online First*

Cenozoic reactivation of the Great Glen Fault, Scotland: additional evidence and possible causes

E. LE BRETON[1,2]*, P. R. COBBOLD[1] & A. ZANELLA[1]

[1]*Géosciences Rennes, Université de Rennes 1, CNRS, 263 Avenue du Général Leclerc, 35042 Rennes, France*

[2]*Present address: Department of Earth Sciences, Freie Universität Berlin, Malteserstr. 74–100, 12249 Berlin, Germany*

**Corresponding author (e-mail: eline.lebreton@fu-berlin.de)*

Abstract: The Great Glen Fault trends NNE–SSW across northern Scotland. According to previous studies, the Great Glen Fault developed as a left-lateral strike-slip fault during the Caledonian Orogeny (Ordovician to Early Devonian). However, it then reactivated right-laterally in the Tertiary. We discuss additional evidence for this later phase. At Eathie and Shandwick, minor folds and faults in fossiliferous Jurassic marine strata indicate post-depositional right-lateral slip. In Jurassic shale, we have found bedding-parallel calcite veins ('beef' and 'cone-in-cone') that may provide evidence for overpressure development and maturation of organic matter at significant depth. Thus, the Jurassic strata at Eathie and Shandwick accumulated deeper offshore in the Moray Firth and were subject to Cenozoic exhumation during right-lateral displacement along the Great Glen Fault, as suggested by previous researchers. Differential sea-floor spreading along the NE Atlantic ridge system generated left-lateral transpressional displacements along the Faroe Fracture Zone from the Early Eocene to the Late Oligocene (*c.* 47–26 Ma), a period of uplift and exhumation in Scotland. We suggest that such differential spreading was responsible for reactivation of the Great Glen Fault. Indeed, left-lateral slip along the Faroe Fracture Zone is compatible with right-lateral reactivation of the Great Glen Fault.

Scotland lies between the NE Atlantic Ocean to the west and north, and the North Sea to the east (Fig. 1). The Great Glen Fault is a major Caledonian tectonic structure that trends NNE–SSW across all of northern Scotland. This strike-slip fault developed left-laterally during the Caledonian Orogeny, in Ordovician to Early Devonian times (e.g. Hutton & McErlean 1991; Soper *et al*. 1992; Stewart *et al*. 2000, 2001; Mendum & Noble 2010). However, previous studies of seismic data from the Inner Moray Firth Basin, Mesozoic strata onshore NE Scotland and Tertiary dyke-swarms in NW Scotland all indicate right-lateral reactivation of the Great Glen Fault during the Cenozoic (e.g. Holgate 1969; Thomson & Underhill 1993; Underhill & Brodie 1993; Thomson & Hillis 1995). The exact timing and the causes of this reactivation are still uncertain.

Underhill & Brodie (1993) showed that the Inner Moray Firth underwent regional uplift during the Cenozoic. This they attributed to reactivation of the Great Glen Fault. More widely, analyses of sonic velocities, vitrinite reflectance and apatite fission tracks have revealed exhumation and uplift of Scotland during the Cenozoic (e.g. Thomson & Underhill 1993; Underhill & Brodie 1993; Hillis *et al*. 1994; Thomson & Hillis 1995; Clift *et al*. 1998; Jolivet 2007; Holford *et al*. 2009, 2010). In the Early Palaeogene, significant uplift occurred. This may have been due to the Iceland mantle plume or part of the North Atlantic Igneous Province (e.g. Brodie & White 1994; Clift *et al*. 1998; Jones *et al*. 2002). However, Cenozoic uplift of Scotland appears to have been episodic from 65 to 60 Ma, 40 to 25 Ma and 15 to 10 Ma (e.g. Holford *et al*. 2009, 2010). Holford *et al*. (2010) suggested that the various episodes of uplift were due to intraplate stress from the Alpine Orogeny and plate reorganization in the NE Atlantic. Thomson & Underhill (1993) and Thomson & Hillis (1995) attributed uplift of the Inner Moray Firth to Alpine and NE Atlantic events. More recently, Le Breton *et al*. (2012) have shown that variations in the amount and direction of sea-floor spreading, along and between the ridge systems of the NE Atlantic, generated relative displacements along major oceanic fracture zones, the Faroe Fracture Zone, between the Reykjanes and Aegir ridges, and the Jan Mayen Fracture Zone, between the Aegir and Mohns ridges. Le Breton *et al*. (2012) have suggested that this differential sea-floor spreading was responsible for post-breakup compressional deformation of the NW European continental margin.

On this basis, the four main possible causes of reactivation of the Great Glen Fault and Cenozoic uplift of Scotland are (1) mantle processes around the Iceland mantle plume, (2) intraplate compression from the Alpine Orogeny, (3) ridge push from the NE Atlantic and (4) variation in the amount and rate of sea-floor spreading and plate reorganization in the NE Atlantic. In this paper, we investigate the fourth hypothesis. To this purpose, we describe some field observations of Jurassic outcrops in NE Scotland and we discuss possible causes and timing of reactivation of the Great Glen Fault.

Geological setting

Onshore rocks of Scotland

Rocks in Scotland have formed over a time span of billions of years. Various orogenies have been responsible for a wide variety of rock types (Fig. 1; Stone 2007). The oldest rocks of Europe (*c.* 3 Ga), the Lewisian gneiss, are visible in the Hebrides Islands, NW Scotland, whereas, on the mainland along the NW coast, they lie beneath the Neoproterozoic sedimentary strata of the Torridonian Sandstone (*c.* 1 Ga). The Moine Thrust is a major fault that separates the Lewisian gneiss and Torridonian Sandstone, to the west, from Neoproterozoic metamorphic rocks of the Moine Supergroup, to the east. In NE Scotland, the Moine Supergroup lies under the Devonian Old Red Sandstone, famous for its fossil fish (Miller 1851). Further south, from Fort William to Inverness, the Great Glen Fault separates the Moine Supergroup from the Dalradian Supergroup. The latter mostly consists of Neoproterozoic metamorphic rocks and late Caledonian magmatic

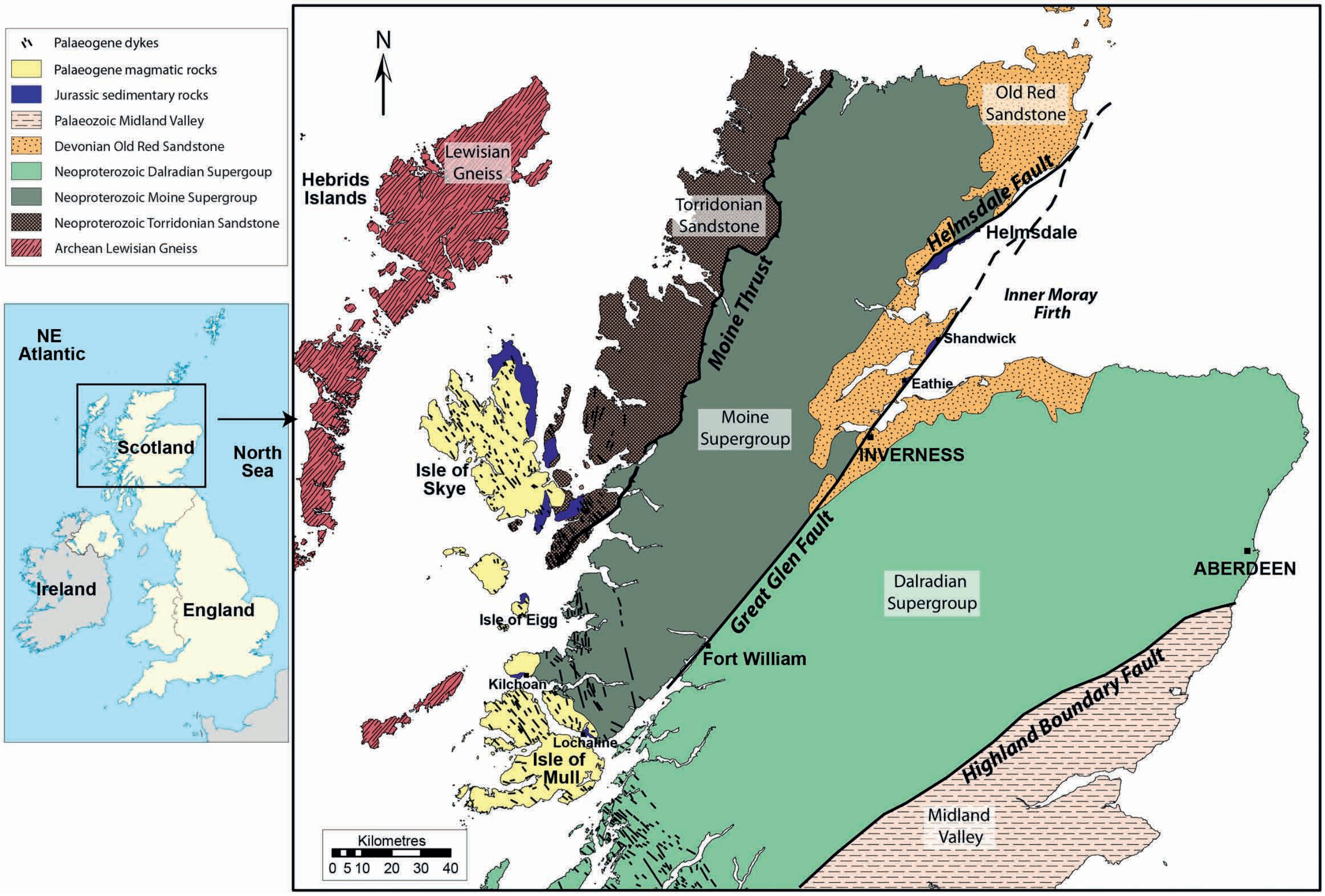

Fig. 1. Simplified geological map of northern Scotland (modified after Stone 2007).

intrusions (Silurian–Devonian). South of the Highland Boundary Fault, the Midland Valley is a rift valley containing mostly Palaeozoic strata. The Moine Thrust, the Great Glen Fault and the Highland Boundary Fault are major tectonic structures, which developed during the Caledonian Orogeny (Ordovician to Early Devonian), during closure of the Iapetus Ocean and continental collision of Laurentia, Baltica and Avalonia (Soper *et al*. 1992).

Mesozoic strata, mostly Jurassic, crop out along the NW and NE coasts. On the NW coast, they occur at Kilchoan, Lochaline and more widely across the Inner Hebrides; on the NE coast, they occur at the mouth of the Inner Moray Firth and along the Helmsdale Fault (Fig. 1). At Eathie and Shandwick, minor faults, trending NE–SW along the Great Glen Fault, put Jurassic strata against Old Red Sandstone or Neoproterozoic basement (Judd 1873; Holgate 1969; Underhill & Brodie 1993). From fossil evidence, the strata are Kimmeridgian at Eathie and Bathonian to Middle Oxfordian at Shandwick (Judd 1873; Sykes 1975; Wright & Cox 2001). In the Golspie–Helmsdale area, Triassic to Late Jurassic strata are more widespread (Stone 2007; Trewin & Hurst 2009). The Helmsdale Fault separates them from Neoproterozoic basement or the Late Caledonian Helmsdale Granite, to the west. The Late Jurassic 'Boulder Beds' accumulated in deep water in the footwall of the Helmsdale Fault, at a time when that fault was active (Roberts 1989; Trewin & Hurst 2009).

