INTERACTIONS BETWEEN COEVAL SEDIMENTATION AND DEFORMATION
FROM THE NIGER DELTA DEEPWATER FOLD BELT

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ABSTRACT: The deepwater fold and thrust belt of the Western Niger Delta provides an ideal natural setting in which to study interactions between coeval sedimentation and deformation. Deformation in this area takes the form of folding due to the up-dip gravitational collapse of the Niger Delta above the overpressured shale detachment of the Akata Formation. The seafloor relief formed by folding is initially oriented perpendicular to the downslope sediment transport direction. This results in a significant barrier to the basinsward transport of material and the creation of accommodation space within the hangingwall and footwall areas of the fold. Coeval sedimentation during uplift results in deposition of a growth sequence composed of a compensationally stacked vertical succession of mass-transport deposits (MTDs), channel–levee systems (CLs), and hemipelagic drape deposits (HD). Variations in the along-strike structural style and relief of a large-scale fold c. 40 km in length control variations in growth-sequence geometry. These variations in fold style along strike also determine sediment flow pathways around the positive relief formed at the seafloor during fold uplift. Switching of sedimentation between the two structurally induced flow pathways around the fold is related to the compensational stacking patterns within the hangingwall which cause a shift in flow pathways from one fold edge to another. The combined structural–stratigraphic approach to the interpretation of sedimentation in deepwater fold belts can provide a useful method for reconstructing the development of relief during folding.

KEY WORDS: deepwater fold and thrust belts, submarine channels, mass-transport deposits, growth sequences

INTRODUCTION

Deepwater fold belts found on passive margins are characterized by zones of thrusts and overlying folds which develop to accommodate up-dip extensional structures at the heads of large gravity-spreading deformational systems (Bornhauser, 1958; Winker, 1982; Jackson, 1995; Letouzey et al., 1995; Morley and Guerin, 1996). The gravitational collapse of large prograding sediment wedges above ductile substrates such as salt or overpressured shale is typical of many of the world’s large deltaically driven depocenters on passive margins such as the Gulf of Mexico, the Niger Delta, the Kwanza–Congo Delta, the Amazon Cone, and the Nile Cone (McClay et al., 2003; Rowan et al., 2004; Cartwright and Jackson, 2008). Compression in these settings is often expressed at the seafloor as asymmetric folds which typically have a positive relief of several hundred meters (Cohen and McClay, 1996; Demyttenaere et al., 2000; Heinio and Davies, 2006) and act as significant barriers to the downslope transport of sediment. This results in complex slope topography with multiple depressions acting as focal points for sedimentation as well as positive bathymetric barriers to downslope sediment transport, all of which contribute to highly complex, tortuous flow pathways in these settings (Smith, 2004).

In deepwater fold-belt settings, the main drivers for sediment accumulation are the interactions between slope topography and sediment transport and deposition. The interplay between evolution of accommodation space controlled by fold amplification and sediment transport are the first-order controls on sediment architecture and facies (reservoir) distribution, and influence, for example, reservoir–seal juxtapositions (Cartwright, 1989; Prather, 1998; Prather, 2003). Due to water depths of up to 4000 m, the influence of eustatic sea level in directly controlling available accommodation space is secondary in such structurally active deep-water settings, but it can still influence long-term variations in sediment supply and in conditioning the shelf–slope boundary zone for net bypass or accumulation (e.g., Jervey, 1988).

Gravity-driven sedimentation in deepwater fold-belt settings can be separated into two well recognized end-member processes, defining a depositional continuum (e.g., Reading and Richards, 1994). Firstly, turbidity-current-driven sedimentation results in the formation of channel–levee complexes (e.g., Babonneau et al., 2002; Kolla et al., 2007; Wynn et al., 2007) but can also include more unchanneled, early-stage sheetlike deposits (e.g., Beaubouf and Friedmann, 2000). Secondly, mass-wasting processes can mobilize and displace large volumes of sediment over varying distances downslope through a range of transport mechanisms such as debris flows, sliding and slumping (Martinsen and Bakken, 1990; Mulder and Cochonat, 1996; Frey-Martinez et al., 2005).

At larger scales, coeval sedimentation and fold growth results in the formation of growth sequences adjacent to fold limbs (Cartwright, 1989; Suppe et al., 1992). The preservation potential of these growth sequences is much higher in deepwater fold belts than in any other setting (e.g., inverted rift basins (Cartwright, 1989) or foreland basins). Growth sequences are characterized by stratal thinning or onlap onto the fold crest and expansion of sedimentary packages into the forelimb or backlimb of the fold, as well as a progressive increase in stratal rotation with depth (e.g., Burbank and Vergés, 1994, Salvini and Storti, 2002). Growth sequences are commonly studied in the context of structural...
geology and provide important indicators of the mechanism of folding (Suppe et al., 1992; Bernal and Hardy, 2002; Salvini and Storti, 2002). Understanding the mechanism of folding is important because the type of fold will determine the rate of uplift over time and also the shape of the fold, which affects sedimentation paths during fold growth (Salvini and Storti, 2002). Growth sequences can also provide information on the relative rates of uplift vs. sedimentation (Burbank and Vergés, 1994; Burbank et al., 1996). Detailed analysis of sediment–structure interactions between features such as submarine channels and emerging topographic relief in a regime of active deformation can provide detailed information which can be used to refine conceptual models of fold growth based upon larger-scale observations such as growth stratal architecture. Deepwater channel–levee systems are highly sensitive indicators of gradient change (Huyge et al., 2004; Ferry et al., 2005; Heiniö and Davies, 2007; Clark and Cartwright, 2009), and one of the aims of this paper is to show how they can be used to identify subtle changes in fold amplitude and surface relief that otherwise would be undetectable from analysis of seismic profiles alone.

