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Deep-water and fluvial sinuous channels—Characteristics, similarities and dissimilarities, and modes of formation

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Abstract

High-resolution 3D seismic data of several subsurface examples reveal significant differences in internal architecture and evolution of fluvial and deep-water sinuous channel systems, although there are many similarities in external morphologies of both systems. Channel migrations or shifts in fluvial systems, with point-bar scrolls, are relatively continuous laterally and show a downstream component; they are commonly a single seismic phase thick, with flat tops. In deep-water systems, channel migrations or shifts, with or without point-bar scroll-like features, may be lateral, either continuous or discrete, and laterally to vertically aggrading, again either continuous or discrete; they are single to multiple seismic phases thick, with or without a downstream component. Even the most laterally migrated channel complex commonly aggrades, to varying degrees, from the inside to the outside of sinuous loops. Similarities between fluvial and deep-water sinuous channel systems discussed here imply that sinuosity enhancements in both cases are the result of gradual processes, involving interaction of flows, sediments and alluvial plain or seafloor in attempts to build equilibrium profiles. Flat gradients, high width to depth ratios of valleys/channel belts, fine sediment grain sizes, a certain degree of bank cohesiveness, and presence of secondary circulations in flows were pre-requisites in both systems. However, a number of factors appear to have caused major differences in the internal architecture and modes of evolution of fluvial and deep-water channels. These include differences in (1) density contrasts of flows relative to ambient fluids, (2) entrainments of ambient fluids into flows, (3) effects of centrifugal and Coriolis forces on flows, (4) frequency, volume and duration of steady vs. catastrophic flows, (5) modes of sediment transport, and (6) effects of sea level changes on deposition. Furthermore, within deep-water systems, changes in flow parameters and sediment grain size can cause erosion, bypassing or deposition in space and time and result, through cuts and fills, in sinuous channels with lateral migrations, vertical aggradations and combinations thereof.

Keywords: Sinuous channels; Channel lateral migration; Aggradation; Architecture

1. Introduction

The characteristics and modes of formation of sinuous and meandering channels in fluvial systems have long been known from aerial photography, as well as sedimentological studies of modern environments and ancient outcrops, experiments in the laboratory, numerical simulations and, to some extent, from seismic and drilling. Only since the early 1980s (e.g. Garrison et al., 1982; Damuth et al., 1983), with the availability of better technologies, have highly sinuous channels also been found to be common depositional elements of modern deep-sea fans, fed by mud-rich terrigenous sediment sources. Several workers have utilized sidescan sonar imagery, multibeam bathymetry and widely spaced 2D high-resolution seismic profiles of modern deep-sea fans, in order to compare deep-water sinuous channels with their fluvial counterparts (e.g. Flood and Damuth, 1987; Amir, 1992; Clark et al., 1992; Pirmez and Flood, 1995; Babonneau et al., 2002). These studies have shown that morphological characteristics of deep-water channels, namely (1) sinuosities and sinuosities vs. valley gradients, (2) relationships between meander wavelengths, channel widths and radii of curvature,

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(3) delayed inflection symmetries indicative of paleo-flows, and (4) avulsions and cut-offs, are similar to those of fluvial channels. However, closer examination also reveals differences in these two types of channel systems. Widths and depths of deep-water channels generally decrease downstream unlike those in the case of fluvial channels (Flood and Damuth, 1987). A significant component of vertical aggradation, often discernible in seismic, is also commonly present in the sinuous loops of deep-water channels (e.g. Stelting et al., 1985; Kastens and Shor, 1986; Kolla and Coumes, 1987; McHargue, 1991; Damuth et al., 1995; Peakall et al., 2000) but is not seen in fluvial sinuous channels. The advent of 3D seismic data in recent years has aided identification and mapping of sinuous channels in the subsurface, and revealed internal architecture and temporal evolution of deep-water sinuous channels with greater clarity than was possible with 2D seismic in prior studies (Roberts and Compani, 1996; Kolla et al., 1998, 2001; Peakall et al., 2000; Mayall and O'Byrne, 2002; Abreu et al., 2003; Deptuck et al., 2003; Posamentier and Kolla, 2003; Samuel et al., 2003). These recent studies suggest that deep-water sinuous channels evolved similar to fluvial channels in some cases, and in more variable and complex ways in many others. However, it is often not clear in these studies how deep-water channel sinuosities evolved in detail and why. Where similarities between deep-water and fluvial channels are interpreted, published 3D seismic attribute images of deep-water sinuous channels are not always as clear as their fluvial counterparts. In addition, the scale of observations and resolution of 3D seismic images of deep-water channels, and those of aerial photos and outcrops of fluvial channels with which they are compared, are not the same. Similarly, deep-water channel outcrops, where 'point-bar type' lateral accretion has been interpreted and compared with 3D seismic images of inferred similar features from the subsurface, are small in extent (Abreu et al., 2003; Deptuck et al., 2003; Beaubouef et al., in press). Also, although several studies (e.g. Burnett, 1996; Posamentier, 2001; Miall, 2002; Carter, 2003) have discussed fluvial channels based on 3D seismic images, no attempt has hitherto been made to compare and contrast the plan- and cross-sectional views, and thereby the internal architecture, of fluvial and deep-water channels.

