PERGAMON

Journal of Structural Geology 25 (2003) 1561–1567

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Scaling of transfer zones in the British Isles

D.C.P. Peacock

Robertson Research International Ltd, Llandudno LL30 1SA, UK

Received 12 June 2002; accepted 1 November 2002

Abstract

Widths of transfer zones between stepping normal faults obey power-law scaling relationships, probably from widths of millimetres to tens or hundreds of kilometres. Relay ramp widths in the Mesozoic sedimentary rocks of the Somerset coast obey a power-law up to ~50 m, above which there is a censoring effect caused by the width of the wave-cut platform. A structural map of the British Isles indicates that transfer zones obey a power-law up to widths of at least 250 km. This indicates that normal faults can interact over tens or hundreds of kilometres, especially where transfer zones occur between stepping half-grabens. Interaction is therefore another aspect of faulting that obeys fractal behaviour.

© 2003 Elsevier Science Ltd. All rights reserved.

Keywords: Normal faults; Transfer zones; Relay ramps; Scaling; Fractal

1. Introduction

A *transfer zone* is an area of deformation and bed tilting between two normal fault segments that step in map view (Fig. 1; e.g. Morley et al., 1990; Peacock et al., 2000a). A *step* is an area of interaction between two sub-parallel, non-colinear faults, the term being synonymous with *overstep* (e.g. Biddle and Christie-Blick, 1985), *jog* (Sibson, 1989), *offset*, *overlapping faults* and *stepover* (Aydin and Nur, 1982). Morley et al. (1990, fig. 1) define *synthetic transfer zones* and *conjugate transfer zones*, in which two stepping normal faults dip in the same and opposite directions, respectively. Synthetic transfer zones are synonymous with *relay ramps* (Fig. 2), which occur between normal faults that dip in the same direction (Goguel, 1952; Larsen, 1988; Peacock et al., 2000a). The term *relay ramp* is used here for the small structures on the Somerset coast (Fig. 2a), and *synthetic transfer zone* is used for larger, basin-bounding structures (Fig. 3a). Relay ramps have been described over a wide range of scales (Peacock and Sanderson, 1994, fig. 14), from millimetre-scales (Schlische et al., 1996) to ~100 km across (Peacock et al., 2000b). Morley et al. (1990) divide conjugate transfer zones into *convergent*- and *divergent*-transfer zones, in which the stepping faults dip towards or away from each other, respectively. Large conjugate transfer zones, in the form of stepping half-grabens, can represent fault interaction over even larger distances than relay ramps (Fig. 3a). For example, the Eastern and Western branches of the East African Rift step by ~400 km (Nelson et al., 1992, fig. 2), and Castro (1987, fig. 4a) shows an ~400 km wide conjugate transfer zone that existed between Brazil and Congo before opening of the South Atlantic.

Interaction and transfer of displacement between stepping normal faults is indicted by tilting of bedding in a transfer zone, high displacement gradients near interacting fault tips (Peacock and Sanderson, 1991), and by *connecting* faults that cut across a transfer zone (Peacock et al., 2000a).

Tchalenko (1970) shows that the geometries and mechanics of microscopic fault zones closely resemble those of continental scale fault zones. Faults are therefore described as being *self-similar* or *scale-invariant*, with the geometry at one scale being very similar to the geometry at any other scale. The development of the concept of *fractals* (e.g. Mandelbrot, 1967, 1982; Turcotte, 1990) has provided a method for describing the self-similarity of different scales of faults. For example, the power-law scaling relationship of fault displacements is given by $N = cU^{-D}$, where $N =$ number of faults with a displacement greater than U, $c =$ a constant, and $D =$ the power-law exponent (e.g. Childs et al., 1990; Scholz and Cowie, 1990). The power-law scaling relationship for fault displacements has been used to estimate the numbers of faults above and below the scale of resolution of a particular survey, and hence to estimate the total fault-related extension or contraction in a region (e.g.

E-mail address: dcp@robresint.co.uk (D.C.P. Peacock).