Intense volcanic activity occurred along the NE Atlantic margins, during continental breakup in early Palaeogene time, and resulted in the development of the North Atlantic Igneous Province (Saunders *et al*. 1997). In NW Scotland, this volcanic event was responsible for the development of large gabbroic intrusive centres (e.g. the islands of Skye and Mull), as well as widespread lava flows and dyke swarms (Fig. 1). Several researchers have suggested that the Iceland mantle plume was responsible for this widespread magmatic activity (e.g. White & McKenzie 1989; Saunders *et al*. 1997).

During the Plio-Pleistocene, glaciation produced U-shaped valleys, such as the Great Glen, and various firths. After the last glacial maximum (*c*. 18 kyr ago), isostatic readjustment produced Quaternary raised beaches. Indeed, the readjustment may still be continuing (Firth & Stewart 2000).

Offshore rocks of NE Scotland

The Mesozoic Inner Moray Firth Basin is a western arm of the North Sea rift (Fig. 2; Underhill 1991*a*; Evans *et al*. 2003). Numerous seismic surveys have provided good insights into the structural development of the Inner Moray Firth and the northeastern end of the Great Glen Fault (Fig. 2; Thomson & Underhill 1993; Underhill & Brodie 1993; Thomson & Hills 1995). Three major faults shaped the basin: the Wick Fault at its northern edge, the Banff Fault to the south and the Helmsdale Fault to the west (Fig. 2). During Late Jurassic rifting, fault blocks formed and tilted (Underhill 1991*a*). However, from interpretation of seismic data, well cores and outcrop data, the overall structure of the basin was that of a half-graben, the depocentre being proximal to the Helmsdale Fault (Thomson & Underhill 1993).

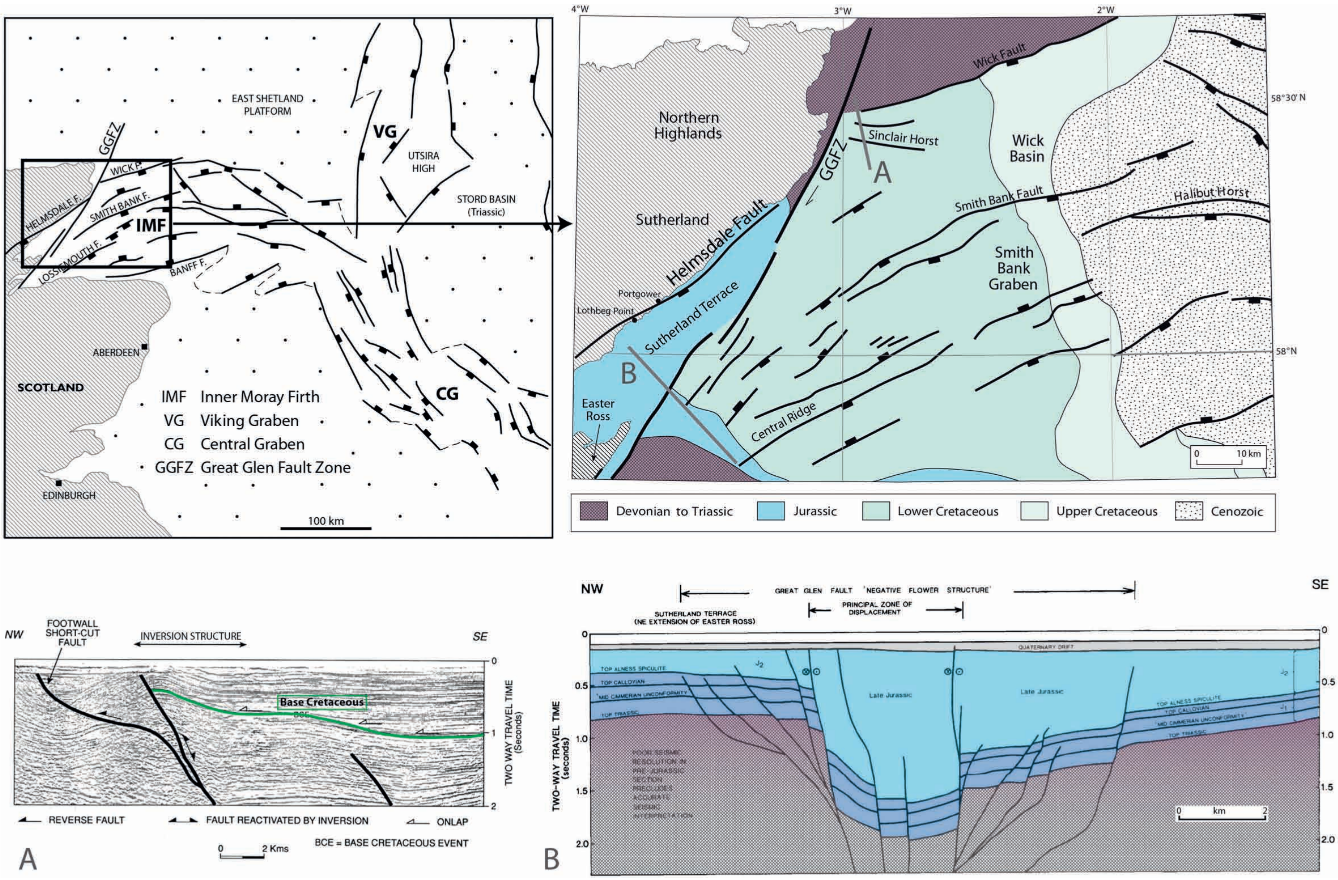

Fig. 2. Top left: structural map of the North Sea Basin and location of the Inner Moray Firth (IMF) Basin (modified after Underhill 1991*a*). Top right: structural map of Inner Moray Firth Basin (modified after Evans *et al*. 2003). Grey lines indicate locations of seismic profiles A and B. Profile A, seismic profile of Inner Moray Firth Basin showing post-Cretaceous inversion structure along Wick Fault at its intersection with Great Glen Fault (from Thomson & Underhill 1993). Profile B, geoseismic section showing a typical 'flower structure' of Great Glen Fault (from Underhill & Brodie 1993).

McQuillin *et al*. (1982) suggested that a post-Carboniferous right-lateral displacement of about 8 km along the Great Glen Fault was a critical factor in the development of the Inner Moray Firth Basin. On the other hand, Underhill & Brodie (1993) argued that the Great Glen Fault was inactive as a strike-slip fault, during phases of extension in the Inner Moray Firth, and that the Helmsdale Fault was then the dominant control on the structure. In contrast, the Great Glen Fault reactivated in the Tertiary, during regional uplift and basin inversion (Underhill 1991*a*).

Evidence for Cenozoic reactivation of the Great Glen Fault

The Great Glen Fault developed as a left-lateral fault during the Caledonian Orogeny (Hutton & McErlean 1991; Stewart *et al*. 2000, 2001). However, according to previous studies, using seismic data from the Inner Moray Firth Basin and analyses of Mesozoic outcrops and Tertiary dyke swarms, the Great Glen Fault reactivated right-laterally in the Tertiary (Holgate 1969; Thomson & Underhill 1993; Underhill & Brodie 1993; Thomson & Hillis 1995).

By analysis of the WNW–ESE-trending Permo-Carboniferous dyke swarm of northern Argyll, on the northwestern side of the Great Glen Fault, Speight & Mitchell (1979) inferred a right-lateral displacement of 7–8 km, as well as a considerable downthrow to the SE. Moreover, Holgate (1969) deduced 29 km of right-lateral slip along the Great Glen Fault since the Late Jurassic, from field observations of Jurassic rocks in Argyll. On the island of Mull, Tertiary dykes are offset right-laterally along the Great Glen Fault (Fig. 1; Thomson & Underhill 1993), which is consistent with the previous suggestions of Holgate (1969) and Speight & Mitchell (1979).

On seismic sections from the Inner Moray Firth Basin, the Great Glen Fault appears as a 'flower structure' and inversion structures are visible in the northwestern corner of the basin, along the Wick Fault (Fig. 2; Thomson & Underhill 1993; Underhill & Brodie 1993). From structural studies along the Great Glen Fault in Easter Ross (Fig. 2), onshore well data from Tain and seismic data from the Inner Moray Firth Basin, Underhill & Brodie (1993) identified folds and faults, trending north–south to NNE–SSW, in Devonian strata adjacent to the Great Glen Fault. Moreover, they suggested that the Jurassic outcrops in Easter Ross along the Great Glen Fault (Fig. 2) may be parts of flower structures that resulted from right-lateral slip along the Great Glen Fault. In Jurassic strata of the Sutherland Terrace (Fig. 2), next to the Helmsdale Fault, Thomson & Underhill (1993) described open folds, attributing them to opposing senses of slip on the Helmsdale Fault (left-lateral) and the Great Glen Fault (right-lateral).

Estimates of right-lateral displacement on the Great Glen Fault during the Tertiary are small, varying from 8 to 29 km, depending on the study (Holgate 1969; McQuillin *et al*. 1982; Rogers *et al*. 1989; Underhill & Brodie 1993). The exact timing of reactivation

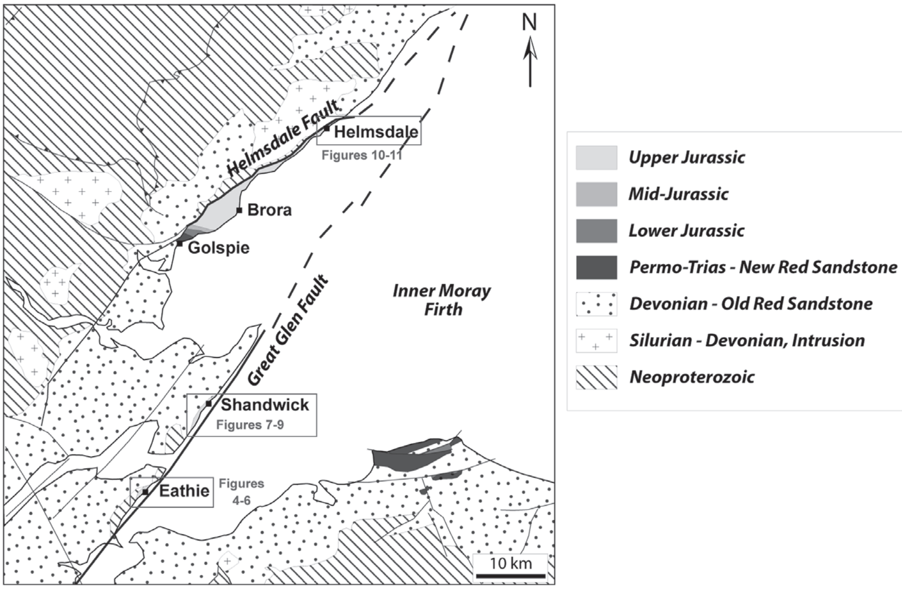

Fig. 3. Geological map of NE Scotland (modified from Stone 2007). Rectangles indicate locations of figures 4–6, 7–9, 10 and 11.