We present here high-resolution 3D seismic images in plan- and cross-sectional view of fluvial and deep-water sinuous channels, mainly from the shallow subsurface but also from deeper, exploration depths from several areas of the world, and point out their similarities and differences. From the seismic characteristics presented here, together with (1) published lithologic and hydrodynamic characteristics of deposits and flows in fluvial and deep-water sinuous channels, and (2) insights from better understood controls of fluvial sinuous channel migrations, we discuss the processes resulting in observed deep-water sinuous channel behaviors, and the geometry and distribution of reservoir lithologies within them.

2. Data utilized

The majority of data presented here are 3D seismic images from shallow subsurface (Pleistocene) and deeper exploration (Miocene, Pliocene age) depths. 3D seismic from shallow subsurface areas is characterized by about 60–90 Hz peak frequencies, whereas data from exploration (deeper subsurface) depths have peak frequencies of about 30 Hz. Visualization techniques include horizon and stratal amplitude slices, and interval amplitude displays. 3D seismic examples of deep-water sinuous channels are drawn from the Gulf of Mexico, offshore Nigeria, offshore eastern Kalimantan, Indonesia, offshore Angola and offshore east coast of India. All fluvial channel examples are from offshore Indonesia. Aerial photos of two modern fluvial channels have also been utilized. Channel examples considered here are primarily a result of both erosion and deposition. Sinuous channel/valley examples that are dominantly the result of structural complexities or incisions do exist, but are not considered here. One unavoidable but serious limitation of our study is the lack of lithological data for many of the examples discussed, although we provide, where available, well logs and summaries of lithological information from published studies.

3. Sinuous channel characteristics and processes

Although differing in scale, aerial photos and 3D seismic amplitude slices of fluvial and deep-water sinuous channels, respectively, show many similarities. These not only include sinuosities, cutoffs, and downstream sweeps of channel bends (Fig. 1), as pointed out by several workers in the past (e.g. Flood and Damuth, 1987; Pirmez, 1994), but also in having point-bar scrolls or similar-looking features within meander bends. But, how do 3D seismic amplitude images of fluvial channels, both in plan- and cross-sectional view, precisely compare with those of deep-water channels? How similar or different are the internal stratigraphic architectures of these sinuous channels in seismic? Sidescan sonar images of deep-sea fan sinuous channels, that formed the basis for comparing deep-water and fluvial channels in previous studies (e.g. Flood and Damuth, 1987), are similar to those of subsurface 3D seismic amplitude slices, except that the former do not commonly show scroll bars. Sidescan sonography primarily reflects present seafloor morphology. The lack of scroll bars in sidescan sonar images suggests either no significant lateral migration during latter stages of channel evolution and/or masking of scroll bars (developed from any lateral migrations) by later sediment cover.

3.1. Fluvial channels

3.1.1. Morphologic and internal architectural characteristics from seismic

All the images of 3D seismic amplitude slices of fluvial channels presented here show well-developed meander