0191-8141/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0191-8141(03)00008-7

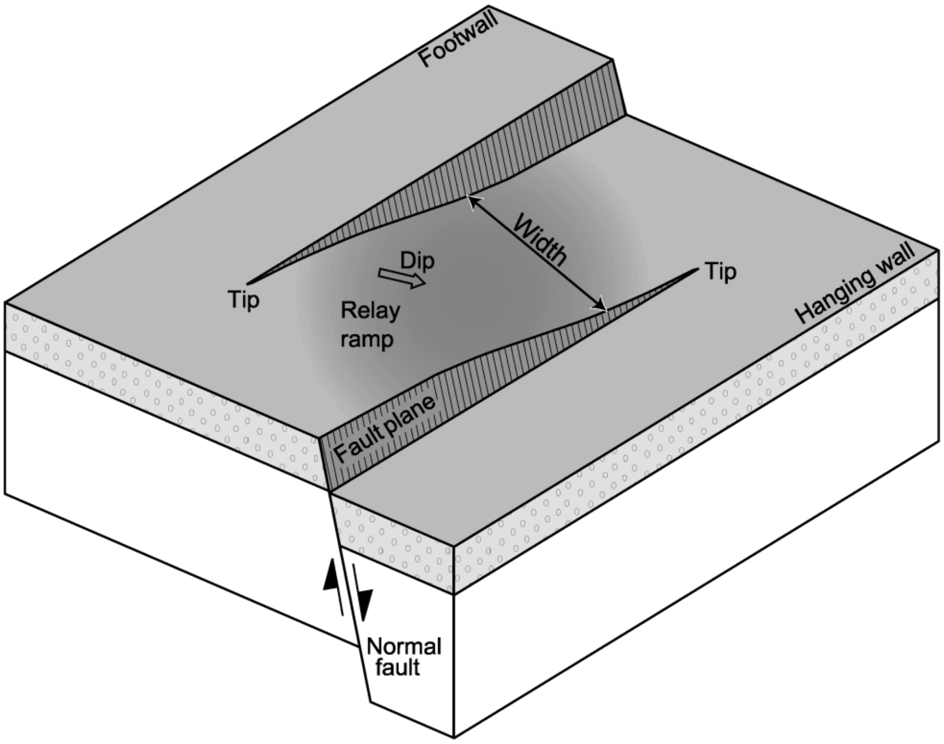

Fig. 1. Block diagram showing the main features of a synthetic transfer zone (i.e. a relay ramp). Bedding is reorientated in the transfer zone to accommodate displacement transfer between the stepping segments (Larsen, 1988; Peacock and Sanderson, 1991, 1994). Transfer zone *width* is the distance between the two interacting fault segments, measured perpendicular to the fault traces.

Marrett and Allmendinger, 1992; Walsh and Watterson, 1992). Other examples of the self-similarity of faults include fault trace lengths (e.g. Villemin et al., 1995) and the ratio of fault trace lengths to maximum displacements for a fault population (e.g. Cowie and Scholz, 1992; Dawers et al., 1993). Note, however, that it is possible some fault populations show non-fractal (e.g. negative-exponential, log-normal, etc.) size–frequency distributions for displacements or trace lengths, which cannot be accounted for by sampling biases of a fractal population (e.g. Nicol et al., 1996).

An (1997) discusses the distances over which strike-slip faults may interact, and shows that linkage usually takes place when the distance between two faults, measured normal to their traces, is $<10\%$ of the combined length of the two faults. Similar results are found by Acocella et al. (2000) for normal faults in Iceland. There also tends to be a characteristic relationship between the lengths and widths of the zones between interacting faults. For example, Acocella et al. (2000) shows that the length to width ratios of step zones between extension fractures and between normal faults have a mean value of 3.5. If fault lengths obey a power-law, it is therefore likely that the distances over which interaction occurs (e.g. widths of transfer zones) also obey a power-law.

This paper describes the distances over which interaction occurs between stepping normal faults. Data are used from the British Isles because there are good data available from a range of scales of normal faults. Normal faults are excellently exposed in the Mesozoic sedimentary rocks of the Somerset coast (e.g. Peacock and Sanderson, 1991, 1994), and these have been mapped from aerial photographs at a scale of approximately 1:1000. Transfer zone widths have also been measured from the Petroleum Exploration Society of Great Britain (2000) 1:1,500,000 scale structural map of the British Isles. Use of the British Isles has historical significance because Mandelbrot (1967) used the coastline of Britain to illustrate the geometry of fractal behaviour. It is shown that the widths of transfer zones between stepping normal faults in the British Isles obey a size–frequency power-law (*fractal*) scaling relationship. Such size–frequency power-law scaling has also been reported for fault displacements (e.g. Childs et al., 1990) and fault trace lengths (e.g. Villemin et al., 1995).

