INTERACTING FAULTS

By Tyler Lagasse

- Faults typically form as a network
- How do we best interpret interacting faults and tell between different types of fault interaction?

INTRODUCTION

HOW DOES A FAULT NETWORK FORM?

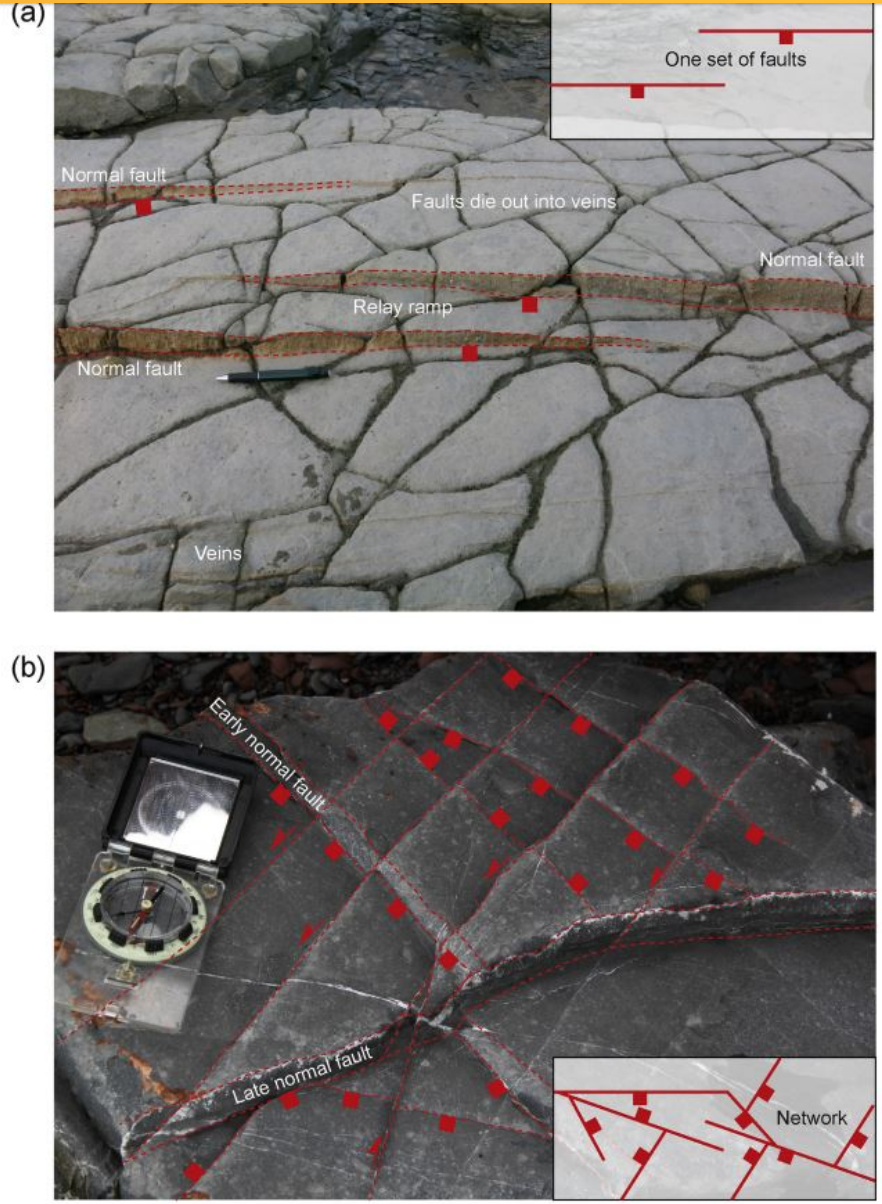


Fig. 3. Different types of fault network and interactions. (a) Normal faults on a bedding plane of Liassic limestone, East Quantoxhead, Somerset. A single stress field, producing interactions between coeval faults, including linkage of sub-parallel faults (e.g., Peacock and Sanderson, 1991). (b) Network of faults on a limestone bedding plane, Watchet, Somerset. The fault network was formed by the overprinting and superposition of two or more stress fields, producing interactions between faults of different ages, resulting in abutting and crosscutting relationships between the non-coeval fault sets (e.g., Duffy et al., 2015). Note that the block was not *in situ*.

Forms within single stress field (top)

By mutual abutting & cross-cutting relationships of conjugate fields

Overprinting/superposition of ≥2 stress fields (bottom)

- Interactions between faults of different ages/type are produced

By reactivation of pre-existing faults

- Geometrically linked
- Kinematically linked
- Combination of the two

INTERACTING FAULT TYPES

- Deformation history
  - Normal faults striking ~95^{o} & related gentle folds
  - Sinistral shear then dextral reactivation of some 95^{o} striking normal faults
  - Reverse-reactivation of Mesozoic & older structures
  - Reverse-activated normal faults cut by strike slip faults
  - Joints post-date faulting