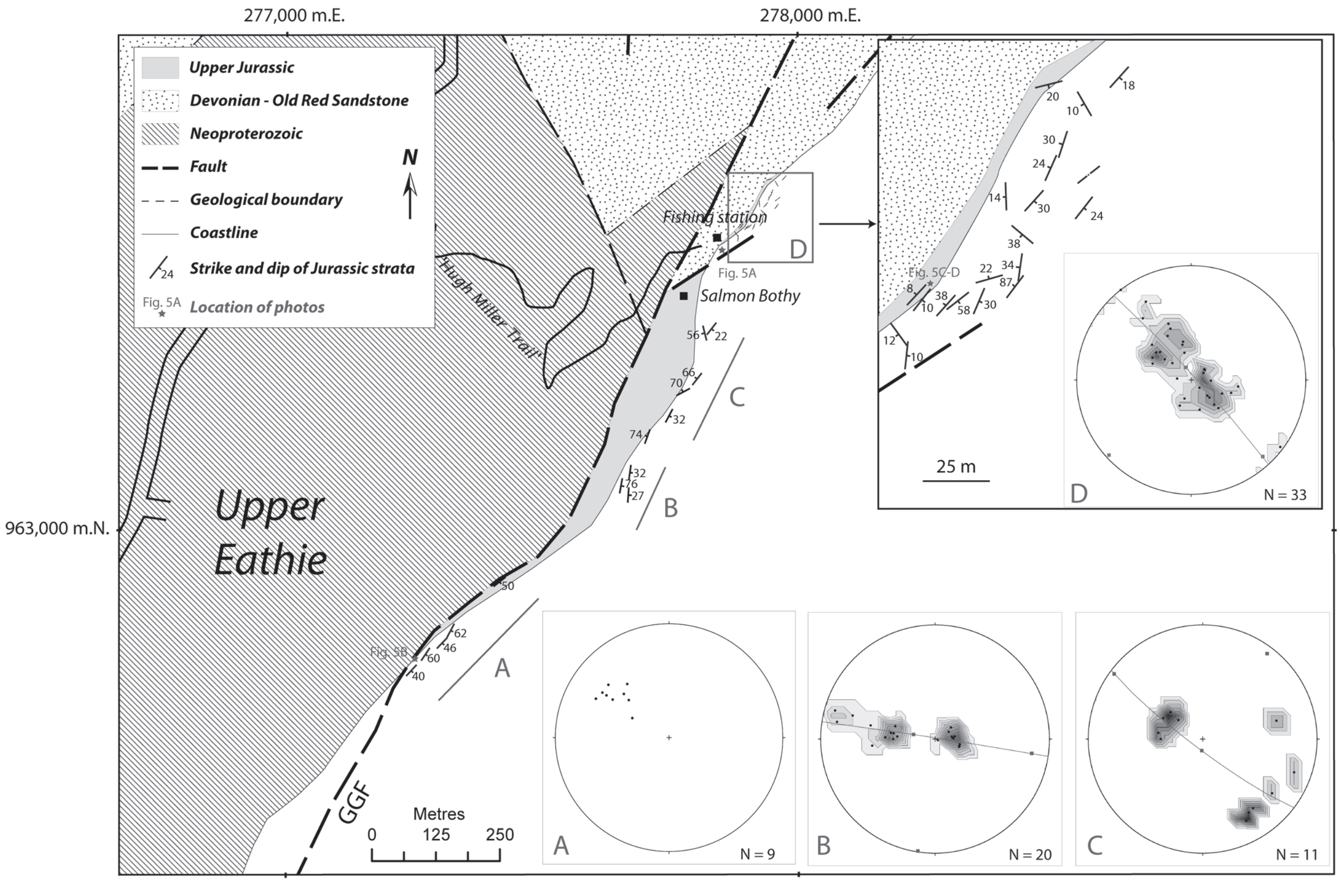

Fig. 4. Geological map of Eathie (modified after Institute of Geological Sciences 1973). Strike and dip of Jurassic strata are variable, as a result of folding next to Great Glen Fault (GGF). Stereonets (lower hemisphere) show poles to strata; great circles are perpendicular to fold axes. Stars indicate locations of photographs in Figure 5.

is uncertain. Several researchers have suggested that reactivation was contemporaneous with regional uplift of the Scottish Highlands during Palaeocene–Eocene events of NE Atlantic rifting or during Oligo-Miocene (Alpine) tectonics (e.g. Underhill 1991*b*; Thomson & Underhill 1993; Underhill & Brodie 1993; Thomson & Hillis 1995).

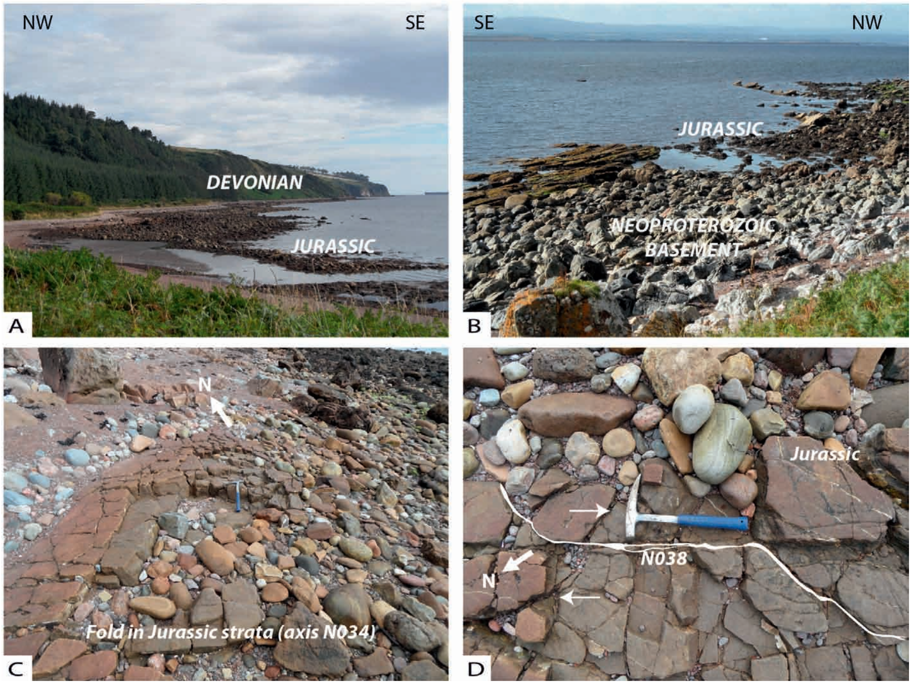

Fig. 5. Photographs of Jurassic outcrops at Eathie. (**a**) Contact between Jurassic strata and Devonian Old Red Sandstone in NE area. (**b**) Contact between Jurassic strata and Neoproterozoic basement in SW area. (**c**) Fold in Jurassic strata adjacent to Great Glen Fault. (**d**) Calcite veins right-laterally offsetting Jurassic strata and striking parallel to Great Glen Fault (*c*. N040°).

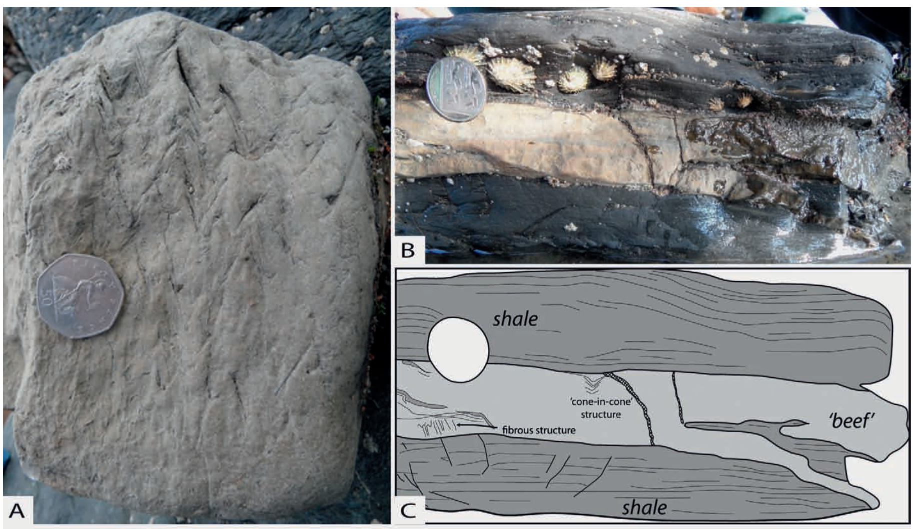

Fig. 6. Photographs of 'cone-in-cone' (**a**, **b**) and 'beef' calcite cement (**b**) in Jurassic shale at Eathie. (**c**) Interpretation of structures in (**b**).

Evidence for Cenozoic exhumation

From interpretation of seismic and well data, the Inner Moray Firth underwent exhumation during the Cenozoic and the western side of the North Sea tilted to the east (e.g. Underhill 1991*b*; Argent *et al*. 2002). Indeed, Jurassic strata in the Inner Moray Firth are *c*. 500–1500 m shallower than they are in the Viking and Central Graben areas to the east. Thomson & Underhill (1993) have estimated about 1 km of uplift in the west, decreasing gradually eastwards, whereas Thomson & Hillis (1995) inferred that exhumation removed about 1.5 km of basin fill from the Inner Moray Firth and Hillis *et al*. (1994) estimated 1 km of Tertiary erosion throughout the whole Inner Moray Firth.

Several researchers have suggested that Scotland experienced a major phase of uplift in the early Palaeogene, as a result of igneous underplating or dynamic uplift, associated with the Iceland mantle plume and widespread magmatic activity west of Scotland (Nadin *et al*. 1997; White & Lovell 1997; Clift *et al*. 1998; Jones *et al*. 2002; Mackay *et al*. 2005; Persano *et al*. 2007; Saunders *et al*. 2007). However, fission-track analyses on apatite have revealed that Cenozoic exhumation of Scotland was episodic, at 65–60 Ma, 40–25 Ma and 15–10 Ma (Jolivet 2007; Holford *et al*. 2009, 2010) and may have continued into Late Neogene time (Hall & Bishop 2002; Stoker 2002). Holford *et al*. (2010) have therefore suggested that regional exhumation of Scotland was due mainly to plate-wide horizontal forces, resulting from Alpine orogeny or NE Atlantic events.