Deepwater fold belts in which sedimentation is coeval with deformation have been extensively described from a structural viewpoint, namely in the Gulf of Mexico (Wu et al., 1990; Trudgill et al., 1999), the Nile Delta (Letouzey et al., 1995; Gaullier et al., 2000; Cartwright and Jackson, 2008), and the Niger Delta (Damuth, 1994; Morley and Guerin, 1996; Wu and Bally, 2000). However, comparatively few studies address the interactions between structural deformation and sedimentation in these or equivalent settings (Cartwright, 1989; Hagen et al., 1994; Huyge et al., 2004; Heiniö and Davies, 2007; Noda et al., 2008). 3D seismic data from deepwater fold belts provide ideal datasets to study detailed sediment–structure interactions and to study growth sequences adjacent to folds, inasmuch as the entire growth sequence architecture can be imaged in detail and placed in its structural context.

This study is based on a high-resolution 3D seismic survey from the deepwater western Niger Delta and aims to present a detailed analysis of a growth sequence associated with a single, well-defined fold. The main aims of the paper are to address the following questions:

1. How can detailed stratigraphic information from the growth sequence be used to reconstruct the seafloor relief during fold growth?
2. What is the architecture of the growth sequence in three dimensions, and how does this relate to the filling of accommodation space created by folding over time?
3. What are the primary sediment pathways during fold growth, and how do these change over time?
4. What is the architecture of the growth sequence in three dimensions, and how does this relate to the filling of accommodation space created by folding over time?
5. How can detailed stratigraphic information from the growth sequence be used to reconstruct the seafloor relief during fold growth?

The underlying theme of this paper is to demonstrate how an integrated structural and stratigraphic analysis of growth sequences can not only be used to aid in reconstructing the structural evolution, but also help to refine depositional models in deepwater fold belts.

GEOLOGICAL SETTING AND STUDY AREA

Evolution and Development of the Niger Delta

The Niger Delta is located at the southern end of a NE–SW oriented failed rift basin (the Benue Trough). Rifting occurred during the separation of equatorial Africa and South America and the opening of the South Atlantic during Early Cretaceous times (Burke et al., 1971; Whitman, 1982; Fairhead and Binks, 1991). By the Late Eocene the delta had begun to prograde across the continental margin, and today the Niger Delta (and its associated deepwater fan) covers an area of 140,000 km² and is up to 12 km in thickness (Damuth, 1994).

The stratigraphy of the Niger Delta is subdivided into three diachronous sequences: the Akata, Agbada and Benin formations (Short and Stuble, 1967; Avbovbo, 1978; Evamy et al., 1978; Whitman, 1982; Knox and Omatsola, 1989; Doust and Omatsola, 1990). In the lower slope region of the western Niger Delta, where this study is focussed, only the lowermost Akata and the overlying Agbada formations are present, and they can be distinguished based on a regional seismic reflection separating two distinctive seismic stratigraphic sequences (Morgan, 2004; Briggs et al., 2006). This contrast results from lithological differences between the lower, mud-rich Akata Formation and the overlying, relatively sand-rich Agbada Formation (Morgan, 2004).

The Niger delta is currently undergoing gravitational collapse above the Akata shales, which forms a regional detachment layer (Briggs et al., 2006). Modelling of the Niger delta by Bilotti and Shaw (2005) showed that the detachment within the Akata Formation is weakened by fluid overpressure, but locally two discrete detachment levels are observed (Briggs et al., 2006). Deformation is active today, resulting in prominent folds expressed on the seafloor within the compressional zone. These folds can be up to 7 km in width and up to 40 km in lateral extent, with a relief of 200 m above the surrounding seafloor. These large folds commonly form above thrust faults showing an array of antithetic and synthetic linkages (Higgins et al., 2007). Many folds are also heavily degraded by erosion and mass-wasting processes (Heiniö and Davies, 2007). The onshore and offshore parts of the Niger Delta can be divided into several structural zones related to gravity-driven tectonics (Fig. 1). Damuth (1994) defined three structural zones: an up-dip extensional zone, a central mud diapir zone, and a down-dip compressive zone. These zones were further subdivided into five domains (Fig. 1; Connors et al., 1998; Corredor et al., 2005):

1. An extensional province located beneath the present continental shelf characterized by regional and counterregional growth faults with associated rollovers and depocenters.
2. A mud diapir zone beneath the upper continental slope (Morley and Guerin, 1996) with inter-diapir depocenters.
3. An inner fold and thrust belt, characterized by basinward-verging thrusts and folds, including detachment folds.
4. A transitional detachment fold zone beneath the lower continental slope characterized by areas of little or no deformation but with occasional large detachment folds above a structurally thickened Akata Formation.
5. An outer fold and thrust belt characterized by basinward- and hinterland-verging thrust faults and associated folds.

Study Area and Methods

The study area is located inboard of the outer fold and thrust belt of the western Niger Delta (Fig. 1) in water depths ranging...
from 2000 to 2300 m below sea level. Structurally, the study area is relatively simple and shows the development of two folds—the Aga and Bobo folds (Fig. 1). Both these structures can be described as thrust-propagation folds (Mitra, 1990) in that along the greater part of their strike they are underlain by large thrust faults. The Aga fold is clearly visible on the present-day sea floor (Fig. 1C); the Bobo fold was reactivated at a late stage and is now buried below sediments which have accumulated within the hangingwall of the Aga fold. This paper focuses on the most recent, and most clearly imaged, upper section of the growth sequence deposited during the latest phase (Plio-Pleistocene) of growth of the Aga fold (Fig. 2). This sequence provides an ideal interval in which to study sediment–structure interactions and three-dimensional stacking architectures within the growth sequence, as well as being the within the highest-resolution interval of the dataset.

The 3D seismic data used in this study covers an area of c. 2000 km² and is zero-phase-time migrated with a positive polarity reflection (black) representing an increase in acoustic impedance. The data are sampled at 4 ms intervals with a line spacing of 12.5 m. Where given, estimates of depth assume an interval velocity of 2000 m/s, calibrated by nearby wells. The dominant frequency of the upper 1.5 s of data is approximately 45 Hz, giving a tuning thickness estimated at 12.5 m.

