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The post-Variscan development of the British Isles within a regional transfer zone influenced by orogenesis

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Abstract

The break-up of Pangaea after the Variscan Orogeny included rifting extending southwards from the Barents Sea via the Norwegian–Greenland Rift and into the North Sea, and northwards from the Central Atlantic. These two major rift systems interacted to form an approximately 1200-km-wide transfer zone across the British Isles, where a complex network of basins developed during the Mesozoic. Fault patterns were commonly controlled by reactivation of Precambrian, Caledonian and Variscan structures. The two main rift systems were unable to breach this regional transfer zone, where the crust had been thickened by the Caledonian and Variscan orogenies, until the Eocene. Breaching did not occur down the North Sea and through the English Channel because of Alpine contraction in NW Europe. Instead, breaching occurred around the west of Ireland and NW Scotland, so the British Isles remained connected to Europe rather than to the North American Plate.

Keywords: British Isles; North Atlantic; Rifting; Transfer zone

1. Introduction

The British Isles have been intensively studied, revealing a complex geological history. The complexity includes a network of Mesozoic basins across NW Europe. This paper presents a model to explain the complexity of the tectonics of the region since the Variscan Orogeny (Carboniferous and Early Permian), involving interaction between two major rift systems that eventually linked to form the North Atlantic Ocean. It is proposed that the network of basins in the British Isles region formed within a regional transfer zone between these rift systems.

A *transfer zone* is an area of deformation and bed rotation between two normal faults or rift systems that step in map view (Morley et al., 1990; Peacock et al., 2000a). Transfer zones include *relay ramps*, in which the stepping faults dip in the same direction (Fig. 1; Goguel, 1952; Larsen, 1988; Peacock et al., 2000a; termed *synthetic transfer zones* by Morley et al., 1990). Interaction and transfer of displacement between the stepping faults is indicated by rotated bedding in the relay ramp, high displacement gradients near interacting fault tips (Peacock and Sanderson, 1991), and by connecting faults that cut across the transfer zone (Peacock et al., 2000a).

Transfer zones can represent regional-scale fault interaction. For example, Standlee et al. (1992) suggest that the initiation of the South Atlantic involved an ~500-km-wide transfer zone, Nelson et al. (1992, fig. 2) show the Eastern and Western branches of the East African Rift to step by ~400 km, and Peacock et al. (2000b) describe an ~100-km-wide relay ramp in NE Greenland. Peacock (2003) shows that the widths of transfer zones in the British Isles obey a power-law scaling relationship up to widths of up to at least 250 km (Fig. 2). The transfer zone described here is the largest such structure so far reported.

2. The development of the British Isles Transfer Zone

2.1. Pre-Permian structures

Precambrian, Caledonian and Variscan orogenic cycles

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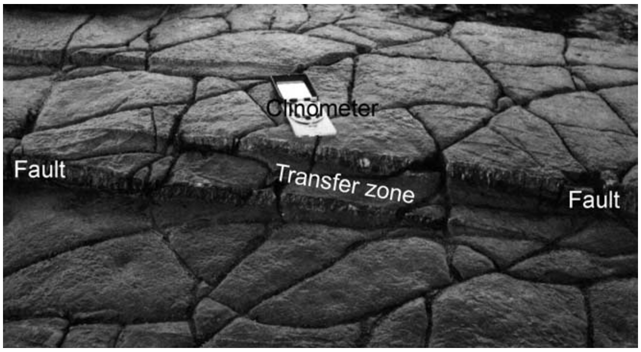


Fig. 1. Photograph of two normal faults stepping and interacting to form a *transfer zone* (e.g. Morley et al., 1990) in the Liassic limestones at Kilve, Somerset. This transfer zone is a *relay ramp* (e.g. Larsen, 1988), formed by faults that dip in the same direction.

