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Cenozoic reactivation of the Great Glen Fault, Scotland: Additional Evidence and Possible Causes

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Abstract

The Great Glen Fault (GGF) trends NNE-SSW across northern Scotland. According to previous studies, the GGF 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 GGF, as suggested by previous authors. Differential sea-floor spreading along the North East Atlantic ridge system generated left-lateral transpressional displacements along the Faroe Fracture Zone (FFZ) 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 GGF. Indeed, left-lateral slip along the FFZ is compatible with right-lateral reactivation of the GGF.

Introduction

Scotland lies between the NE Atlantic Ocean to the west and north, and the North Sea to the east (**Figure 1**). The Great Glen Fault (GGF) 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 (IMF) Basin, Mesozoic strata onshore NE Scotland and Tertiary dyke-swarms in NW Scotland, all indicate right-lateral reactivation of the GGF during the Cenozoic (e.g. *Holgate*, 1969; *Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993; *Thomson & Hillis*, 1995). The exact timing and the causes of this reactivation are still uncertain.

Underhill & Brodie (1993) showed that the IMF underwent regional uplift during the Cenozoic. This they attributed to reactivation of the GGF. More widely, analyses of sonic velocities, vitrinite reflectance and apatite fission tracks have revealed exhumation and uplift of Scotland during the Cenozoic (e.g. *Underhill & Brodie*, 1993; *Thomson & Underhill*, 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 (NAIP) (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 reorganisation in the NE Atlantic.

Thomson & Underhill (1993) and *Thomson & Hillis* (1995) attributed uplift of the IMF 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 (FFZ), between the Reykjanes and Aegir ridges, and the Jan Mayen Fracture Zone (JMFZ), 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 GGF and Cenozoic uplift of Scotland are: (1) mantle processes around the Iceland Mantle Plume, (2) intra-plate 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 reorganisation 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 GGF.

1. Geological Setting

1.1 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 (**Figure 1;** *Stone*, 2007). The oldest rocks of Europe (~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 (~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 GGF separates the Moine Supergroup from the Dalradian Supergroup. The latter mostly consists of Neoproterozoic metamorphic rocks and late-Caledonian magmatic intrusions (Silurian-Devonian). South of the Highland Boundary Fault, the Midland Valley is a rift valley containing mostly Palaeozoic strata. The Moine Thrust, the GGF 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, at the mouth of the IMF and along the Helmsdale Fault (**Figure 1**). At Eathie and Shandwick, minor faults, trending NE-SW along the GGF, 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 Upper 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 Upper 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 NAIP (*Saunders et al.*, 1997). In NW Scotland, this volcanic event was responsible for the development of large gabbroic intrusive centres (e.g. Isles of Skye and Mull), as well as widespread lava flows and dyke swarms (**Figure 1**). Several authors have suggested that the Iceland Mantle Plume was responsible for this widespread magmatic activity (e.g. *White & McKenzi*e, 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 (approx. 18 kyr ago), isostatic readjustment produced Quaternary raised beaches. Indeed, the readjustment may still be ongoing (*Firth & Stewart*, 2000).

1.2 Offshore rocks of NE Scotland

The Mesozoic IMF Basin is a western arm of the North Sea rift (**Figure 2**, *Evans et al.*, 2003; *Underhill,* 1991a). Numerous seismic surveys have provided good insights into the structural development of the IMF and the northeastern end of the GGF (**Figure 2**; *Underhill & Brodie*, 1993; *Thomson & Underhill*, 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 (**Figure 2**). During Upper Jurassic rifting, fault blocks formed and tilted (*Underhill,* 1991a). 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).

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

1.3 Evidence for Cenozoic reactivation of the GGF

The GGF 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 IMF Basin and analyses of Mesozoic outcrops and Tertiary dyke swarms, the GGF reactivated right-laterally in the Tertiary (*Holgate*, 1969; *Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993; *Thomson & Hillis*, 1995).

By analysis of the WNW-trending Permo-Carboniferous dyke swarm of northern Argyll, on the northwestern side of the GGF, *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 GGF since the Upper Jurassic, from field observations of Jurassic rocks in Argyll. On the island of Mull, Tertiary dykes are offset right-laterally along the GGF (**Figure 1**; *Thomson & Underhill*, 1993), which is consistent with the previous suggestions of *Holgate* (1969) and *Speight & Mitchell* (1979).

On seismic sections from the IMF Basin, the GGF appears as a ‘flower structure’ and inversion structures are visible in the northwestern corner of the basin, along the Wick Fault (**Figure 2**; *Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993). From structural studies along the GGF in Easter Ross (**Figure 2**), onshore well data from Tain and seismic data from the IMF Basin, *Underhill & Brodie* (1993) identified folds and faults, trending N-S to NNE-SSW, in Devonian strata adjacent to the GGF. Moreover, they suggested that the Jurassic outcrops in Easter Ross along the GGF (**Figure 2**) may be parts of flower structures that resulted from right-lateral slip along the GGF. In Jurassic strata of the Sutherland Terrace

(**Figure 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 GGF (right-lateral).

Estimates of right-lateral displacement on the GGF during the Tertiary are small, from 8 km to 29 km, depending on the studies (*Holgate*, 1969; *McQuillin et al.*, 1982; *Rogers et al.*, 1989; *Underhill & Brodie*, 1993). The exact timing of reactivation is uncertain. Several authors 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*, 1991b, *Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993; *Thomson & Hillis*, 1995).

1.4 Evidence for Cenozoic exhumation

From interpretation of seismic and well data, the IMF underwent exhumation during the Cenozoic and the western side of the North Sea tilted to the east (e.g. *Underhill*, 1991b; *Argent et al.*, 2002). Indeed, Jurassic strata in the IMF 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 IMF and *Hillis et al.* (1994) estimated 1 km of Tertiary erosion throughout the whole IMF.

Several authors 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 (*White & Lovell*, 1997; *Nadin et al.*, 1997; *Clift et al.*, 1998; *Jones et al.*, 2002; *Mackay et al.*, 2005; *Saunders et al.*, 2007; *Persano 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 (*Holford et al.*, 2009, 2010; *Jolivet*, 2007) 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; *Hitchen*, 2004; *Johnson et al.*, 2005; *Ritchie et al.*, 2003, 2008; *Smallwood*, 2004; *Stoker et al.*, 2005; *Tuitt et al.*, 2010). South of the Faroe Islands, such structures (e.g. the Wyville-Thomson ridge, Ymir ridges (WYTR), 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 ongoing 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) or (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 GGF and we discuss possible causes, such as differential sea-floor spreading along the NE Atlantic.

2. Method

Our data are from observations of Jurassic outcrops along both the GGF and the Helmsdale Fault (**Figure 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 IMF, in order to discuss the timing and possible causes of reactivation of the GGF.

3. Results

3.1 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 (**Figures 4 and 5**). Previous studies, notably a drilling site for coal exploration, indicate that the Jurassic strata abut a fault that trends NNE-SSW (**Figure 4**; *Miller*, 1851; *Judd,* 1873; *Institute of Geological Sciences, Sheet 94*, 1973). This fault is probably an eastern splay of the GGF (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 approx. 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 N-S to NE-SW (**Figures 4 and 5**). Moreover, several steep calcite veins, parallel to the GGF, cut the entire Jurassic sequence and their sigmoidal shapes indicate right-lateral slip along the fault (**Figure 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 (**Figure 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 oil field of the Outer Moray Firth, attributing these structures to overpressure. In other sedimentary basins (for example, the Neuquén Basin of Argentina, or the Wessex Basin, UK) ‘beef’ veins provide evidence of overpressure and maturation of organic matter at a depth of several km, 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 IMF Basin and then have been subject to post-Jurassic exhumation (*Hillis et al.*; 1994). This may have occurred during right-lateral slip along the GGF.

3.2 Shandwick

Two outcrops of Jurassic strata are accessible on the coast at low tide, south of Shandwick (**Figure 7**). At Port-an-Righ, the strata are Lower 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 GGF (e.g. *Judd*, 1873, *Underhill & Brodie*, 1993).

Port-an-Righ

The Jurassic strata at Port-an-Righ dip generally seaward at approx. 14° to 32° (**Figures 7 and 8**). However, from the top of the cliffs, a large fold is visible on the wave-cut platform, next to the GGF. 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 S, through 28-70° to the W, to 10-23° to the E; **Figure 7**). Throughout the area, steep calcite veins offset the Jurassic strata right-laterally (**Figure 8**). The veins strike at approx. 45° to the GGF. 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 (**Figure 8**; *Jonk et al.*, 2003), but we did not observe any striae.

Cadh'-an-Righ

Another Jurassic outcrop is visible at Cadh'-an-Righ (**Figure 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° (**Figure 7**). Once again, we found 'beef' in the Jurassic strata, as well as coal (**Figure 9**).

