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Research paper

Growth history of fault-related folds and interaction with seabed channels in the toe-thrust region of the deep-water Niger delta

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ABSTRACT

The deep-water fold and thrust belt of the southern Niger Delta has prominent thrusts and folds oriented perpendicular to the regional slope that formed as a result of the thin-skinned gravitational collapse of the delta above overpressured shale. The thrust-related folds have grown in the last 12.8 Ma and many of the thrusts are still actively growing and influencing the pathways of modern seabed channels. We use 3D seismic reflection data to constrain and analyse the spatial and temporal variation in shortening of four thrusts and folds having seabed relief in a study area of 2600 km^2 size in 2200–3800 m water depth. Using these shortening measurements, we have quantified the variation in strain rates through time for both fault-propagation and detachment folds in the area, and we relate this to submarine channel response. The total amount of shortening on the individual structures investigated ranges from 1 to 4 km, giving a time-averaged maximum shortening rate of between 90 ± 10 and 350 ± 50 m/Myr (0.1 and 0.4 mm/yr). Fold shortening varies both spatially and temporally: The maximum interval shortening rate occurred between 9.5 Ma and 3.7 Ma, and has reduced significantly in the last 3.7 Ma. We suggest that the reduction in the Pliocene-Recent fold shortening rate is a response to the slow-down in extension observed in the up-dip extensional domain of the Niger Delta gravitational system in the same time interval. In the area dominated by the fault-propagation folds, the channels are able to cross the structures, but the detachment fold is a more significant barrier and has caused a channel to divert for 25 km parallel to the fold axis. The two sets of structures have positive bathymetric expressions, with an associated present day uphill slope of between 1.5° and 2°. However, the shorter uphill slopes of the fault-propagation folds and increased sediment blanketing allow channels to cross these structures. Channels that develop coevally with structural growth and that cross structures, do so in positions of recent strain minima and at interval strain rates that are generally less than $-0.02\ \text{Ma}^{-1}$ ($-1 \times 10^{-16}\ \text{s}^{-1}$). However, the broad detachment fold has caused channel diversion at an even lower strain rate of c. $-0.002\ \text{Ma}^{-1}$ ($-7 \times 10^{-17}\ \text{s}^{-1}$).

1. Introduction

Passive margin, deep-water fold and thrust belts, such as that of the Niger Delta toe-thrust region, are areas of tectonic shortening in which the main driving force is the thin-skinned gravitational collapse of deltaic sediment wedges above a ductile substrate of weak shale (e.g., Niger Delta; Billoti and Shaw, 2005; Cohen and McClay, 1996; Morley and Guerin, 1996; Rowan et al., 2004; Wu and Bally, 2000) or mobile salt (e.g., Angolan passive margin, Gulf of Mexico; Anderson et al., 2000; Cramez and Jackson, 2000; Rowan et al., 2004; Wu and Bally, 2000). Contractional deformation within these fold and thrust belts is generally associated with the development of sedimentary growth sequences, deposited coevally with deformation. The growth sequences synchronously fill the accommodation space created by the growing structures and are characterized by stratal thinning or onlap onto the fold crests, and expansion away from the structural highs, into the associated piggy-back or mini-basins.

Submarine channel-levee systems are an important component of the deep-water depositional system (e.g., Deptuck et al., 2003; Normark, 1978; Walker, 1978; amongst many others) and consequently the pathways of sediment gravity flows are often influenced by the growth of structures at, or near the seabed. Folds and

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diapiric structures have been shown to divert, deflect, block or confine turbidite channels (e.g., Clark and Cartwright, 2009, 2011, 2012; Cronin, 1995; Gee and Gawthorpe, 2006; Huyghe et al., 2004; Mayall et al., 2010; Morley, 2009; Oluboyo et al., 2014). Despite the growing number of studies addressing the interaction between active structures and submarine channels, there are very few studies that have attempted to examine in a more quantitative way the links between structural growth and submarine channel systems. The primary aims of this paper are (1) to quantify the spatial and temporal variations in syn-growth shortening of thrust structures and (2) for those with bathymetric relief, assess how variations in these parameters have affected the pathways of submarine slope channels forming coevally with deformation.

The history of structural deformation can be determined by the geometries of the growth sequences associated with the growing structures. This means that, in principle, growth sequence geometries can serve as indicators of how variations in sedimentation and structural growth evolution have varied over time (e.g., Burbank and Verges, 1994; Burbank et al., 1996; Poblet and Hardy, 1995; Suppe et al., 1992 among others). The increasing availability of high quality 3D reflection seismic data driven by extensive hydrocarbon exploration in deep-water settings has led to a renewed focus on fold-related thrusting in deep-water gravitational systems (e.g., Briggs et al., 2006; Clark and Cartwright, 2012; Corredor et al., 2005; Higgins et al., 2007, 2009; Morley and Leong, 2008; Morley, 2009; Maloney et al., 2010). The availability of such seismic data means that individual growth sequences can be mapped, and the shortening accumulated during the growth of folds and thrusts can be quantified. This information can therefore help to determine how strain varies through time in such settings, and how it may affect the sedimentary depositional systems that interact with the growing structures.