Coeval with Cenozoic uplift, widespread compressional folds and reverse faults developed on the NW European continental margin, offshore Scotland (Boldreel & Andersen 1993, 1998; Brekke 2000; Ritchie *et al*. 2003, 2008; Hitchen 2004; Smallwood 2004;

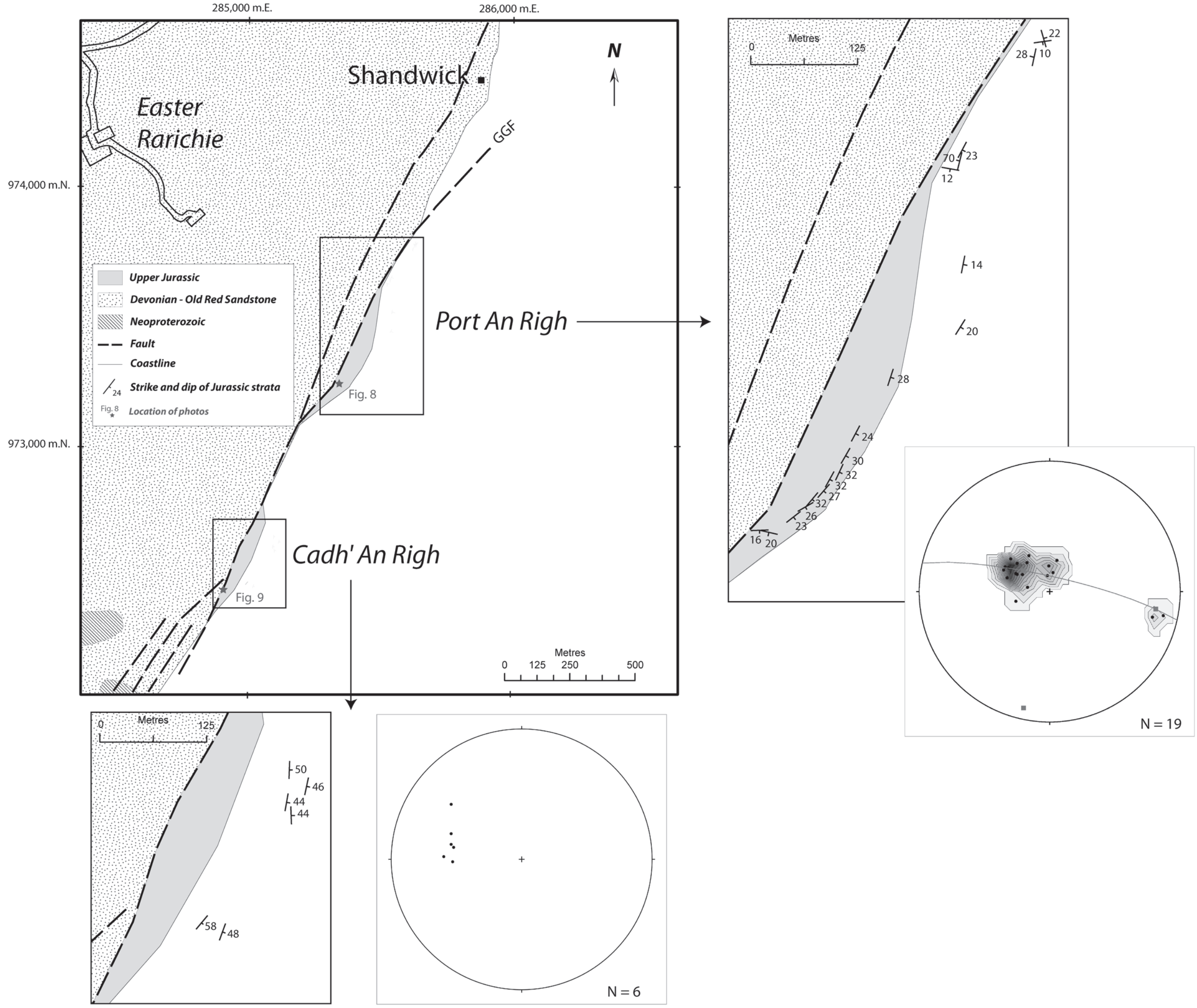

Fig. 7. Geological map of Shandwick (modified after Institute of Geological Sciences 1973). Strike and dip of Jurassic strata are variable at Port-an-Righ and Cadh'-an-Righ because of folding next to Great Glen Fault (GGF). A stereonet for Port-an-Righ (lower hemisphere, right) shows poles to strata; great circle is perpendicular to nearly horizontal fold axis, but some data deviate from this. Stereonet for Cadh'-an-Righ (lower hemisphere, left) shows great circles (for bedding planes) intersecting at steep fold axis. Stars indicate locations of photographs (Figs 8 and 9).

Johnson *et al*. 2005; Stoker *et al*. 2005; Tuitt *et al*. 2010). South of the Faroe Islands, such structures (e.g. the Wyville-Thomson and Ymir ridges, Alpin Dome and Judd Anticline) formed from the Middle Eocene to the Early Miocene (Smallwood 2004; Johnson *et al*. 2005; Ritchie *et al*. 2008; Tuitt *et al*. 2010). The possible causes of shortening are a subject of continuing debate: (1) Alpine stress field (e.g. Boldreel & Andersen 1993, 1998); (2) ridge push from the NE Atlantic (e.g. Boldreel & Andersen 1993, 1998); (3) plume-enhanced ridge push (Lundin & Doré 2002); (4) stress associated with the development of the Iceland Plateau (Doré *et al*. 2008); (5) differential sea-floor spreading along the NE Atlantic (Mosar *et al*. 2002; Le Breton *et al*. 2012).

In this paper, we further investigate the structural evidence for Cenozoic right-lateral reactivation of the Great Glen Fault and we discuss possible causes, such as differential sea-floor spreading along the NE Atlantic.

Method

Our data are from observations of Jurassic outcrops along both the Great Glen Fault and the Helmsdale Fault (Fig. 3). Upper Jurassic outcrops at Eathie (Kimmeridgian) and south of Shandwick (Port-an-Righ, Lower and Middle Oxfordian, and Cadh'-an-Righ, from Bathonian to Middle Oxfordian) are accessible only at low tide. Along the Helmsdale Fault, between Golspie and Helmsdale, Jurassic outcrops are more numerous.

The objectives of our fieldwork were to identify, measure and analyse structures within Jurassic strata and the nature of their contact with the Old Red Sandstone or Neoproterozoic–Caledonian basement. We compared our observations with previous studies and with published interpretations of seismic data from the Inner Moray Firth, to discuss the timing and possible causes of reactivation of the Great Glen Fault.

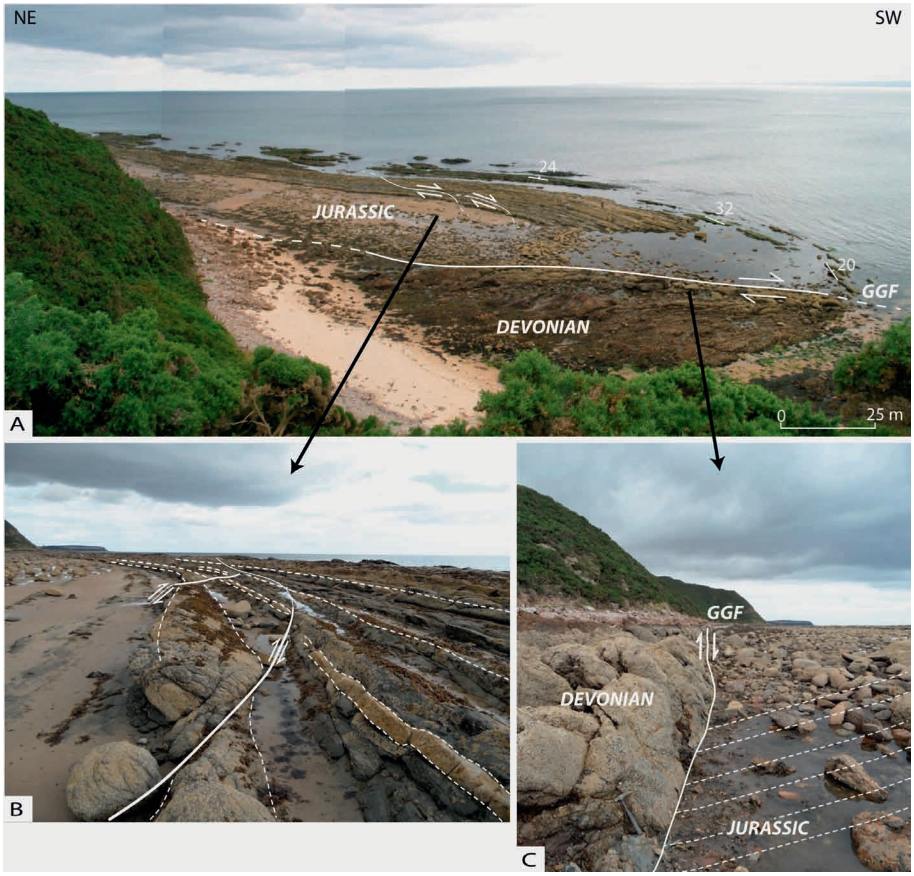

Fig. 8. Photographs of Jurassic outcrops at Port-an-Righ. (**a**) Panoramic view that shows the sigmoidal shape of Jurassic folds next to Great Glen Fault (GGF). This shape is diagnostic of right-lateral slip along the Great Glen Fault. (**b**) Calcite veins right-laterally offsetting Jurassic strata. (**c**) Fault contact between Jurassic and Devonian strata.

Fig. 9. Photographs of Jurassic outcrops at Cadh-an-Righ. (**a**) Wide-angle view of fault contact between Jurassic and Devonian strata. (**b**) Close-up view of same showing reverse and right-lateral slip along the Great Glen Fault. (**c**) ‘Beef’ in Jurassic shale. (**d**) Fragment of Jurassic coal next to the Great Glen Fault.

Results

Eathie

The Jurassic outcrops on the coast at Eathie are easily accessible at low tide, via the ‘Hugh Miller Trail’. The sequence consists of alternating shale (containing Kimmeridgian ammonites) and argillaceous limestone, with some sandstone at the northeastern end of the outcrop. The Upper Jurassic rocks at Eathie are in contact mostly with Neoproterozoic basement, except in the northeastern area, where they are in contact with the Old Red Sandstone (Figs 4 and 5).