At Cadh'-an-Righ there is a clear fault contact between Jurassic and Devonian strata (**Figure 9**). The strike of the fault is parallel to the GGF (approx. N040). We found striae that pitch at approx. 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 where temperature is high enough for maturation of organic matter (*Rodrigues et al.*, 2009), its exhumation would imply a right-lateral displacement along the GGF of approx. 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).

3.3 Helmsdale

Between Golspie and Helmsdale, Permo-Trias to Upper Jurassic strata crop out along the Helmsdale Fault (**Figure 10**). At Helmsdale, Jurassic strata are in contact with the Helmsdale Granite (Silurian-Devonian; **Figures 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 syn-tectonic 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 (**Figure 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 (**Figure 11**). Such a motion is compatible with right-lateral displacement on the GGF. Indeed, according to previous studies, folds between the Helmsdale Fault and the GGF may have developed as a result of opposing senses of slip on these two faults (*Thomson & Underhill*, 1993).

4. Discussion

At Eathie and Shandwick, folds, faults and veins provide structural evidence for post-Jurassic right-lateral reactivation of the GGF. Furthermore, 'beef' at outcrop is one indication that the Mesozoic strata were subject to several km 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 GGF (*Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993). At Cadh'-an-Righ our observations provide further evidence for right-lateral reactivation of the GGF. However, the reverse faulting would indicate a local context of transpression, rather than transtension.

Our observations show clearly that right-lateral reactivation of the GGF was post-Jurassic, but we know of no younger strata onshore, other than Quaternary. Subsurface data from the offshore IMF Basin and the apparent offsets of Palaeocene-Eocene dykes in NW Scotland all indicate that reactivation occurred in Tertiary time (*Holgate*, 1969; *Underhill & Brodie*, 1993; *Thomson & Underhill*, 1993; *Thomson & Hillis*, 1995). However, the exact timing remains uncertain. *Underhill & Brodie* (1993) showed that the IMF Basin underwent regional uplift during the Cenozoic and they attributed this to reactivation of the GGF. 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 GGF occurred during one of these periods (**Figure 12**).

Hillis et al. (1994) suggested that exhumation in the IMF occurred in mid-late Danian time (65.5 – 61.7 Ma, early Palaeogene), when a major unconformity developed. As we have explained earlier, 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 GGF 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 GGF 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 IMF 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 maybe coeval with reactivation of the GGF. Thus, it is most likely that reactivation of the GGF occurred in Palaeogene time (after 52 Ma).

Amongst the possible causes for reactivation of the GGF and for Cenozoic uplift of Scotland are: (1) mantle processes from the Iceland Plume, (2) intra-plate compression from the Alpine Orogeny, (3) ridge push from the NE Atlantic and (4) variations in 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 (**Figure 13**), generated left-lateral transpressional displacement along the FFZ, 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 (JMMC) 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 (**Figures 12 and 13**). According to the stationary hot spot 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 JMMC from Greenland.

The Middle Eocene to Late Oligocene was a period of uplift in Scotland and of compressional deformation on the NW United Kingdom Continental Margin (**Figure 12**). Numerous compressional structures developed offshore Scotland (e.g. the Wyville-Thomson, Ymir ridges (WYTR), the Alpin Dome and the Judd Anticline) from the Middle Eocene to the Early Miocene (**Figure 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 GGF. Indeed, a left-lateral displacement along the FFZ is compatible with a right-lateral reactivation of the GGF (**Figure 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 GGF. 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 GGF probably occurred in this interval (**Figure 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 GGF, under transpression.

(2) The ‘beef’ structures in Jurassic shale at Eathie and Shandwick provide evidence that this formation accumulated deeper offshore in the IMF Basin and has been subject to post-Jurassic exhumation. This exhumation would be compatible with right-lateral displacement on the GGF. Assuming that ‘beef’ structures form at approx. 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 GGF was in the order of 10-18 km.

(3) The timing of reactivation of the GGF remains uncertain; however we suggest that the GGF reactivated right-laterally in a time interval from Late Eocene to Late Oligocene, *c*. 37 to 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 FFZ due to differential sea-floor spreading and plate readjustment in the NE Atlantic (separation of the JMMC, ‘ridge jump’ from the Aegir to the Kolbeinsey ridges). Indeed, left-lateral slip along the FFZ is compatible with right-lateral reactivation of the GGF.

(4) In the future, low-temperature geochronological studies may provide better constraints on the timing of reactivation of the GGF. However, the vertical motion along the GGF may not have been significant enough to be detectable in such studies. Similar work along the MTF, Norway, would provide better constraints on the relationships between differential spreading along the NE Atlantic, left-lateral slip along the FFZ and JMFZ, uplift of Scotland and Norway, and Tertiary reactivation of the GGF and MTF.

Acknowledgements

We would like to thank Chevron USA for funding the PhD project of E. Le Breton and in particular Gavin Lewis and Peter Connolly for instigating the project. We are grateful to

Andrew Hurst and John Parnell for providing maps, publications, data and encouragement, during our visit to Aberdeen University in August 2011. We also thank Marc Jolivet of the University of Rennes 1 for information on reactivation of the GGF. Finally, we thank Andrew Hurst and Howard Johnson for their helpful reviews.

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Figure Captions

Figure 1. Simplified geological map of northern Scotland (modified after *Stone*, 2007).

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

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

Figure 4. Geological map of Eathie (modified after *Institute of Geological Sciences, Sheet 94,* 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.

Figure 5. Photographs of Jurassic outcrop at Eathie. A. Contact between Jurassic strata and Devonian Old Red Sandstone in north east area. B. Contact between Jurassic strata and Neoproterozoic basement in south west area. C. Fold in Jurassic strata adjacent to Great Glen Fault . D. Calcite veins right-laterally offsetting Jurassic strata and striking parallel to GGF (approx. N040°).

Figure 6. Photographs of 'cone-in-cone' (A and B) and 'beef' calcite cement (B) in Jurassic shale at Eathie. C. Interpretation of structures in B.

Figure 7. Geological map of Shandwick (modified after *Institute of Geological Sciences, Sheet 94,* 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 (Figures 8 and 9).

Figure 8. Photographs of Jurassic outcrop 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 GGF. B. Calcite veins right-laterally offsetting Jurassic strata. C. Fault contact between Jurassic and Devonian strata.

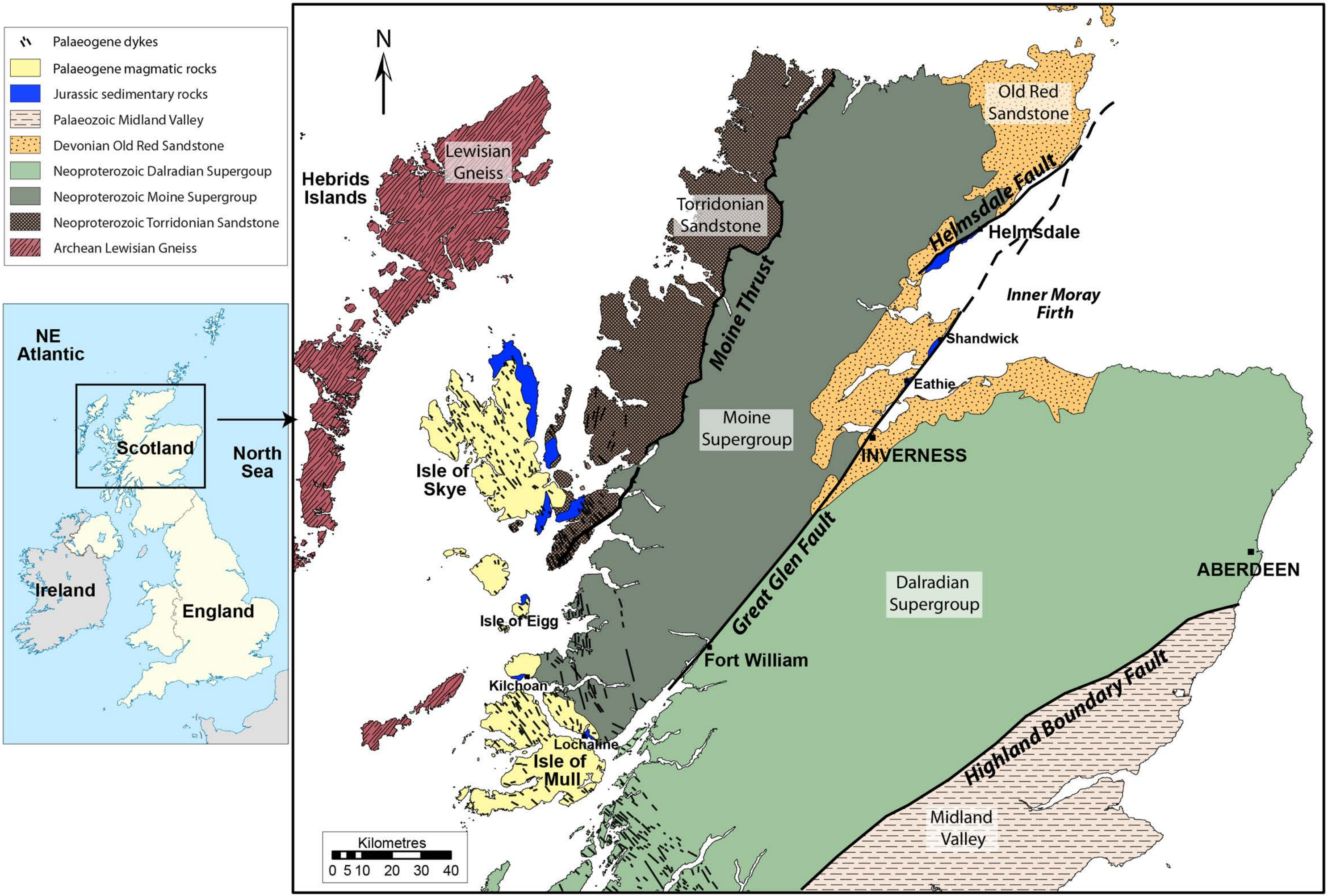
Figure 9. Photographs of Jurassic outcrop at Cadh-an-Righ. A. Wide-angle view of fault contact between Jurassic and Devonian strata. B. Close-up view of same showing reverse and right-lateral slip along GGF. C. 'Beef' in Jurassic shale. D. Fragment of Jurassic coal next to GGF.