The methods used in this study involved detailed mapping of individual seismic-stratigraphic units within the growth sequence deposited adjacent to the Aga fold. The aim of this was to establish the three-dimensional architecture of the growth sequence and to document the effects of coeval uplift and deposition. Subdivision of the growth sequence into discrete architectural elements was based on standard seismic stratigraphic characteristics such as reflection continuity, amplitude, internal seismic character of the package, and also relationships such as onlap, downlap, and erosional truncation.

RESULTS AND OBSERVATIONS

Structural Framework of the Aga Thrust and Fold

This section provides an overview of the structural characteristics of the Aga thrust and fold in order to demonstrate the link between the underlying structural characteristics and resulting fold topography. The primary Aga thrust verges towards the southwest and is continuous over a length of 40 km. Vertical displacement reaches c. 500 m in the central portion of the structure and decreases laterally towards the thrust lateral tips (Fig. 2). The fault plane is well imaged on the seismic data, but the limbs of the overlying fold show severe amplitude attenuation in some areas, particularly within the forelimb, which dips at a steeper angle than the backlimb (Fig. 2, lines B and C). The thrust ramps upwards from a detachment level located at the top of the Akata Formation and increases in dip upwards into the overlying Agbada Formation. Typical values for the dip of the fault plane are 14° near the detachment, increasing to 35° towards the fault tip. The primary thrust splits into several frontal splay thrusts which propagate into the forelimb and footwall; these are most well developed in the central area of the primary Aga thrust (Fig. 2, lines C and D). Towards the lateral tips of the primary thrust, north-eastwards-verging backthrusts are developed which tip out at a lower stratigraphic level than the primary thrust (Fig. 2, lines A, E, and F). The dip of these backthrusts is typically 26°. The seafloor expression of the Aga fold exhibits significant mass wasting (see also Heinio and Davies, 2007), with maximum degradation concentrated on the forelimb (Fig. 3).

The geometry of the Aga fold is typically asymmetric, with the forelimb dipping at a steeper angle than the backlimb (Fig. 2, lines C and D). At the seafloor, the dip of the forelimb is difficult to measure due to extensive mass wasting which has modified the fold geometry (Fig. 3); the backlimb has typical seafloor dips of c. 6° (Fig. 2, lines B and C). The asymmetry of the fold decreases with fold amplitude towards both the northwestern and the southeastern lateral tips of the fold. The lateral tips of the Aga fold extend just beyond the resolvable limit of the underlying thrust lateral tips. In these regions, the fold has a broader, less asymmetric profile associated with decreased fold relief at the seafloor. In these lateral tip regions, fold style is similar to that of a faulted detachment fold (Fig. 2, lines A, E, and F). In contrast, the fold style in the central portion is similar to fault-propagation folding (Fig. 2, line C and D), suggesting an evolutionary sequence as fold amplitude and thrust displacement increase (Higgins et al., 2007).

Growth-Sequence Geometry

The hangingwall growth sequence can be subdivided into two units (lower and upper; Fig. 2) based on reflection continuity over the fold crest and onlap relationships of reflections against the backlimb (Fig. 2). The upper interval of the growth sequence forms the focus of this study, because it is the most clearly imaged and is contained entirely within the survey area. The stratigraphic geometry of reflections within the upper growth sequence show that deposition was coeval with increased relative rates of uplift over this interval, compared to the lower growth-sequence interval (Fig. 2; see also Burbank and Vergés, 1994). The increased rate of relative uplift over the upper growth-sequence interval has resulted in clear interactions between uplift and sedimentation, particularly in the hangingwall of the Aga thrust and fold.

The lower unit of the growth sequence is characterized by largely continuous reflection packages that thin and converge over the fold crest with little observable onlap against the backlimb of the Aga fold (Fig. 2). Mass wasting of the fold forelimb has removed much of this sequence from the front of the fold (Fig. 2C). The lower growth sequence is eroded by the upper growth sequence at the lateral tips of the fold, where erosional truncation by the upper growth sequence can be seen (Fig. 2). The isochron map of the lower growth-sequence unit shows an elongate zone of increased thickness deposited against the backlimb of the Aga fold, which thins towards the northwest (Fig. 4A). Deposition of the lower growth sequence was also affected by the growth of a separate fold which extends out of the study area to the southeast, and appears to link with the Aga fold described here (Fig. 4A).

The upper sequence shows a clear increase in thickness passing from the fold crest to the upslope limb, with clear onlap of its internal reflections against the uppermost surface of the lower synkinematic sequence of the fold (Fig. 2). Thinning of this unit from the limb towards the crest is seen clearly on an isochron map of the upper synkinematic interval (Fig. 4B), which also shows a more general thickening of this sequence towards the southeast corresponding to the entry point for sedimentation into the study area. The upper growth sequence is affected by late-stage uplift of the smaller Bobo fold to the north-east of Aga, resulting in thinning of the upper sequence across the fold crest, although the greatest amount of stratatal thinning is observed during the lower growth sequence for the Bobo fold (compare Figs. 4A and B). These observations help illustrate an important point with respect to analyzing isochron maps of growth sequences: it is imperative to set the local fold within a broader context to recognize larger-scale thickness variations and to distinguish them from short-range effects related to folding and spatially varying sedimentation rates.

Variations in growth-sequence geometry occur along strike of the Aga fold. The upper growth sequence displays a progressive
increase in the occurrence of onlap and thinning onto the backlimb towards the central zone of the fold (Fig. 2). The top of the lower growth sequence often forms the onlap surface, and continued uplift of the Aga fold has resulted in progressive rotation of the points of onlap towards the base of the upper growth sequence (Fig. 5). At the southeast and northwest lateral hinges of the fold, the stratal architecture of the upper growth sequence is that of overlap where thinning, but continuous reflection packages occur across the fold crest with little onlap onto the fold limbs observed (Figs. 5B, D). Overlap is accompanied by erosion of the lower growth sequence, as can be seen by the increased truncation of reflections against the base of the upper growth sequence at the fold edges (Fig. 2). The transition along strike from lateral fold tips to the central area is associated with a change from erosional truncation and overlap of the lower growth sequence by the upper sequence to one of increasing conformity between
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Fig. 1 (continued).—

the two, with increasing development of onlap onto the lower synkinematic sequence (Fig. 5C).