produced major structures with a wide range of orientations in the British Isles. Precambrian structures include the N–S-trending (‘Malvernoid’) structures in the English Midlands (Chadwick et al., 1989). The Caledonian Orogeny (Early Palaeozoic and Early Devonian) is dominated by NE–SW striking structures in the northern British Isles (e.g. Lefort, 1989, fig. 12), although the Caledonian structures in eastern England appear to strike NW–SE (Chadwick et al., 1989, fig. 1). Rifting occurred in the British Isles during the Late Devonian and Early Carboniferous (e.g. Church and Gawthorpe, 1994). The ∼N–S contraction during the Variscan Orogeny (Late Carboniferous to Early Permian) is most intense in the southern British Isles. The Variscan structures have a dominant ∼E–W trend, including south-dipping thrusts, but major NW–SE striking strike-slip faults occur (e.g. Lefort, 1989, fig. 51). The Variscan Orogeny resulted in the development of Pangaea, but rifting of parts of this super-continent started as early as the Namurian, with the initiation of the N–S striking Norwegian–Greenland Rift (Fig. 3a; e.g. Ziegler, 1989; Stemmerik, 2000).

2.2. The Permo-Triassic

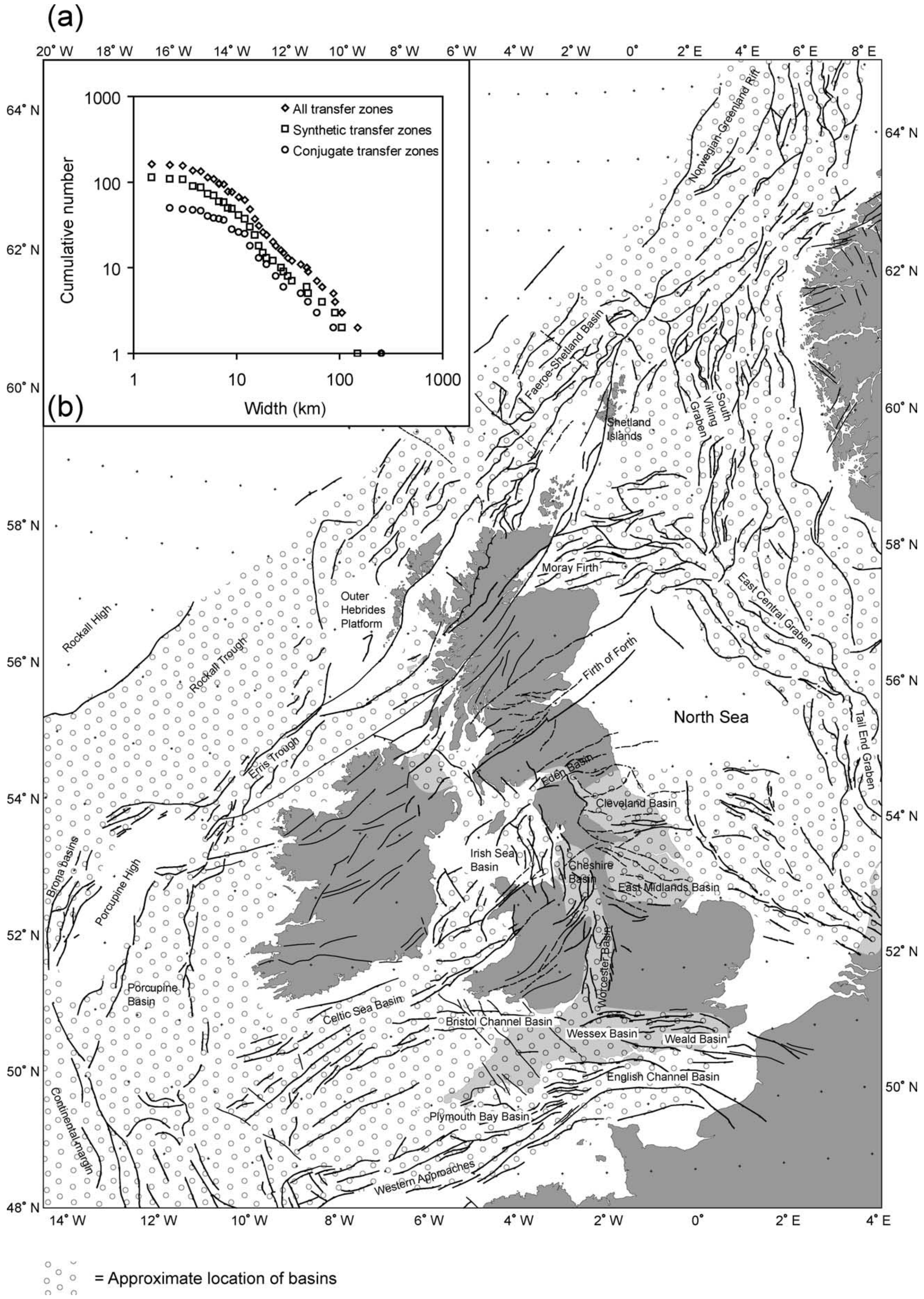
The Norwegian–Greenland Rift continued to develop through the Permian and Mesozoic, probably propagating into the Shetlands area during the Permian (Fig. 3b; Larsen, 1988; Ziegler, 1989). Rifting also started in the Tethys region during the Permian. Subsidence accelerated in the Norwegian–Greenland Rift at the end of the Permian, with marine conditions throughout the Triassic. The Norwegian–Greenland Rift propagated into the North Sea in the Early Triassic, with development of the Viking, Central and Moray Firth grabens (Fig. 2). Rapid subsidence also occurred in the Faeroe–Rockall rift system during the Triassic, with subsidence in the Porcupine, Celtic Sea and Western Approaches basins. Rifting initiated to the east of Newfoundland and between Grand Banks and Iberia during the Middle Triassic, and between Nova Scotia and Morocco during the Ladinian (Middle Triassic) and Carnian (Late Triassic) (Fig. 3c). Rifting occurred across much of NW Europe by the Late Triassic, as far east as Poland, with Tethys-related rifting in the Bay of Biscay and NW Africa (Ries, 1978; Ziegler, 1989, fig. 4). A widespread marine transgression occurred during the Rhaetian.