Figure 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 (GGF). Stereonets for Golspie and Helmsdale (lower hemisphere) show great circles (for bedding planes) that intersect at shallowly-plunging fold axes. Stars indicate locations of photographs (Figure 11).

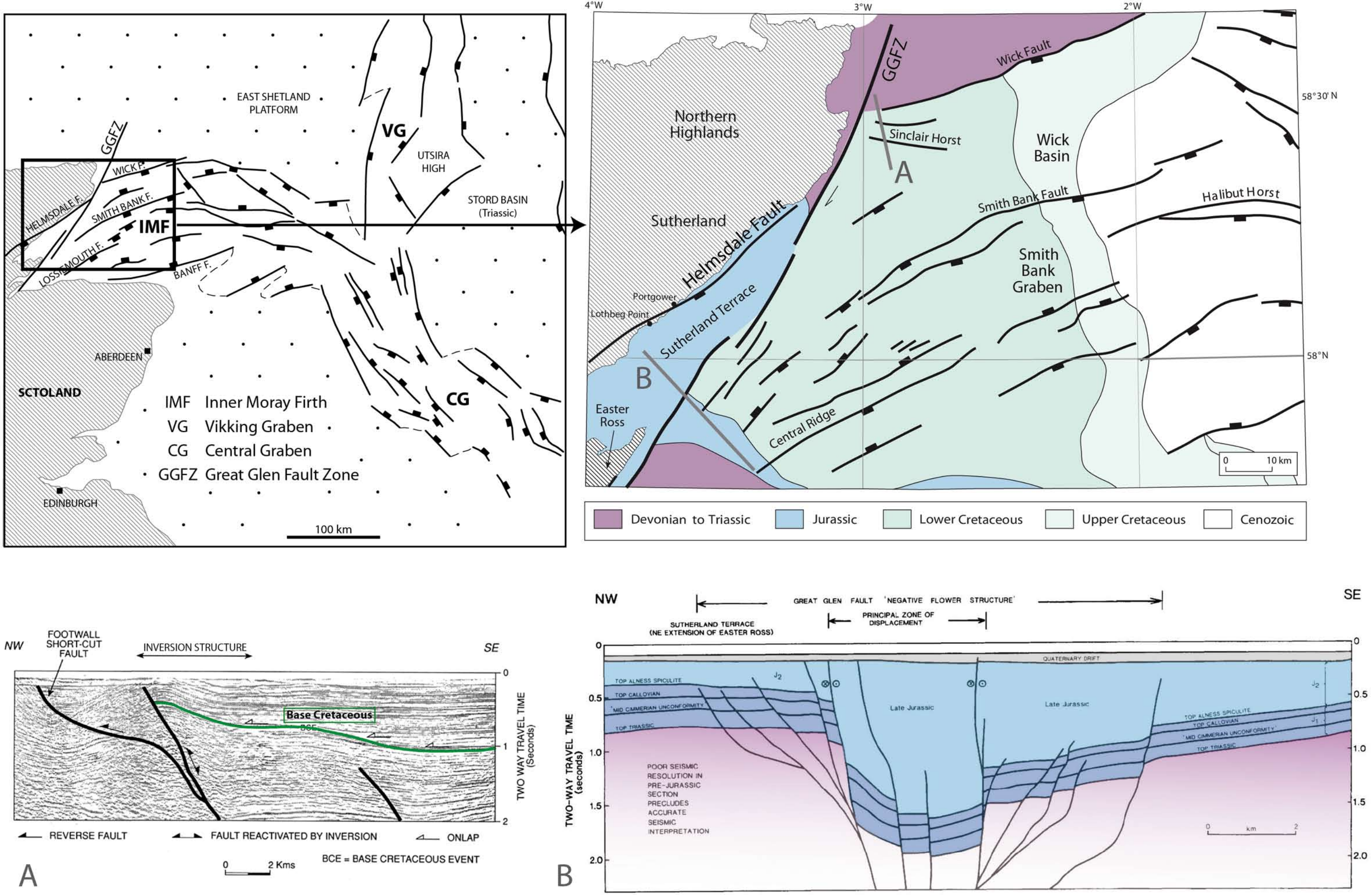
Figure 11. Photographs of Jurassic outcrop near Helmsdale. A. Jurassic 'Boulder Beds' in contact with Helmsdale Granite. B. Syn-tectonic Jurassic conglomerate containing clasts of Devonian strata and extensional calcite veins. C. Sigmoidal calcite veins left-laterally offsetting Jurassic strata and striking parallel to Helmsdale Fault.

Figure 12. Summary and correlation of events. Numbers refer to (1) post-breakup compressional deformation offshore Scotland (*Smallwood et al.*, 2004; *Johnson et al.*, 2005; *Ricthie 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), ridge push, Iceland Mantle Plume pulse (correlation between age of V-shaped ridges and plume pulses from *White & Lovell*, 1997), development of Iceland Plateau, and compressional Alpine and Pyrenean stress field (*Tuitt et al.*, 2010). Period of synchronous events (hachured) may represent timing of reactivation of Great Glen Fault (GGF). For locations of post-breakup compressional structures offshore Scotland, see Figure 13.

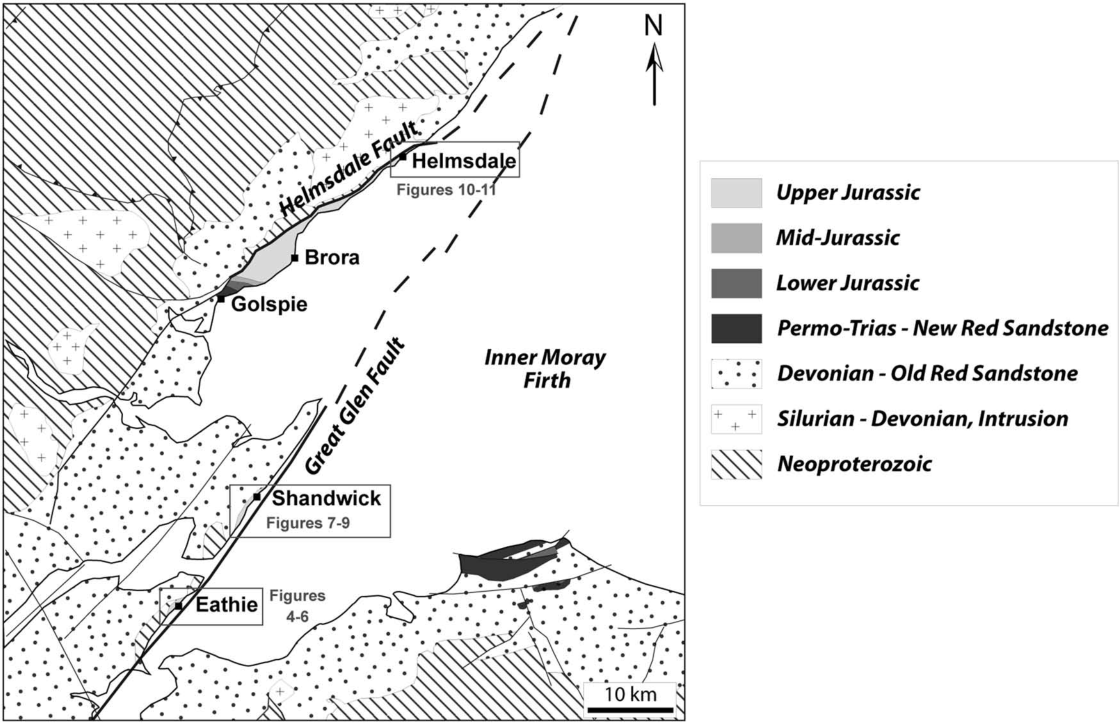
Figure 13. Position of Europe at 36.6 Ma (Late Eocene) relative to a stationary Greenland plate. According to a new method of restoration differential sea-floor spreading along Reykjanes, Aegir and Mohns ridges generated left-lateral displacements along Faroe and Jan Mayen fracture zones (*Le Breton et al,.* 2012). Such displacements are compatible with right-lateral reactivation of Great Glen Fault and possibly of Møre Trøndelag Fault, respectively. Abbreviations: 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).