Seismic Stratigraphic Architecture of the Upper Growth Sequence

This section describes the principal seismic stratigraphic units which make up the upper growth sequence in the hangingwall of the Aga fold. Description of each seismic stratigraphic unit is followed by its interpretation. The three-dimensional stacking patterns and interactions with deformation of these units are then described in the following section. The distribution of these units is illustrated in Figure 5, which shows a series of dip-oriented lines as well as a profile parallel to the strike of the Aga fold to illustrate the distribution of the growth-sequence elements.

Channel–levee Systems (CLSs).—

Submarine channel–levee systems and their architectural elements have been extensively described from many different basin settings (e.g., Abreu et al., 2003; Deptuck et al., 2003; Posamentier, 2003; Posamentier and Kolla, 2003). Many of the architectural elements identified from these previous studies can be identified here, and we describe only the key features of each system, because a detailed description of all of the architectural elements is beyond the scope of this study.
Fig. 2.—Variations in style along strike of the Aga thrust. The location map shows the top prekinematic surface for the Aga fold, with the lateral-tip regions indicated. Both the upper and lower growth sequences are shown, with the lower growth sequence becoming increasingly affected by erosional truncation towards the lateral tips of the fold.
Fig. 3.—Seafloor dip map showing extensive mass wasting and degradation of the Aga fold forelimb, visible in Part A. Part B shows a representative seismic line through one of the prominent scars and shows material derived from mass wasting interbedded with the pelagic drape in the footwall.
Channel–levee systems (CLSs) are a common component of the growth sequence in the hangingwall of the Aga fold. Three channel systems are described here, termed CLS 1–3, with CLS 1 being most recently deposited (Fig. 6). The channel–levee systems show a significant variation in scale, morphology, and architectural complexity (see next section). The youngest of these channel systems, CLS 1, lies below a recent c. 100-ms-thick package of parallel reflections which cover most of the survey area, interpreted to result from hemipelagic draping. CLS 1 displays large-scale outer levees that flank a channel belt up to 2 km wide (Fig. 6). This system is characterized by large-scale outer levees with a channel axis that shows a combination of lateral migration and vertical aggradation over time (Fig. 6). The channel axis of all of these systems is typically U-shaped and infilled with high-amplitude, often discontinuous reflections which terminate against the margins of the channel axis. The depth of incision of the channel axis varies between different channel systems but generally shows some degree of erosion into the pre-channel sequence (Fig. 6B). CLS 1 also displays terraces related to meander-loop abandonment as well as semicircular scarps due to collapse of the channel sidewalls (Fig. 6A). In contrast to large-scale channels such as CLS 1, smaller systems are also observed (see CLS 2 described later). Smaller channel–levee systems, such as CLS 2, are typically no more than 500 m in width and show a lesser degree of architectural complexity compared to the larger channel–levee systems. A common characteristic of all channel–levee systems in this area is that they display a high sinuosity, regardless of the scale of the system (Fig. 6). Levees are also clearly recognizable from all channel–levee systems by the characteristic tapering of the levee away from the channel axis, with individual reflections within levee packages showing downlap onto a basal surface (Fig. 6B).

Mass-Transport Deposits (MTDs).—

Mass-transport deposits (MTDs) are a common element of the synkinematic sequence (e.g., Fig. 4). They are easily recognizable as units of generally low-amplitude, chaotic seismic character, in contrast to the higher-amplitude and more continuous channel sequences which often incise into them (Fig. 6). Three major MTDs can be identified and traced throughout the hangingwall.
Fig. 5.—Series of seismic profiles across the upper growth sequence in the hanging-wall of the Aga fold. For line locations, see Figure 4. Each seismic profile is accompanied by an interpretation which shows the seismic stratigraphic units described in this paper and shows the links to the relevant figures which show isochron maps of each unit. Part A shows a profile oriented parallel to the strike of the Aga fold showing an overall northwest-dipping slope. Profiles B, C, and D show a series of profiles across the northwest fold tip, the central area of the fold, and the southeast fold tip, respectively. At the lateral fold tips (profiles B and D), the fold relief is not sufficient to block sedimentation, resulting in overlap by the various seismic stratigraphic units. At the central area (profile C), the increased fold relief results in onlap and confinement of sedimentation in the hangingwall.
Fig. 6.—A) A dip attribute map of the upper surface of CLS 1. Key features include a sinuous channel axis, terraces formed by abandoned meander loops, and slump scars formed by collapse of the channel sidewalls. Sediment waves orthogonal to the channel axis are also apparent on the channel levees. B) A seismic line through CLS 1 illustrating some key CLS features, including channel levees, internal levees, and the channel axis, which incises into the underlying deposits.
of the Aga fold. These units exhibit a number of key characteristics widely recognized in these types of deposit (e.g., Frey-Martinez et al., 2005; Bull et al., 2009):

1. Basal grooves are common and consist of linear and curved erosional scours incised into the detachment surface of each MTD (Fig. 7).

Fig. 7.—A) A coherence surface flattened on the top of CLS 2. This image shows the basal scours seen on the lower surface of MTD 1. These features are typical to all of the MTD deposits in this area. As well as the linear scours, larger-scale erosion also occurs to form irregular depressions at the base of the MTD (labelled erosional scouring in the figure). Pressure ridges are also seen towards the southeast of the image. B) A representative seismic line through MTD 1 showing the chaotic, low-amplitude internal seismic character and also U- and V-shaped scours in the basal surface corresponding to the linear scours seen in Part A.
2. Step-like erosional depressions also occur, and are often filled by material of seismic character similar to the surrounding MTD. These depressions have very sharp lateral boundaries and are rectangular in cross section (see MTD 2, described later).