Because fold-related seabed bathymetry is likely to exert some control on the pathway of any sediment gravity flows an important issue is how shortening is related to the structural deformation of the seabed. It is conceptually simple to envisage how the growth of most types of fault-related fold should elevate the crest of the fold relative to its limbs, and relatively 'uplift' the seafloor. A number of attempts have been made to quantitatively understand the relationship between the structural elevation of the fold crest and the amount of fold shortening in fault-related folds using geometrical kinematic models (e.g., Hardy and Poblet, 1994; Hardy and Poblet, 1995, 2005; Poblet and Hardy, 1995; Poblet et al., 1997, 2004; Suppe et al., 1992). In general, uplift continues as shortening progresses except for the case of a simple fault-bend fold, where once the lowest unit in the hanging-wall reaches the upper footwall flat, the fold broadens (increases in width) without generating any further vertical relief. For other fold types, the conversion of shortening into a vertical component of uplift requires knowledge of an appropriate geometrical and kinematic model for the fault-fold type. Consequently in this study we clearly separate well-constrained estimates of fold shortening from estimates of crestal uplift.

Three-dimensional (3D) seismic reflection data from the toe-thrust area of the Niger Delta is used for our study. In this area, fold-thrust structures are well-preserved, and the deep-water setting minimises the problems of sub-aerial erosion that removes growth strata in terrestrial fold and thrust belts and tends to hamper similar studies on land. We mapped age-constrained stratigraphic horizons, in both the pre- and syn-kinematic strata, across actively growing thrust-related folds with seabed relief. We then used line-length balancing methods (Dahlstrom, 1969) to calculate the spatial (along-strike) and temporal variation in the cumulative strain that the horizons have accumulated in response to the continual growth of the folds. We discuss the implication of the strain variations at two scales; on a local scale to examine the effect on Pleistocene to modern seabed channel pathways through time, and at a large scale to elucidate the structural development of the Niger Delta.

2. Structural setting of the study area

The study area is in the eastern lobe of the outer fold and thrust belt of the deep water Niger Delta, at the down-dip contractional toe of the gravitational system, and covers an area of 75 km by 35 km (Fig. 1a). The Niger Delta forms the seaward-end of a NE–SW oriented failed rift basin called the Benue Trough. It formed during the opening of South Atlantic following the separation of Equatorial Africa from South America in Early Cretaceous times (Fairhead and Binks, 1991; Whiteman, 1982; Mascle et al., 1986). By Late Eocene times a delta had begun to build across the continental margin (Burke, 1972; Damuth, 1994). Today, the delta covers an area of 140,000 km^2 with includes both the subaerial fluvial delta and the associated deep-water slope to basin-floor depositional system. Stratigraphically, the delta has been divided traditionally into three diachronous units of Eocene to Recent age named the Akata, Agbada and Benin Formations (Avbovbo, 1978; Doust and Omatsola, 1990; Evamy et al., 1978; Knox and Omatsola, 1989; Short and Stauble, 1965; Whiteman, 1982). In the slope and deep-water parts of the Niger Delta, only the Agbada and Akata formations are recognised, where the Neogene mixed clastic slope and deep-water succession of the Agbada Formation overlies the pro-delta marine shales of the Akata Formation (Morgan, 2004; Rouby et al., 2011). In distal deep-water regions the upper parts of the Agbada Formation consist of slope channel-complexes, mass-transport deposits and shales. Submarine channels flowing parallel to slope and perpendicular to structural trends have been identified and mapped at the seabed and in the shallow subsurface extending from the shelf edge to the deep-water Niger delta (e.g., Clark and Cartwright, 2012; Deptuck et al., 2003; Mitchum and Wach, 2002; Morgan, 2004).

The delta is currently undergoing thin-skinned gravitational collapse (Cohen and McClay, 1996; Corredor et al., 2005; Damuth, 1994; Morley and Guerin, 1996) driven by differential loading of the advancing delta, resulting in downslope translation of the delta front and slope deposits on major detachment levels within the pro-delta marine shales of the Akata Formation (Bilotti and Shaw, 2005; Briggs et al., 2006; Rouby et al., 2011). Three main structural zones are recognised within the Niger Delta: an extensional province onshore and beneath the shelf, with basinward dipping and counter-regional listric growth faults; a zone dominated by mud diapirism beneath the upper continental slope; and a down-dip, distal contractional zone (Damuth, 1994) (e.g., Fig. 1a and b). Subsequently Corredor et al. (2005) further subdivided the deep-water contractional zone into two: an inner fold and thrust belt characterised by basinward-verging imbricate thrust faults and an outer fold and thrust belt characterised by both basinward- and landward-verging thrust faults and associated folds. The inner and outer belts are separated by a transitional zone with large, broad detachment folds interspersed with areas of little deformation (Fig. 1 a, b).

Previous studies of folding and thrusting in the deep-water Niger Delta have mostly focussed on the structural styles, evolution of the structures, and the structural controls on thrust and fold growth (e.g., Bilotti and Shaw, 2005; Briggs et al., 2006; Corredor et al., 2005; Higgins et al., 2009; Maloney et al., 2010; Morley and Guerin, 1996). However, only a few studies have examined the structural control on the morphology of the submarine channels. At a broad scale Hooper et al. (2002) discuss how the structural evolution controls the development of accommodation space in the form of ponded-slope basins that are closely linked to the evolution