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Antithetic fault linkages in a deep water fold and thrust belt

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Abstract

Deep water fold and thrust belts consist of both forethrusts and backthrusts that can link along strike to form continuous folds in the overburden. The interaction of faults of opposing dip are termed 'antithetic thrust fault linkages' and share the common feature of a switch in vergence of overlying hangingwall anticlines. Using three-dimensional seismic data, on the toe-of-slope of the Niger Delta, linkages are classified into three distinct structural styles. This preliminary classification is based on the vertical extent of faulting within a transfer zones relative to the branch line of the antithetic faults. The stratigraphic level of the lateral tip of the fault, the shape of lateral tip region of a fault plane and the stratal deformation within the transfer zones is also distinctive in each type of fault linkage. A Type 1 linkage comprises faults that overlap exclusively above the level of the branch line. A 'pop-up' structure forms within the transfer zone with sediments below remaining planar. The lower tip lines of faults climb stratigraphically towards the linkage zone creating asymmetric, upward-tapering lateral tip regions. In Type 2 linkages fault overlap occurs lower than the level of the branch line such that lateral fault tips are located within the footwall of the counterpart fault. Faulting is thus limited to the deeper section within the transfer zone and creates unfaulted, symmetric, bell-shaped folds in the overburden. Upper tip lines of faults lose elevation within the transfer zone creating asymmetric, downwards-tapering lateral tip regions. In Type 3 linkages both faults continue above and below the branch line within the transfer zone resulting in cross-cutting fault relationships. Horizon continuity across the folds, through the transfer zones, varies significantly with depth and with the type of fault intersection.

Keywords: Thrust faults; Fault linkage; Antithetic; Transfer zones; Vergence

1. Introduction

Research into the growth, propagation and linkage of faults has predominantly focused upon extensional rather than reverse displacement. Numerous studies on extensional faults have provided insights into along strike and down-dip displacement variations (e.g. Peacock and Sanderson, 1991), fault growth (e.g. Watterson, 1986; Barnett et al., 1987; Cartwright et al., 1995), fault scaling laws (e.g. Dawers and Anders, 1995), and classifications of fault linkage geometries (e.g. Gawthorpe and Hurst, 1993). Thrust faults are fundamental as a mechanism for accommodating shortening in convergent tectonic settings and in gravitational detachment systems. Despite this, the mechanisms by which thrusts initiate, propagate and link are not well defined. Most studies have focused on fault geometries, displacement variations and growth using dip-parallel outcrop exposures (e.g. Williams and Chapman, 1983; Eisenstadt and De Paor, 1987; Ellis and Dunlap, 1988). Analyses of along-strike variations and linkage are fewer (e.g. Dahlstrom, 1970; Aydin, 1988; Harrison and Bally, 1988; Nicol et al., 2002; Davis et al., 2005), possibly due to partial exposure and the preferential erosion of hangingwalls within ancient thrust systems (Davis et al., 2005). Analogue modelling of thrust systems provide useful indications as to how thrusts may initiate and grow by segment linkage (e.g. Liu and Dixon, 1991) but remain largely untested in the field. This paper describes and classifies along-strike linkages of

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thrust faults of opposing dip and demonstrates an associated change in fold geometry. This is intended as a preliminary classification to form a basis for further research.

The acquisition of high resolution three-dimensional seismic data over deep water fold and thrust belts offers an opportunity to better resolve fault plane geometries and linkages in three-dimensions. We have selected the compressional domain of the deep water Niger Delta fold and thrust belt, as it provides first class examples of along-strike linkage of thrusts.

1.1. Along-strike thrust fault linkage

Thrust faults can link in the direction of strike such that displacement reduces to zero on one fault, whilst increasing in the same direction on the next (e.g. Davis et al., 2005) in a similar manner to extensional fault systems (Larsen, 1988). This can take place on faults that have similar or opposing direction of dip, termed synthetic and antithetic respectively (Peacock et al., 2000). The regions where fault displacement is transferred from one fault to the next are termed 'transfer zones' (Dahlstrom, 1970). Connectivity of thrusts through transfer zones is not a new concept (e.g. Douglas, 1958; Dahlstrom, 1970; Boyer and Elliot, 1982). Pfiffner (1985), for instance, described a decrease in master fault displacement by the "consumption" of slip by minor splays, whilst Dahlstrom (1970) illustrated the transfer of displacement between paired faults (and folds) along a through-going sole thrust. This led to a simple three-dimensional model of a synthetic transfer zone of en echelon thrust faults (Dahlstrom, 1970 their Figure 26).