GEOLOGICAL BACKGROUND OF FIELD EXAMPLES

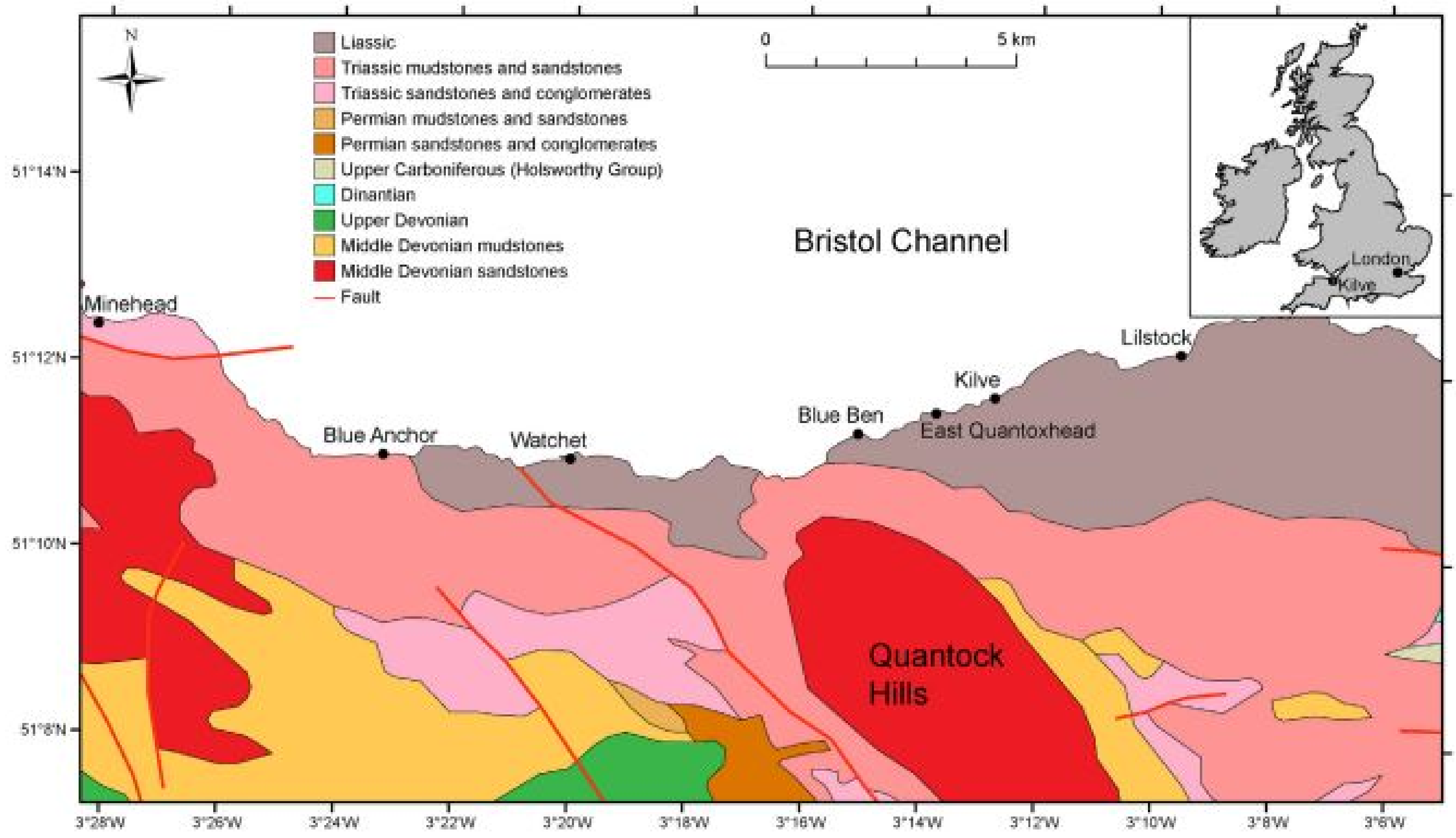


Fig. 4. Geological map of part of the Somerset coast, reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved. The locations of Lilstock, Kilve, East Quantoxhead, Watchet and Blue Anchor Bay are shown.

Range of fault interactions occurring along the Somerset coast in the United Kingdom

- Faults are isolated, fail to interact & are not connected (Figure 4)
- Faults interact when approaching each other (Figure 5A)
  - Kinematically, but not geometrically linked
- One fault abuts another (Figure 5B)
- Earlier fault cut by & displaced by later fault (Figure 5C)
- 2 faults mutually crosscut each other (Figure 5D)