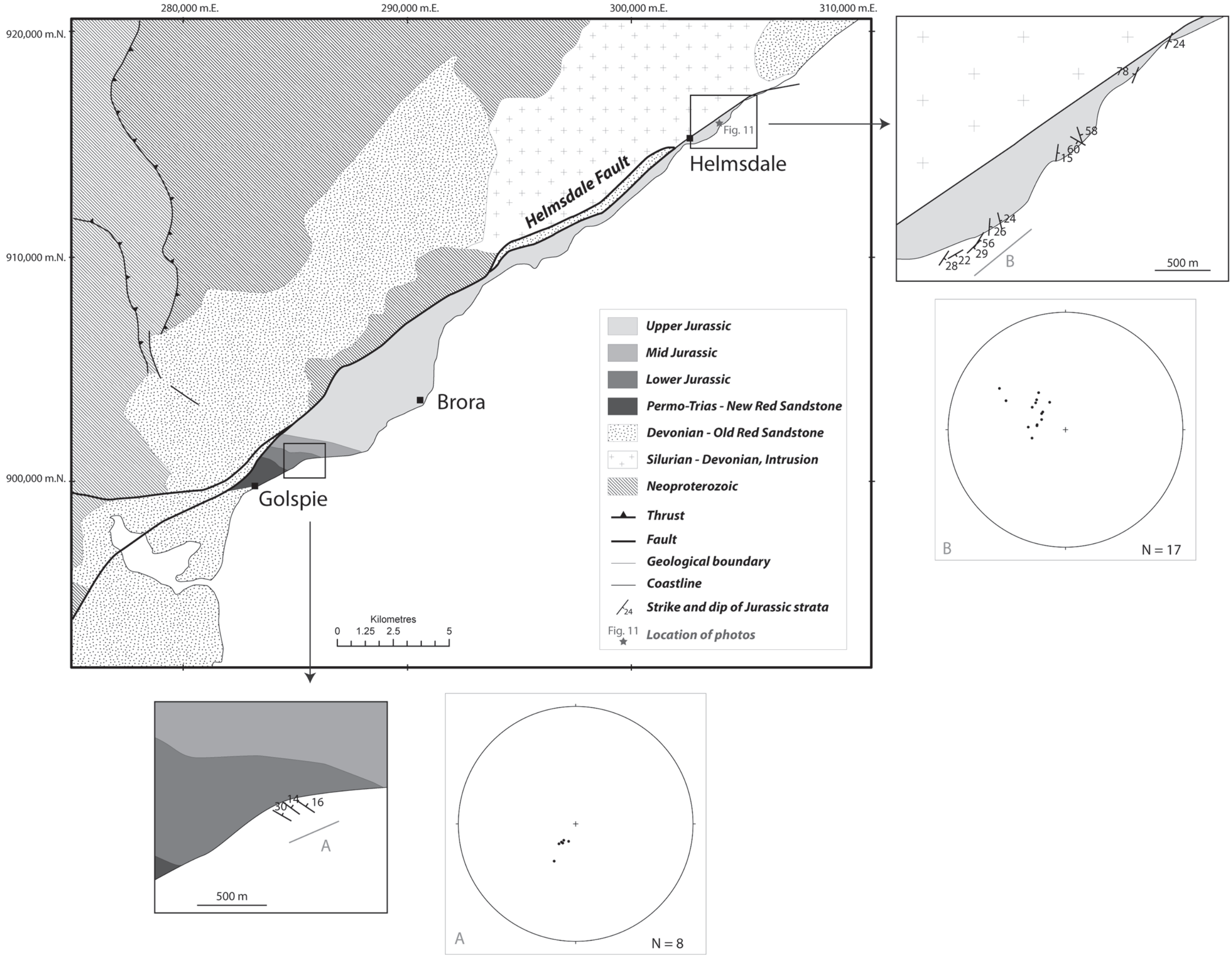

Fig. 10. Geological map of Helmsdale (modified after Stone 2007). Strike and dip of Jurassic strata are variable as a result of folding next to Great Glen Fault. Stereonets for Golspie and Helmsdale (lower hemisphere) show great circles (for bedding planes) that intersect at shallowly plunging fold axes. Star indicates location of photographs (Fig. 11).

Previous studies, notably a drilling site for coal exploration, indicate that the Jurassic strata abut a fault that trends NNE–SSW (Fig. 4; Miller 1851; Judd 1873; Institute of Geological Sciences 1973). This fault is probably an eastern splay of the Great Glen Fault (e.g. Underhill & Brodie 1993). We did not observe a sharp fault contact, but there is evidence for faulting in the form of fault brecciation between Jurassic strata and Neoproterozoic basement.

In the south, the Jurassic strata dip seaward at *c.* 40–60°. However towards the NE, the dips vary more strongly (from 10° to 90°) around numerous folds, the axes of which plunge gently and trend from north–south to NE–SW (Figs 4 and 5). Moreover, several steep calcite veins, parallel to the Great Glen Fault, cut the entire Jurassic sequence and their sigmoidal shapes indicate right-lateral slip along the fault (Fig. 5).

In the same general area, Jonk *et al.* (2003) described sills and dykes of injected sand. We found that some of these sills resemble ‘beef’ (bedding-parallel veins of fibrous calcite; see Rodrigues *et al.* 2009), in the sense that they locally contain fibrous calcite or cone-in-cone structures (Fig. 6). We note that Hillier & Cosgrove (2002) described ‘beef’ and ‘cone-in-cone’, together with sandstone intrusions, at a depth of about 2000 m within Eocene sandstone in the Alba oilfield of the Outer Moray Firth, attributing these structures to overpressure. In other sedimentary basins (e.g. the Neuquén Basin, Argentina, or the Wessex Basin, UK) ‘beef’ veins provide evidence of overpressure and maturation of organic matter at a depth of several kilometres, in the ‘oil window’, where temperature is high enough (60–120 °C) for maturation of organic matter (Selley 1992; Rodrigues *et al.* 2009). Similarly, the Jurassic shale at Eathie may have accumulated deeper offshore in the Inner Moray Firth Basin and then have been subject to post-Jurassic exhumation (Hillis *et al.* 1994). This may have occurred during right-lateral slip along the Great Glen Fault.

Shandwick

Two outcrops of Jurassic strata are accessible on the coast at low tide, south of Shandwick (Fig. 7). At Port-an-Righ, the strata are Early to Middle Oxfordian in age, whereas at Cadh’-an-Righ there is a complete section, from Bathonian to Middle Oxfordian (Sykes 1975; Wright & Cox 2001). In both areas the Jurassic strata abut the Old Red Sandstone. As at Eathie, this contact is a NNE–SSW fault zone, an eastern branch of the Great Glen Fault (e.g. Judd 1873; Underhill & Brodie 1993).

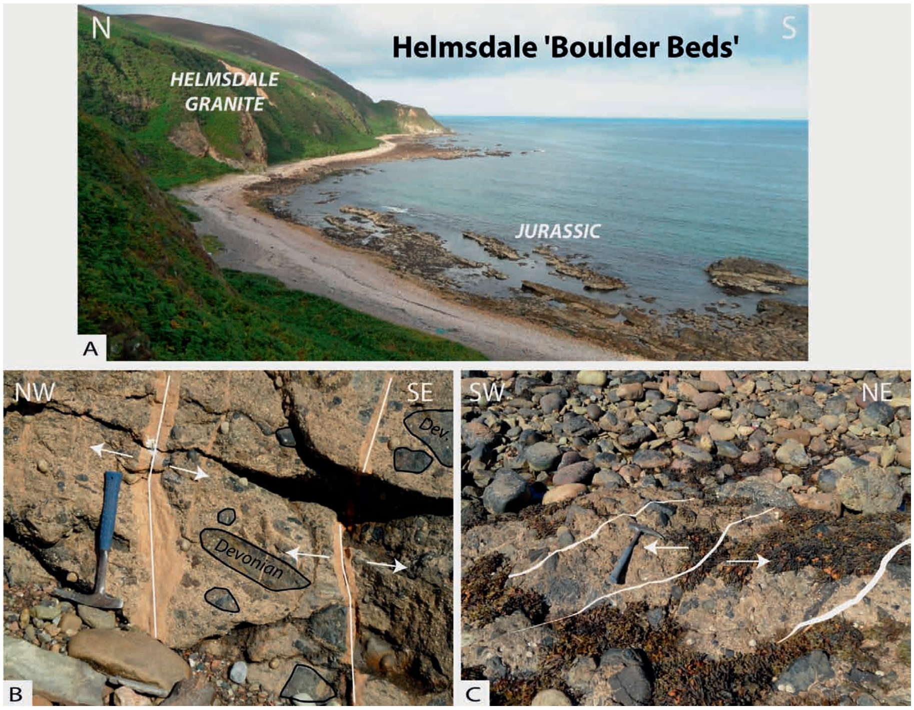

Fig. 11. Photographs of Jurassic outcrops near Helmsdale. (**a**) Jurassic 'Boulder Beds' in contact with Helmsdale Granite. (**b**) Syntectonic Jurassic conglomerate containing clasts of Devonian strata and extensional calcite veins. (**c**) Sigmoidal calcite veins left-laterally offsetting Jurassic strata and striking parallel to Helmsdale Fault.

Port-an-Righ. The Jurassic strata at Port-an-Righ dip generally seaward at *c*. 14–32° (Figs 7 and 8). However, from the top of the cliffs, a large fold is visible on the wave-cut platform, next to the Great Glen Fault. The fold is asymmetric and sigmoidal. At its northeastern end, the fold is broadly cylindrical and the fold axis strikes NE–SW, but at its southeastern end, the axis plunges at 16–20° to the SW. Such folds are typical of right-lateral slip within a multilayer (Richard *et al*. 1991). Further toward the NE, the dip of the bedding varies even more (from 12° to the south, through 28–70° to the west, to 10–23° to the east; Fig. 7). Throughout the area, steep calcite veins offset the Jurassic strata right-laterally (Fig. 8). The veins strike at *c*. 45° to the Great Glen Fault. In this area, Jonk *et al*. (2003) described right-lateral faults, trending NE–SW and bearing calcite cement. A fault separates Jurassic from Devonian strata (Fig. 8; Jonk *et al*. 2003), but we did not observe any striae.

Cadh'-an-Righ. Another Jurassic outcrop is visible at Cadh'-an-Righ (Fig. 7), although access to it is more difficult. In this area, the Devonian strata dip steeply seaward (at about 80° next to the Jurassic strata), whereas the Jurassic strata dip generally seaward at 44–58° (Fig. 7). Once again, we found 'beef' in the Jurassic strata, as well as coal (Fig. 9).

At Cadh'-an-Righ there is a clear fault contact between Jurassic and Devonian strata (Fig. 9). The strike of the fault is parallel to the Great Glen Fault (*c*. N040). We found striae that pitch at *c*. 8° to the NE, indicating both right-lateral and reverse slip. Thus if the 'beef' formed at a depth of 1500–2500 m, close to the 'oil window' (Rodrigues *et al*. 2009), its exhumation would imply a right-lateral displacement along the Great Glen Fault of *c*. 10–18 km. This magnitude is consistent with previous estimates (e.g. Holgate 1969; McQuillin *et al*. 1982; Rogers *et al*. 1989; Underhill & Brodie 1993).

Helmsdale

Between Golspie and Helmsdale, Permo-Trias to Late Jurassic strata crop out along the Helmsdale Fault (Fig. 10). At Helmsdale, Jurassic strata are in contact with the Helmsdale Granite (Silurian–Devonian; Figs 10 and 11). In this area, the Jurassic strata are Kimmeridgian, as at Eathie; however, at Helmsdale units of conglomerate (Helmsdale Boulder Beds) alternate with shale, as a result of syntectonic sedimentation in the footwall of a normal fault (Thiérault & Steel 1995; Trewin & Hurst 2009). The conglomerate contains Devonian clasts, indicating that Devonian strata lay above the Helmsdale Granite at the time of faulting. Moreover, steep calcite veins cut the conglomerate, indicating extension in a direction perpendicular to the Helmsdale Fault (Fig. 11b). We did not find any 'beef' in Jurassic strata at Helmsdale and this is consistent with shallow burial, by comparison with the Jurassic strata at Eathie and Shandwick.