2. Scaling of relay ramps on the Somerset coast

The Somerset coast contains exceptional exposures of normal faults in Lower Jurassic limestones and shales. The large tide range has created a wide wave-cut platform (~100 m wide when the aerial photographs were taken), with fresh cliffs produced by rapid erosion of the relatively soft rocks. The structures were produced by the N–S extension of the Bristol Channel Basin during the Mesozoic, and by N–S contraction of the Basin in the Tertiary, during

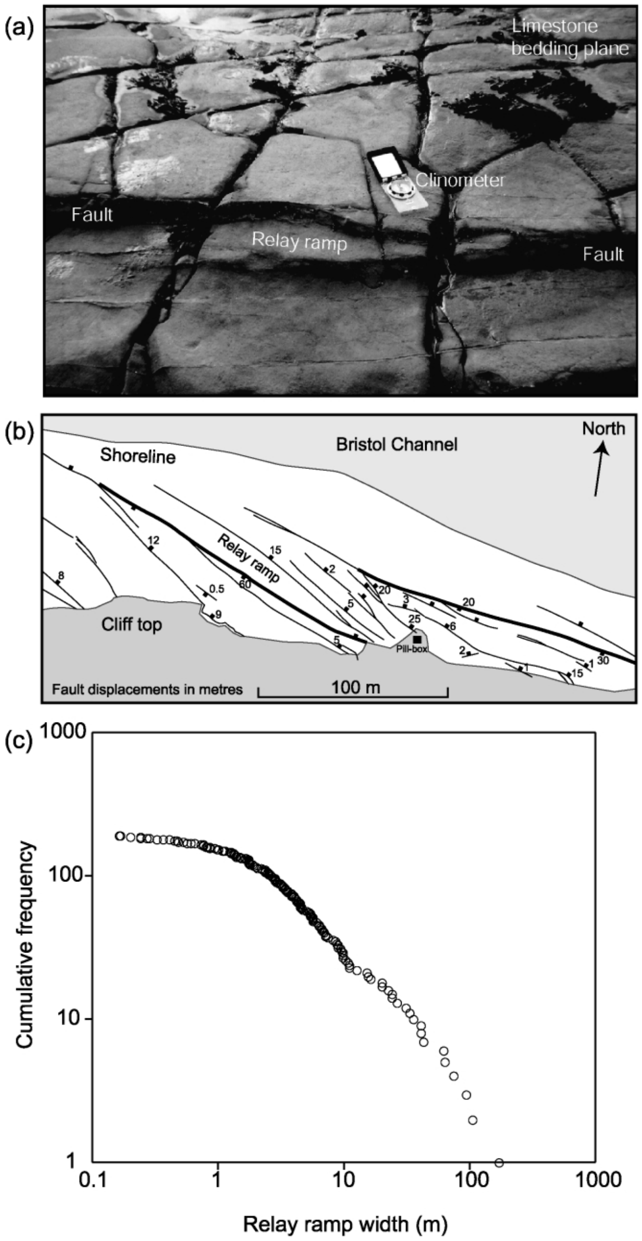

Fig. 2. (a) and (b) Different scales of relay ramp exposed in Lower Jurassic limestones and shales on the Somerset coast. (a) Photograph of an ~150 mm wide relay ramp at East Quantoxhead. The stepping faults have maximum displacements of ~100 mm. (b) Map of a relay ramp between south-dipping faults with maximum throws of >30 m. North-dipping faults, mostly with <20 m displacement, transfer displacement across the relay ramp. (c) Size–frequency of widths of relay ramps measured between Blue Ben and east of Lilstock ($n = 192$). They obey a power-law up to ~50 m, with a power-law exponent of ~0.96. The upper cut-off is probably caused by the ~100 m width of the wave-cut platform, which means that wider relay ramps are under-sampled.

the Alpine Orogeny (Peacock and Sanderson, 1992, 1999; Dart et al., 1995). Structures present include normal faults (Peacock and Sanderson 1991, 1994), reverse-reactivated normal faults (Dart et al., 1995; Kelly et al., 1999), strike-slip faults (Peacock and Sanderson, 1995b), veins (Peacock and Sanderson, 1995a) and joints (Rawnsley et al., 1998). Whittaker and Green (1983) give a detailed description of the stratigraphy of the Lower Jurassic rocks of the Somerset coast, and of the larger faults and folds. Bowyer and Kelly (1995) describe scaling relationships of faults and veins on the Somerset coast, and show that normal fault displacements obey a power-law with an exponent of ~0.47.