GEOMETRIC RELATIONSHIPS BETWEEN INTERACTING FAULTS

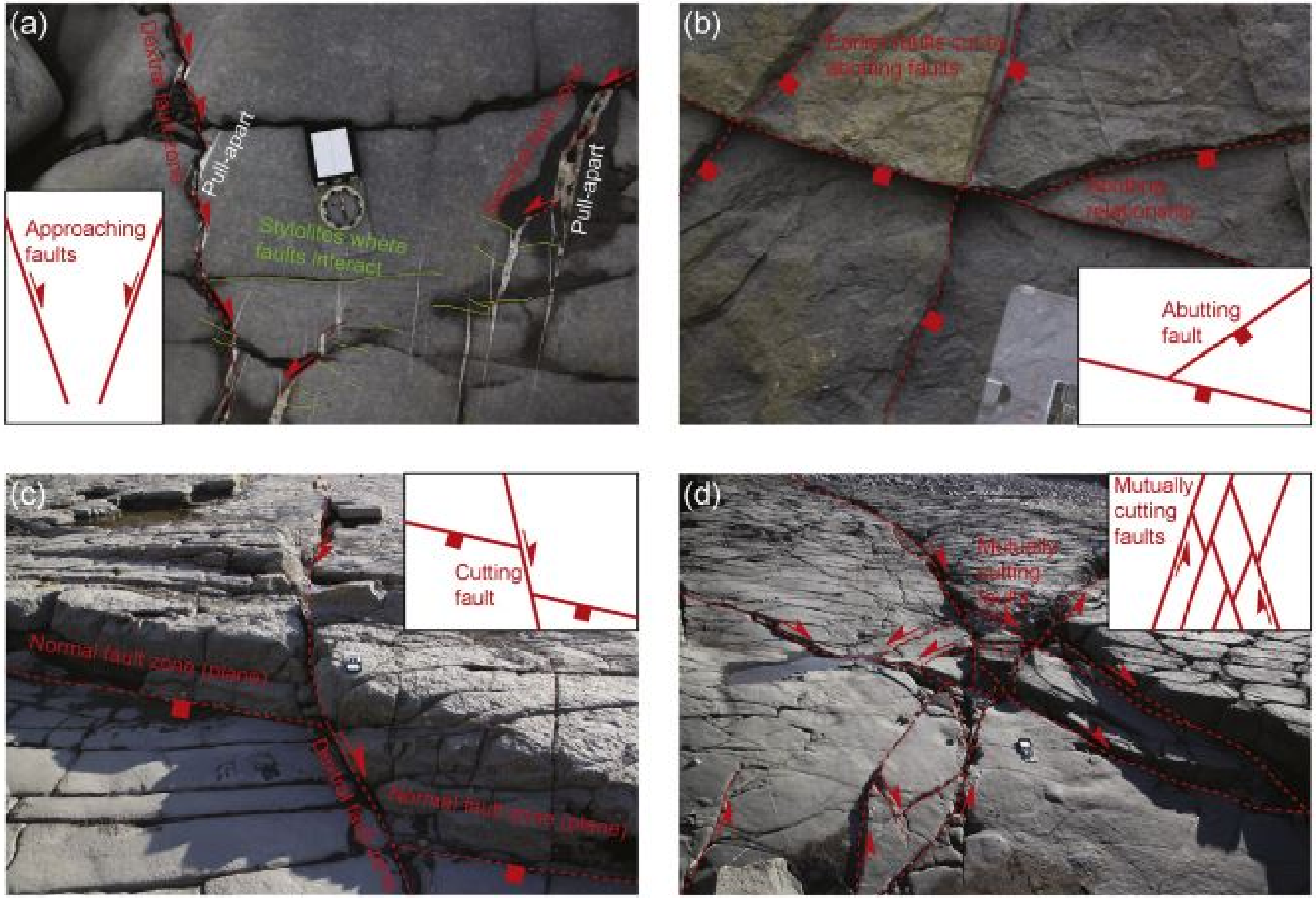


Fig. 5. Examples of faults from the Liassic limestones and shales of Somerset, UK, showing different geometric relationships between the faults. (a) Conjugate strike-slip faults at Kilve that approach each other and interact but do not actually meet. Interaction is indicated by stylolites (green) in the acute bisector between the faults and between segments along the sinistral fault. (b) A normal fault abuts another normal fault on a bedding plane of Liassic limestone at Watchet. Note that this rock was not *in situ*. (c) Oblique view of a strike-slip fault cutting and displacing a normal fault zone at East Quantoxhead. (d) Oblique view of two conjugate strike-slip fault zones at East Quantoxhead that appear to mutually crosscut each other. This is indicated by the intricate pattern of fault segments and areas of relative uplift and subsidence in the interaction zone.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Geometric relationships between faults are characterized and identified based on if and how they intersect.

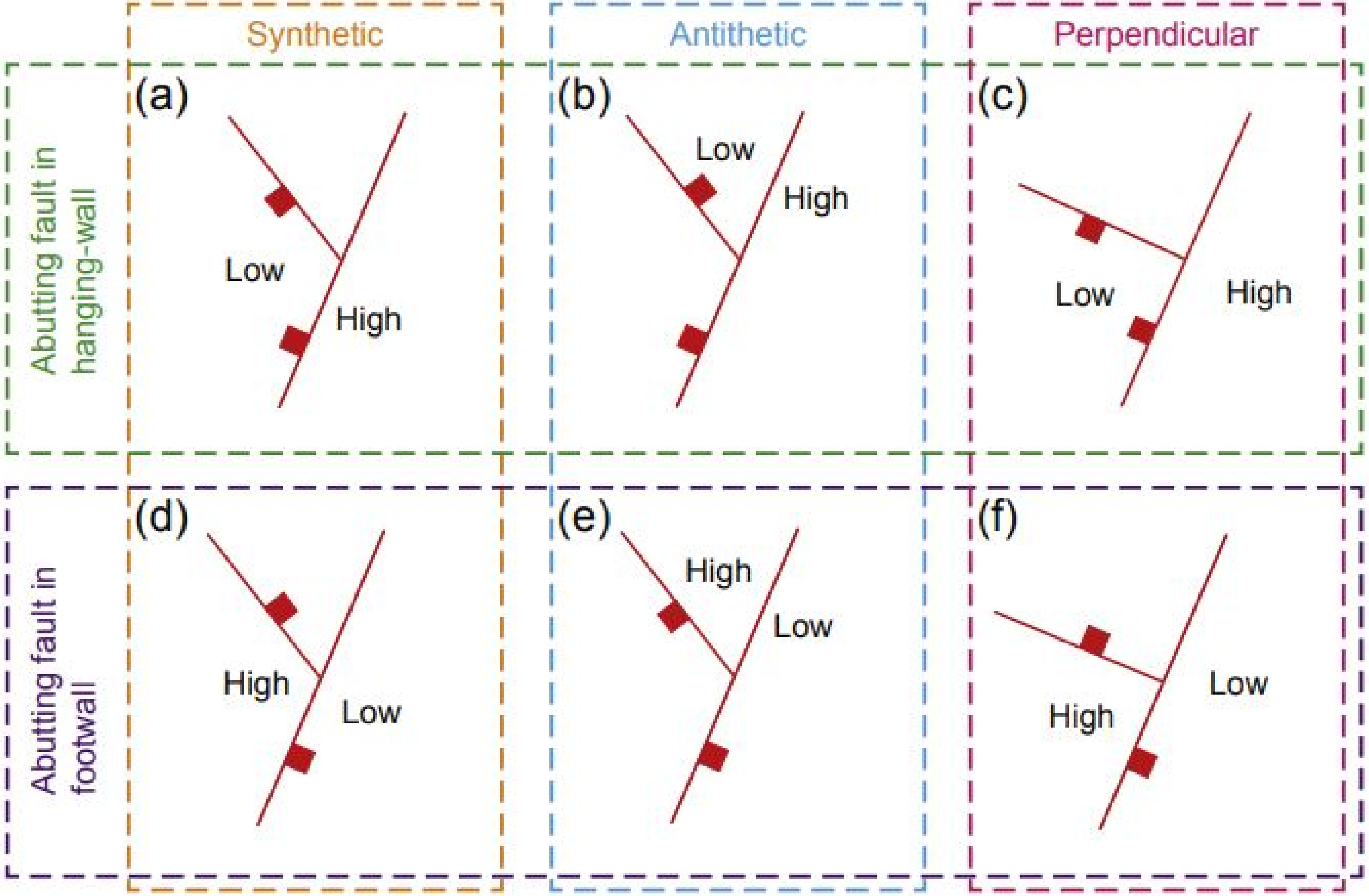
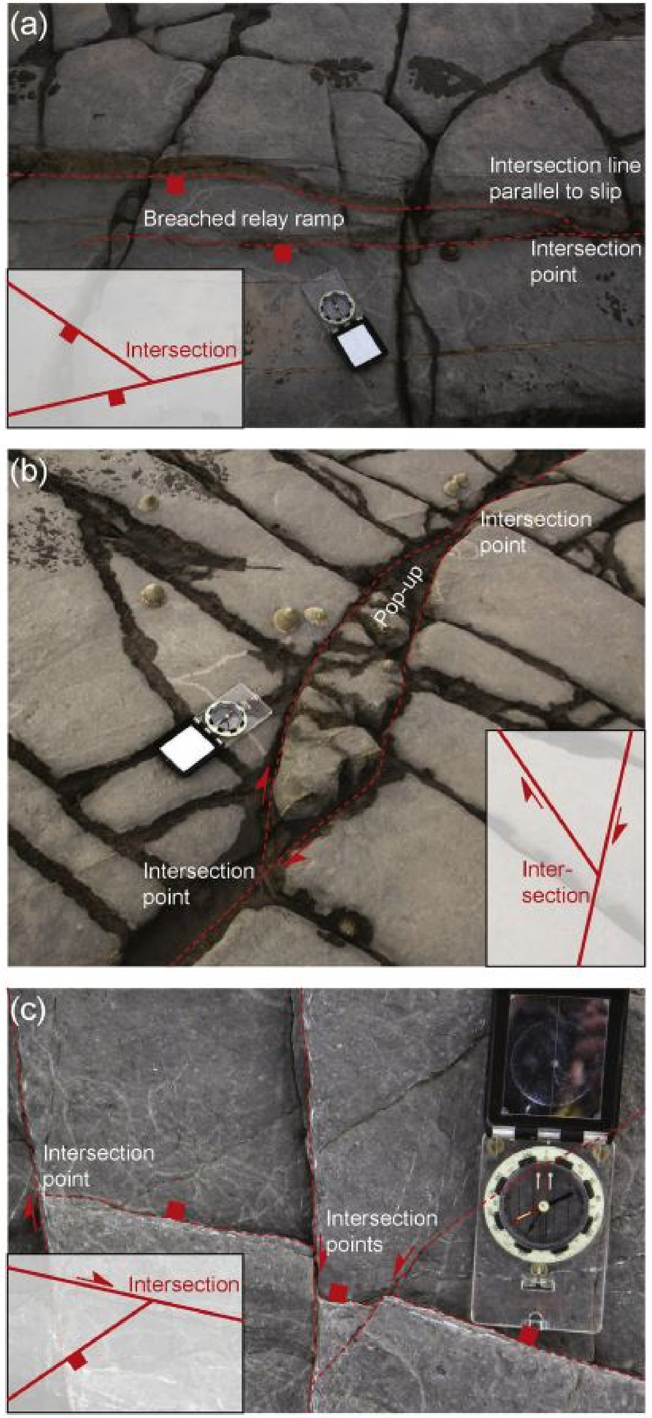


