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Comparison of upwards splaying and upwards merging segmented normal faults

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ABSTRACT

A common model for normal fault growth involves a single fault at depth splaying upwards into a series of en-echelon segments. This model is applied to faults as well as a range of extension fractures, including veins, joints and igneous dykes. Examples of splaying growth fault systems in the Columbus Basin, offshore Trinidad, are presented. They include the commonly described upwards splaying type, but also one fault zone with an upward change from disconnected overlapping synthetic faults to a continuous fault. One fault zone with high-displacement fault segments is separated by a relay ramp at depth, becomes breached higher up, developing into a continuous fault at its upper part, where displacements are least. This example suggests that whilst kinematic linkage typically precedes geometric linkage in the evolution of relay ramps, low-displacement parts of a fault system may be geometrically linked whereas higher displacement areas are only kinematically linked.

1. Introduction

Faults are characteristically segmented. For example, normal faults typically step in map view (Goguel, 1952; Macdonald, 1957; Larsen, 1988; Peacock and Sanderson, 1991; Cartwright et al., 1995; Cartwright and Mansfield, 1998), and commonly in cross-section (Childs et al., 1995; Mansfield and Cartwright, 1996; Rykkelid and Fossen, 2002), such that the displacement between normal faults that dip in the same direction is transferred by rotation of the rocks, as occurs in relay ramps (e.g., Peacock and Sanderson, 1994). Models for the development of relay ramps through time (Peacock and Sanderson, 1991; Cartwright et al., 1995) and through space (Huggins et al., 1995) were suggested. The development of relay ramps is reviewed by Fossen and Rotevatn (2016).

These models were developed from studies of outcrops and 2D seismic reflection data, largely prior to the widespread availability of high-quality 3D seismic data (e.g., Conneally et al., 2014; Fossen and Rotevatn, 2016). Improved imaging allows both a fuller characterisation of the fault geometry with depth and an appreciation of the kinematic variation based on variations in sediment thickness (e.g., growth sequences). This paper compares two normal fault systems from the Columbus Basin, offshore Trinidad, which have well-preserved growth sequences. The first example involves a continuous fault surface that splays upwards into a series of segments separated by relay ramps. The second involves a segmented fault system at depth, with a well-developed relay ramp, that merges upwards into a single fault surface.

The geometries of these two fault zones are described and schematic models are presented for their kinematic development. We demonstrate that the first example exhibits many features of the model for fault growth and relay ramp evolution as illustrated by Peacock and Sanderson (1991) (see review by Fossen and Rotevatn, 2016), with connectivity decreasing as displacement decreases upwards. The second example shows the opposite relationship, with segmented faults at depth becoming more connected as displacement decreases upwards. The terminology used in this paper follows that of Peacock et al. (2016).

2. Existing models for splaying faults

To better understand the geometries and evolution of relay ramps, and fault systems in general, it is important to understand the three-dimensional geometry of the faults. The three commonly-used models for the three-dimensional geometries of

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stepping faults are closely related to the origin of the steps (Fig. 1).

Firstly, the geometry may result from the interaction of initially unconnected stepping faults, where two originally isolated faults propagate towards each other (Aydin and Nur, 1985; Crider and Pollard, 1998) and interact to form a relay ramp (Peacock and Sanderson, 1991) (Fig. 1a).

Secondly, the stepping faults may twist off a common fault with a similar displacement direction and orientation (Fig. 1b). Segall and Pollard (1980) and Jackson (1987) show stepping faults branching off a propagating fault. This model has been applied to strike-slip (e.g., Woodcock and Fischer, 1986) and normal faults (e.g., Huggins et al., 1995; Willemse, 1997; Walsh et al., 1999), most typically with the faults splaying upwards. This view of faults is perhaps partly informed by observations of extension fractures, which can splay into stepping segments in the propagation direction (Pollard et al., 1982; Granier, 1985; Pollard and Aydin, 1988) when shear is imposed on the propagating fracture (Engelder, 1987). Splaying extension fractures include joints (e.g., Pollard and Aydin, 1988), veins (Nicholson and Pollard, 1985) and dykes (e.g., Delaney and Pollard, 1981; Pollard and Segall, 1987; Montgomery-Brown et al., 2010).

A third geometry involves stepping faults curving upwards off a common (Fig. 1c). This interpretation is commonly made for thrusts (e.g., Boyer and Elliott, 1982) but has also been applied to normal faults that step in map view (e.g., Larsen, 1988).

Whilst one fault system described in this paper follows the geometry of en-echelon segments splaying upwards off a normal fault at depth (e.g., Huggins et al., 1995), the other fault system consists of two stepping faults at depth that link upwards with a decrease in displacement. This geometry does not fit into any of the three common situations.