The ~6.5 km long coastline from Blue Ben (grid reference ST120438) to ~2 km east of Lilstock (ST187455) has been mapped from a set of vertical aerial photographs taken from heights of ~500 m. Hundreds of E–W striking normal faults with displacements of up to ~300 m are exposed in this area. The faults are characteristically segmented, with excellent exposures of relay ramps occurring (Peacock and Sanderson, 1991, 1994). These relay ramps are millimetres to tens of metres across (Fig. 2a and b). The widths of the relay ramps plot as a straight line on a log–log graph of width against cumulative frequency, so obey a power-law scaling relationship (Fig. 2c). The lower cut-off is ~2 m, which reflects the resolution of the aerial photographs. Smaller relay ramps occur (Fig. 2a), and it is likely that the power-law scaling relationship extends below the 2 m cut-off shown in Fig. 2c. Censoring (the upper cut-off) is at ~50 m, which reflects the width of the wave-cut platform. Larger relay ramps probably occur in the area. Peacock and Sanderson (1999) suggest that the Somerset coast is within a 5–10 km wide relay ramp between basin-bounding faults that are inferred to run along the northern edges of the Quantock and Exmoor hills. These north-dipping faults would have hundreds of metres of displacement.

3. Transfer zones around the British Isles

Widths of transfer zones (Fig. 1) have been measured from the Petroleum Exploration Society of Great Britain (2000) 1:1,500,000 scale structural map of the region around the British Isles. A simplified version of this map is shown in Fig. 3a. Interaction between faults is inferred by tilting of bedding in the transfer zone, or by connecting faults cutting across the transfer zone. In many instances, however, interaction can only be inferred from the fault trace geometries; interaction is inferred to have occurred between two faults where the proposed transfer zone has a width of less than ~10% of their combined trace lengths (An, 1997; Acocella et al., 2000). It is acknowledged that this inference of interaction between faults is speculative, especially for the very largest transfer zones between stepping rifts (listed in Table 1).

Widths of transfer zones measured off the Petroleum Exploration Society of Great Britain (2000) map of the British Isles have been plotted on a log–log graph of width against cumulative frequency (Fig. 3b). They obey a power-law scaling relationship between widths of ~10 km (probably the lower resolution of the map) and ~250 km.