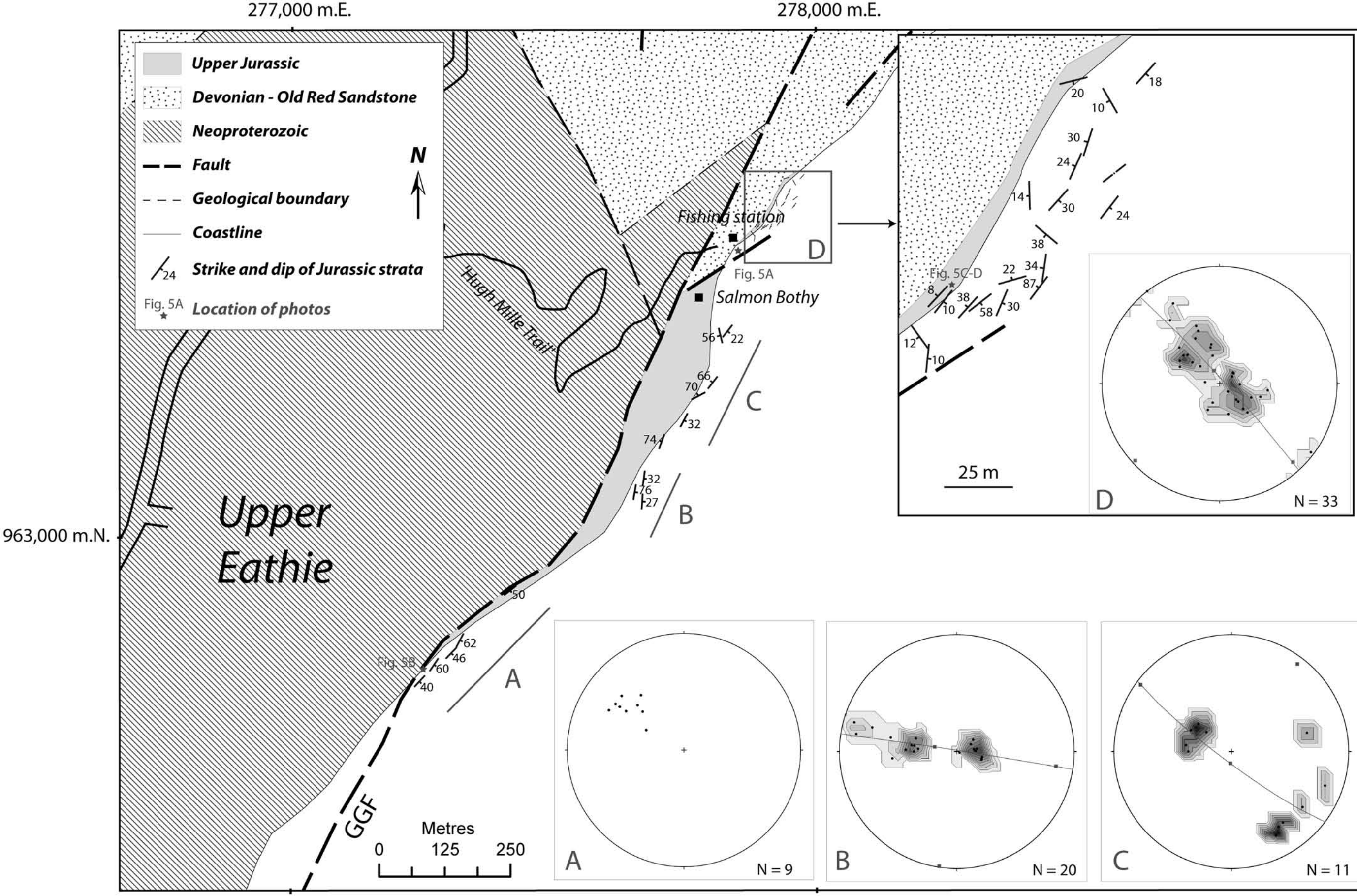


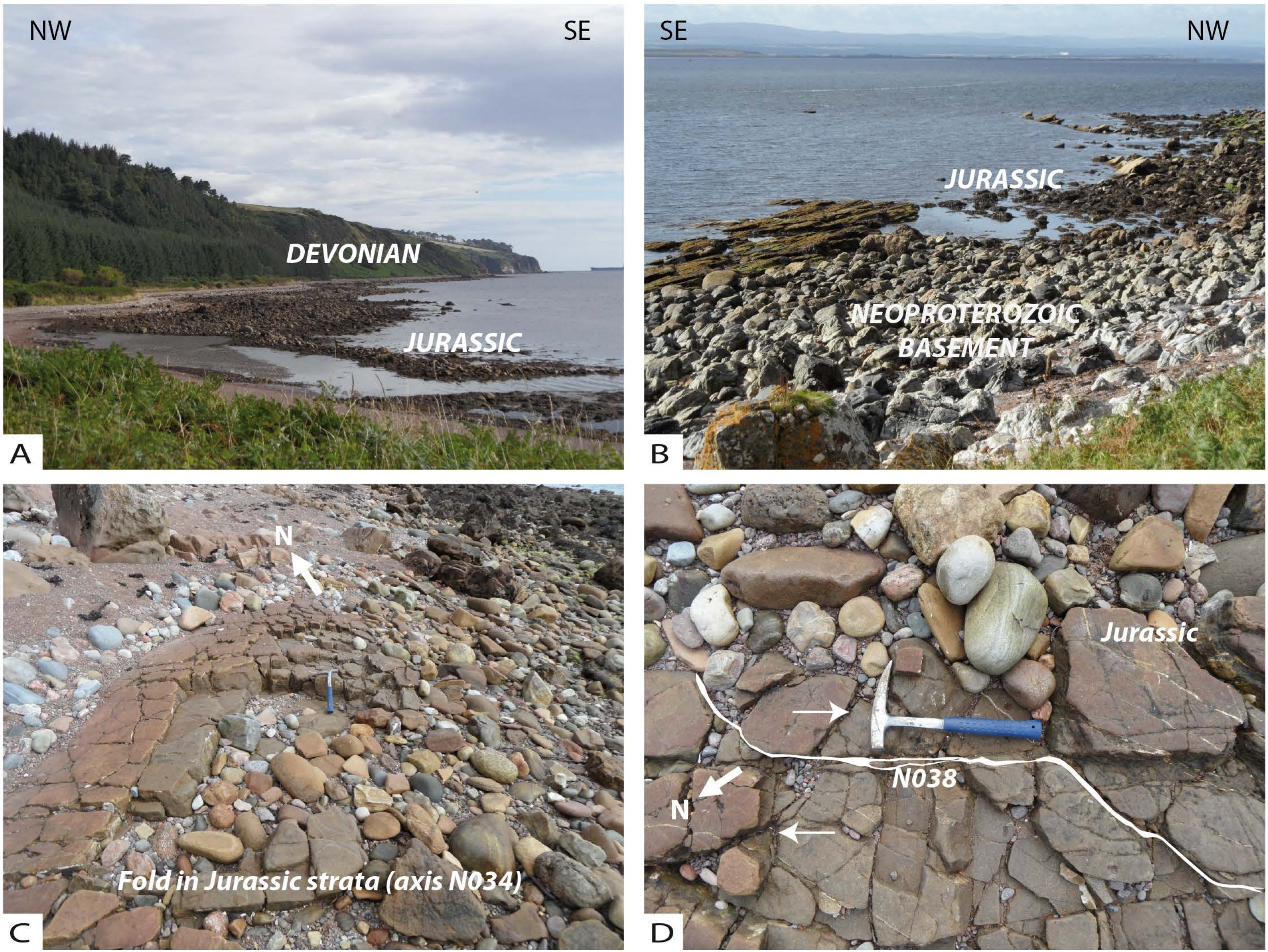
Palaeogene dykes
Palaeogene magmatic rocks
Jurassic sedimentary rocks
Palaeozoic Midland Valley
Devonian Old Red Sandstone
Neoproterozoic Dalradian Supergroup
Neoproterozoic Moine Supergroup
Neoproterozoic Torridonian Sandstone
Archean Lewisian Gneiss
NE Atlantic
Scotland
North Sea
Ireland
England
N
Hebrids Islands
Lewisian Gneiss
Torridonian Sandstone
Moine Thrust
Moine Supergroup
Old Red Sandstone
Helmsdale Fault
Helmsdale
Inner Moray Firth
Shandwick
Eathie
INVERNESS
Isle of Skye
Isle of Eigg
Great Glen Fault
Fort William
Dalradian Supergroup
ABERDEEN
Kilchoan
Lochaline
Isle of Mull
Highland Boundary Fault
Midland Valley
Kilometres
0 5 10 20 30 40