3. Examples of interacting normal faults from the Columbus Basin

3.1. Geological background of the study area

The study area is located in the Columbus Basin (Leonard, 1983) situated SE offshore Trinidad on the South American shelf. The geology and tectonic setting of Trinidad and adjacent areas are controlled by their position at the dextral transverse plate margin between the South American and Caribbean plates (Fig. 2) (e.g., Magnani et al., 2009). The advance of the Caribbean plate from the west relative to the South American plate since the Oligocene (Pindell and Kennan, 2009) led to the development of the Caribbean-South American plate margin, which is characterised by a Late Oligocene to Middle Miocene transpressional fold-and-thrust belt (Gibson et al., 2012). The East Venezuela Basin and its continuation to the east, the Columbus Basin, form the foreland basin to this deformed belt. This foreland basin evolved in a time-transgressive manner with the relative eastward motion of the Caribbean plate (Pindell and Kennan, 2009). Foreland basin subsidence in eastern Venezuela and Trinidad began in the Late Oligocene to Early Miocene (Duerto and McClay, 2010; Escalona and Mann, 2011; Gibson et al., 2012).

A change in relative plate motion between the Caribbean and South American plates from transpression to transtension led to cessation of thrusting in the foreland basins by the Middle-Late Miocene (Gibson et al., 2012). From then on, the plate margin evolved into a transform system with dextral strike-slip motion localised onto a few major fault strands offshore northern Trinidad (Algar and Pindell, 1993). Displacement transfer from the strike-slip system at the Caribbean-South American plate boundary southeastward to the deformation front of the Barbados accretionary prism during the Plio-Pleistocene enabled the formation of the Gulf of Paria and Columbus pull-apart basins (Garciacaro et al., 2011; Gibson et al., 2012). The normal faults in the Columbus Basin generally detach onto a near top-Cretaceous unit, involving a significant component of down-to-the-NE gravitational sliding (Gibson et al., 2012).

The Columbus Basin is bound to the north by the Darien Ridge, a structural uplift that marks a change in structural style from thrust-dominated in the north to extension in the south (Leonard, 1983; Gibson et al., 2004). To the west and south of the basin, the Miocene-Pleistocene succession thins onto the shelf of the East Venezuela Basin and the Amacuro continental-margin platform, respectively (Gibson et al., 2004). To the east, the basin continues past the present-day shelf edge into deep-water regions of the continental slope. The Miocene-Pleistocene strata of Trinidad and the Columbus Basin are affected by syn-to post-depositional, NW-SE striking normal faulting, and NE-SW trending contractional folding and local thrusting (Gibson et al., 2012).

The largest faults in the study area show considerable thickness variations across the faults, strongly indicating that they are growth faults (Wood, 2000; Sydow et al., 2003; Garciacaro et al., 2011). Our example faults have much smaller throws, so the thickness variations are not as marked. The faults do, however, show increased thicknesses of hangingwall strata and are therefore interpreted to also be growth faults.

3.2. Data

The dataset used for this project was provided by BP Trinidad and Tobago. The 3D seismic survey was acquired in 1998 and reprocessed in 2003 using 3DDMO-based pre-stack time migration (Yilmaz and Doherty, 1987). The dataset covers an area of ca.

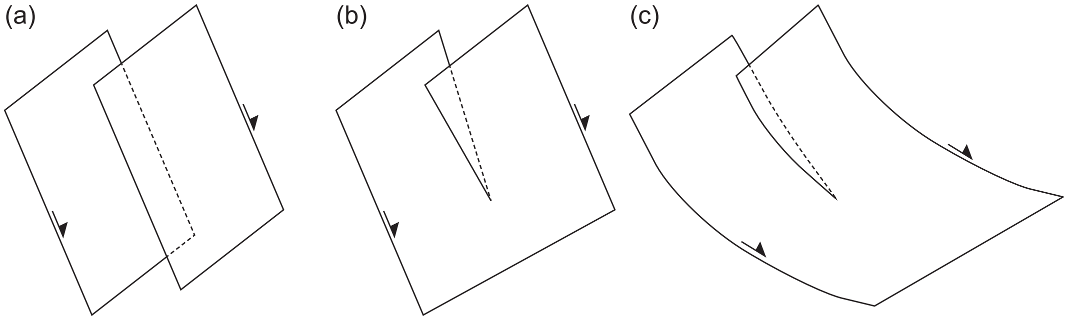

Fig. 1. Schematic figures showing different models of the three-dimensional geometries of normal faults that step in map view. a) The normal faults are approximately planar and are not connected (Peacock and Sanderson, 1991). b) The normal faults are connected at depth and splay upwards (Huggins et al., 1995). c) The stepping normal faults are listric (Larsen, 1988).