3. Compression ridges and thrusting are also observed at the bases and at the tops of several MTDs (Fig. 7).

All of the MTDs identified in this study extend outside of the area of data coverage, both in an upslope and downslope direction, and are assumed to be sourced from the east of the survey area, according to the orientation of features such as the prominent basal grooves and pressure ridges (Fig. 7). In the upper growth sequence there is a clear and predictable stratigraphic relationship between MTDs and the CLS, where in all cases channel systems tend to incise into a previously deposited MTD. It is unclear from this dataset alone whether this represents cyclic deposition or whether the relationship is coincidental, arising simply because the MTD and CLS represent the most common depositional products in this part of the slope sequence.

Hemipelagic Drape Deposits (HDs).—

These deposits possess a seismic facies composed of high-amplitude, continuous reflections that often can be traced across the whole study area. Reflections making up this sequence typically exhibit configurations that passively drape onto the previous topography of the underlying unit (Brown and Fisher, 1977). Some thickness variations do occur in this unit, however, and it is possible that this unit has been modified by bottom-current activity in some areas, with reflection configurations and planform topography similar to contourite drift deposits identified on 3D seismic elsewhere (cf. Knutz and Cartwright, 2003). One such area can be seen on the present-day seafloor (Fig. 1C—northwest fold-tip area). Here, bottom-current activity seems to have scoured a depression (moat) around the northwest edge of the Aga fold.

Stacking Patterns in the Upper Growth Sequence and the Effects of Fold Uplift on Deposition

This section describes in chronological order the influence of fold development on the deposition of the most recent architectural elements of the upper growth sequence. We also highlight some of the characteristic relationships that reveal the interactions between fold-controlled topography and deposition. These relationships include diversion of the basal scours of MTDs, and changes in submarine channel morphology in response to uplift of the Aga fold.

At the base of the mapped interval in the upper growth sequence, MTD 3 exhibits an east–west thickness trend (Fig. 8). The thickest portions of the deposit are concentrated above a set of prominent scour features at the base of this deposit; these scours are up to 500 m wide and 20 m deep (Fig. 8). The orientation of these scours and the thickness distribution of the overlying deposit indicate that MTD 3 was sourced from the east, outside of the study area. Importantly, the scours imaged on the basal surface of this MTD show a change in orientation on crossing the subtle relief due to the Bobo fold (Fig. 8). This highlights a potential use of recognizing basal scour geometry associated with MTD deposition in revealing subtle variations in topography over which the flow passed. MTD 3 tapers towards its southern margin, where erosion by CLS 3 has partially removed material (Fig. 8).

CLS 3 lies stratigraphically above MTD 3, which is incised by this channel in some areas (Fig. 9). The pathway of this channel within the hangingwall of the Aga fold is controlled by the southwards thinning and pinchout of MTD 3 (Fig. 9), and thus provides a good example of a compensational relationship between channel positioning and pinchout of an underlying MTD deposit. This channel also exhibits a clear diversion related to fold-controlled topography as it passes around the northwest lateral tip of the Aga fold (see also Clark and Cartwright, 2009). Diversion of this channel shows no significant change in sinuosity as CLS 3 passes from the hangingwall to the footwall (Fig. 9C), possibly suggesting little change in
gradient upon passing from the hangingwall to the footwall (see also Ferry et al., 2005). The only change in channel morphology associated with this transition is a thickening of the channel–levee deposits and the deposition of a high-amplitude, sheetlike deposit at the forelimb-to-footwall transition located at the base of the CLS3 sequence (Fig. 9C). This channel system has also suffered significant erosion in the northeast where it enters the survey area by the overlying MTD 2, with erosion appearing to preferentially remove the channel levees (Fig. 9B). Preservation of the channel levees in the forelimb of the Aga fold may be a result of the decreased thickness of the overlying MTD 2 in this area.

The distribution of MTD 2 is much more extensive compared to MTD 3 and shows general thinning in deposition to the north of the survey area, with this deposit being sourced from the east with a westwards transport direction, indicated by the thickness trends seen in this unit (Fig. 10). There are several key controls on the deposition of MTD 2. Firstly, relief resulting from aggradation of the channel levees deposited by CLS 3 results in run-up relationships where the material from MTD 2 thins against the wedge-shaped levees which obstruct deposition (Fig. 10B). In the northeast of the survey area, MTD 2 causes significant erosion of the channel levees of CLS 3, leaving only the channel axis preserved (Fig. 9B). Erosion of the underlying channel system is concentrated in the northeast where MTD2 enters the survey area. The isochron map of CLS 3 shows that the channel levees have been removed during emplacement of MTD 2, particularly on the southern margin of the channel where MTD 2 increases in thickness (Fig. 10A). The second control on the distribution of MTD 2 is the relief of the Aga fold and its primary role in shaping the accommodation space upslope and in obstructing the downslope flow pathway of this deposit (see also Beaubouf and Friedmann, 2000; Prather, 2003; Smith, 2004). This results in thinning of the MTD against the backlimb and diversion of material around the southeast lateral tip of the fold (Fig. 10). In this area deposition of MTD 2 resulted in the formation of a lobelike deposit which infilled negative relief in the footwall of the Aga fold (Fig. 10A). Basal grooves are also observed to be diverted around the lateral hinge and diverge within the footwall. This echoes the relationship already noted for MTD 3, whereby basal grooves carry important directional information that reveals subtle gradient changes (Bull et al., 2009).

