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The diversity of deep-water sinuous channel belts and slope valley-fill complexes

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ABSTRACT

The study combines interpretation of 3D seismic imagery of submarine sinuous channel belts in offshore West Africa with observations from a range of outcrop analogues. Five main architectural elements of slope channel belts are recognized: lateral-accretion packages (LAPs), channel-bend mounds, levées, non-turbiditic mass-transport deposits (MTDs) and last-stage channel-fills. Channel belts differ in their planform, cross-section and the range of architectural elements involved. Four end-member types of sinuous channel belts are distinguished, formed by meandering non-aggradational channels, levéed aggradational channels, erosional cut-and-fill channels and hybrid channels. Analysis indicates that meandering channels form when system is near its potential equilibrium profile. They evolve from nearly straight to highly sinuous by increasing first the bend amplitude and then the conduit length. Levéed channels are thought to evolve from incipient meandering conduits perturbed by aggradation and erosional channels to evolve from either levéed or meandering conduits, inheriting their sinuosity. Hybrid channels signify a failed or incomplete transformation. The channel belts occur isolated or stacked into multi-storey complexes, unconfined or formed within incised valleys. Unconfined complexes, composed of levéed channel belts, are relatively uncommon. Valley-confined complexes predominate and are overlain by isolated channel belts, often confined by the valley external levées.

Valley-fill complexes are characterized by an upward fining and a general decrease in sandstone net/gross. The majority of slope valley-fills in the study area and other reported cases show a development from deep incision to a transient equilibrium state recorded by the deposition of coarse sediment lag or non-aggradational channel belts, which are commonly overlain by MTDs emplaced when the valley reached its maximum relief. The middle to upper part of valley-fill consists of levéed channel belts recording aggradation, with possible development of non-aggradational meandering channel belts in the uppermost part prior to the valley abandonment. Similar meandering channel belts may also occasionally occur in the middle part of valley-fill succession. It is suggested that the variation among valley-fills can be due to external factors, such as slope tectonics and salt movements, or to an internal forcing through the interplay of valley incision depth, base-level change, turbidite–system equilibrium profile and slope general aggradation rate.

1. Introduction

The last decade saw significant advances in the sedimentological understanding of deep-water sinuous channels and their features. Detailed studies of side-scan sonar and 3D seismic-reflection imagery have revealed a range of architectural elements associated with sinuous channels, such as lateral-accretion packages (LAPs) (Abreu et al., 2003; Mayall et al., 2006; Kolla et al., 2007; Labourdette, 2007), nested mounds (Clark and Pickering, 1996; Peakall et al., 2000), outer-bank bars (Nakajima et al., 2009), non-turbiditic mass-transport deposits (Deptuck et al., 2003; Samuel et al., 2003; Heiniö and Davies, 2007; Armitage et al., 2009), levées (Clemenceau et al., 2000; Skene et al., 2002; Babonneau et al., 2004; Hubbard et al., 2009), crevasse splays (Demyttenaere et al., 2000; Mayall and Stewart, 2000; Posamentier and Kolla, 2003; Cross et al., 2009) and last-stage channel-fills (Kneller, 2003; Wynn et al., 2007). Most of these elements have been recognized in outcrops as sandy to gravelly deposits (e.g., Morris and Normark, 2000; Lien et al., 2003; Dykstra and Kneller, 2009; Kane et al., 2009; Kane and Hodgson, 2011) and are considered to be important components of hydrocarbon reservoirs (Prather, 2003; Mayall et al., 2006).

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However, the previous studies have also indicated that elements of one type vary as sedimentary deposits and that it is unlikely for all architectural elements to occur within a single channel belt (e.g., Abreu et al., 2003; Kane et al., 2008; Amos et al., 2010; Janocko et al., 2013). Although some elements may be genetically linked, the development of one type of element may require flow conditions that virtually preclude formation another element type. This depositional variability of channelized flows and the variability of elements as sedimentary deposits may have a direct bearing on the observed diversity of deep-water channels (Abreu et al., 2003; Kneller, 2003; Nakajima et al., 2009). Studies of architectural elements in connection with the planform and cross-sectional geometry of channels may thus shed more light on the formative processes of these highly diversified systems and help predict their reservoir properties.

2. The aim of the present study

The present study documents the seismic characteristics of deep-water sinuous channels in an upper- to middle-slope setting in offshore West Africa and supplements these observations with well-core data and a range of outcrop analogues. We revisit further the taxonomic concept of channel classification (cf. Mayall and Stewart, 2000; Morris and Normark, 2000; Pirmez et al., 2000; Kneller, 2003), with a special focus on intra- and extra-channel architectural elements and the temporal changes in channel development within deep-water slope valleys.