Fig. 7. Characterisation of normal fault interactions based on whether the abutting fault is synthetic or antithetic to the other fault and whether it is in the hanging-wall or footwall of the other fault. (a)–(c) Abutting faults in the hanging-wall. (a) The abutting fault is synthetic to and in the hanging-wall of the fault it abuts. (b) The abutting fault is antithetic to and in the hanging-wall of the fault it abuts. (c) The abutting fault is in the hanging-wall of the fault it abuts, and they are perpendicular to each other. (d)–(f) Abutting faults in the footwall. (d) The abutting fault is synthetic to and in the footwall of the fault it abuts. (e) The abutting fault is antithetic to and in the footwall of the fault it abuts. (f) The abutting fault is in the footwall of the fault it abuts, and they are perpendicular to each other.

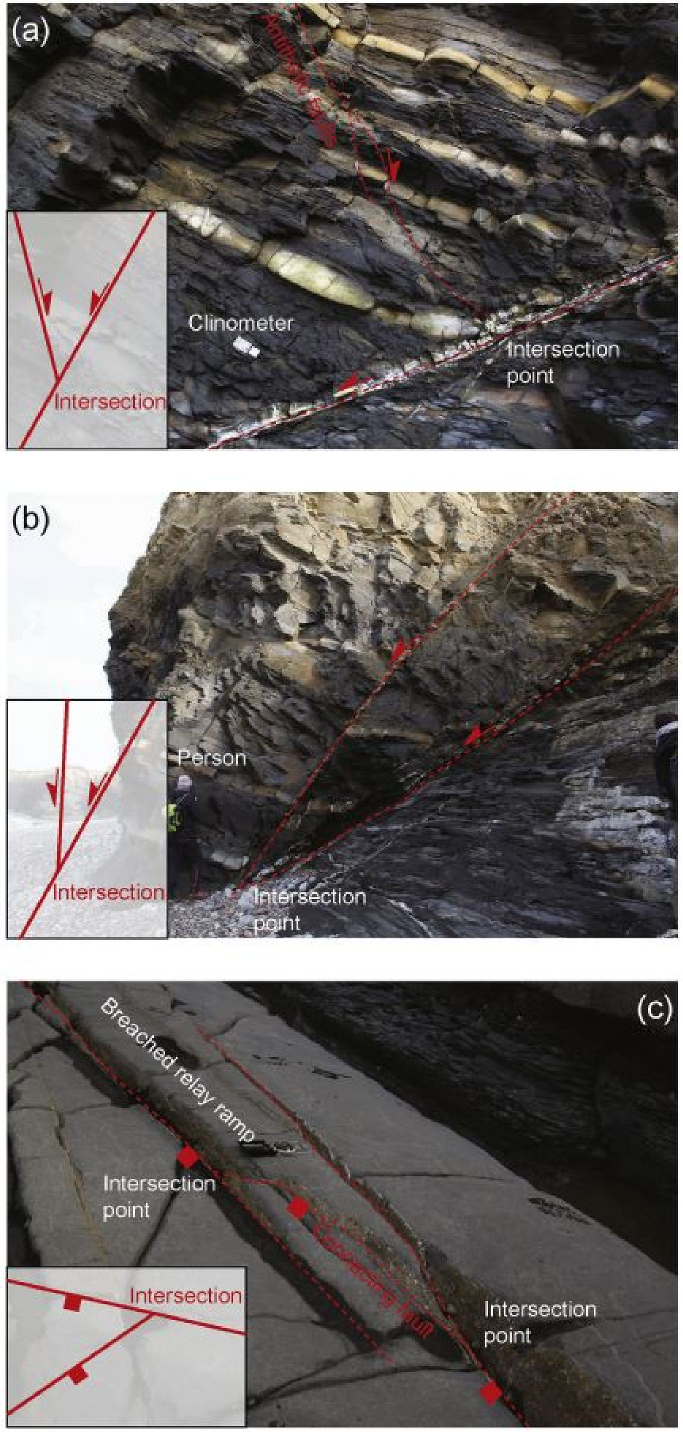
Additional characterization for intersections between normal faults, according to relative dip directions of faults, & whether it's in the hanging wall or footwall.