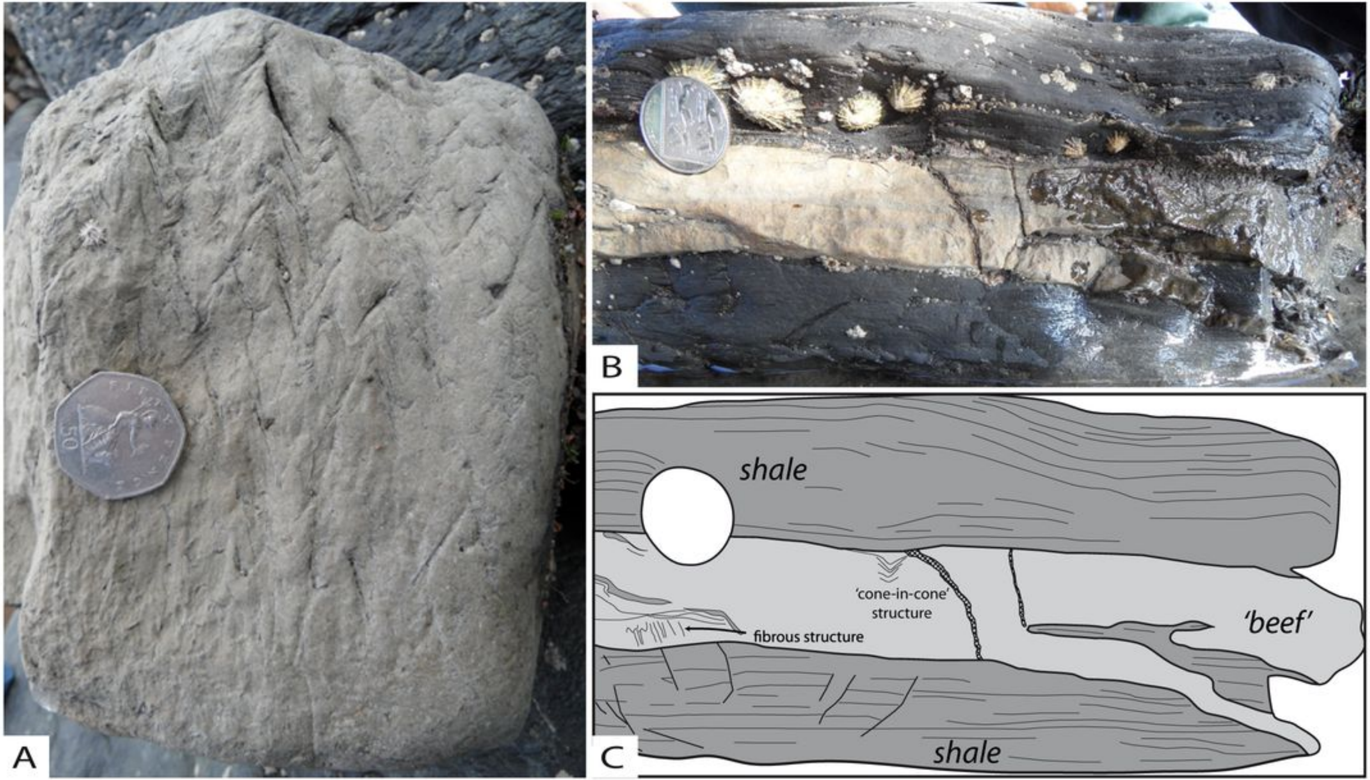


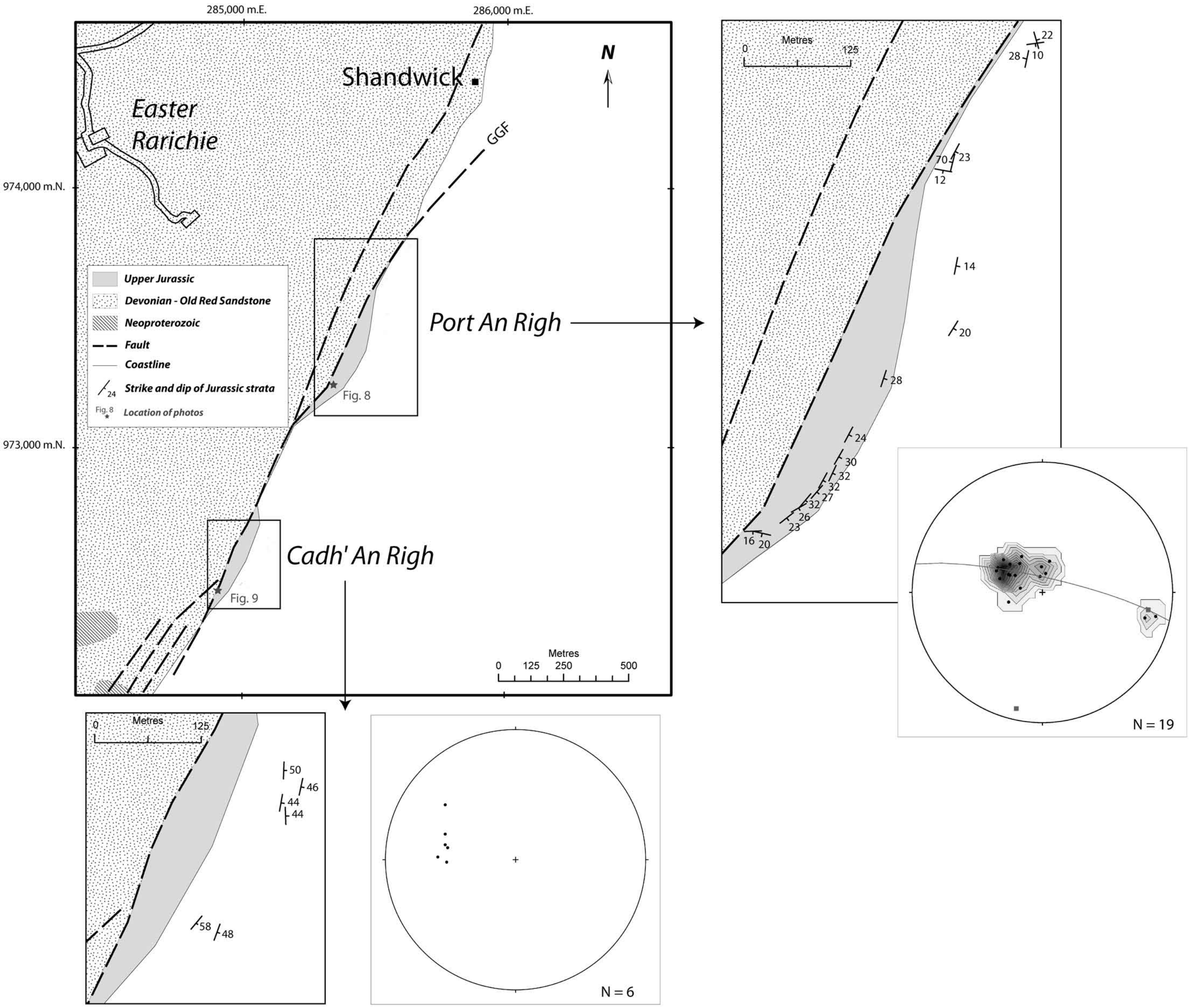
EAST SHETLAND PLATFORM
VG
UTSIRA HIGH
STORD BASIN (Triassic)
GGFZ
WICK F.
HELMSDALE F.
SMITH BANK F.
IMF
LOSSIEMOUTH F.
BANFF F.
ABERDEEN
SCTOLAND
EDINBURGH
CG
IMF Inner Moray Firth
VG Vikking Graben
CG Central Graben
GGFZ Great Glen Fault Zone
100 km
4°W
3°W
2°W
58°30' N
58°N
Wick Fault
GGFZ
Northern Highlands
Sinclair Horst
A
Wick Basin
Sutherland
Helmsdale Fault
Smith Bank Fault
Halibut Horst
Smith Bank Graben
Portgower
Lothbeg Point
Sutherland Terrace
B
Easter Ross
Central Ridge
0 10 km
Devonian to Triassic
Jurassic
Lower Cretaceous
Upper Cretaceous
Cenozoic
NW
SE
FOOTWALL SHORT-CUT FAULT
INVERSION STRUCTURE
Base Cretaceous
BCE
TWO WAY TRAVEL TIME (Seconds)
0
1
2
REVERSE FAULT
FAULT REACTIVATED BY INVERSION
ONLAP
0 2 Kms
BCE = BASE CRETACEOUS EVENT
A
NW
SE
GREAT GLEN FAULT 'NEGATIVE FLOWER STRUCTURE'
SUTHERLAND TERRACE (NE EXTENSION OF EASTER ROSS)
PRINCIPAL ZONE OF DISPLACEMENT
QUATERNARY DRIFT
TOP ALNESS SPICULITE
TOP CALLOVIAN
'MID CIMMERIAN UNCONFORMITY'
TOP TRIASSIC
J2
J1
Late Jurassic
POOR SEISMIC RESOLUTION IN PRE-JURASSIC SECTION PRECLUDES ACCURATE SEISMIC INTERPRETATION
TWO-WAY TRAVEL TIME (seconds)
0
0.5
1.0
1.5
2.0
0 km 2
B