Descriptions of antithetic interactions are less common and are largely contained within studies of triangle zones and descriptions of back thrust splays on larger synthetic 'master' faults (e.g. Mandl and Crans, 1981). McClay (1992) and Couzens and Wiltschko (1996) classify two types of triangle zone from existing literature; the first involving two thrusts detaching on a single decollement (Fig. 1a) and the second, also described as an intercutaneous wedge (McClay, 1992), containing multiple decollements (Fig. 1b). The first type can be described as a structure composed of two dipping reflections underlain by horizontal reflections (Couzens and Wiltschko, 1996) (Fig. 1a). Some interactions between faults in this study fulfill this criteria but, importantly, overlap both laterally and downdip within the transfer zone. Back thrust splays have less relevance to this study as they are not thought to be due to the interaction and linkage of two distinct, independent faults and may exist to accommodate strain induced in the hangingwall during ramp climb of the master fault (Butler, 1982).

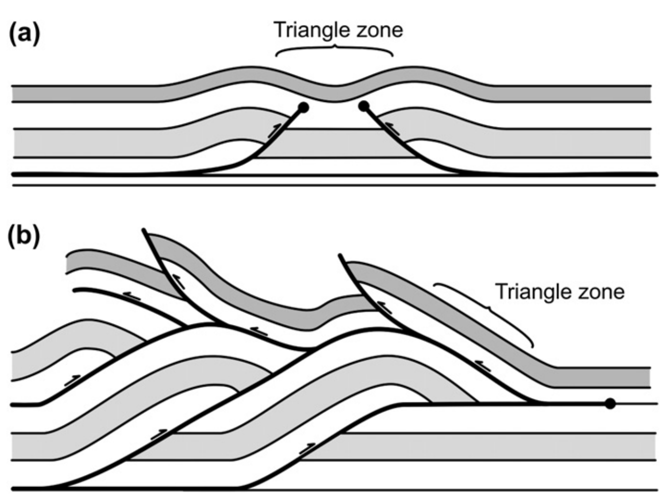

Fig. 1. Illustration of triangle zone geometries (from Couzens and Wiltschko, 1996). (a): "Type I triangle zone" (Couzens and Wiltschko, 1996). (b) Intercutaneous wedge (McClay, 1992) or "Type II triangle zone" (Couzens and Wiltschko, 1996).

The initiation and propagation of thrusts can lead to the development of an asymmetric hangingwall anticline ahead of the fault (e.g. Suppe, 1985 their Figure 9.47). Fig. 2 describes how this asymmetry can be given as a direction of fold vergence, defined here as being towards the shorter, commonly steeper limb from the axial surface. The most evident indication that thrust faults of opposing dip are linking along strike, within the subsurface, can be a switch in the direction of vergence of associated folds in the overburden (Fig. 2). These changes in vergence of hangingwall anticlines are common in the deep water Niger Delta and represent the interaction of detaching forethrusts and backthrusts in the underlying sediments. The seismic data used here contain examples of along-strike overlap and interaction of fault tip regions, although the considerable scale of the faults means it is uncommon for both ends of a particular fault to lie within data limits. Displacement transfer, indicated by horizon geometries, heave-length profiles and the complimentary shape of overlapping fault tip lines, implies kinematic interaction between all the fault pairs identified in this study (Huggins et al., 1995). As a result, the rock volume within a zone of geometric overlap between two fault tips is referred to here as a 'transfer zone' (Dahlstrom, 1970). The examples of transfer zones, imaged using three-dimensional seismic data, are classified into distinct structural styles and geometries.

2. Study area

The 3D seismic survey used in this study covers ~3000 km^2 of the compressional toe-of-slope fold and thrust belt of the Niger Delta. Inline and crossline spacing is 12.5 m (e.g. Brown, 1999) with vertical resolution varying from approximately 7.5 m in shallow levels to 20 m at the base of the studied interval. A review of the geology of the Niger Delta is provided by Doust and Omatsola (1990). Extension and contraction within the delta system is driven by large-scale gravitational collapse on regional detachment levels existing within the Akata Formation (e.g. Bilotti and Shaw, 2005) resulting in the downslope translation of the overlying Agbada Formation. Individual thrust faults have been documented as detaching at numerous levels within the succession of the Niger Delta (Corredor et al., 2005; Briggs et al., 2006). There are two detachments levels imaged in this data set; at the Agbada-Akata Formation boundary and a regional detachment within the Akata itself. Within the study area the Agbada Formation