It is possible that the power-law scaling for transfer zones

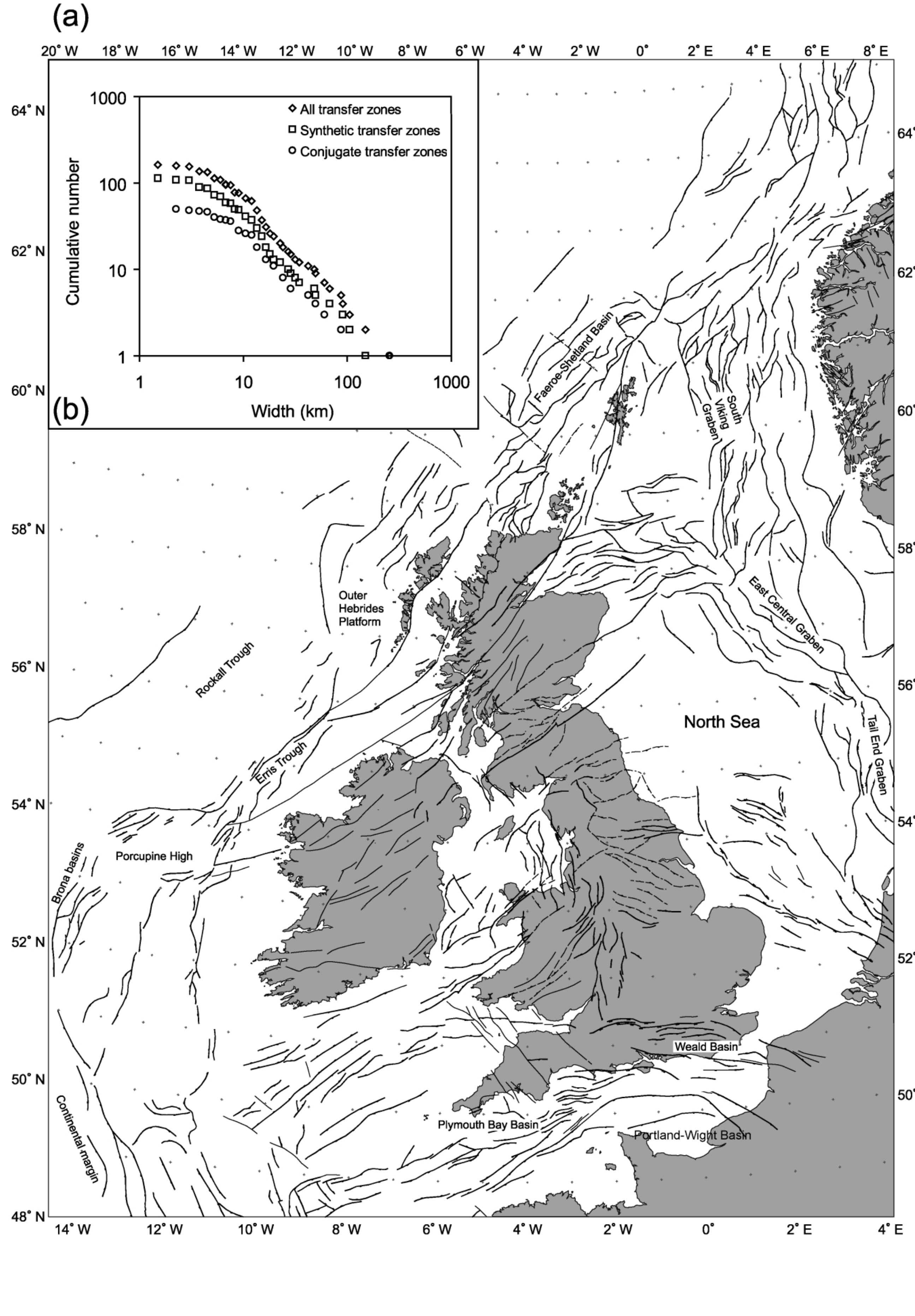
(a)
(b)
1000
100
10
1
Cumulative number
Width (km)
All transfer zones
Synthetic transfer zones
Conjugate transfer zones
Faeroe-Shetland Basin
South Viking Graben
Outer Hebrides Platform
Rockall Trough
East Central Graben
North Sea
Tail End Graben
Erris Trough
Porcupine High
Brona basins
Weald Basin
Plymouth Bay Basin
Portland-Wight Basin
Continental margin
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

Table 1
The largest transfer zones measured from the Petroleum Exploration Society of Great Britain (2000) structural map of the area around the British Isles. Measured widths are probably accurate to about ±5%. The interpretation of these structures as transfer zones is somewhat speculative, as there is limited evidence of interaction between the stepping fault systems. The interpretation of a massive transfer zone between the continental margin off the west of Ireland to the North Sea graben system is highly speculative, and this measurement is not included in Fig. 3b

Location	Transfer zone type	Width (km)
Continental margin off the west of Ireland to the North Sea graben system	Synthetic transfer zone?	1155
South Viking Graben to the Tail End Graben, across the East Central Graben	Conjugate transfer zone	255
Faeroe–Shetland Basin to the Rockall Trough, across the Outer Hebrides Platform	Synthetic transfer zone	150
Brona basins to Erris Trough, across the Porcupine High	Synthetic transfer zone	105
Plymouth Bay Basin to Portland–Wight Basin	Synthetic transfer zone	90
Portland–Wight Basin to Weald Basin	Synthetic transfer zone	67.5

extends above ~250 km shown in Fig. 3b. It is speculated that there is a massive transfer zone, extending for ~1155 km between the continental margin off the west of Ireland and the North Sea graben system. These rift systems were synchronously active in the Mesozoic (Ziegler, 1989, fig. 5), with a complex network of basins between. This inferred transfer zone is too speculative, however, to be included in Fig. 3b.

4. Discussion of scaling relationships for fault interaction

Measurements for the Somerset coast and from the Petroleum Exploration Society of Great Britain (2000) map indicate that transfer zone widths obey a power-law size–frequency relationship over ~5 orders of magnitude. The power-law exponent for the regional-scale faults (Fig. 3a) is higher than for the smaller faults exposed on the Somerset coast. This may reflect the longer, more complex history of the regional-scale faults. For example, Chadwick (1993) shows that the largest E–W striking faults on the south coast of England were Variscan thrusts, reactivated as normal faults during the Mesozoic and then reverse-reactivated during the Alpine Orogeny. This greater complexity is illustrated by the wide range of fault orientations across the British Isles (Fig. 3a) compared with the simple ~E–W strike of normal faults on the Somerset coast (Fig. 2).