Onshore British Isles, normal faults were related to post-orogenic collapse during the Permian (e.g. Shail and Alexander, 1997), but there was limited basin development until the Triassic. Extension in the network of Triassic basins (Fig. 2) was commonly along reactivated Precambrian, Caledonian and Variscan structures (e.g. Chadwick et al., 1989), with displacement transferred across and between basins in southern England via reactivated NW–SE striking Variscan structures (e.g. Miliorizos and Ruffell, 1998). Basins active during the Permo-Triassic include the E–W striking Bristol Channel and Wessex basins, N–S striking Worcester Basin, and NE–SW striking Cheshire Basin (Chadwick et al., 1989, fig. 2a). Chadwick et al. (1989) suggest that the Permo-Triassic to Early Jurassic basins developed in an overall E–W extensional regime, but this does not explain the development of E–W striking basins. The basins appear to have formed in a variety of stress and strain systems. For example:

- Ruffell et al. (1995) suggest NW–SE extension in the rhomb-shaped Plymouth Bay Basin, perhaps in a pull-apart within a strike-slip fault system.
- Nemcok and Gayer (1996) show that NE–SW extension occurred from Late Triassic to Early Cretaceous in the north of the Bristol Channel Basin, while Peacock and Sanderson (1999) show that N–S extension occurred in the south of the Basin.
- Hibsch et al. (1995) show there was E–W to ENE–WSW extension from the Late Triassic to Late Jurassic in central and NE England.

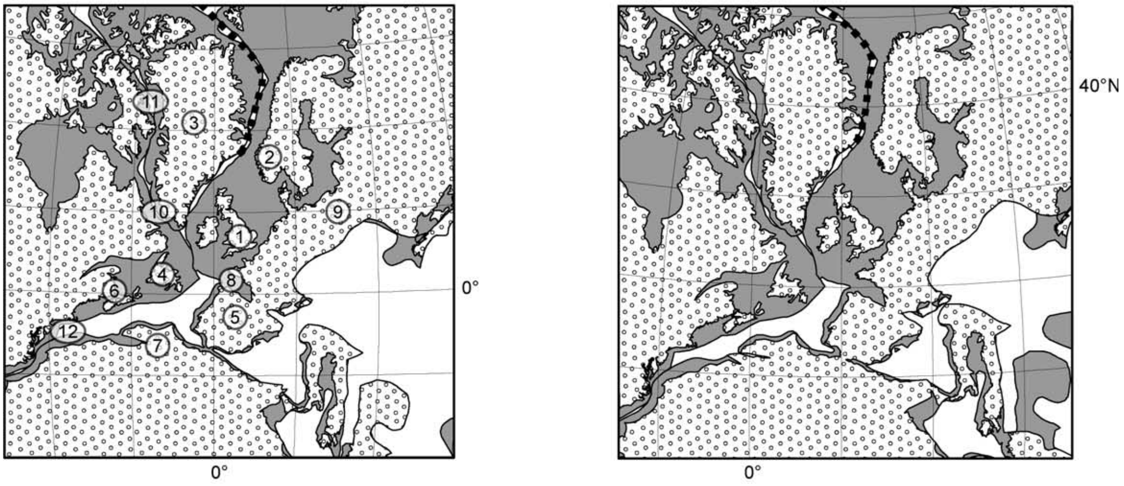
I suggest that the network of rifts that developed across the British Isles during the Late Triassic formed in the complex stress and strain system and the complexly anisotropic crust between the Norwegian–Greenland (and North Sea) Rift System and the rift system propagating northwards from the Central Atlantic. This deformation is variable between and within basins (e.g. Peacock and Sanderson, 1999). For example, Permo-Triassic development of the Bristol Channel and Wessex basins involved ∼N–S extension and reactivation of E–W striking Variscan structures (e.g. Chadwick, 1993), while development of