N
Helmsdale Fault
Helmsdale
Figures 10-11
Brora
Golspie
Great Glen Fault
Inner Moray Firth
Shandwick
Figures 7-9
Eathie
Figures 4-6
10 km
Upper Jurassic
Mid-Jurassic
Lower Jurassic
Permo-Trias - New Red Sandstone
Devonian - Old Red Sandstone
Silurian - Devonian, Intrusion
Neoproterozoic

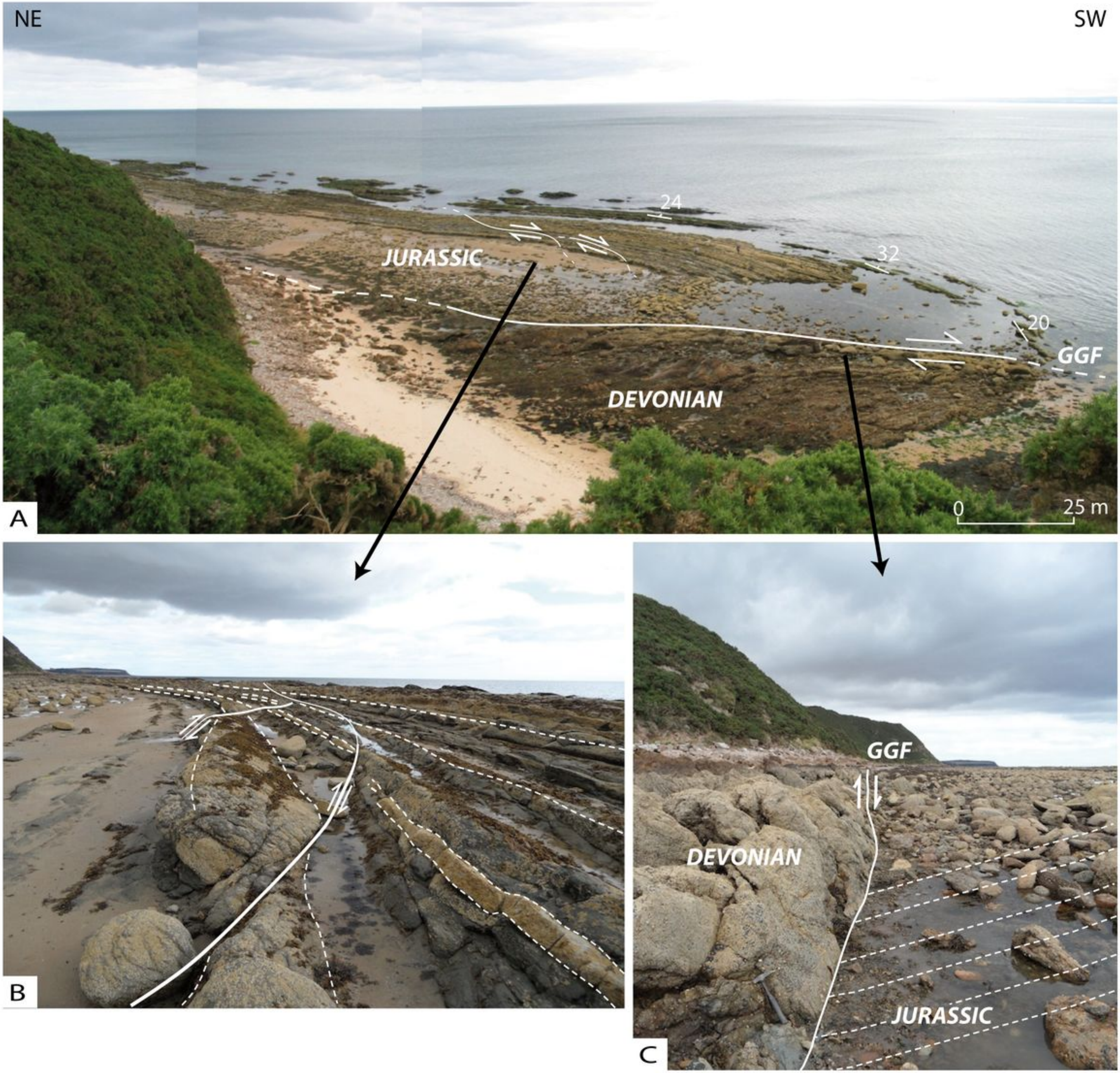

277,000 m.E.
278,000 m.E.
963,000 m.N.
Upper Jurassic
Devonian - Old Red Sandstone
Neoproterozoic
Fault
Geological boundary
Coastline
24
Strike and dip of Jurassic strata
Fig. 5A
Location of photos
N
Upper Eathie
'Hugh Mille Trail'
Fishing station
Salmon Bothy
Fig. 5A
Fig. 5B
Fig. 5C-D
GGF
Metres
0
125
250
25 m
A
B
C
D
N = 9
N = 20
N = 11
N = 33


NW
SE
DEVONIAN
JURASSIC
A
SE
NW
JURASSIC
NEOPROTEROZOIC
BASEMENT
B
N
Fold in Jurassic strata (axis N034)
C
Jurassic
N038
N
D