Although large conjugate transfer zones appear to have the same scaling relationship as large synthetic transfer zones (Fig. 3b), conjugate transfer zones have not been identified at the exposure-scale on the Somerset coast. Indeed, there does not appear to be a published map or description of a metre-scale conjugate transfer zone. It is possible that conjugate transfer zones scale down only to hundreds of metres wide, and there does appear to be a breakdown in the power-law scaling of conjugate transfer zones at ~20 km (Fig. 3b).

This fractal scaling relationship for transfer zones is probably a consequence of fault trace lengths obeying a power-law (e.g. Villemin et al., 1995) and faults interacting when the distance between segments is less than about 10 times their combined trace lengths (An, 1997; Acocella et al., 2000). The widths of transfer zones would therefore be expected to coincide approximately with the fractal scaling of the trace lengths of the interacting fault segments. The data presented in Figs. 2 and 3 illustrate that fault interaction is characteristic across a full range of scales (Fig. 4), and that faults can interact over distances as large as hundreds of kilometres. To understand the deformation in faulted regions therefore requires understanding of fault interaction across a full range of scales.

5. Conclusions

Faults obey power-law scaling relationships for displacement (e.g. Childs et al., 1990; Scholz and Cowie, 1990) and for fault lengths (e.g. Villemin et al., 1995). This paper illustrates that the distances over which faults interact, as indicated by the widths of transfer zones around the British Isles, also obey a power-law scaling relationship over at least five orders of magnitude. The relay ramps exposed on the Somerset coast obey a power-law up to widths of at least 50 m, beyond which a censoring effect is related to the width of the wave-cut platform. Transfer zones shown on the 1:1,500,00 scale Petroleum Exploration Society of Great Britain (2000) map of the British Isles obey a power-law relationship up to widths of at least 250 km. This suggests that the largest faults can interact over tens or hundreds of kilometres.

Acknowledgements

I am very grateful to Paul Kelly, Alison McGurk and

Fig. 3. (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. (b) Size–frequency of widths of transfer zones measured off the Petroleum Exploration Society of Great Britain (2000) map, divided into synthetic and conjugate transfer zones (inset). 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 ($n = 163$).