Fig. 2. (a) Simplified version of the Petroleum Exploration Society of Great Britain (2000) 1:1,500,000 scale map of the British Isles, showing major faults and rift systems. (b) Size-frequency of widths of transfer zones measured off the Petroleum Exploration Society of Great Britain (2000) map, divided into synthetic (relay ramps) and conjugate transfer zones (Peacock, 2003). The total population of transfer zones obeys a power-law scaling relationship between widths of about 10 and 250 km, with a power-law exponent of ∼1.23 ($n=163$).


(a)
Cumulative number
Width (km)
1000
100
10
1
1
10
100
1000
All transfer zones
Synthetic transfer zones
Conjugate transfer zones
(b)
20° W
18° W
16° W
14° W
12° W
10° W
8° W
6° W
4° W
2° W
0°
2° E
4° E
6° E
8° E
64° N
62° N
60° N
58° N
56° N
54° N
52° N
50° N
48° N
14° W
12° W
10° W
8° W
6° W
4° W
2° W
0°
2° E
4° E
Norwegian-Greenland Rift
Faeroe-Shetland Basin
Shetland Islands
South Viking Graben
Moray Firth
East Central Graben
Outer Hebrides Platform
Rockall High
Rockall Trough
Firth of Forth
North Sea
Tail End Graben
Erris Trough
Eden Basin
Cleveland Basin
Brona basins
Porcupine High
Irish Sea Basin
Cheshire Basin
East Midlands Basin
Worcester Basin
Porcupine Basin
Celtic Sea Basin
Bristol Channel Basin
Wessex Basin
Weald Basin
English Channel Basin
Plymouth Bay Basin
Continental margin
Western Approaches
= Approximate location of basins