KINEMATIC RELATIONSHIPS BETWEEN INTERACTING FAULTS

Defined on basis of relationships between intersection line

- Parallel to displacement direction (top)
- Perpendicular to displacement direction (middle)
- Parallel to displacement direction of one fault & perpendicular to that of the other (bottom)
- May also be curved



DISPLACEMENT & STRAINS BETWEEN INTERACTING FAULTS

Defined on basis of relative shear stress of interacting faults

- Antithetic relationship (top)
- Synthetic relationship (middle)
- Neutral relationship (bottom)

RELATIVE AGE RELATIONSHIPS BETWEEN INTERACTING FAULTS

- 2 intersecting normal faults synchronously active (a)
- Normal fault cut by a later dextral strike-slip fault (b)
- Calcite veins showing trailing relationship (c)
- East Quantoxhead fault (d)
- Trailing: two faults/fractures connected through an older fault/fracture
- Descriptive schemes break down for faults involving more than one deformation event
- Some early faults passively folded by later fault, found in footwall-propagating thrust systems

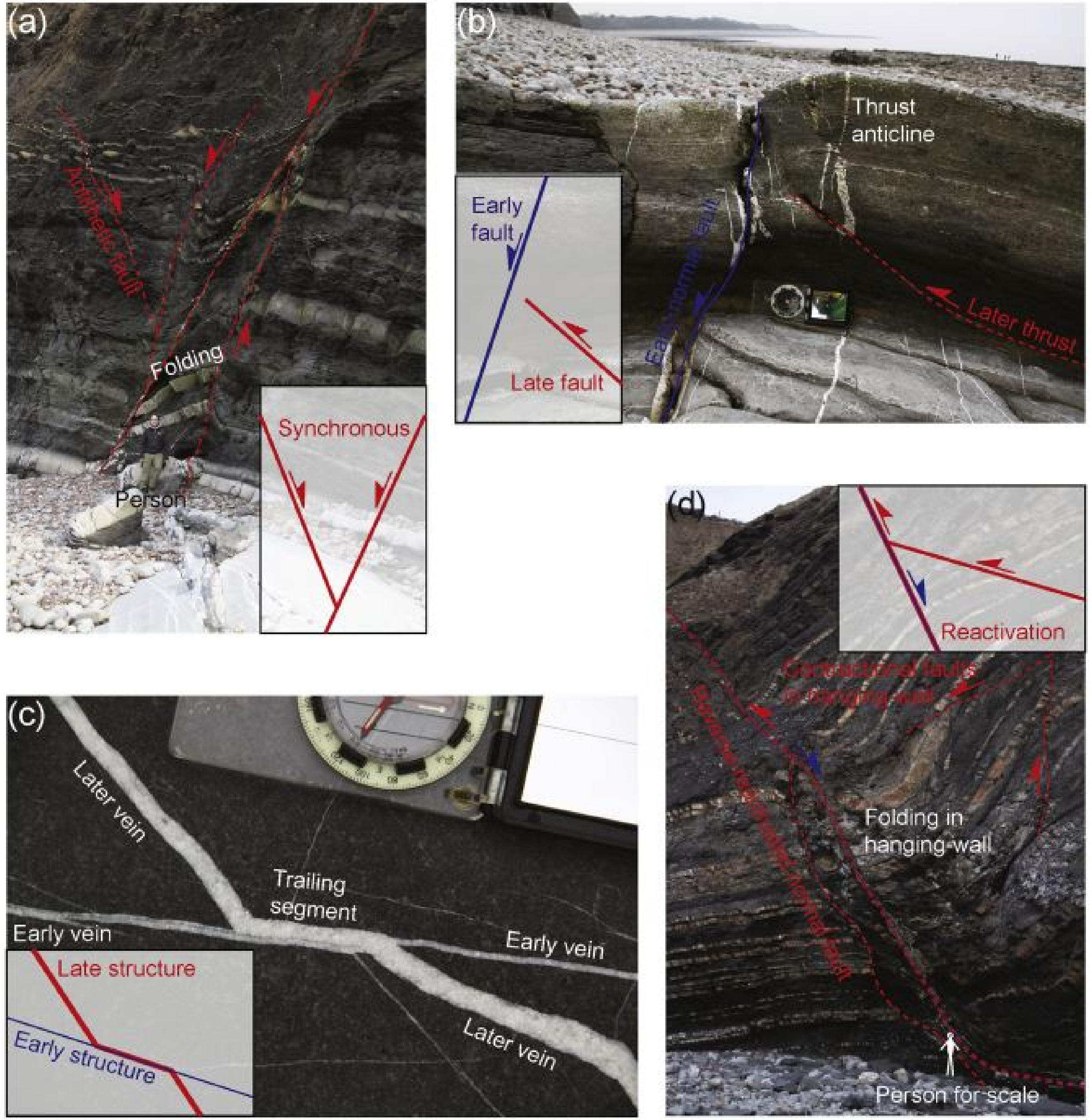


Fig. 12. Examples of faults and veins showing interacting faults with different relative ages, from the Liassic limestones and shales of Somerset, UK. (a) Two intersecting normal faults at Kilve that appear to have been synchronously active, as indicated by the folding of bedding between the faults. (b) A normal and a later thrust fault at Lilstock showing an approaching relationship. (c) Calcite veins on a bedding plane of Liassic limestone at Lilstock. Two later veins intersect and utilise an earlier, with the trailing geometry causing an increase in aperture of the earlier vein between the later veins. (d) The East Quantoxhead fault, which has ~50 m of net normal displacement but that has been partially reactivated as a reverse fault (Whittaker and Green, 1983). Antithetic thrusts occur in the hanging-wall, kinematically interacting with the reverse-reactivated normal fault.