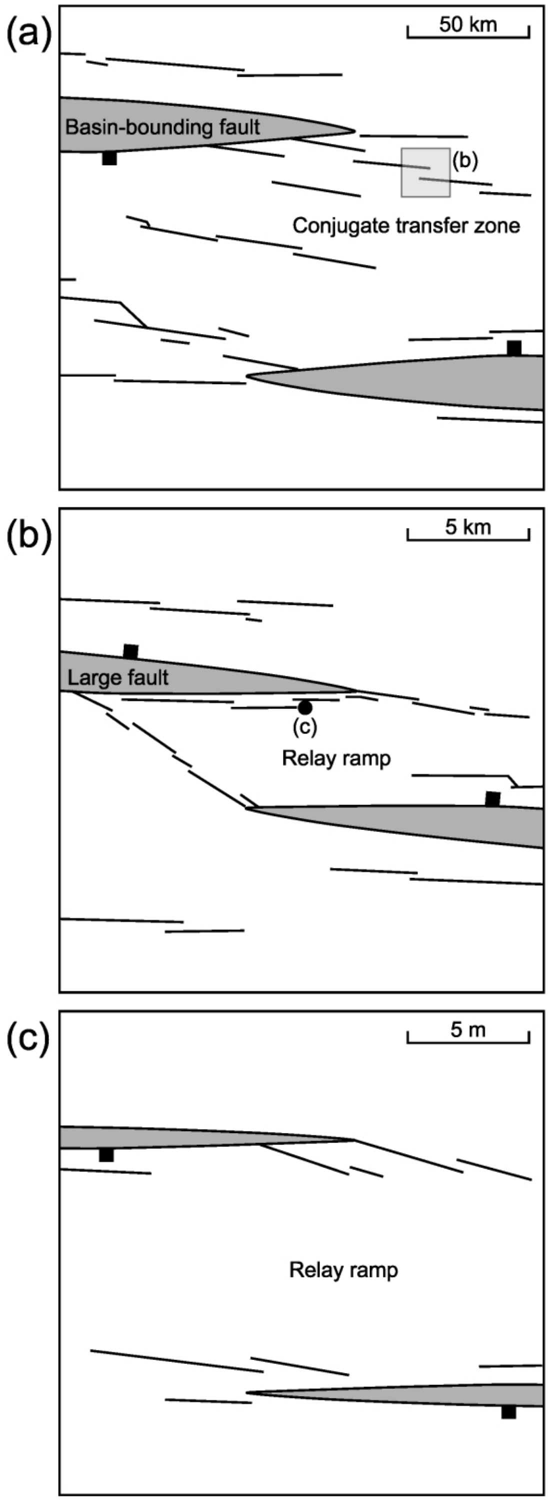

Fig. 4. Schematic illustration of the scaling of transfer zones. (a) Regional structure is dominated by stepping half grabens. (b) Transfer zones, including relay ramps, occur at kilometre-scales. (c) Relay ramps (synthetic transfer zones) are common at exposure-scales. Shaded areas = fault planes.

Dave Sanderson for mapping normal faults on the Somerset coast, and to Robertson Research for permission to publish Fig. 3a. I am also grateful to Rolf Ackermann, Valerio Acocella and Tom Blenkinsop and for providing very useful reviews.

References

Acocella, V., Gudmundsson, A., Funiciello, R., 2000. Interaction and linkage of extension fractures and normal faults: examples from the rift zone of Iceland. Journal of Structural Geology 22, 1233–1246.

An, L.J., 1997. Maximum link distance between strike-slip faults: observations and constraints. Pure and Applied Geophysics 150, 19–36.

Aydin, A., Nur, A., 1982. Evolution of pull-apart basins and their scale independence. Tectonics 1, 91–105.

Biddle, K.T., Christie-Blick, N., 1985. Glossary—strike-slip deformation, basin formation, and sedimentation. In: Biddle, K.T., Christie-Blick, N. (Eds.), Strike-Slip Deformation, Basin Formation, and Sedimentation. Society of Economic Mineralogists Special Publication 37, pp. 375–386.

Bowyer, M.O.'N., Kelly, P.G., 1995. Strain and scaling relationships of faults and veins at Kilve, Somerset. Proceedings of the Ussher Society 8, 411–415.

Castro, A.C.M., 1987. The northeastern Brazil and Gabon basins: a double rifting system associated with multiple crustal detachment surfaces. Tectonics 6, 727–738.

Chadwick, R.A., 1993. Aspects of basin inversion in southern Britain. Journal of the Geological Society of London 150, 311–322.

Childs, C., Walsh, J.J., Watterson, J., 1990. A method for estimation of the density of fault displacements below the limits of seismic resolution in reservoir formations. In: Buller, A.T., Berg, E., Hjelmeland, O., Kleppe, J., Torsaeter, O., Aasen, J.O. (Eds.), North Sea Oil and Gas Reservoirs: II. Proceedings of the North Sea Oil and Gas Reservoirs Conference, pp. 309–318.

Cowie, P.A., Scholz, C.H., 1992. Displacement–length scaling relationship for faults: data synthesis and discussion. Journal of Structural Geology 14, 1149–1156.

Dart, C.J., McClay, K., Hollings, P.N., 1995. 3D analysis of inverted extensional fault systems, southern Bristol Channel basin, U.K. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion. Geological Society, London, Special Publications 88, pp. 393–413.

Dawers, N.H., Anders, M.H., Scholz, C.H., 1993. Growth of normal faults: displacement–length scaling. Geology 21, 1107–1110.

Goguel, J., 1952. Traité de Tectonique. Masson, Paris. Translated by Thalmann, H.E., 1962. Tectonics. Freeman, San Francisco.

Kelly, P.G., Peacock, D.C.P., Sanderson, D.J., McGurk, A.C., 1999. Selective reverse-reactivation of normal faults, and deformation around reverse-reactivated faults in the Mesozoic of the Somerset coast. Journal of Structural Geology 21, 493–509.

Larsen, P.-H., 1988. Relay structures in a Lower Permian basement-involved extension system, East Greenland. Journal of Structural Geology 10, 3–8.

Mandelbrot, B.B., 1967. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science 156, 636–638.

