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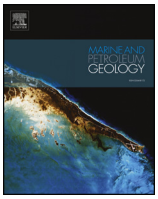

Research paper

Development of a partially-avulsed submarine channel on the Niger Delta continental slope: Architecture and controlling factors

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ABSTRACT

On the Niger Delta slope a partially-avulsed channel, named Tombia Channel (TC), was recognized. This work used high-resolution 3D seismic data to investigate its external morphology, internal architecture and the detailed association with the feeder channel, i.e. Bukuma Channel System (BCS). TC emanated from a slope transition zone of BCS where a sharp bend as well as the channel-floor aggradation increased the instability of BCS and triggered by an outsize flow event, the avulsion happened. The initial flow path of TC appeared to follow discontinuous linear trains of small scours and residual pockmarks; as it evolved, TC developed a very low sinuosity and did not have levees. Preserved cross-sectional profiles of TC changed from dish, deep-U, V to shallow-U shape downstream, which was mainly controlled by increasing then decreasing background slope.

Three channel forms were recognized within TC, forming a fining upward sequence, which may be associated with the progressive abandonment of BCS; each channel form also showed a trend of increasing grain size along the flow direction. TC evolved through four stages: Stage 1 was characterized by the interaction of overspilling flow stripped off from BCS with the inherited overbank topography; Stage 2 was featured by the full establishment of a channelized flow pathway and then by deposition of early Channel form 1; Stage 3 was dominated firstly by further development of the flow pathway and then by deposition of latter Channel form 2; Stage 4 occurred in the abandonment phase and referred to the hemipelagic draping on the residual negative relief (Channel form 3).

If TC commonly develops so as to fully capture the sediment gravity flows from BCS, architectural records of this type would have low preservation potential. However, the shut-down of BCS make that preservation possible and it provides potentially important insights into submarine channel avulsion processes.

1. Introduction

As important components of deep-water systems (Wynn et al., 2007; Mchargue et al., 2011), submarine channels are conduits to tranport nutrient to deep-sea ecosystems (Pichevin et al., 2004; Biscara et al., 2011) and geohazards for seafloor infrastructure planning and construction (Paull et al., 2002; Xu, 2010), however, what is the particular focus of previous studies is their great hydrocarbon reservoir potential (Clark and Pickering, 1996; Posamentier and Kolla, 2003; Labourdette et al., 2006; Mayall et al., 2006; Covault et al., 2014; Liu et al., 2013; Zhang et al., 2015). Submarine channels can not only act as repositories for sediment entrapped within them, but can also control the distribution of sheet sands, lobe sands (Piper and Normark, 2001) and even shape sediment dispersal pattern to influence the evolution and growth of submarine fans through the avulsion events (Manley and Flood, 1988; Pirmez and Flood, 1995).

Submarine channel avulsion events have long been recognized in deep-water submarine fan systems (Damuth et al., 1983a; b; Kolla and Coumes, 1987; Manley and Flood, 1988; Flood et al., 1991); these avulsion channels all resulted in the abandonment of parent channels downstream of the avulsion sites. That is, only one channel is largely active at any one time (Damuth et al., 1983a; b; Droz et al., 2003). Such essential characteristic make it possible to study the triggering mechanisms and patterns of submarine channel avulsions (Pirmez and Flood, 1995; Flood and Piper, 1997; Kolla, 2007; Armitage et al., 2012; Ortiz-Karpf et al., 2015) but hinders the further understanding of

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detailed avulsion process. The recognition of partially-avulsed channels (channel arms *sensu* Fildani et al., 2013; Maier et al., 2013) might address that problem; the term 'partial avulsion' is defined from the fluvial realm (Slingerland and Smith, 2004) and refers to a incomplete avulsion or aborted avulsion, which means the partially-avulsed channel temporarily coexists with the parent channel. Different from the fully-avulsed channel, the sedimentary sequence of partially-avulsed channels could preserve characteristic signatures resulted from avulsion flows and provide a unique opportunity to study the avulsion process and subsequent evolution of avulsion channels.

The present study focused on the development of a partially-avulsed channel on the Niger Delta continental slope, informally termed the 'Tombia Channel' (abbreviated as TC), which avulsed from a channel-levee system, referred to here as Bukuma Channel System (abbreviated as BCS). Utilizing high-resolution seismic data, we characterized the external morphology, internal architecture and background slope of TC and part of BCS. These detailed descriptions lead to some new interpretations of avulsion process and avulsion channel evolution, which in turn is of great significance for the hydrocarbon exploration and development.

2. Geological background

The study area is defined by a 350 km^2 3D seismic volume located in the Niger Delta slope along the South Atlantic margin, with a water depth ranging from 1300 to 1800 m (Fig. 1A). Its provenance is a large regressive delta, named Niger Delta and with an area of 12×10^4 km^2 (Doust and Omatsola, 1989). As a passive continental margin basin, Niger Delta Basin contains three main tectonic regimes (Doust and Omatsola, 1989), namely the upper extensional zone, which extends from the onshore to the outer shelf, the translational zone on the upper continental slope, and the lower compressional zone, which extends from the lower slope to the continental rise (Damuth, 1994) (Fig. 1B). The compressional zone can be further subdivided into two belts: an inner fold and thrust belt characterised by basinward-verging imbricate thrust faults and an outer fold and thrust belt typified by mixed basinward- and landward-verging thrust faults (Corredor et al., 2005). The study area is located in the most basinward part of the translational zone (Fig. 1B).