- On Synchronously Active Faults
  - Displacement transferred between sub-parallel interacting normal faults going across relay ramps
  - Relay Ramps: came from high displacement gradients near tips of interacting faults & displacement transferred between them
- On Non-synchronous Faults
  - A fault can control displacement activities of another fault, despite differences in age
  - Some earlier faults act as mechanical barriers to later faults
  - Some faults show "trailing" geometries/kinematics
  - Older fault renews displacement between younger faults (Figure 12c)

DISPLACEMENTS ALONG INTERACTING FAULTS

- An area of deformation from interaction of >2 faults
  - Approaching Damage Zones
    - Area of deformation related to intersection between ≥2 non-intersecting faults
  - Intersection Damage Zones
    - Area of deformation around intersection point of ≥2 faults

INTERACTION DAMAGE ZONES

- Deformation centered in zones of interacting & intersecting faults
  - Fluid migration & entrapment are influenced by said faults
- Strain is concentrated in deformation areas to take up displacement variations along faults & to set up space problems from fault interaction
- Interaction damage zones supposedly control fluid flow around interacting faults, provided fluid flow takes place in subsurface

INTERACTION DAMAGE ZONES (CONT.)

- Faults serve as mechanical barriers controlling subsequent deformation
  - In situ stresses are perturbed around non-active faults
  - Perturbation appears especially acute in fault interaction zones