A
B
C
shale
'cone-in-cone'
structure
fibrous structure
'beef'
shale

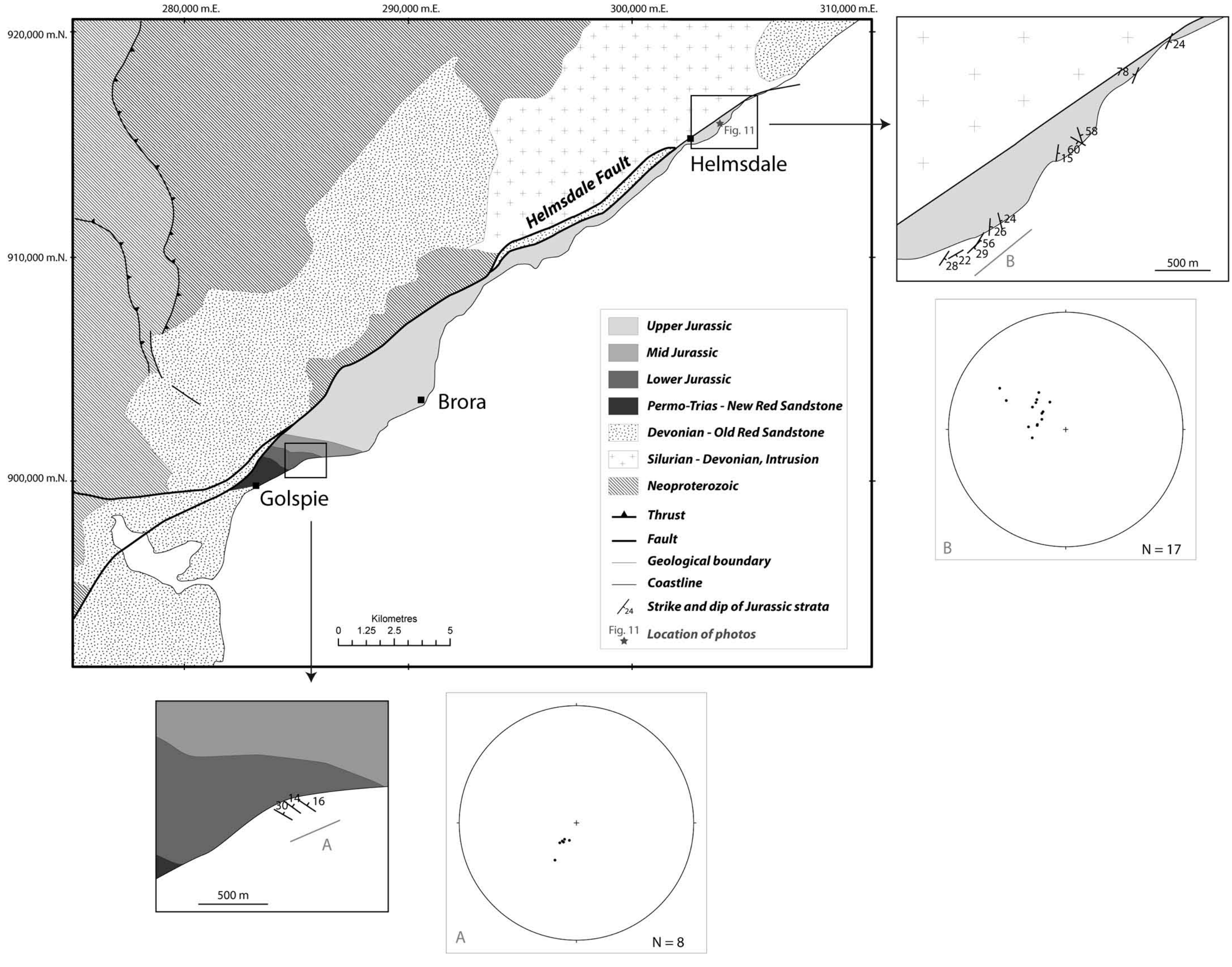


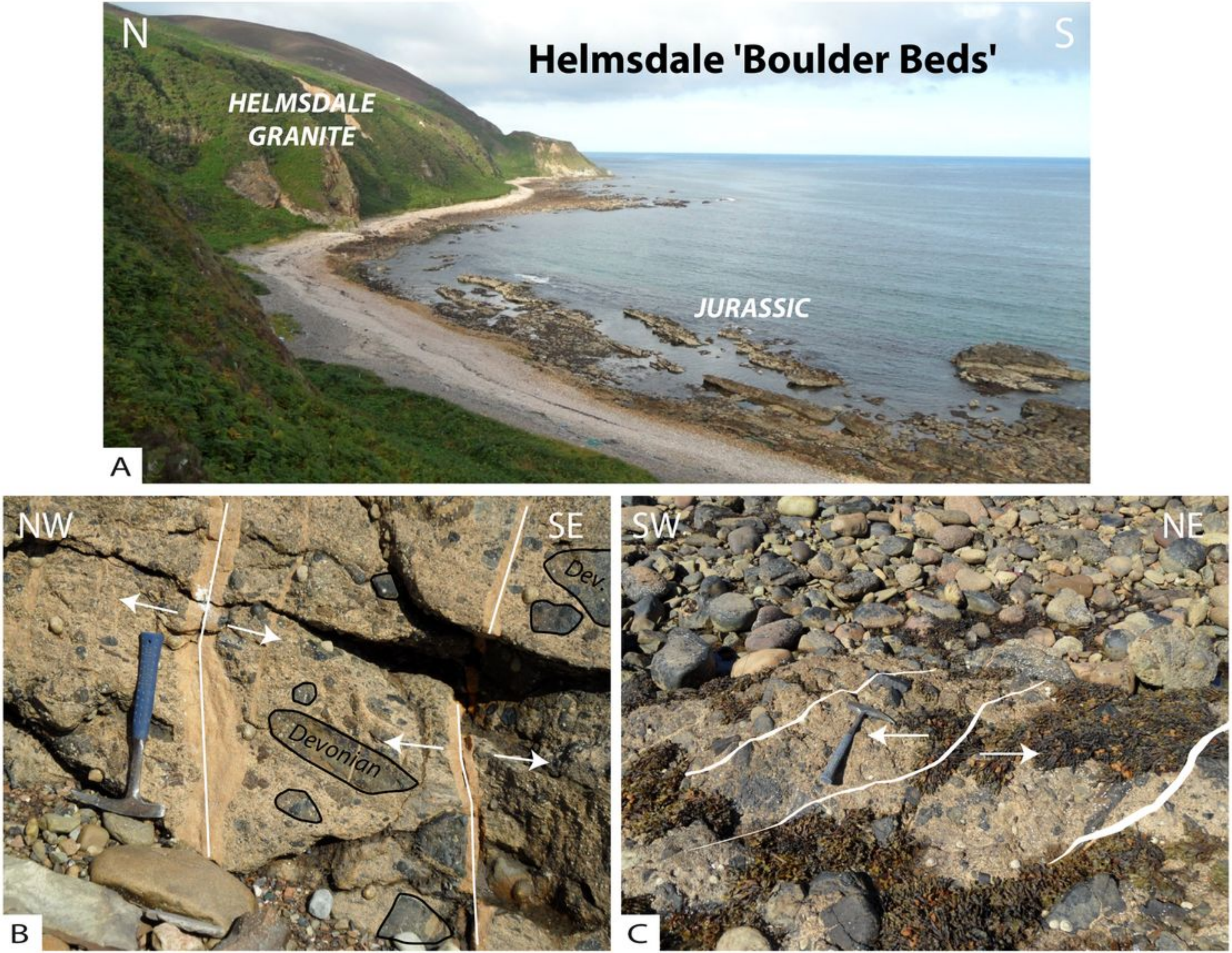
285,000 m.E.
286,000 m.E.
N
Shandwick
Easter Rarichie
GGF
974,000 m.N.
973,000 m.N.
Upper Jurassic
Devonian - Old Red Sandstone
Neoproterozoic
Fault
Coastline
Strike and dip of Jurassic strata
Location of photos
Port An Righ
Fig. 8
Cadh' An Righ
Fig. 9
Metres
0
125
250
500
N = 19
N = 6