Three main sedimentary successions were developed in the Niger Delta Basin during the Tertiary to Quaternary interval, in sequence, the Akata, Agbada and Benin formations (Short and Stäuble, 1967) (Figs. 1B and 2). The precise age of the study interval is uncertain, but it is deduced to be Quaternary Agbada Formation, according to its shallow burial depth (Figs. 1B and 2), similar water depth to the study subject of Deptuck et al. (2007) and the specific geographical location of the study area. The Agbada Formation, with a thickness of > 3500 m, consists mainly of fluvial to marine sandstones interbedded with mudstones and marine shales, and is the main oil producing interval (Corredor et al., 2005; Doust and Omatsola, 1989).

3. Database and methods

3.1. Database

The primary source database used in this work is 350 km^2 of 3D seismic data, which were acquired and provided by China National Offshore Oil Corporation (CNOOC). All seismic-reflection data were processed to zero phase and displayed in SEG (Society for Exploration Geologists) reversed polarity, such that an increase in acoustic impedance corresponds to a high-amplitude trough (negative) reflection. The data have a sample rate of 3 ms and bin size of 12.5 m × 12.5 m. The seismic frequency bandwidth is 5–90Hz, with a dominant frequency of approximately 70 Hz within the study interval. Depth conversions are made assuming a seismic velocity of 1480m/s for seawater and 1900m/s for shallow sediments, yielding a vertical resolution of approximately 6 m, which enables the target channels of this study to be well characterised.

3.2. Methods

3.2.1. Seismic-based characterizing methods of subsurface channels

This study is principally based on 'classical' 2D seismic facies analysis (Vail et al., 1977) and 3D seismic geomorphology approach (Posamentier et al., 2007), through which the external morphology, internal architecture and the background slope and topography of subsurface channels are qualitatively and quantitatively analyzed. In the process of 'traditional' 2D seismic facies analysis, strike-view, dip-view and composite-view seismic lines were all made; the subsequent recognition and analysis of seismic facies were based on the configuration of reflectors (reflection continuity and amplitude), cross-sectional geometry and strata terminations. The 3D seismic geomorphology approach enables enhanced visualization of facies distribution and hence inference of depositional process through the extractions of Coherency and RMS (Root mean square) seismic amplitudes. Coherence images could provide details of small-scale depositional features and allow accurate mapping the boundaries of submarine channels (Posamentier et al., 2007). Root-mean-square (RMS) amplitude is a seismic attribute that calculates the square root of the sum of time-domain energy (square of amplitude), affording high amplitudes the maximum opportunity to stand out from background contamination. Therefore, it can be used to infer the lithological characteristics of channel fills.

Due to the absence of lithological calibration from wells in this study, the interpretation of seismic facies as the specific deposits was based on seismic-reflection characters and comparisons with previous published and widely cited seismic-based studies of deep-water channels (Kastens and Shor, 1985; Abreu et al., 2003; Deptuck et al., 2003; Posamentier and Kolla, 2003; Cross et al., 2009; Mchargue et al., 2011; Armitage et al., 2012).

3.2.2. Quantitative indicators of TC

Morphometric parameters, including width, height and sinuosity, have commonly acted as quantitative descriptors of submarine channels (Abreu et al., 2003; Mayall et al., 2006; Wynn et al., 2007; Wood and Mize-Spansky, 2009; Catterall et al., 2010; Mulder et al., 2012) and they are also used here to quantitatively characterize the external geometries of TC. However, for the quantitative characterization of multiple channel forms within TC such parameters seem to be inappropriate. To resolve such problem, this study defined three new terms: pre-channel slope gradient (measured from the pre-channel slope surface), confinement height, and residual thickness.

3.2.2.1. (1) Pre-channel slope gradient. The pre-channel slope gradient refers to a palaeotopographic gradient that existed before the channel development. Different from the measuring method of channel-thalweg gradient (Catterall et al., 2010; Clark and Cartwright, 2009), its measurement is to calculate the lateral changes of the deeps of the pre-channel slope surface (Fig. 3). In the dip-view seismic section of TC such gradient was calculated at 15 m intervals and the average value was acquired using a smoothing window of 5 measurements. It must be pointed out that each channel forms within TC developed in different stages and hence they have their own pre-channel slope surfaces (Fig. 3).

3.2.2.2. (2) Confinement height. The confinement height of the channel form is defined as the vertical difference between the pre-channel slope surface and the channel thalweg (Fig. 3). In fact, the confinement degree of submarine channels is contributed by both the erosion of flows and the aggradation of levees (Parsons et al., 2002; Baas et al., 2010; Rowland et al., 2010). However, the studied confinement heights of channel forms were mainly determined by erosional processes of