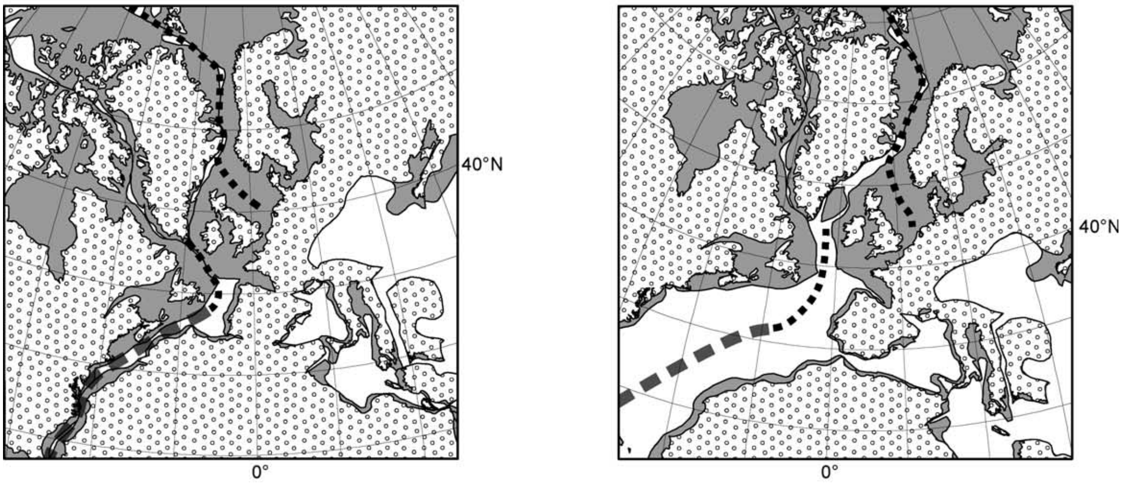
(a) End Carboniferous

(b) End Permian



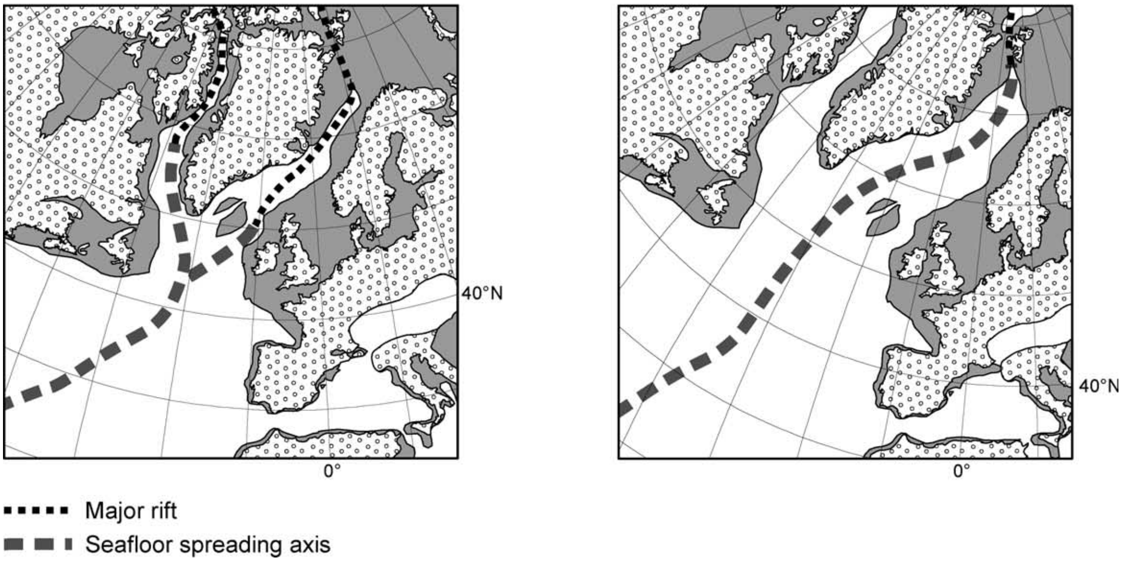
(c) End Triassic

(d) End Jurassic



(e) End Cretaceous

(f) End Eocene



basins in the Irish Sea area involved E–W extension and reactivation of NW–SE striking faults (e.g. Floodpage et al., 2001). Transfer zones are commonly breached by a set of faults striking at a low angle to the main stepping faults (e.g. Peacock and Sanderson, 1991). The Permo-Triassic rifts of the British Isles are, however, analogous to 'box faults', which are a network of faults developed between two overstepping normal faults (Griffiths, 1980; Peacock et al., 2000a). A small-scale analogue for such deformation is shown in Fig. 4, where a network of small veins has developed to connect two stepping veins.

2.3. The Jurassic Period

After the southwards propagation of the Norwegian–Greenland Rift until the Middle Jurassic, the Late Jurassic to Early Tertiary was dominated by northward propagation of ocean spreading from the Central Atlantic, where seafloor spreading initiated in the Early to Middle Jurassic (Ziegler, 1989; McHone, 2000). This opening was transferred via a transform fault into the Tethys Ocean during the Late Jurassic and Early Cretaceous. Ziegler (1989) also shows that the Norwegian–Greenland Rift was active during the Early and Middle Jurassic, with rifting in the Rockall–Faeroe and North Atlantic rift systems (Fig. 3d).

Chadwick et al. (1989) suggest that E–W extension continued across much of NW Europe in the Late Jurassic and Early Cretaceous, but N–S extension dominated in southern England, probably because of the opening of the Bay of Biscay. The basins active in the British Isles during the Jurassic include the southern North Sea, the E–W striking Wessex and Cleveland basins, and the N–S striking Worcester Basin (Chadwick et al., 1989, fig. 2b).