Following the emplacement of MTD 2, a small-scale channel–levee system—CLS 2—was deposited (Fig. 11) that is up to 500 m in width, with the channel axis being no more than 50 m deep. This channel system is sourced from the east and exhibits a clear diversion around the northwest lateral tip of the Aga fold. The levee distribution for CLS 2 is uniform in the backlimb of the Aga fold, with levee thickness and lateral extent approximately equal on each flank of the channel (Fig. 11A). The channel and levee deposits thicken upon crossing from the forelimb to the footwall.
Fig. 9 (above and facing page).—A) Isochron map of CLS 3, which has been extensively modified by erosion caused by the overlying MTD 2. Erosion by MTD 2 has resulted in removal of significant volumes of levee material and also formation of positive relief caused by “perched” MTD material on top of CLS 3; this can be seen clearly in Part B. C) An amplitude map of the base CLS 3 surface. The highly sinuous nature of the channel can be seen as well as the change in depositional style of the earliest channel deposits upon crossing into the footwall.
Fig. 9 (continued).—
Fig. 10.—A) Isochron map of MTD 2. This deposit is concentrated around the region of the southeast fold tip, where diversion is observed into the hangingwall and into the footwall. Diversion of material into the footwall results in a lobe-like depositional geometry of the MTD in this area as it responds to the available accommodation space in this area. B) The compensational relationship between levee relief and overlying MTD deposition where MTD material thins against the underlying channel levee. Perched MTD material can still be seen on this section; see also Fig. 9B for comparison.
Fig. 11.—A) Isochron map of CLS 2. The channel levees are symmetrical about the channel axis in plan view in the hangingwall. As the channel is diverted around the northwest fold edge, levee distribution becomes asymmetric due to the confining effect of fold relief. Also apparent is the increase in thickness of the channel deposits in the footwall, immediately downdip from the forelimb to footwall break in slope. B) A coherence slice flattened to the top of CLS 2. The change in channel morphology is emphasized. In this image, the channel shows increased lateral migration limited to the footwall area, with the formation of an abandoned meander loop labeled in Part B.
and is associated with a localized increase in channel migration in this area. See for example, the abandoned meander loop in Fig. 11B. The change in channel morphology is located at the transition from forelimb to footwall, in a manner similar to that previously observed for CLS 3.

The deposition of CLS 2 was followed by a hemipelagic interval (unit HD 2, Fig. 5). This unit shows no systematic thickness variations due to structural growth, but some material has been eroded by MTD 1, which overlies this interval.

Deposition of MTD 1 was influenced by both the Aga and Bobo folds, as can be seen from the thinning of this deposit against the backlimb of the Aga fold and against the forelimb of the reactivated Bobo fold (Fig. 12). Scours are also present at the base of this deposit (Fig. 6A), and these observations, combined with the isochron map, show that MTD 1 was sourced from the east, with deposition being confined entirely to the hangingwall of the Aga fold. The basal grooves of MTD 1 show convergent and divergent relationships in response to the relief present at the time of deposition by the forelimb of the Bobo fold, which has resulted in confinement of this deposit into the accommodation space between the two folds (Fig. 7). MTD 1 is entirely confined within the hangingwall of the Aga fold and cannot be traced into the footwall (Fig. 12A), indicating that the seafloor relief prior to deposition was sufficient to confine MTD 1 within the hangingwall.

The isochron of CLS1, the most recent channel–levee system, shows that the levees are evenly distributed on either side of the channel axis but that the overall thickness of this system and the lateral extent of the levees decrease towards the west (Fig. 13). The positioning of this channel in the study area is related to the northwards thinning and pinchout of the underlying MTD 1 unit to the southwest and the reactivated Bobo fold towards the northeast. Late stage of uplift of the Bobo fold is shown by tilted levee relationships seen along this channel (Fig. 13B). Despite tilting of the channel levees caused by uplift of the Bobo fold, the lowermost levee reflections onlap the fold, demonstrating that fold-controlled relief affected the course of CLS 1 early on in its development. Relatively rapid subsequent sedimentation due to

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**Fig. 12.—** A) Isochron map of MTD 1, showing a strong southeast-to-northwest orientation in deposition due to confinement of this deposit against the backlimb of the Aga fold and the forelimb of the reactivated Bobo fold. B) A seismic line which further illustrates the confined nature of this MTD deposit. Note the location of the overlying channel–levee system (CLS 1), the axis of which is located between the pinchout of MTD 1 and the axis of uplift of the Bobo fold.
levee deposition then resulted in local overlap of the fold crest. This was followed by a phase of renewed uplift resulting in the final, folded levee geometry observed in Figure 13B.

The final and youngest stratigraphic unit (HD1) is composed mainly of parallel reflections that drape the relief of the underlying channel–levee system (Fig. 4A). In the forelimb of the Aga fold, the extensive degradation resulted in local mass-wasting deposits which are intercalated with the draping facies (Fig. 3).

DISCUSSION

The detailed description of the architectural elements constituting the upper growth sequence illustrates a number of key processes regarding the interaction between structurally controlled topography and depositional processes and products. These include the three-dimensional stacking of individual architectural elements constituting the growth sequence, and also more detailed interactions between deposition of these units and structurally induced relief present at the time of deposition. These generic themes are observable on similar folds in many deepwater fold belts, or indeed in inverted rift systems (Cartwright, 1989) and foreland basins (Burbank and Vergés, 1994). These themes are discussed further below, in an effort to draw some wider conclusions that may help in predictive studies in areas of active deepwater exploration.

**Development of Bathymetric Relief during Fold Growth**

Considerable insights into relief development during folding can be obtained when analyzing growth sequences by comparing the central most highly deformed region with the lateral tips of the structure. At the lateral-tip regions of the Aga fold, for example, the observed pattern of thinning of the upper growth sequence across the fold crest and general lack of onlap against the backlimb suggest that no opposing slope was developed in these areas to block sediment transport into the footwall (cf. Burbank and Vergés, 1994; Burbank et al., 1996). This is in contrast

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**Fig. 13.—**The isochron of CLS 1 showing a uniform levee distribution about the channel axis. The levees and channel fill thicken towards the source direction, indicating that this channel was backfilled during the latest stage of its deposition. B) Reactivation of the Bobo fold has uplifted the northeast channel levee, resulting in a unique levee geometry compared to the southwest channel levee, which is undeformed.
to the central area of the fold, where the upper growth sequence onlaps the backlimb of the Aga fold, indicating that the fold formed positive seafloor relief and a barrier to flow across this area of the fold (Fig. 2). Although no opposing slope developed at the lateral-tip regions during deposition of the upper growth sequence, an overall basinwards-dipping slope was maintained during uplift—as can also be seen on the present-day seafloor (Fig. 1C).