Another set of steep calcite veins cuts the entire sequence and therefore post-dates the Jurassic. These veins are sigmoidal, indicating left-lateral slip along the Helmsdale fault zone (Fig. 11). Such a motion is compatible with right-lateral displacement on the Great Glen Fault. Indeed, according to previous studies, folds between the Helmsdale Fault and the Great Glen Fault may have developed as a result of opposing senses of slip on these two faults (Thomson & Underhill 1993).

Discussion

At Eathie and Shandwick, folds, faults and veins provide structural evidence for post-Jurassic right-lateral reactivation of the Great Glen Fault. Furthermore, 'beef' at outcrop is one indication that the Mesozoic strata were subject to several kilometres of burial and then to post-Jurassic exhumation. In contrast, at Helmsdale there is no 'beef' and Jurassic conglomerate accumulated at shallower depth, in the footwall of the active Helmsdale Fault. Sigmoidal calcite veins, which cut the Jurassic sequence at Helmsdale, indicate left-lateral displacement on the Helmsdale Fault. This is compatible with right-lateral displacement along the Great Glen Fault (Thomson & Underhill 1993; Underhill & Brodie 1993). At Cadh'-an-Righ our observations provide further evidence for right-lateral reactivation of the Great Glen Fault. However, the reverse faulting

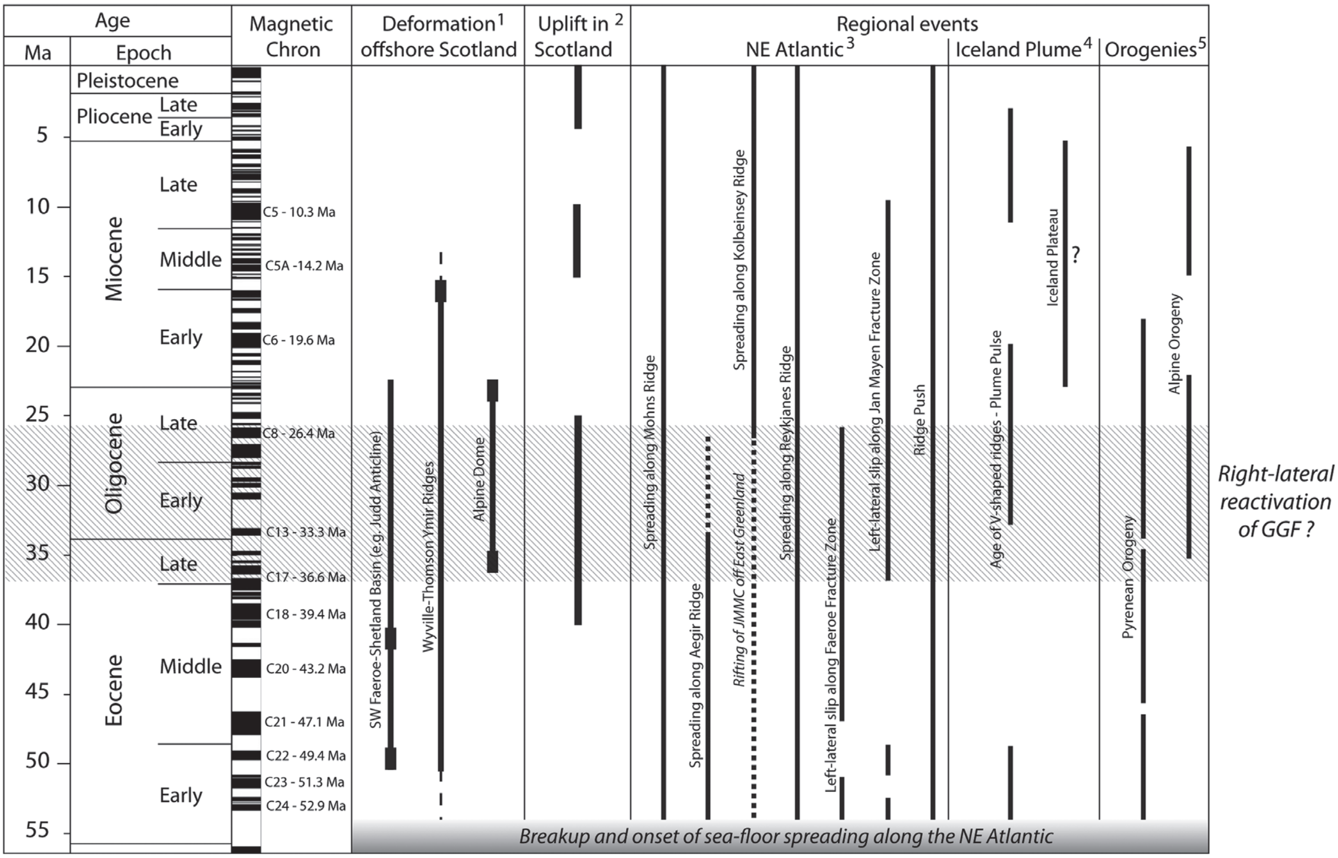

Fig. 12. Summary and correlation of events: (1) post-breakup compressional deformation offshore Scotland (Smallwood *et al*. 2004; Johnson *et al*. 2005; Ritchie *et al*. 2008; Tuitt *et al*. 2010); (2) main phases of uplift in Scotland during Cenozoic time (Hall & Bishop 2002; Holford *et al*. 2009); (3) sea-floor spreading along NE Atlantic ridge system, differential sea-floor spreading along NE Atlantic that resulted in left-lateral slip along Faroe Fracture Zone (FFZ) and Jan Mayen Fracture Zone (JMFZ) (Le Breton *et al*. 2012), and ridge push; (4) Iceland mantle plume pulse (correlation between age of V-shaped ridges and plume pulses from White & Lovell 1997), and development of Iceland Plateau; (5) development of compressional Alpine and Pyrenean stress field (Tuitt *et al*. 2010). Period of synchronous events (diagonally shaded) may represent timing of reactivation of Great Glen Fault (GGF). (For locations of post-breakup compressional structures offshore Scotland, see Fig. 13.) JMMC, Jan Mayen Microcontinent.

would indicate a local context of transpression, rather than transtension.

Our observations show clearly that right-lateral reactivation of the Great Glen Fault was post-Jurassic, but we know of no younger strata onshore, other than Quaternary. Subsurface data from the offshore Inner Moray Firth Basin and the apparent offsets of Palaeocene–Eocene dykes in NW Scotland all indicate that reactivation occurred in Tertiary time (Holgate 1969; Thomson & Underhill 1993; Underhill & Brodie 1993; Thomson & Hillis 1995). However, the exact timing remains uncertain. Underhill & Brodie (1993) showed that the Inner Moray Firth Basin underwent regional uplift during the Cenozoic and they attributed this to reactivation of the Great Glen Fault. More generally, periods of uplift occurred at 65–60 Ma, 40–25 Ma and 15–10 Ma and may have continued into Late Neogene time (Hall & Bishop 2002; Holford *et al*. 2009, 2010). Therefore, it seems likely that reactivation of the Great Glen Fault occurred during one of these periods (Fig. 12).

Hillis *et al*. (1994) suggested that exhumation in the Inner Moray Firth occurred in mid- to late Danian time (65.5–61.7 Ma, early Palaeogene), when a major unconformity developed. As we have explained above, a period of uplift did affect Scotland in Early Palaeogene time, probably in connection with the Iceland mantle plume and widespread magmatic activity west of Scotland. However, the Great Glen Fault has offset right-laterally the Palaeocene–Eocene dykes of NW Scotland. The youngest of those dykes formed at about 52 Ma (Holgate 1969). Thus dextral reactivation of the Great Glen Fault continued after that time. Moreover, several unconformities developed during the Cenozoic, in the North Sea rift system, and during the Palaeogene, offshore Scotland (e.g. Evans *et al*. 2003; Stoker *et al*. 2012). Furthermore, Evans *et al*. (2003) have described several phases of local inversion in the Inner Moray Firth in middle Eocene, Oligocene and Miocene times. Thus the significant uplift of Scotland in Early Palaeocene time may have been due to processes other than tectonic reactivation. In Northern Ireland, a recent high-resolution aeromagnetic survey has demonstrated that Caledonian faults reactivated during Palaeogene time, and, more precisely, in Early Palaeocene and Oligocene time. The latter phase was associated with the development of Oligocene pull-apart basins (Cooper *et al*. 2012) and was possibly coeval with reactivation of the Great Glen Fault. Thus, it is most likely that reactivation of the Great Glen Fault occurred in Palaeogene time (after 52 Ma).

Amongst the possible causes for reactivation of the Great Glen Fault and for Cenozoic uplift of Scotland are (1) mantle processes from the Iceland plume, (2) intraplate compression from the Alpine Orogeny, (3) ridge push from the NE Atlantic and (4) variations in

