Journal of Structural Geology 58 (2014) 59–68

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Contrasting origins of breached relay zone geometries

J. Conneally*, C. Childs, J.J. Walsh

Fault Analysis Group, UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form
3 October 2013
Accepted 18 October 2013
Available online 30 October 2013

Keywords:
Fault segmentation
Relay zone
Displacement backstripping
Fault splaying

ABSTRACT

Relay zones accommodate transfer of displacement between pairs of adjacent segments of a fault array that become linked to form a through-going fault as displacement increases. 3D geometric and kinematic analysis of two vertically aligned relay zones, that form a complex boundary between two fault segments, generally support this model of relay zone growth but they also highlight some departures from this scheme. The two seismically mapped relay zones, although separated vertically by 100 m, were synchronously active over most of their development history. A causal relationship between them is proposed with the geometric complexity arising from the formation of the lower relay zone triggering the formation of the upper. The lower relay zone is now breached but originally formed a hole within the fault surface up to throws of ca. 50 m. The upper relay zone displays both breached and intact relay zone geometries at different structural levels demonstrating that relay zone breaching is a protracted rather than geologically instantaneous process. Geometrically the lower part of this structure resembles a breached relay zone, but it formed by propagation of a splay fault from a pre-existing bend to enclose an intervening and steepening ramp, a growth scheme which is the opposite of conventional relay zone models.

1. Introduction

Normal faults commonly occur as arrays of overlapping segments (Segall and Pollard, 1980; Walsh and Watterson, 1991; Peacock and Sanderson, 1991; 1994; Cartwright et al., 1995; McLeod et al., 2000; Young et al., 2001; Marchal et al., 2003; Fossen et al., 2005; Childs et al., 2009). Adjacent segments display complementary variations in displacement, so that when the displacements on the individual segments are added together the aggregate displacement distribution resembles that of a single fault (Peacock and Sanderson 1991; Childs et al., 1995; Walsh et al., 2003a; Soliva and Benedicto 2004; Long and Imber, 2012); this property of arrays of faults is termed geometric coherence (Walsh and Watterson, 1991). The transfer of displacement between two adjacent fault segments is accommodated by strain within the intervening rock volume. Such rock volumes have been termed “relay zones” irrespective of the mode of faulting or nature of the strain (Walsh et al., 1999). The nature of the strain within relay zones varies according to the 3-D geometrical arrangement of the relay zone bounding fault segments and Fig. 1 shows the three end members of the continuum of potential overlap arrangements for normal faults. Transfer of displacement between normal faults which overlap in the vertical requires extensional or contractional strain within relay zones depending on the sense of overlap (Fig. 1). Transfer of displacement between normal faults which overlap in the horizontal can be accommodated by a volumetric shearing or rotation of the rock volume; following previous work (Walsh et al., 1999; Kristensen et al., 2008) this type of relay zone is referred to here as a neutral relay zone because transfer of displacement does not demand volumetric strain. In normal faults offsetting horizontally bedded sequences rotation within a neutral relay zone gives rise to a relay ramp (Larsen, 1988; Peacock and Sanderson, 1991). The overlap geometries illustrated in Fig. 1 are end members of a continuum of possible geometries and oblique overlap between fault segments may occur (Huggins, 1996). Nevertheless in bedded sequences relay zones on normal faults are frequently either sub parallel or sub perpendicular to the slip direction as discussed below.

The geometry of relay zones has been studied extensively at outcrop (Larsen, 1988; Peacock and Sanderson, 1991; 1994; Soliva and Benedicto, 2004) and on seismic reflection data (Walsh et al., 1999; Hus et al., 2006; Worthington, 2006; Giba, 2010; Long and Imber, 2011). From these and other studies a widely accepted model for the geometric development of relay zones has emerged as illustrated in Fig. 2(A–D); the displacement distributions associated with the different stages of this development are shown by the bold lines in Fig. 2(E–H). At low displacements (Fig. 2A) two fault segments are physically unconnected and displacement is

---

* Corresponding author. Tel.: +353 1 716 2604; fax: +353 1 716 2607.
E-mail address: johnc@fag.ucd.ie (J. Conneally).

0191-8141/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2013.10.010

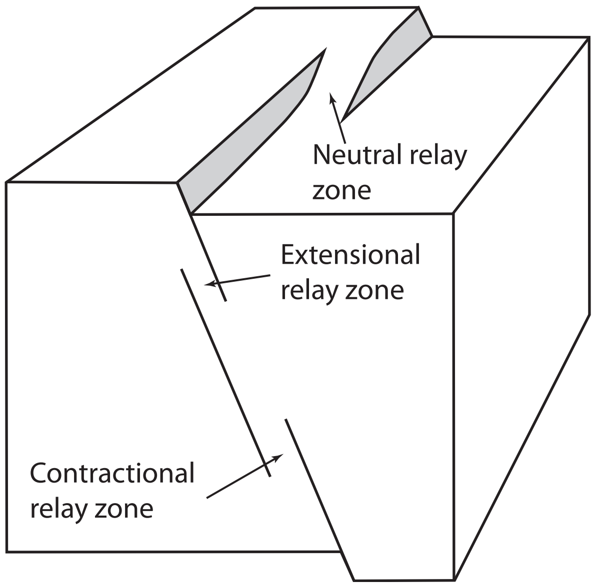

Fig. 1. Block diagram showing the three end member geometries of relay zones on normal faults (modified from Kristensen et al. 2008). Neutral relay zones are developed when the tip-lines of the relay zone bounding fault segments are orientated parallel to the slip vector. Extensional and contractional relay zones are developed when the tip lines of the relay zone bounding fault segments are perpendicular to the slip vector.

transferred between the segments by the development of an intervening ramp. As displacement increases the ramp remains intact and rotates to higher ramp dips. As the throw continues to increase the fault segments may become physically linked and the relay zone is breached to form a through-going continuous fault with an associated splay; the characteristic geometry of a breached relay ramp is illustrated in Fig. 2(C). The branchline along which the faults connect is seen as a step in the displacement on the through-going fault (Fig. 2G) As throw continues to accumulate a second connecting fault may propagate across the ramp to form a double breached relay zone, or fault bounded lens (Fig 2D; Peacock and Sanderson, 1994).