Evidence that a basinward-dipping slope was maintained during fold growth at the transition from forelimb to footwall can be seen in the subsurface where CLS 3 and CLS 2 are diverted around the northwest lateral tip of the Aga fold (Figs. 9, 11). CLS 2 thickens as it is diverted around the Aga fold, resulting in a lobe-shaped depocenter localized in the immediate footwall (Fig. 11). Another example of how the depositional style of channel–levee systems changes at the forelimb–footwall transition is shown by the amplitude map at the base of CLS 3 (Fig. 9C). This shows development of a fanlike feature at the base of the channel sequence, characterized by high seismic amplitudes located at the base of slope of the forelimb–footwall transition. CLS 3 also shows an increase in overall channel-deposit thickness in the footwall and slight ponding of the left-hand levee against the forelimb (Fig. 9). These observations suggest that:

1. At the scale of individual flow events, there is a change in flow character at the forelimb-to-footwall transition caused by the decrease in slope. The decrease in slope at this transition point results in flows becoming increasingly depositional in the footwall. This could be a result of processes such as hydraulic jumps (Garcia, 1993) occurring as a response to the change in gradient from the steep forelimb to the reduced slope of the footwall.

2. At the larger scale of slope architectural elements, the increased deposition in the footwall may be caused by the local perturbation in the base level of the channel profile due to folding. The channel response to this local lowering of gradient is to aggrade within the forelimb of the fold in order to reach its hypothetical equilibrium profile (Pirmez et al., 2000; Ferry et al., 2005).

At the lateral tips of the Aga fold, the relief resulting from fold growth did not create an opposing slope to block sedimentation around the fold. The curvature seen in growth strata in the upslope limb close to the lateral-tip regions reflects progressive rotation during uplift towards the base of the sequence during sedimentation, and not actual fold relief expressed on the seafloor (Fig. 5). An estimate can be obtained of the magnitude of uplift which has occurred during deposition of the upper growth sequence by taking the change in thickness of the upper growth sequence across the fold crest at the lateral-tip regions of the Aga fold (see Masaferro et al., 2002, for more detail). Using an average interval velocity of 3000 m s⁻¹, the upper growth sequence records approximately 430 m of uplift at the lateral tips of the Aga fold. This compares to a minimum of 1000 m of cumulative positive relief being developed towards the central area of the fold over the same interval. Note that due to the increasing occurrence of onlap towards the central portion of the Aga fold, this estimate only provides a minimum value for fold relief in this area.

Evidence of low slope gradients during submarine channel deposition can be assessed based on observations of channel morphology. Large-scale sinuosity variations of submarine channel systems downslope have been documented by Clark et al. (1992), Pirmez and Imran (2003), and Babonneau et al. (2002). Submarine channel systems also exhibit localized morphological variations in response to varying slope gradients (Ferry et al., 2005; Huyghe et al., 2004; Gee and Gawthorpe, 2006). These responses can be summarized as:

- Increases in slope gradient result in localized increased channel incision, often associated with a decrease in sinuosity.
- Decreases in slope gradient result in localized channel aggradation, corresponding to a local increase in sinuosity.

There is also some evidence that highly sinuous submarine channels occur only where the underlying slope gradient is below a certain threshold value. Clark et al. (1992) also have shown that sediment caliber of the flows forming submarine channel systems also play a key role in determining the maximum sinuosity for a variety of given slope values. Babonneau et al. (2002) suggested that a slope value of approximately 0.3° acts as the threshold value for the Zaire and Amazon systems. Whilst it is not known whether this figure is generally applicable to all submarine channel systems, the implication is that wherever highly sinuous submarine channels occur, it is in association with a certain underlying slope gradient for a given series of flows with particular characteristics in terms of sediment caliber. CLS 3 displays high sinuosity along its length throughout the study area, despite being diverted around the northwest lateral tip of the Aga fold (Fig. 9). The high sinuosity of this system is evidence that low gradients (likely below 0.5°) were present at the seafloor despite active uplift of the Aga fold during deposition of the upper growth sequence. These low seafloor gradients implied by submarine-channel morphology reflect a rapid relative rate of sedimentation compared to uplift at the fold lateral tip. This is not surprising; the lateral-tip regions are often the preferential flow pathways around the fold, and a laterally increasing sedimentation rate is thus to be expected. The underlying control is the lateral variation in fold structural style along strike, and in particular the way in which fold relief varies along strike, which can be affected by factors such as synthetic and antithetic thrust-fault linkages (Higgins et al., 2007).

Analysis of isochron data for individual architectural elements which make up the upper growth sequence show that development of sufficient fold relief to block deposition into the footwall occurred only after, or during, the deposition of unit HD2 (compare Figs. 10 and 12). Deposition of MTD 1 is not associated with any overspill of sediment into the footwall due to the backlimb of the Aga fold forming an obstacle to flow against which MTD 1 terminates along its southwest margin (Fig. 12). Deposition of MTD 1 was also affected by a late-stage reactivation of the Bobo fold, which caused partial confinement of this deposit and diversion of basal grooves around the edges of the topography created by reactivation of this fold. This reactivation is a relatively late-stage event in the development of the upper growth sequence and is associated with a shift in the direction of sedimentation from being fold-perpendicular (MTDs 3 and 2 and CLSs 3 and 2) to fold-parallel (MTD 1 and CLS 1). Based on this information a two-phase model of growth sequence development can be described (Fig. 14):

1. The first phase of growth-sequence development (Fig. 14A–D) involves a significant element of deposition that is perpendicular to the strike of the fold. This can be seen where CLSs 3 and 2 are diverted around the northwest fold edge, and MTD 2 is diverted around the southeast lateral hinge to deposit within the forelimb. During this phase of deposition, only the central area of the fold presented an obstruction to flow.
Fig. 14.—Summary of observations from the various growth-sequence architectural elements. Phase 1 (Parts A–D) is characterized by a fold-perpendicular sediment transport and deposition in which the various architectural elements are compensationally stacked within the hangingwall but are diverted around the fold edges due to the decreased fold relief in these areas. Phase 2 (Parts E and F) is characterized by increased relative rates of uplift vs. sedimentation where the relief of the Aga fold, and partly of the reactivated Bobo fold, confines deposition in the hangingwall of the Aga fold. This phase of deposition involves fold-parallel sedimentation.
2. The second phase of deposition (Fig. 14E and F) was preceded by uplift of the Aga fold and also by reactivation of the Bobo fold. Following this renewed period of uplift, the deposition of MTD 1 and CLS 1 does not show diversion around the fold tips and is confined to the upslope limb of the Aga fold.