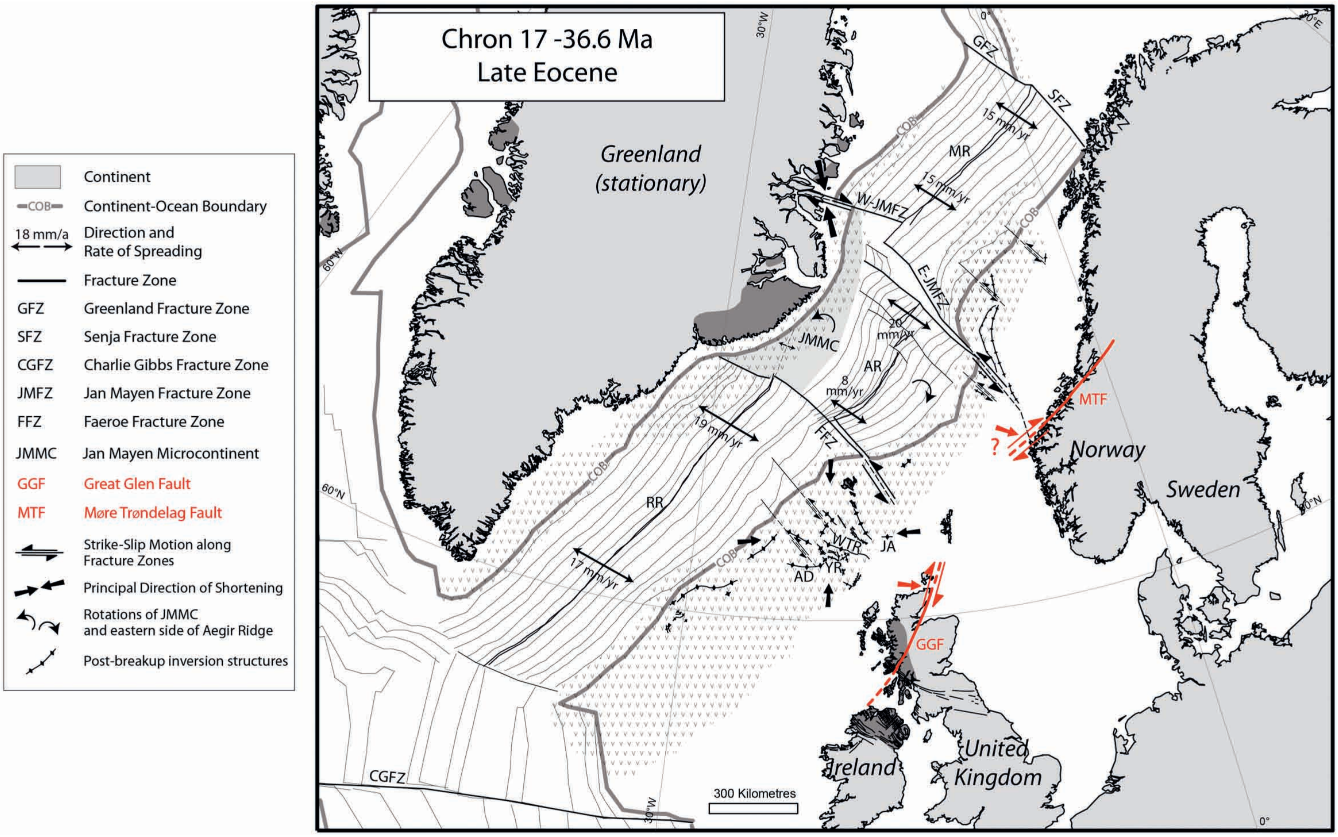

Fig. 13. Position of Europe at 36.6 Ma (Late Eocene) relative to a stationary Greenland plate. According to a new method of restoration differential sea-floor spreading along Reykjanes, Aegir and Mohns ridges generated left-lateral displacements along Faroe and Jan Mayen fracture zones (Le Breton *et al*. 2012). Such displacements are compatible with right-lateral reactivation of the Great Glen Fault and possibly of the Møre–Trøndelag Fault, respectively. AD, Alpin Dome; AR, Aegir Ridge; JA, Judd Anticline; MR, Mohns Ridge; RR, Reykjanes Ridge; YR, Ymir Ridge; WTR, Wyville-Thomson Ridge. Map projection is Universal Transverse Mercator (UTM, WGS 1984 zone 27N).

the amount and rate of sea-floor spreading in the NE Atlantic. According to recent restorations (Le Breton *et al*. 2012), variations in the amount and direction of sea-floor spreading, between the Reykjanes and Aegir ridges of the NE Atlantic (Fig. 13), generated left-lateral transpressional displacement along the Faroe Fracture Zone, first in the Early Eocene (*c*. 56–51 Ma) and then from the Early Eocene to Late Oligocene (*c*. 47–26 Ma). During the latter phase, the Jan Mayen Microcontinent rifted progressively (from south to north) off East Greenland. When these continental areas finally separated, sea-floor spreading transferred from the Aegir Ridge to the Kolbeinsey Ridge (Figs 12 and 13). According to the stationary hotspot model of Lawver & Müller (1994), the head of the Iceland plume was beneath the eastern Greenland margin at that time (*c*. 40–30 Ma). Müller *et al*. (2001) suggested that the Iceland mantle plume was responsible for (1) rifting at the edge of the eastern Greenland margin, (2) formation of the Kolbeinsey Ridge, west of Jan Mayen, (3) subsequent extinction of the Aegir Ridge and (4) separation of the Jan Mayen Microcontinent from Greenland.

The Middle Eocene to Late Oligocene was a period of uplift in Scotland and of compressional deformation on the NW UK continental margin (Fig. 12). Numerous compressional structures developed offshore Scotland (e.g. the Wyville-Thomson and Ymir ridges, the Alpin Dome and the Judd Anticline) from the Middle Eocene to the Early Miocene (Fig. 13; Smallwood 2004; Johnson *et al*. 2005; Ritchie *et al*. 2008; Tuitt *et al*. 2010; Stoker *et al*. 2012). Le Breton *et al*. (2012) have suggested that differential sea-floor spreading of NE Atlantic ridges was responsible for compressional deformation on the continental margin at those times. Here we suggest furthermore that this differential sea-floor spreading was also responsible for reactivation of the Great Glen Fault. Indeed, a left-lateral displacement along the Faroe Fracture Zone is compatible with a right-lateral reactivation of the Great Glen Fault (Fig. 13). The stress field from the Alpine Orogeny and pulses from the Iceland mantle plume may have amplified the intraplate stress in Scotland, so contributing to reactivation of the Great Glen Fault. Because all these processes were active simultaneously, from the Late Eocene to the Late Oligocene (*c*. 37–26 Ma), we consider that reactivation of the Great Glen Fault probably occurred in this interval (Fig. 12).

Conclusions

(1) Our field observations of Jurassic outcrops in Eathie, Shandwick and Helmsdale, NE Scotland, provide additional evidence for post-Jurassic right-lateral reactivation of the Great Glen Fault, under transpression.

(2) The ‘beef’ structures in Jurassic shale at Eathie and Shandwick provide evidence that this formation accumulated deeper offshore in the Inner Moray Firth Basin and has been subject to post-Jurassic exhumation. This exhumation would be compatible with right-lateral displacement on the Great Glen Fault. Assuming that ‘beef’ structures form at *c*. 1500–2500 m depth (Rodrigues *et al*. 2009) and from the 8°

pitch of striae on fault planes at Cadh'-an-Righ, we estimate that right-lateral displacement along the Great Glen Fault was of the order of 10–18 km.

(3) The timing of reactivation of the Great Glen Fault remains uncertain; however, we suggest that the Great Glen Fault reactivated right-laterally in a time interval from Late Eocene to Late Oligocene, *c*. 37–26 Ma. This period coincides with (1) an uplift episode of Scotland, (2) intraplate stress from the Alpine Orogeny, (3) a pulse of the Iceland mantle plume, and, more importantly, with (4) left-lateral slip along the Faroe Fracture Zone owing to differential sea-floor spreading and plate readjustment in the NE Atlantic (separation of the Jan Mayen Microcontinent; 'ridge jump' from the Aegir to the Kolbeinsey ridges). Indeed, left-lateral slip along the Faroe Fracture Zone is compatible with right-lateral reactivation of the Great Glen Fault.

(4) In the future, low-temperature geochronological studies may provide better constraints on the timing of reactivation of the Great Glen Fault. However, the vertical motion along the Great Glen Fault may not have been significant enough to be detectable in such studies. Similar work along the Møre–Trøndelag Fault, Norway, would provide better constraints on the relationships between differential spreading along the NE Atlantic, left-lateral slip along the Faroe Fracture Zone and Jan Mayen Fracture Zone, uplift of Scotland and Norway, and Tertiary reactivation of the Great Glen Fault and Møre–Trøndelag Fault.

We would like to thank Chevron USA for funding the PhD project of E. Le Breton, and in particular G. Lewis and P. Connolly for instigating the project. We are grateful to A. Hurst and J. Parnell for providing maps, publications, data and encouragement, during our visit to Aberdeen University in August 2011. We also thank M. Jolivet of the University of Rennes 1 for information on reactivation of the Great Glen Fault. Finally, we thank A. Hurst and H. Johnson for their helpful reviews.

References

Argent, J.D., Stewart, S.A., Green, P.F. & Underhill, J.R. 2002. Heterogeneous exhumation in the Inner Moray Firth, UK North Sea: Constraints from new AFTA(R) and seismic data. *Journal of the Geological Society, London*, **159**, 715–729, doi:10.1144/0016-764901-141.

Boldreel, L.O. & Andersen, M.S. 1993. Late Pliocene to Miocene compression in the Faeroe–Rockall area. *In*: Parker, J.R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 1025–1034.

Boldreel, L.O. & Andersen, M.S. 1998. Tertiary compressional structures on the Faroe–Rockall Plateau in relation to northeast Atlantic ridge-push and Alpine foreland stresses. *Tectonophysics*, **300**, 13–28.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and More Basins. *In*: Nøttvedt, A. (ed.) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 327–378.

Brodie, J. & White, N. 1994. Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf. *Geology*, **22**, 147–150.

Clift, P.D., Carter, A. & Hurford, A.J. 1998. The erosional and uplift history of NE Atlantic passive margins: Constraints on a passing plume. *Journal of the Geological Society, London*, **155**, 787–800.

Cooper, M.R., Anderson, H., Walsh, J.J., Cab Dan, C.L., Young, M.E., Earl, G. & Walker, A. 2012. Palaeogene Alpine tectonics and Icelandic plume-related magmatism and deformation in Northern Ireland. *Journal of the Geological Society, London*, **169**, 29–36, doi:10.1144/0016-76492010-182.

Doré, A.G., Lundin, E.R., Kusznir, N.J. & Pascal, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: Pros, cons and some new ideas. *In*: Johnson, H., Doré, A.G., Gatliff, R.W., Holdsworth, R., Lundin, E.R. & Ritchie, J.D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 1–26.

Evans, D., Graham, C., Armour, A. & Bathurst, P. 2003. *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. Geological Society, London.

Firth, C.R. & Stewart, I.S. 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews*, **19**, 1469–1493.

Hall, A. & Bishop, P. 2002. Scotland's denudational history: An integrated view of erosion and sedimentation at an uplifted passive margin. *In*: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*. Geological Society, London, Special Publications, **196**, 271–290.

Hillier, R.D. & Cosgrove, J.W. 2002. Core and seismic observations of overpressure-related deformation within Eocene sediments of the Outer Moray Firth, UKCS. *Petroleum Geoscience*, **8**, 141–149.

Hillis, R.R., Thomson, K. & Underhill, J.R. 1994. Quantification of Tertiary erosion in the Inner Moray Firth using sonic velocity data from the Chalk and the Kimmeridge Clay. *Marine and Petroleum Geology*, **11**, 283–293.

Hitchen, K. 2004. The geology of the UK Hatton–Rockall margin. *Marine and Petroleum Geology*, **21**, 993–1012, doi:10.1016/j.marpetgeo.2004.05.004.

Holford, S.P., Green, P.F., Duddy, I.R., Turner, J.P., Hillis, R.R. & Stoker, M.S. 2009. Regional intraplate exhumation episodes related to plate-boundary deformation. *Geological Society of America Bulletin*, **121**, 1611–1628, doi:10.1130/B26481.1.

Holford, S.P., Green, P.F., Hillis, R.R., Underhill, J.R., Stoker, M.S. & Duddy, I.R. 2010. Multiple post-Caledonian exhumation episodes across NW Scotland revealed by apatite fission-track analysis. *Journal of the Geological Society, London*, **167**, 675–694, doi:10.1144/0016-76492009-167.

Holgate, N. 1969. Palaeozoic and Tertiary transcurrent movements on the Great Glen Fault. *Scottish Journal of Geology*, **5**, 97–139.

Hutton, D.H.W. & McErlean, M. 1991. Silurian and Early Devonian sinistral deformation of the Ratagain granite, Scotland: constraints on the age of Caledonian movements on the Great Glen fault system. *Journal of the Geolocal Society, London*, **148**, 1–4.

Institute of Geological Sciences. 1973. *Geological Map of Cromarty, Sheet 94, 1:50000*. British Geological Survey, Keyworth, Nottingham.

