Journal of African Earth Sciences 125 (2017) 151–165

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Structural controls on channel-related seismic facies distribution in the toe-thrust of deepwater Niger Delta

Byami A. Jolly [a, *], Okwudiri A. Anyiam [b], Tuviere Omeru [c]

[a] Ahmadu Bello University, Zaria, Nigeria
[b] University of Nigeria, Nsukka, Nigeria
[c] University of Lagos, Nigeria

A R T I C L E I N F O

Article history:
Received 28 July 2016
Received in revised form
20 October 2016
Accepted 9 November 2016
Available online 10 November 2016

Keywords:
Deepwater sediments
Seismic facies
Structural control
Delta

A B S T R A C T

Deepwater gravitational settings are often characterised by active structures at, or near the seabed. Consequently, these structures exert significant control on sediment distribution especially on the distribution of reservoir-grade sediments often transported to deepwater by turbidity flows. This study investigates structural controls on the spatial and temporal facies distribution in the deepwater Niger Delta using 3D seismic reflection data. The study shows that the main seismic facies include: (a) channel-axis sands and channel levees; (b) sheet sands deposited immediately outboard of channel levees; (c) pelagic deposits; and (d) slump deposits. The distribution and overall geometry/architecture of these facies vary from the west of the study area (dominated by growing fault-propagation folds) to the east where a piggyback basin had developed, and bounded by a broad detachment fold. Reservoir grade sheet sands (splays) are common, and their deposition is triggered by a sudden increase in seabed gradient (between 0.8° and 4°) at fold locations. The spatial distribution of the splays is controlled by the distribution of seabed scarps – located on the forelimbs of growing folds. Splays deposited in sub-basins in the west of the study area are lobate-shaped (up to 10 × 15 km). In contrast, splays deposited within the piggyback basin have shapes that are elongated parallel to a growing detachment fold that is causing channels to divert. This study has provided great insight into the distribution of seismic facies in a complex deepwater setting, and in particular, into the temporal evolution of reservoir facies and their potential organization into hydrocarbon traps as they interact with growing structures through time.

1. Introduction

Deepwater seismic facies have been recognised and studied for a long time (e.g., Normark, 1970, 1978; Mutti and Normark, 1987, 1991). For example, Mutti and Normark (1991) documented five basic elements of turbidite systems which include; (1) major erosional features such as grooves from mass flows, (2) channels, (3) overbank deposits, (4) lobes, and (5) channel-lobe-transition deposits. However, we are yet to fully understand the relationship between these elements and deepwater structures that are often associated with them. The increasing availability of 3D seismic data as a result of hydrocarbon exploration in passive margin settings in recent times means that both submarine channels and geological structures at, or near, the seabed are better imaged (e.g., Mayall and Stewart, 2000; Pirmez et al., 2000; Mayall et al., 2006, 2010; Deptuck et al., 2003, 2007; Clark and Cartwright, 2009, 2011; Jolly et al., 2016). Hence, several workers have taken advantage of the development of 3D seismic imaging in deepwater settings to study the relationship between submarine channels and structures (e.g., Pirmez et al., 2000; Fonnesu, 2003; Morgan, 2004; Huyghe et al., 2004; Ferry et al., 2005; Heinio and Davies, 2007; Gee and Gawthorpe, 2006; Clark and Cartwright, 2009, 2011; Mayall et al., 2010; Jolly et al., 2016). While these studies have greatly improved our understanding of the channel-structure interaction in passive margin settings; there remains the need to improve the knowledge of how deepwater channel systems distribute sediments across actively growing structures in time and space. In particular, a better insight into the spatial and temporal variations of reservoir facies in deepwater settings requires detailed analyses of these interactions on a range of scales with the aid of good-quality seismic datasets. Many studies describing seismic facies

* Corresponding author. Department of Geology, Ahmadu Bello University, Zaria, Nigeria.
E-mail address: byami.jolly@gmail.com (B.A. Jolly).

http://dx.doi.org/10.1016/j.jafrearsci.2016.11.012
1464-343X/

distribution and stacking pattern through time have alluded to the fact that a large proportion of channel-reservoir facies are often deposited outside the channel system in the form of crevasse splays, and their deposition is often controlled by active structures at, or near the seabed (e.g., Pirmez and Flood, 1997; Mayall and Stewart, 2000; Pirmez et al., 2000; Posamentier and Kolla, 2003; Mayall et al., 2010; McHargue et al., 2011).

This study is aimed at constraining the factors that control the deposition of channel-related facies (such as channel-axis sands, levees and sheet sands/splays) in deepwater Niger Delta. The specific objectives of this study are: (1) to use the 3D seismic data to map the distribution of channel-related reservoir facies (specifically sands) in the study area; (2) to gain a better insight into the distribution of structures having seabed relief and/or impacting on seabed channels associated with the reservoir facies and (3) to understand how the distribution of these reservoir facies relates to the spatial distribution of actively growing structures having seabed relief since Pleistocene times.