The geometrical evolution of relay ramps described above has been demonstrated in (the relatively few) kinematic analyses of breached relay zones in growth faulted sequences (Childs et al., 1993, 1995; Dutton and Trudgill, 2009; Giba et al., 2012). Morewood and Roberts, (2000) and Walsh et al. (1999) presented examples, mapped from seismic reflection datasets, that illustrate the equivalent progression in 3D structure from an intact relay ramp to a fault-bounded lens enclosed by a branchline loop. Recent mapping of relay zones, however, has shown that they may have complex 3D geometries that require extension of the simple relay zone evolutionary model illustrated in Fig. 2 (Huggins et al., 1995; Kristensen et al., 2008; Giba, 2010; Long and Imber, 2012). These complexities include, obliquity of relay zone bounding tip-lines (e.g. Huggins et al., 1995), intact and breached geometries at different levels on the same relay zone (Giba et al., 2012) and multiple linkages between the faults bounding a relay zone (Long and Imber, 2012). In this paper we add to the relatively few detailed 3D descriptions of relay zones and to the even fewer kinematic analyses. Using detailed seismic mapping and displacement backstripping we determine the geometry and the kinematic history of two spatially related relay zones on a segmented fault with a related growth sequence. Our analyses demonstrate, not only the complex 3D geometry described in previous studies, but also suggest a further modification to the model of relay zone evolution.

The fault zone studied is imaged in a very high-resolution 3D seismic reflection dataset from the South China Sea (Hodgetts et al., 2001), offshore Brunei Darussalam (Fig. 3). The fault is an antithetic fault related to the hanging wall roll-over adjacent to a large west-dipping, gravity driven listric fault (McClay et al., 1991; Imber et al., 2003) and offsets a sand/shale, shoreface/tidal estuarine sequence of Late Miocene age (Hodgetts et al., 2001). The seismic dataset has an in-line spacing of 6.25 m and cross line spacing of 12.5 m (Fig. 4). The vertical resolution of the survey is very high and sedimentary bodies down to 5 m thickness can be resolved (Hodgetts et al., 2001), with resolvable fault offsets which are significantly lower (<2 m). Fault throw, the vertical component of displacement, was measured as the difference in elevation between the seismically mapped horizon/fault intersection cut-offs on either side of the faults. All depths and fault throws are given in metres, with conversion carried out using a constant conversion factor of 1 ms:1.25 m (equivalent to an average seismic velocity of 2.5 km/s) based on nine wells located within ~10 km of the study area (for methodology of well to seismic ties see Hodgetts et al., 2001). The use of a single conversion factor is justified partly because the survey is located in a uniform water depth of 30 m, with no

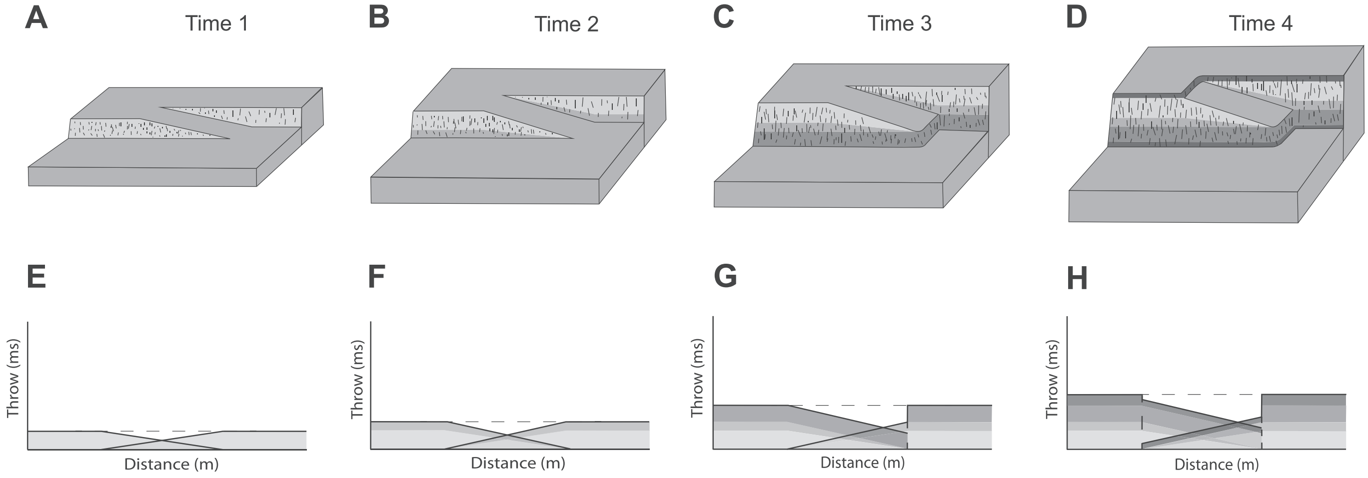

Fig. 2. Block diagrams (A to D) and horizontal throw profiles (E to H) showing four time steps in the evolution of a double breached relay zone. The heavy black lines in E–H represent the observed throw profiles and the filled areas indicate the fault throw increments by which that profile was achieved; the equivalent throw increments are shown on the block diagrams. The horizontal dashed lines in Fig. 2 E–H are the aggregate throws of the faults.