2.4. The Cretaceous Period

Spreading propagated into the southern parts of the North Atlantic during the Early Cretaceous (e.g. Keen et al., 1977; Ziegler, 1989), at which time the Alpine Orogeny began. Ziegler (1989) also shows that seafloor spreading reached the area between the Galicia Bank and the Flemish Cap, and occurred in the Bay of Biscay, by the Aptian. Seafloor spreading occurred between the Porcupine Basin and Newfoundland, and into the Rockall Trough, during the Albian. Rifting started in the Labrador Sea and Baffin Bay during the Early Cretaceous, developing into seafloor spreading during the early Campanian, when the Bay of Biscay and Rockall Trough were becoming inactive (Fig. 3e).

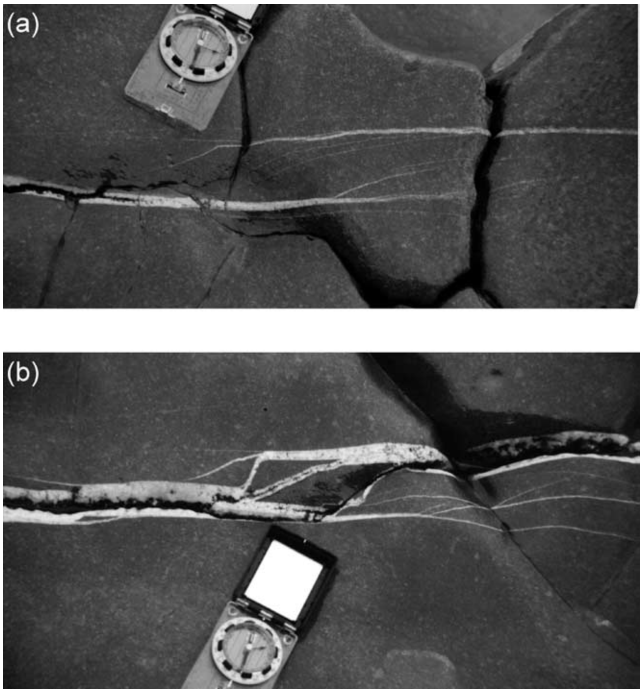


Fig. 4. Calcite veins in the Liassic limestones at Kilve, Somerset, UK, as analogues of the network of rifts that developed across the British Isles during the Mesozoic. (a) A simple pattern of small veins linking two interacting veins. (b) A more complex network of small veins linking the interacting veins. One of these linking veins is at ~80° to the interacting veins. Note how the lower vein has propagated beyond (to the right of) the linkage point between the veins; this is analogous to Cretaceous and Early Tertiary seafloor spreading in the Labrador Sea before the Atlantic Ocean linked with the Norwegian–Greenland Rift.

There was limited normal faulting in southern Britain and in the North Sea from the Middle Cretaceous (e.g. Chadwick et al., 1989, fig. 2c), with thermal subsidence occurring as extension became more concentrated in the rift systems to the west of the British Isles. The failure of the North Sea Rift System (South Viking Graben–East Central Graben–Tail End Graben) may be related to the onset of Alpine contraction or with seafloor spreading in the Bay of Biscay (Ziegler, 1989). Seafloor spreading in the Labrador Sea and Baffin Bay was possibly an attempt to bypass the transfer zone in the British Isles region. The overlap between seafloor spreading in the Labrador Sea and the later seafloor spreading in the Norwegian–Greenland Rift is typical of much smaller extensional systems (Fig. 4a). There was also a general tilting of the British Isles to the SE, with a major unconformity during the Mid Cretaceous (e.g. Ruffell, 1992). This tilting may be a form of displacement transfer between the Norwegian–Greenland and North Sea Rift System and the Atlantic Rift. Such tilting towards the footwall has occurred within an ~100-km-wide relay ramp in NE Greenland (Peacock et al., 2000b).