EFFECTS OF FAULT INTERACTION ON SUBSEQUENT DEFORMATION

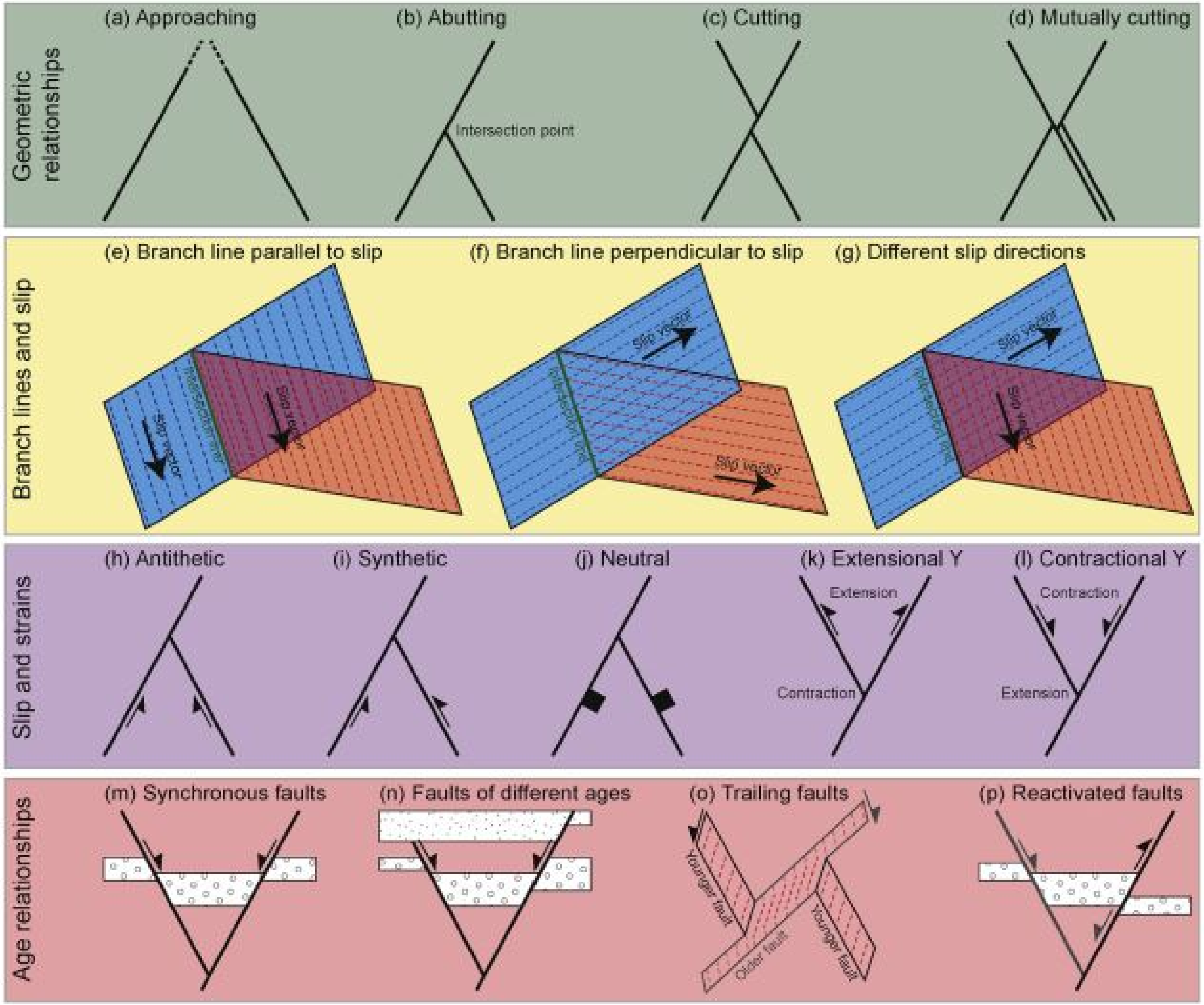


Fig. 15. Classification of intersecting faults. (a) to (d) Classification based on the geometric relationships between the faults. (a) The faults interact as they *approach* each other, but they need not be connected by faults or other fractures (can be similar to the *linkage-damage zone* of Kim et al., 2004). (b) One fault abuts the other. (c) One fault (earlier) is cut by the other (later). (d) The faults mutually crosscut each other. (e) to (g) Classification based on the relationship between the intersection line and the displacement direction. (e) The intersection line is parallel to the displacement direction. (f) The intersection line is perpendicular to the displacement direction. (g) The intersection line is parallel to the displacement direction of one fault and perpendicular to the displacement direction of the other fault. (h) to (l) Classification based on the relative shear senses of the faults and the dominant strains at the interactions. (h) Antithetic relationship, where the faults have opposite senses of displacement. (i) Synthetic relationship, where the faults have the same senses of displacement, approximately perpendicular to the intersection line. (j) Neutral relationship, where the faults have the same senses of displacement, approximately parallel to the intersection line. (k) and (l) Sub-classification for antithetic interactions based on the dominant strain in the acute bisectors of the faults. (k) Extension dominates in the acute bisector, although contraction may dominate in the obtuse bisector. (l) Contraction dominates in the acute bisector, although extension may dominate in the obtuse bisector. (m) to (o) Classification based on the relative ages of the intersecting faults. (m) The faults are synchronous. (n) The faults are different ages. (o) "Trailing" geometry, where part of an earlier fault is reactivated by interaction with later faults. (p) One or both faults have been reactivated.

CLASSIFICATION SCHEME

Based on the following

- Geometric relationships
- Angles between intersection lines & displaced directions
- Strain occurring at & around interaction/intersection zones

Useful tool to analyze fault systems

- Puts emphasis on geometric, kinematic, & temporal relationships between network components

- Certain criteria is used to determine & identify fault interactions
  - Geometric relationships
  - Relationship between intersection line & displacement direction
  - Displacement & strain in interaction zone
  - Relative age relationships
- Scheme allows us to understand stresses & strains occurring around fault interaction, & determine its damage
- Interaction damage zones defined as forming between ≥2 faults of any behavior/age interacting w/each other

CONCLUSION

- Bailey, W.R., Walsh, J.J., Manzocchi, T., 2005. Fault populations, strain distribution and basement fault reactivation in the East Pennines Coalfield, UK. J. Struct. Geol. 27, 913e928.
- Bastesen, E., Rotevatn, A., 2012. Evolution and structural style of relay zones in layered limestoneeshale sequences: insights from the Hammam Faraun Fault Block, Suez rift, Egypt. J. Geol. Soc. Lond. 169, 477e488.
- Bourne, S.J., Willemse, E.J.M., 2001. Elastic stress control on the pattern of tensile fracturing around a small fault network at Nash Point. J. Struct. Geol. 23, 1753e1770.
- Butler, R.W.H., 1982. The terminology of structures in thrust belts. J. Struct. Geol. 4, 239e245.
- Choi, J.H., Edwards, P., Ko, K., Kim, Y.S., 2016. Definition and classification of fault damage zones: a review and a new methodological approach. Earth-Sci. Rev. 152, 70e87.
- Dart, C.J., McClay, K., Hollings, P.N., 1995. 3D analysis of inverted extensional fault systems, southern Bristol Channel basin, UK. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin inversion, Special Publications, Vol. 88. Geological Society, London, pp. 393e413.
- Duffy, O.B., Bell, R.E., Jackson, C.A.L., Gawthorpe, R.L., Whipp, P.S., 2015. Fault growth and interactions in a multiphase rift fault network: the Horda Platform, Norwegian North Sea. J. Struct. Geol. 80, 99e119.
- Ferrill, D.A., Morris, A.P., McGinnis, R.N., 2009. Crossing conjugate normal faults in field exposures and seismic data. Am. Assoc. Pet. Geol. Bull. 93, 1471e1488.
- Fossen, H., Johansen, T.E.S., Hesthammer, J., Rotevatn, A., 2005. Fault interaction in porous sandstone and implications for reservoir management; examples from southern Utah. Am. Assoc. Pet. Geol. Bull. 89, 1593e1606.
- Gartrell, A., Zhang, Y., Lisk, M., Dewhurst, D., 2004. Fault intersections as critical hydrocarbon leakage zones: integrated field study and numerical modelling of an example from the Timor Sea. Aust. Mar. Pet. Geol. 21, 1165e1179.
- Giba, M., Walsh, J.J., Nicol, A., 2012. Segmentation and growth of an obliquely reactivated normal fault. J. Struct. Geol. 39, 253e267.
- Hibsch, C., Jarrige, J.J., Cushing, E.M., Mercier, J., 1995. Palaeostress analysis, a contribution to the understanding of basin tectonics and geodynamic evolution. Example of the Permian/Cenozoic tectonics of Great Britain and geodynamic implications in western Europe. Tectonophysics 252, 103e136.
- Horsfield, W.T., 1980. Contemporaneous movement along crossing conjugate normal faults. J. Struct. Geol. 2, 305e310.
- Huggins, P., Watterson, J., Walsh, J.J., Childs, C., 1995. Relay zone geometry and displacement transfer between normal faults recorded in coal-mine plans. J. Struct. Geol. 17, 1741e1755.
- Kattenhorn, S.A., Aydin, A., Pollard, D.D., 2000. Joints at high angles to normal fault strike: an explanation using 3-D numerical models of fault-perturbed stress fields. J. Struct. Geol. 22, 1e23.
- Kelly, P.G., Sanderson, D.J., Peacock, D.C.P., 1998. Linkage and evolution of conjugate strike-slip fault zones in limestones of Somerset and Northumbria. J. Struct. Geol. 20, 1477e1493.
- Kelly, P.G., McGurk, A., Peacock, D.C.P., Sanderson, D.J., 1999. Reactivated normal faults in the Mesozoic of the Somerset coast, and the role of fault scale in reactivation. J. Struct. Geol. 21, 493e509.
- Kim, Y.S., Peacock, D.C.P., Sanderson, D.J., 2004. Fault damage zones. J. Struct. Geol. 26, 503e517.