Johnson, H., Ritchie, J.D., Hitchen, K., McInroy, D.B. & Kimbell, G.S. 2005. Aspects of the Cenozoic deformational history of the Northeast Faroe–Shetland Basin, Wyville–Thomson Ridge and Hatton Bank areas. *In*: Doré, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives*. *Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 993–1007.

Jolivet, M. 2007. Histoire de la dénudation dans le corridor du loch Ness (Écosse): mouvements verticaux différentiels le long de la Great Glen Fault. *Comptes Rendus Géosciences*, **339**, 121–131, doi:10.1016/j.crte.2006.12.005.

Jones, S.M., White, N., Clarke, B.J., Rowley, E. & Gallagher, K. 2002. Present and past influence of the Iceland Plume on sedimentation. *In*: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*. Geological Society, London, Special Publications, **196**, 13–25.

Jonk, R., Duranti, D., Parnell, J., Hurst, A. & Fallick, A.E. 2003. The structural and diagenetic evolution of injected sandstones: Examples from the Kimmeridgian of NE Scotland. *Journal of the Geological Society, London*, **160**, 881–894.

Judd, J.W. 1873. The Secondary Rocks of Scotland. *Quarterly Journal of the Geological Society of London*, **29**, 97–195, doi:10.1144/GSL.JGS.1873.029.01-02.16.

Lawver, L.A. & Müller, R.D. 1994. Iceland Hotspot track. *Geology*, **22**, 311–314.

Le Breton, E., Cobbold, P.R., Dauteuil, O. & Lewis, G. 2012. Variations in amount and direction of sea-floor spreading along the North East Atlantic Ocean and resulting deformation of the continental margin of North West Europe. *Tectonics*, **31**, TC5006, doi:10.1029/2011TC003087.

Lundin, E.R. & Doré, A.G. 2002. Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian–Greenland Sea. *Marine and Petroleum Geology*, **19**, 79–93.

Mackay, L.M., Turner, J., Jones, S.M. & White, N.J. 2005. Cenozoic vertical motions in the Moray Firth Basin associated with initiation of the Iceland Plume. *Tectonics*, **24**, 1–23, doi:10.1029/2004TC001683.

McQuillin, R., Donato, J.A. & Tulstrup, J. 1982. Development of basins in the Inner Moray Firth and the North Sea by crustal extension and dextral displacement of the Great Glen Fault. *Earth and Planetary Science Letters*, **60**, 127–139.

Mendum, J.R. & Noble, S.R. 2010. Mid-Devonian sinistral transpressional movements on the Great Glen Fault: the rise of the Rosemarkie Inlier and the Acadian event in Scotland. *In*: Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) *Continental Tectonics and*

Mountain Building: the Legacy of Peach and Horne. Geological Society, London, Special Publications, **335**, 161–187.

Miller, H. 1851. *The old red sandstone or, New walks in an old field*. Gould and Lincoln, Boston, MA [from the 4th London edition].

Mosar, J., Lewis, G. & Torsvik, T. 2002. North Atlantic sea-floor spreading rates: implications for the Tertiary development of inversion structures of the Norwegian–Greenland Sea. *Journal of the Geological Society, London*, **159**, 503–515, doi:110.1144/0016-764901-135.

Müller, R.D., Gaina, C., Roest, W.R. & Hansen, D.L. 2001. A recipe for micro-continent formation. *Geology*, **29**, 203–206.

Nadin, P.A., Kusznir, N.J. & Cheadle, M.J. 1997. Early Tertiary plume uplift of the North Sea and Faeroe–Shetland Basins. *Earth and Planetary Science Letters*, **148**, 109–127.

Persano, C., Barfod, D.N., Stuart, F.M. & Bishop, P. 2007. Constraints on early Cenozoic underplating-driven uplift and denudation of western Scotland from low temperature thermochronometry. *Earth and Planetary Science Letters*, **263**, 404–419, doi:10.1016/j.epsl.2007.09.016.

Richard, P., Mocquet, B. & Cobbold, P.R. 1991. Experiments on simultaneous faulting and folding above a basement wrench fault. *Tectonophysics*, **188**, 133–141.

Ritchie, J.D., Johnson, H. & Kimbell, G.S. 2003. The nature and age of Cenozoic contractional deformation within the NE Faroe–Shetland Basin. *Marine and Petroleum Geology*, **20**, 399–409, doi:10.1016/S0264-8172(03)00075-8.

Ritchie, J.D., Johnson, H., Quinn, M.F. & Gatliff, R.W. 2008. The effects of Cenozoic compression within the Faroe–Shetland Basin and adjacent areas. *In*: Johnson, H., Doré, A.G., Gatliff, R.W., Holdsworth, R., Lundin, E.R. & Ritchie, J.D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 121–136.

Roberts, D.G. 1989. Basin inversion in and around the British Isles. *In*: Cooper, M.A. & Williams, G.D. (eds) *Inversion Tectonics*. Geological Society, London, Special Publications, **44**, 131–150, doi:10.1144/GSL.SP.1989.044.01.09.

Rodrigues, N., Cobbold, P.R., Loseth, H. & Ruffet, G. 2009. Widespread bedding-parallel veins of fibrous calcite ('beef') in a mature source rock (Vaca Muerta Fm, Neuquen Basin, Argentina): evidence for overpressure and horizontal compression. *Journal of the Geological Society, London*, **166**, 695–709.

Rogers, D.A., Marshall, J.E.A. & Austin, T.R. 1989. Devonian and later movements on the Great Glen fault system, Scotland. *Journal of the Geolocal Society, London*, **146**, 369–372.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J. & Kent, R.W. 1997. The North Atlantic Igneous Province. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monograph, **100**, 45–93.

Saunders, A.D., Jones, S.M., Morgan, L.A., Pierce, K.L., Widdowson, M. & Xu, Y.G. 2007. Regional uplift associated with continental large igneous provinces: The roles of mantle plumes and the lithosphere. *Chemical Geology*, **241**, 282–318, doi:10.1016/j.chemgeo.2007.01.017.

Selley, R.C. 1992. Petroleum seepages and impregnations in Great Britain. *Marine and Petroleum Geology*, **9**, 226–244.

Smallwood, J.R. 2004. Tertiary inversion in the Faroe–Shetland Channel and the development of major erosional scarps. *In*: Davies, R.J., Cartwright, J.A., Stewart, S.A., Lappin, M. & Underhill, J.R. (eds) *3D Seismic Technology: Application to the Exploration of Sedimentary Basins*. Geological Society, London, Memoirs, **29**, 187–198, doi:10.1144/GSL.MEM.2004.029.01.18.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A. & Geiling, R.O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geolocal Society, London*, **149**, 871–880.

Speight, J.M. & Mitchell, J.G. 1979. The Permo-Carboniferous dyke-swarm of northern Argyll and its bearing on dextral displacement on the Great Glen Fault. *Journal of the Geological Society, London*, **139**, 3–11.

Stewart, M., Holdsworth, R.E. & Strachan, R.A. 2000. Deformation processes and weakening mechanisms within the frictional ± viscous transition zone of major crustal-scale faults: Insights from the Great Glen Fault Zone, Scotland. *Journal of Structural Geology*, **22**, 543–560.

Stewart, M., Strachan, R.A., Martin, M.W. & Holdsworth, R.E. 2001. Constraints on early sinistral displacements along the Great Glen Fault Zone, Scotland: Structural setting, U–Pb geochronology and emplacement of the syn-tectonic Clunes tonalite. *Journal of the Geological Society, London*, **158**, 821–830, doi:10.1144/jgs.158.5.821.

Stoker, M.S. 2002. Late Neogene development of the UK Atlantic Margin. *In*: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*. Geological Society, London, Special Publications, **196**, 313–329.

Stoker, M.S., Hoult, R.J., Nielsen, T., Hjelstuen, B.O., Laberg, J.S. & Shannon, P.M. 2005. Sedimentary and oceanographic responses to early Neogene compression on the NW European margin. *Atlantic*, **22**, 1031–1044, doi:10.1016/j.marpetgeo.2005.01.009.

Stoker, M.S., Kimbell, G.S., McInroy, D.B. & Morton, A.C. 2012. Eocene post-rift tectonostratigraphy of the Rockall Plateau, Atlantic margin of NW Britain: linking early spreading tectonics and passive margin response. *Marine and Petroleum Geology*, **30**, 98–125.

Stone, P. 2007. *Bedrock geology UK North, An explanation of the bedrock geology map of Scotland, northern England, Isle of Man and Northern Ireland, 1:625000*, 5th edn. British Geological Survey, Keyworth, Nottingham.

Sykes, R.M. 1975. The stratigraphy of the Callovian and Oxfordian stages (Middle–Upper Jurassic) in northern Scotland. *Scottish Journal of Geology*, **11**, 51–78.

Thiérault, P. & Steel, R.J. 1995. Syn-rift sedimentation in the Upper Jurassic (Helmsdale Boulder Beds) of the Inner Moray Firth. *In*: Steel, R.J., Felt, V.L., Johannessen, E.P. & Mathieu, C. (eds) *Sequence Stratigraphy on the Northwest European Margin*. Norwegian Petroleum Society Special Publication, **5**, 365–387.

Thomson, K. & Hillis, R.R. 1995. Tertiary structuration and erosion of the Inner Moray Firth. *In*: Scrutton, R.A., Stoker, M.S., Shimmield, G.B. & Tudhope, A.W. (eds) *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region*. Geological Society, London, Special Publications, **90**, 249–269.

Thomson, K. & Underhill, J.R. 1993. Controls on the development and evolution of structural styles in the Inner Moray Firth Basin. *In*: Parker, J.R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 1167–1178.

Trewin, N.H. & Hurst, A. 2009. *Excursion Guide to the Geology of East Sutherland and Caithness*, 2nd edn, Aberdeen Geological Society.

Tuitt, A., Underhill, J.R., Ritchie, J.D., Johnson, H. & Hitchen, K. 2010. Timing, controls and consequences of compression in the Rockall–Faroe area of the NE Atlantic Margin. *In*: Vining, B.A. & Pickering, S.C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers. Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 963–977.

Underhill, J.R. 1991*a*. Controls on Late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: A critical test of key segments of Exxon's original global cycle chart. *Basin Research*, **3**, 79–98.

Underhill, J.R. 1991*b*. Implications of Mesozoic–Recent basin development in the western Inner Moray Firth, UK. *Marine and Petroleum Geology*, **8**, 359–369.

Underhill, J.R. & Brodie, J.A. 1993. Structural geology of Easter Ross, Scotland: Implications for movement on the Great Glen fault zone. *Journal of the Geological Society, London*, **150**, 515–527, doi:10.1144/gsjgs.150.3.0515.

White, N. & Lovell, B. 1997. Measuring the pulse of a plume with the sedimentary record. *Nature*, **387**, 888–891.

White, R. & McKenzie, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685–7729, doi:10.1029/JB094iB06p07685.

Wright, J.K. & Cox, B.M. 2001. *British Upper Jurassic Stratigraphy (Oxfordian to Kimmeridgian)*. Joint Nature Conservation Committee, Geological Conservation Review Series, **21**.

Received 21 May 2012; revised typescript accepted 11 January 2013.
Scientific editing by Ian Alsop