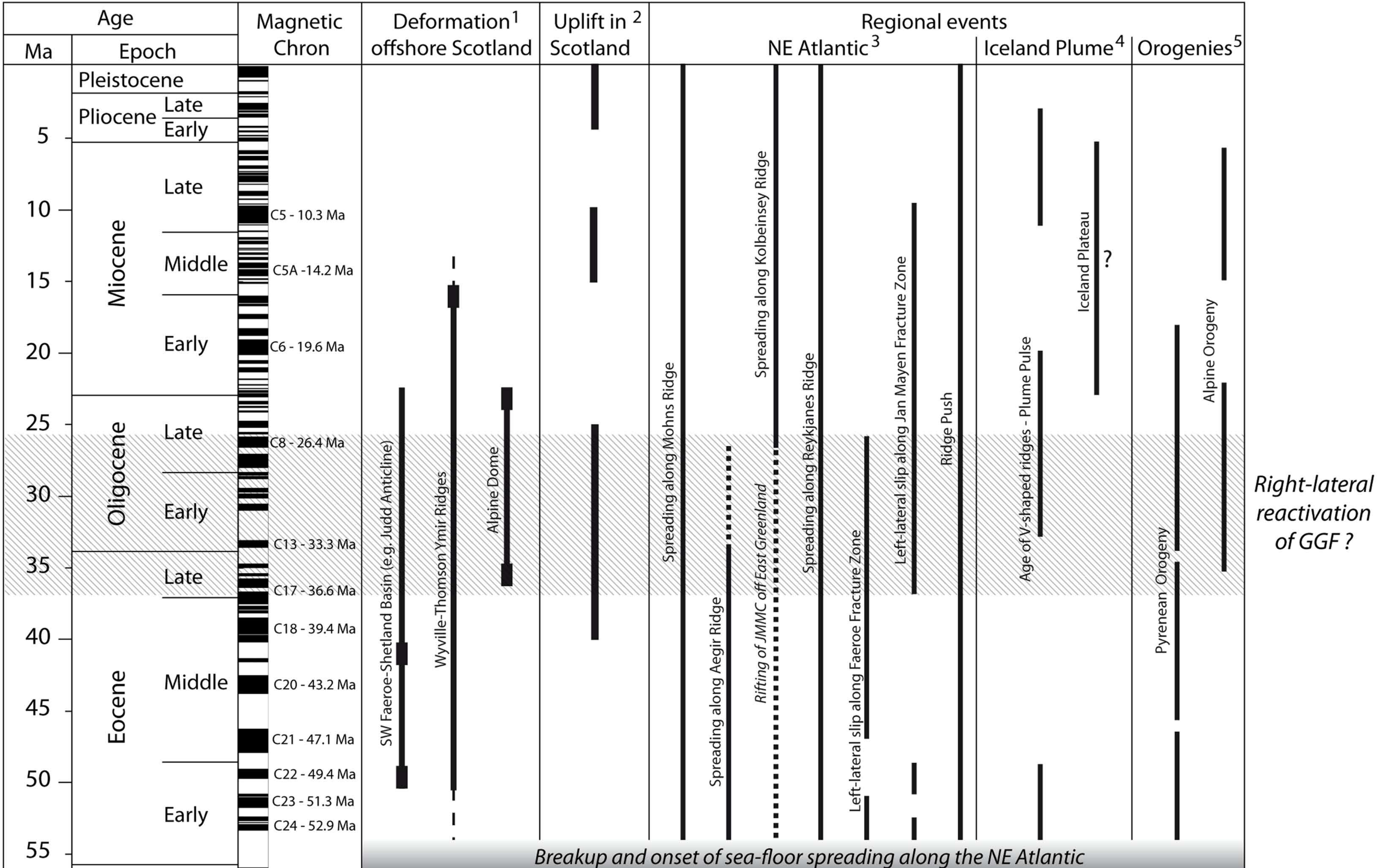
NE
SW
24
32
20
JURASSIC
GGF
DEVONIAN
0
25 m
A
B
GGF
DEVONIAN
JURASSIC
C


DEVONIAN
N020
JURASSIC
A
coal
breccia
N040
coal
B
'beef'
nodule
C
shale
coal
D

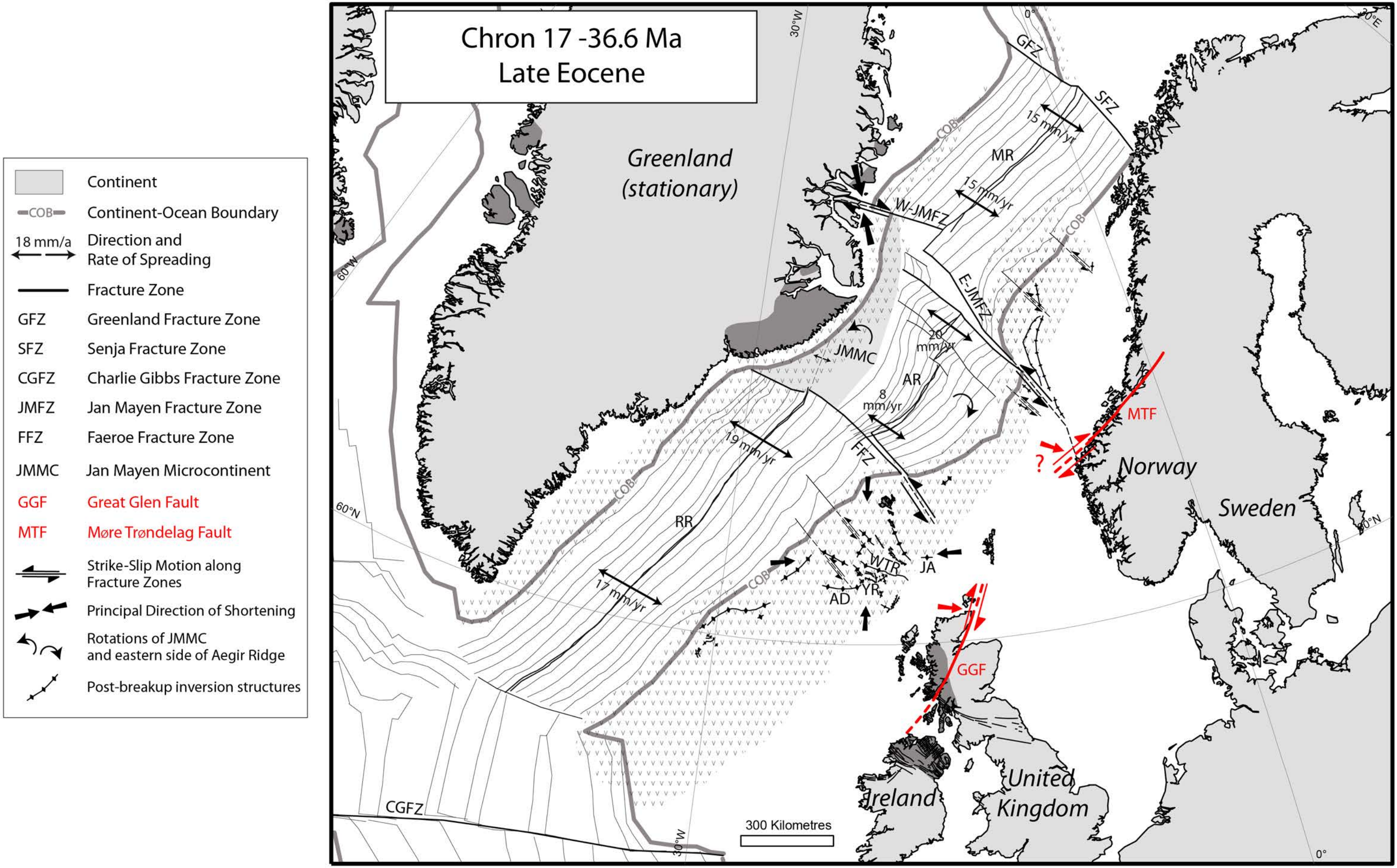

280,000 m.E.
290,000 m.E.
300,000 m.E.
310,000 m.E.
920,000 m.N.
910,000 m.N.
900,000 m.N.
Helmsdale Fault
Helmsdale
Fig. 11
Brora
Golspie
Upper Jurassic
Mid Jurassic
Lower Jurassic
Permo-Trias - New Red Sandstone
Devonian - Old Red Sandstone
Silurian - Devonian, Intrusion
Neoproterozoic
Thrust
Fault
Geological boundary
Coastline
Strike and dip of Jurassic strata
24
Fig. 11
Location of photos
Kilometres
0 1.25 2.5 5
24
78
58
60
15
24
26
56
29
22
28
B
500 m
B
N = 17
30
14
16
A
500 m
A
N = 8



N
S
Helmsdale 'Boulder Beds'
HELMSDALE
GRANITE
JURASSIC
A
NW
SE
Dev.
Devonian
B
SW
NE
C



Age
Ma
Epoch
Magnetic Chron
Deformation[1] offshore Scotland
Uplift in Scotland[2]
Regional events
NE Atlantic[3]
Iceland Plume[4]
Orogenies[5]
Pleistocene
Pliocene
Late
Early
Miocene
Late
Middle
Early
Oligocene
Late
Early
Eocene
Late
Middle
Early
5
10
15
20
25
30
35
40
45
50
55
C5 - 10.3 Ma
C5A -14.2 Ma
C6 - 19.6 Ma
C8 - 26.4 Ma
C13 - 33.3 Ma
C17 - 36.6 Ma
C18 - 39.4 Ma
C20 - 43.2 Ma
C21 - 47.1 Ma
C22 - 49.4 Ma
C23 - 51.3 Ma
C24 - 52.9 Ma
SW Faeroe-Shetland Basin (e.g. Judd Anticline)
Wyville-Thomson Ymir Ridges
Alpine Dome
Spreading along Mohns Ridge
Spreading along Aegir Ridge
Spreading along Kolbeinsey Ridge
Rifting of JMMC off East Greenland
Spreading along Reykjanes Ridge
Left-lateral slip along Faeroe Fracture Zone
Left-lateral slip along Jan Mayen Fracture Zone
Ridge Push
Age of V-shaped ridges - Plume Pulse
Iceland Plateau
?
Pyrenean Orogeny
Alpine Orogeny
Right-lateral reactivation of GGF ?
Breakup and onset of sea-floor spreading along the NE Atlantic



Chron 17 -36.6 Ma
Late Eocene
Continent
COB
Continent-Ocean Boundary
18 mm/a
Direction and Rate of Spreading
Fracture Zone
GFZ Greenland Fracture Zone
SFZ Senja Fracture Zone
CGFZ Charlie Gibbs Fracture Zone
JMFZ Jan Mayen Fracture Zone
FFZ Faeroe Fracture Zone
JMMC Jan Mayen Microcontinent
GGF Great Glen Fault
MTF Møre Trøndelag Fault
Strike-Slip Motion along Fracture Zones
Principal Direction of Shortening
Rotations of JMMC and eastern side of Aegir Ridge
Post-breakup inversion structures
Greenland
(stationary)
Norway
Sweden
United Kingdom
Ireland
GFZ
SFZ
W-JMFZ
E-JMFZ
FFZ
CGFZ
MR
AR
RR
JMMC
WTR
JA
YR
AD
MTF
GGF
15 mm/yr
20 mm/yr
8 mm/yr
19 mm/yr
17 mm/yr
60°N
30°W
60°W
0°
30°E
300 Kilometres