The 3D seismic dataset used in the study extends about 25 km seawards, from the West African palaeo-shelf edge to the middle zone of continental slope, and covers an area of 80 × 55 km (4400 km^2). The stratigraphic interval studied is of Miocene age. The dataset is a post-stack time-migrated volume with a bin spacing of 12.5 × 12.5 m and a sampling interval of 4 ms. Seismic frequency ranges from 20 to 60 Hz, with an average of 40 Hz corresponding to a vertical resolution of ca. 10 m. The volume has been processed to zero-phase and displayed in SEG normal polarity, such that the positive amplitude (black or dark-blue hue in the display) reflects higher acoustic impedance. An average seismic velocity of 2000 m/s was used in the conversion of two-way travel time to metric depth for the purpose of calculating rock thicknesses in metres.

More than 1600 m of core samples were recovered from 29 wells in the study area. However, the samples and gamma logs from only five wells are utilized in this study, because the majority of the drilling targets are in areas with poor seismic resolution, where both seismic interpretation and well-to-seismic ties are extremely difficult. The problems with resolution are due to salt diapirism.

The quality of seismic data allows recognition of such stratigraphic features as valley-fills, palaeochannels, channel belts and their main architectural elements. The seismic recognition and interpretation of architectural elements have been bolstered by outcrop analogue studies from the Miocene Mt. Messenger Fm. of New Zealand, the Eocene Kırkgecit Fm. of Turkey, the Late Cretaceous Rosario Fm. of Mexico and the Late Carboniferous Ross Fm. of Ireland. The purpose of using outcrop analogues was to get an insight in the facies composition and depositional process of the elements from which no drilling samples were available. Although the selected field examples are often smaller in scale than the elements identified in seismic imagery, they are considered to be valid analogues in terms of geometry, facies assemblages and formative processes. Suffice it to note that elements such as levées, point bars, nested mounds, intra-channel mass-transport deposits and last-stage channel-fills occur in a range of settings and on a wide range of scales (Phillips, 1987; Timbrell, 1993; Elliott, 2000; Abreu et al., 2003; Arnott, 2007; Cronin et al., 2007; Euzen et al., 2007; Wynn et al., 2007; Dykstra and Kneller, 2009; Amos et al., 2010; Kane and Hodgson, 2011; Janocko et al., 2013; Janocko and Nemec, in press).

3. Terminology

Descriptive sedimentological terminology is after Harms et al. (1982) and Collinson and Thompson (1982). *Submarine channel* is defined as a conduit formed by and conveying sediment-gravity flows. Channelized flows deposit coarse sediment both inside and directly outside the conduit, which itself may migrate, and the resulting sand-prone and possibly gravel-bearing sedimentary body is referred to broadly as a *channel belt* (Bridge, 2003). Channel belts with a laterally-inactive sinuous planform, formed by simple downcutting and vertical aggradation are referred to as *erosional channel belts* (Fig. 1A); those showing significant lateral accretion and conduit sideways migration are referred to as *meandering channel belts* (Fig. 1B; cf. Nanson and Knighton, 1996); and those with seismically detectable levées and relatively stable sinuous planform are referred to as *levéed channel belts* (Fig. 1C). Some channel belts show major vertical aggradation combined with lateral accretion of sediment, which is called aggradational lateral accretion (Fig. 1C, lower part). Multi-storey channel belts, stacked vertically upon one another with or without significant offset, are referred to as *channel-belt complexes* (Fig. 1A–C).

The deepest, hydraulic axial zone of a channel is referred to as the *channel thalweg* (Bridge, 2003). It does not correspond strictly to the plan-view geometrical axis, or centreline, of the channel (Fig. 1D), which is more convenient to use in the analysis of channel-belt seismic maps. Accordingly, the sinuosity index of a channel or its particular segment is defined as the ratio of the centreline length to the corresponding straight-line distance (Bridge, 2003). Channels with a sinuosity index equal or greater than 1.1 are considered to be sinuous, non-straight. Other geometrical parameters of channel planform used in the study are (Fig. 1D):

- *channel width* – considered to be the maximum local distance between the channel banks;
- *channel depth* – measured as the vertical relief from the channel base in axial zone to the bank or levée crest;
- *channel bend amplitude* (or radius of curvature) – defined as the maximum departure of channel centreline from a straight-line path through the centreline inflection points; and
- *channel bend half-wavelength* – the distance between centreline inflection points measured along the channel centreline.

A *submarine incised valley* (Carlson et al., 1982; Prather, 2003) is an underwater slope conduit incomparably deeper than the system largest channels, cut in earlier deposits by excessively erosive sediment-gravity flows. In contrast to the more permanent deep submarine conduits, such as bedrock canyons, the incised valleys are cut and filled by the channelized turbiditic system, possibly several times over during the time-span of its activity. Submarine incised valleys may not necessarily be related to sea-level changes and the fluvial incised valleys formed by forced regressions (Dalrymple et al., 1994), but they similarly result from major readjustments of the system morphometric profile.

Large-scale levées that flank an incised valley are referred to as *external levées*, whereas the smaller-scale levées flanking individual channels are called *internal levées* (Kane and Hodgson, 2011). Channel belts formed within the valley confinement are considered to be *erosionally confined* (Fig. 1E), whereas those constrained laterally by external levées are considered to be *levée-confined* (Fig. 1F). A submarine incised valley-fill commonly evolves from