This change in the sediment distribution pathways from fold-perpendicular to fold-parallel results from increased relative uplift rates compared to sedimentation, which may be caused by an increase in the rate of shortening and uplift causing rapid development of positive relief, or alternatively a decrease in sediment volume input into the hangingwall of the Aga fold. With lack of chronostratigraphic information and the limited coverage of this 3D dataset, it cannot be determined which of these two mechanisms is responsible for the change in sedimentation patterns over time.

**Three-Dimensional Growth-Sequence Architecture and Implications for Reservoir Development**

From the observations presented above, we suggest that the three-dimensional stacking relationships seen in the upper growth sequence are controlled primarily by two factors:

1. Compensational relationships within the hangingwall area upslope of the zone affected by fold relief. Here, deposition of each successive unit is affected partly by the topography resulting from the previous deposit.

2. The relief generated by the Aga fold, which results in onlap of deposits onto the backlimb and diversion of sedimentation around the fold lateral tips, resulting in overlap at these regions.

Compensational relief is largely generated by the deposition of MTD units and also results to some extent from the positive relief constructed during deposition of channel levees. The location of CLS 3 in the hangingwall is partly related to the southward pinchout of underlying MTD 3 (Fig. 9). Thus the relief generated by the previous MTD deposit has also influenced the course of this channel in addition to the effect of the Aga fold, whose structurally induced relief results in channel diversion around the northwest lateral tip. The effect of compensational relief formed by a channel–levee system in the hangingwall can also be seen where MTD 2 thins against the levees of CLS 3 (Fig. 10B). Overall, a shift in the locus of deposition towards the south of the study area is seen over the depositional interval represented by MTD 3 to MTD 2 (Figs. 14A–D). This is accompanied by southward shift in the input points into the study area.

This southwards shift in sedimentation in the hangingwall is also associated with a shift in sediment pathways around the fold edges. During deposition of MTD 3 and CLS 3 and 2, the northwest lateral tip was the preferred flow pathway for sediment to be deposited in the footwall. However, deposition of MTD 2 was shifted to the south, due to compensational effects from the levee relief of CLS 3 and due to the southwards shift in the input point into the study area (Fig. 14). MTD 2 utilizes the southeast lateral tip, where diversion of material is seen around the Aga fold and is associated with lobelike deposition of sediment in the forelimb (Fig. 10). Switching of the primary flow pathways between the northwest and the southeast fold lateral tips is related to the compensational stacking and southwards shift in deposition away from the northwest lateral tip of the Aga fold.

The structural relief which developed during the upper growth sequence can be assessed by comparing the thickness change from the upslope limb to the fold crest. As discussed above, both of the fold lateral-tip regions show approximately equal amounts of development of structural relief during deposition of the upper growth sequence (c. 430 m). Therefore, the dominant control on flow-path switching around the Aga fold appears to be the compensational backfilling of the hangingwall by alternating MTD and CLS deposition, as opposed to variable shortening and differences in fold relief at the lateral tips, resulting in a preferred sedimentation pathway around the fold.

**CONCLUSIONS**

In conclusion, the central themes explored in this paper are presented in Figure 15, and are summarized as follows:

1. Variations in structural style along strike of the Aga thrust and fold are controlled by factors such as shortening and the development of backthrusts. This in turn controls development of fold relief at the seafloor.

2. Fold relief developed at the seafloor and its evolution through time combined with the effect of compensational stacking within the hangingwall control the sediment distribution pathways around the fold-tip regions.

3. The varying fold relief along strike controls the response seen in the stratal geometries of the growth sequence. At the fold lateral hinges, the growth sequence displays overlap and thinning across the fold crest, as well as erosional truncation of the underlying sequences. Across the central area of the fold, onlap against the fold limb results from an increased relative rate of uplift compared to sedimentation.

4. Although the fold geometry controls the accommodation space in the hangingwall, stratigraphic architectures are controlled by a combination of compensational stacking patterns and structurally confined deposition.

5. The growth sequence itself is composed of a complex, three-dimensionally stacked series of channel–levee complexes, mass-transport deposits, and hemipelagic intervals. Many of these units exhibit a response to the emerging relief during fold growth which can be assessed using features such as scours at the bases of MTDs and changes in channel morphology and depositional style which respond to slope gradient.

The relationships between sedimentation and deformation documented in this case study are not specific to this particular area, and similar expressions of the interplay between tectonics and sedimentation have been observed by us in many other deepwater fold belts. As such, we suggest that these examples can be used as a reference set to base more general exploration play models wherever a slope system is being actively deformed, as well as forming a basis for further work involving comparative studies of the interactions between sedimentation and deformation from separate deepwater fold-belt settings.

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Structural control on growth-sequence architecture

Increase in fold relief towards center of fold = increased barrier to flow

Overlap of growth sequence at lateral hinges

I:

Increase in fold relief towards central zone

Primary thrust

Decrease in fold relief towards lateral hinges

Mass wasting from forelimb

Backthrust

Primary thrust

Hangingwall

Erosion of lower growth sequence at lateral hinges

Backthrust

Footwall

Forethrust

Onlap onto backlimb

Onlap onto backlimb

Along-strike transition from erosion and overlap to rotated onlap

Fig. 15.—Conceptual model of the key factors affecting the evolution of the growth sequence in this study area.

REFERENCES


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