Mandelbrot, B.B., 1982. The Fractal Geometry of Nature, W.H. Freeman, San Francisco.

Marrett, R., Allmendinger, R.W., 1992. Amount of extension on "small" faults: an example from the Viking Graben. Geology 20, 47–50.

Morley, C.K., Nelson, R.A., Patton, T.L., Munn, S.G., 1990. Transfer zones in the East African rift system and their relevance to hydrocarbon exploration in rifts. Bulletin of the American Association of Petroleum Geologists 74, 1234–1253.

Nelson, R.A., Patton, T.L., Morley, C.K., 1992. Rift segment interaction and its relation to hydrocarbon exploration in rift systems. Bulletin of the American Association of Petroleum Geologists 76, 1153–1169.

Nicol, A., Walsh, J.J., Watterson, J., Gillespie, P.A., 1996. Fault size distributions—are they really power-law? Journal of Structural Geology 18, 191–197.

Peacock, D.C.P., Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. Journal of Structural Geology 13, 721–733.

Peacock, D.C.P., Sanderson, D.J., 1992. Effects of layering and anisotropy on fault geometry. Journal of the Geological Society of London 149, 793–802.

Peacock, D.C.P., Sanderson, D.J., 1994. Geometry and development of relay ramps in normal fault systems. Bulletin of the American Association of Petroleum Geologists 78, 147–165.

Peacock, D.C.P., Sanderson, D.J., 1995a. Pull-aparts, shear fractures and pressure solution. Tectonophysics 241, 1–13.

Peacock, D.C.P., Sanderson, D.J., 1995b. Strike-slip relay ramps. Journal of Structural Geology 17, 1351–1360.

Peacock, D.C.P., Sanderson, D.J., 1999. Deformation history and basin-controlling faults in the Mesozoic sedimentary rocks of the Somerset coast. Proceedings of the Geologists Association 110, 41–52.

Peacock, D.C.P., Knipe, R.J., Sanderson, D.J., 2000a. Glossary of normal faults. Journal of Structural Geology 22, 291–305.

Peacock, D.C.P., Price, S., Whitham, A., Pickering, C., 2000b. The World's largest relay ramp (Hold With Hope, NE Greenland). Journal of Structural Geology 22, 843–850.

Petroleum Exploration Society of Great Britain, 2000. Structural Framework of the North Sea and Atlantic Margin. Petroleum Exploration Society of Great Britain map.

Rawnsley, K.D., Peacock, D.C.P., Rives, T., Petit, J.P., 1998. Jointing in the Mesozoic sediments around the Bristol Channel Basin. Journal of Structural Geology 20, 1641–1661.

Schlische, R.W., Young, S.S., Ackermann, R.V., Gupta, A., 1996. Geometry and scaling relations of a population of very small rift-related normal faults. Geology 24, 683–686.

Scholz, C.H., Cowie, P.A., 1990. Determination of total strain from faulting using slip measurements. Nature 346, 837–839.

Sibson, R.H., 1989. Earthquake faulting as a structural process. Journal of Structural Geology 11, 1–14.

Tchalenko, J.S., 1970. Similarities between shear zones of different magnitudes. Bulletin of the Geological Society of America 81, 1625–1640.

Turcotte, D.L., 1990. Implications of chaos, scale-invariance, and fractal statistics in geology. Palaeogeography, Palaeoclimatology and Palaeoecology 89, 301–308.

Villemin, T., Angelier, J., Sunwoo, C., 1995. Fractal distribution of fault length and offsets: implications of brittle deformation evaluation: the Lorraine coal basin. In: Barton, C.C., LaPointe, P.R. (Eds.), Fractals in the Earth Sciences, Plenum Press, New York, pp. 205–226.

Walsh, J.J., Watterson, J., 1992. Populations of faults and fault displacements and their effects on estimates of fault-related regional extension. Journal of Structural Geology 14, 701–712.

Whittaker, A., Green, G.W., 1983. Geology of the Country Around Weston-super-Mare. Memoir of the Geological Survey of Great Britain. Sheet 279 and parts of 263 and 295.

Ziegler, P.A., 1989. Evolution of the North Atlantic—an overview. In: Tankard, A.J., Balkwill, H.R. (Eds.), Extension Tectonics and Stratigraphy of the North Atlantic Margins, American Association of Petroleum Geologists Memoir 46, pp. 111–129.