- Larsen, P.-H., 1988. Relay structures in a Lower Permian basement-involved 20 D.C.P. Peacock et al. / Journal of Structural Geology 97 (2017) 1e22 extension system, East Greenland. J. Struct. Geol. 10, 3e8.
- Maerten, L., 2000. Variation in slip on intersecting normal faults: implications for paleostress inversion. J. Geophys. Res. 105, 25565e25565.
- Maerten, L., Pollard, D.D., Maerten, F., 2001. Digital mapping of three-dimensional structures of the Chimney Rock fault system, central Utah. J. Struct. Geol. 23, 585e592.
- Maerten, L., Gillespie, P., Pollard, D.D., 2002. Effects of local stress perturbation on secondary fault development. J. Struct. Geol. 24, 145e153.
- Manzocchi, T., Childs, C., Walsh, J.J., 2010. Faults and fault properties in hydrocarbon flow models. Geofluids 10, 94e113.
- Muraoka, H., Kamata, H., 1983. Displacement distribution along minor fault traces. J. Struct. Geol. 5, 483e495.
- Nemcok, M., Gayer, R., Miliorizos, M., 1995. Structural analysis of the inverted Bristol Channel Basin: implications for the geometry and timing of fracture porosity. In: Buchanan, J.G., Buchanan, P. (Eds.), Basin Inversion, Special Publications, vol. 88. Geological Society, London, pp. 355e392.
- Nicol, A., Walsh, J.J., Watterson, J., Bretan, P.G., 1995. Three-dimensional geometry and growth of conjugate normal faults. J. Struct. Geol. 17, 847e862.
- Nixon, C.W., Sanderson, D.J., Bull, J.M., 2011. Deformation within a strike-slip fault network at Westward Ho!, Devon U.K.: domino vs conjugate faulting. J. Struct. Geol. 33, 833e843.
- Nixon, C.W., Sanderson, D.J., Dee, S., Bull, J.M., Humphreys, R., Swanson, M., 2014a. Fault interactions and reactivation within a normal fault network at Milne Point, Alaska. Am. Assoc. Pet. Geol. Bull. 98, 2081e2107.
- Nixon, C.W., Bull, J.M., Sanderson, D.J., 2014b. Localized vs distributed deformation associated with the linkage history of an active normal fault, Whakatane Graben, New Zealand. J. Struct. Geol. 69, 266e280.
- Odonne, F., Massonnat, G., 1992. Volume loss and deformation around conjugate fractures: comparison between a natural example and analog experiments. J. Struct. Geol. 14, 963e972.
- Peacock, D.C.P., 2001. The temporal relationship between joints and faults. J. Struct. Geol. 23, 329e341.
- Peacock, D.C.P., Sanderson, D.J., 1991. Displacements, segment linkage and relay ramps in normal fault zones. J. Struct. Geol. 13, 721e733.
- Peacock, D.C.P., Sanderson, D.J., 1999. Deformation history and basin-controlling faults in the Mesozoic sedimentary rocks of the Somerset coast. Proc. Geol. Assoc. 110, 41e52.
- Peacock, D.C.P., Nixon, C.W., Rotevatn, A., Sanderson, D.J., Zuluaga, L.F., 2016. Glossary of fault and fracture networks. J. Struct. Geol. 92, 12e29.
- Rawnsley, K.D., Peacock, D.C.P., Rives, T., Petit, J.-P., 1998. Jointing in the Mesozoic sediments around the Bristol Channel Basin. J. Struct. Geol. 20, 1641e1661.
- Rotevatn, A., Fossen, H., 2011. Simulating the effect of subseismic fault tails and process zones in a siliciclastic reservoir analogue: implications for aquifer support and trap definition. Mar. Pet. Geol. 28, 1648e1662.
- Rotevatn, A., Tveranger, J., Howell, J.A., Fossen, H., 2009b. Dynamic investigation of the effect of a relay ramp on simulated fluid flow: geocellular modelling of the Delicate Arch Ramp, Utah. Pet. Geosci. 15, 45e58.
- Rotevatn, A., Fossen, H., Hesthammer, J., Aas, T.E., Howell, J.A., 2007. Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah. In: Lonergan, L., Jolly, R.J.H., Sanderson, D.J., Rawnsley, K. (Eds.), Fractured Reservoirs, Special Publications Vol. 270. Geological Society, London, pp. 55e71.
- Soliva, R., Benedicto, A., 2004. A linkage criterion for segmented normal faults. J. Struct. Geol. 26, 2251e2267.

- Underhill, J.R., Patterson, S., 1998. Genesis of tectonic inversion structures: seismic evidence for the development of key structures along the Purbeck-Isle of Wight Disturbance. J. Geol. Soc. Lond. 155, 975e992.
- Vandycke, S., 2002. Palaeostress records in Cretaceous formations in NW Europe: extensional and strike-slip events in relations with Cretaceous-Tertiary inversion tectonics. Tectonophysics 357, 119e136.
- Vandycke, S., Bergerat, F., 2001. Brittle tectonic structures and palaeostress analysis in the Isle of Wight, Wessex basin, southern England. J. Struct. Geol. 23, 393e406.
- Walsh, J.J., Watterson, J., 1991. Geometric and kinematic coherence and scale effects in normal fault systems. In: Roberts, A.M., Yielding, G., Freeman, B. (Eds.), The Geometry of Normal Faults, Special Publications, Vol. 56. Geological Society, London, pp. 193e203.
- Walsh, J.J., Watterson, J., Bailey, W.R., Childs, C., 1999. Fault relays, bends and branch-lines. J. Struct. Geol. 21, 1019e1026.
- Whittaker, A., 1972. The Watchet Fault e a post-Liassic transcurrent reverse fault. Bull. Geol. Survey G. B. 41, 75e80.
- Whittaker, A., Green, G.W., 1983. Geology of the Country Around Weston-supermare. Memoir of the Geological Survey of Great Britain, Sheet 279 and parts of 263 and 295.
- Zoback, M.L., Richardson, R.M., 1996. Stress perturbation associated with the Amazonas and other ancient continental rifts. J. Geophys. Res. 101, 5459e5475.