Fig. 3. Reconstructions of the British Isles and surrounding regions (Scotese, 1994), showing the approximate positions of the main Atlantic rifts and spreading centres (simplified from Ziegler 1989). (a) End Carboniferous (290 Ma). 1 = British Isles. 2 = Norway. 3 = Greenland. 4 = Newfoundland. 5 = Iberia. 6 = Nova Scotia. 7 = Morocco. 8 = Bay of Biscay. 9 = Poland. 10 = Labrador Sea. 11 = Baffin Bay. 12 = Central Atlantic Rift. (b) End Permian (248 Ma). (c) End Triassic (206 Ma), at which time a network of basins developed across the British Isles (Fig. 2). (d) End Jurassic (144 Ma). (e) End Cretaceous (65 Ma). (f) End Eocene (34 Ma). See text for details.

2.5. The Tertiary

A hotspot, probably centred on Iceland, developed during the Palaeocene, and this led to the separation between Greenland and Rockall High at the earliest Eocene (e.g. Ziegler, 1989; Clift and Turner, 1998). Seafloor spreading ceased in the Labrador Sea by the late Eocene, when the present-day configuration of spreading centres came into existence (Fig. 3f). A passive margin has existed around NW Europe since the Oligocene. Collision of Iberia with Europe occurred during the Eocene–Oligocene, causing subduction in the Bay of Biscay (e.g. Rosenbaum et al., 2002), which led to late Eocene–Miocene N–S contraction in southern England and in the English Channel, Celtic Sea and Western Approaches (Ziegler, 1989). The contraction involved reverse reactivation of E–W striking Mesozoic normal faults, which were originally Variscan thrusts (e.g. Chadwick, 1993; Underhill and Paterson, 1998). NW–SE striking faults were active in southern England during the Tertiary (e.g. Arthur, 1989), these having dextral displacements related both to Atlantic opening and to Alpine contraction (Bristow and Robson, 1994). The present-day maximum horizontal compressive stress is orientated ∼NW–SE across NW Europe (e.g. Bergerat and Vandycke, 1994).

The failure of the North Sea Rift System in the Cretaceous, and the Alpine N–S contraction in southern Britain during the Tertiary caused the eventual linkage between the Atlantic and Norwegian–Greenland rift systems to be to the west of the British Isles rather than via the North Sea and English Channel. It is possible that Early Tertiary uplift and igneous activity between the British Isles and Greenland was related to linkage between the Atlantic and Norwegian–Greenland rift systems, and so may not have been caused simply by a hot spot.

3. Significance of the model

Gibbs (1989, fig. 9) suggests that the Mesozoic basins of the British Isles are linked by transfer faults and lower crustal detachments to form a network. The model presented here gives an explanation for this linked system as accommodating the stresses and strains between two major interacting rift systems. The ∼1200-km-wide transfer zone across the British Isles during the Mesozoic is analogous to the Gulf of Aden (linking the Indian Ocean Ridge with the Red Sea), being a complex linking system on a continental scale. It is, however, the biggest transfer zone so far described. The transfer zone model helps to explain much of the complexity in the geology of the British Isles, including the faults that were active and the pattern of sedimentation during the Mesozoic. Such fault networks within transfer zones have been observed across a wide range of scales, from veins (Fig. 4) to the kilometre scale (Griffiths, 1980), so it is likely that they will occur at larger scales, especially in such complexly anisotropic material as the crust of the British Isles. The Mesozoic rifts commonly utilised earlier contractional faults, and many of the Mesozoic normal faults across southern Britain (e.g. Chadwick, 1993) and in the North Sea (Hibsch et al., 1995) were reverse-reactivated during the Alpine Orogeny. This Alpine contraction controlled the failure of the North Sea rift system (Ziegler, 1989) and therefore the location of the breaching of the transfer zone. The post-Variscan structural development of the British Isles region is therefore the result of interplay between rifting and orogenesis.

4. Conclusions

The break-up of Pangaea involved the Norwegian–Greenland Rift System, which extended southwards into the North Sea, interacting with the Central Atlantic Rift System. This interaction created an approximately 1200-km-wide transfer zone across the British Isles from the Late Triassic. Rift interaction occurred in this region because the crust was thickened by the Caledonian and Variscan orogenies, so linkage was unable to occur between the major rift systems until the Eocene. A complex network of minor rift basins developed in the transfer zone during the Mesozoic, with local fault patterns commonly controlled by reactivated Precambrian, Caledonian and Variscan faults. Final breaching of the transfer zone and complete linkage between the major rift systems occurred to the west of the British Isles, and not via the North Sea and English Channel rift systems because of contraction related to the Alpine Orogeny.

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