2. Tectonic setting and sediment supply

This study focuses in the outer fold and thrust belt of the deep water Niger Delta, at the down-dip contractional toe developed from the gravitational collapse of the delta (Morley and Guerin, 1996; Cohen and McClay, 1996; Wu and Bally, 2000; Rowan et al., 2004; Bilotti and Shaw, 2005). The study area lies in the water depths of 1700–2800 m and covers an area of approximately 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 and is bounded to the east by the Cameroon volcanic line, to the west by the Dahomey Basin, and to the south (seaward) by the 4000 m bathymetry contour (Corredor et al., 2005). The trough formed during the opening of South Atlantic following the separation of Equatorial Africa from South America in the Early Cretaceous times (Whiteman, 1982; Mascle et al., 1986; Fairhead and Binks, 1991). From the early stages of the trough development, it was progressively filled with younger post-rift deposits; and by Late Eocene times, a delta had begun to build across the continental margin (Burke, 1972; Damuth, 1994). Today, the delta has an area of 140,000 km^2 both in sub-aerial exposure and associated deepwater fans, and it is up to 12 km in vertical thickness (Damuth, 1994). The delta is stratigraphically divided into three diachronous sequences of Eocene to Recent age named the Akata, Agbada and Benin Formations; (Short and Stauble, 1965; Avbovbo, 1978; Evamy et al., 1978; Whiteman, 1982; Knox and Omatsola, 1989; Doust and Omatsola, 1990). The gravitational collapse of the delta has resulted in the formation of structural zones that are clearly imaged on high resolution bathymetry maps (e.g., Fig. 1a) and in regional seismic sections (e.g., Fig. 1b). The structural zones according to Corredor et al. (2005) comprised of the extensional province on the shelf, the mud diapirs province, the detachment fold province, the inner fold and thrust belt, the translational province, and the outer fold and thrust belt in the deepwater-end, where our study area is located (Fig. 1a).

The main source of sediment supply to the delta is through the Niger River, which today has a mean water discharge of approximately 6140 m^3s^{-1} and a sediment load of 1270 kgs^{-1} (Mulder and Syvitski, 1995). It has the capacity to transport bedload sediments up to coarse-grained sand and gravel size fractions during flood events (Allen, 1965). It is inferred that sediments from the Niger River and other sediment sources (including fine-medium sands from barrier islands, tidal channel mouth bars amongst others) can all make their way to the shelf-edge during periods of low Pleistocene sea level. These sediments could ultimately reach deepwater environments through submarine canyons (Deptuck et al., 2007). Several Pleistocene turbidite systems are preserved both in the near-subsurface and on the modern bathymetry of the Niger Delta (Mitchum and Wach, 2002). These systems developed at the same time as the structural deformation associated with the thin-skinned gravitational collapse of the delta.

3. Dataset and methods

Approximately 2600 km^2 of 3D seismic data provided by Petroleum Geo-Services (PGS) in deepwater Niger Delta is used for this study. The data was processed to near zero-phase and is displayed using SEG-Normal polarity where an increase in acoustic impedance is represented by a peak (positive amplitude-red on seismic sections). The data was migrated using Kirchhoff pre-stack migration and bending ray post-stack migration to generate a 12.5 m by 12.5 m grid with a 4 ms sampling interval and was displayed every 4-inlines and cross-lines giving it a bin-size of 50 m which corresponds to the maximum horizontal resolution. The recorded length of the seismic data volume is 9.5 s with a velocity grid of 250 m; however, for most of this study, it is the upper 1 s of the data where the studied channels occur that we are most concerned with. Calibration of seismic reflections from the 3D survey with confidential age data provided by Shell Petroleum Development Company - Nigeria indicates that this upper 1 s of data is of predominantly Pleistocene – Recent age. This age interval reveals a high concentration of submarine channels whose interaction with growing folds having seabed relief is the focus of this study. This interval has a dominant frequency of 50 Hz with an estimated vertical resolution of 10 m (assuming a uniform velocity of 2000 m/s).

In this study we mapped growing structures having seabed relief and interacting with Pleistocene channels that are either buried or still open at the seabed. Information derived from the mapping of structures and channels was used as a basis for analysing the role of growing structures in governing the seismic facies distribution of Pleistocene to Recent sediments in the study area. Of particular interest is the extent to which the interaction between folds, scarps and submarine channels has controlled the distribution of deepwater facies through time.

The description of seismic facies is based on seismic reflection characteristics of the different units because of the absence of well control (e.g., Mayall and Stewart, 2000; Mayall et al., 2006; Gee et al., 2007). The seismic facies were identified from a combination of seismic reflection characteristics such as (a) amplitude variation, (b) the chaotic or coherent nature of the reflections, (c) parallelism of the reflections; (d) continuity/discontinuity of reflections and (e) the relationship of reflections to growing structures (e.g., onlap, downlap).

Various seismic attributes such as edge, dip-magnitude/dip-azimuth maps and Root-Mean-Square (RMS) amplitude maps were used in this study to identify and analyse seismic facies (e.g., Sheriff, 2002). For example, the RMS amplitude map can distinguish between sand-rich facies (high-amplitudes) such as channel-axis fills, splays and some higher amplitude levees. Mud-rich areas will be dominated by low amplitudes. Where it was difficult to calculate RMS amplitudes using a 'user-defined window' from a single mapped horizon because the chosen window would cut-through structures having seabed relief; a package of dipping stratigraphy was divided into iso-proportional layers and the surfaces used to define the RMS amplitude extraction windows. This method was applied to the piggyback basin strata on the northern flanks of Fold C (see section 4.2.3 for details).