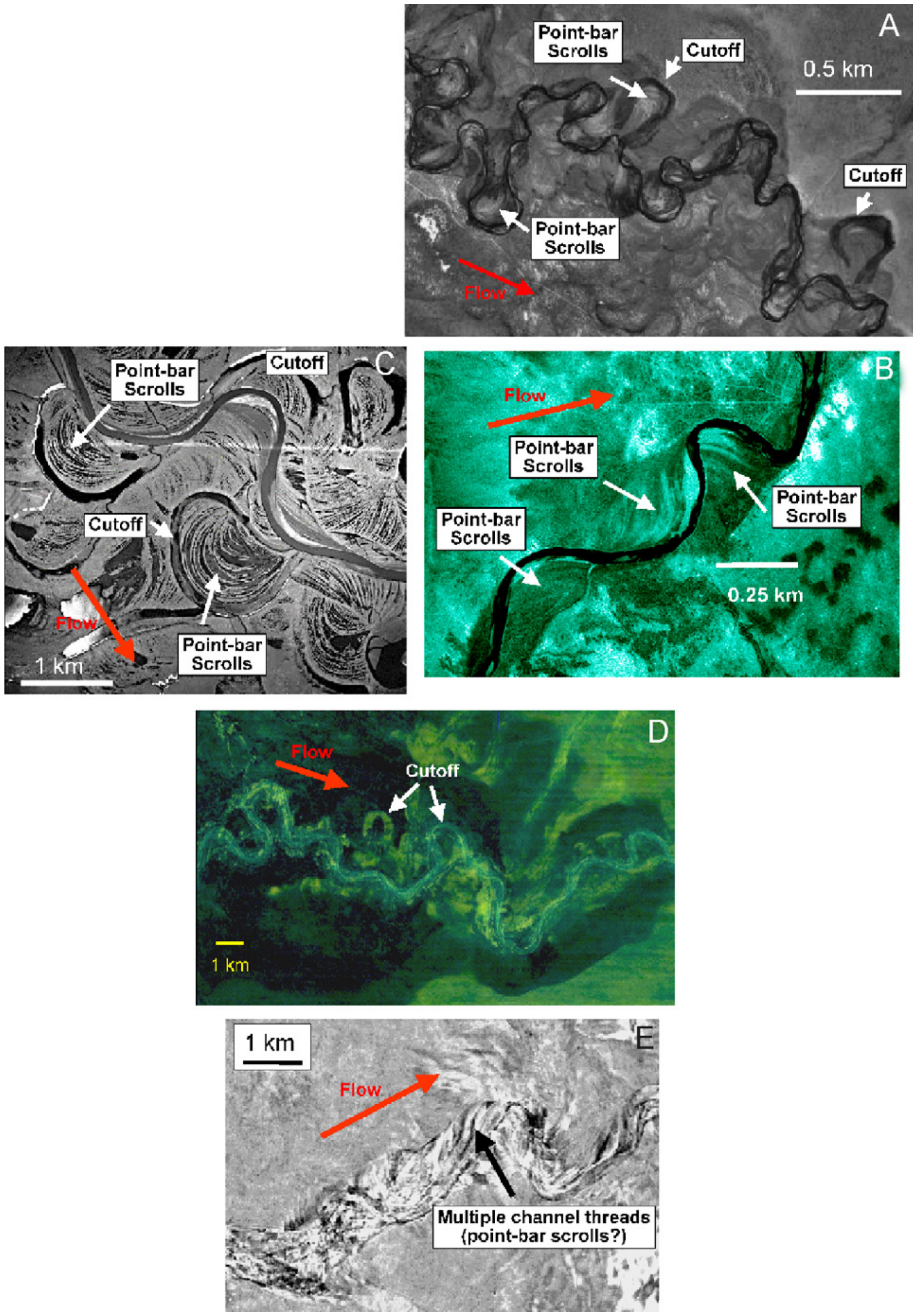

Fig. 1. Aerial photos of portions of Bighorn River (A and B), and Colville River (C) sinuous channels, and amplitude slices of deep-water leveed channels from Gulf of Mexico (D) and offshore eastern Borneo, Kalimantan, Indonesia (E), showing high sinuosities, point-bar scrolls and cutoffs. Red arrows indicate flow directions.

bends with high-amplitude facies within them, interpreted to be point-bars (Figs. 2–6). Point-bar facies in many of the examples also exhibit meander scrolls. These facies appear truncated towards one side and tangential towards the other, and are interpreted to indicate upstream and downstream flow directions, respectively (Figs. 2, 3, 5 and 6). The channel examples commonly show downstream sweeps and lateral swings of point-bars during their growth, typical of fluvial systems. Thus, all images presented here clearly resemble aerial photos of fluvial channels (Fig. 1). Scroll bars in seismic slices (Figs. 2–4, and 6) appear conformable with one another and are not easily separable. We interpret them to be the result of continuous channel migrations, typical of fluvial channels. In seismic sections across sinuous loops, some channels exhibit shingled, subtle or somewhat widely separated, off-lapping or discontinuous reflections (Figs. 2, 3, and 6; Mitchum, 1977) whereas some show relatively continuous reflections, corresponding to point-bar scrolls in slices (Figs. 2, 4, and 5). Point-bar reflection facies are about

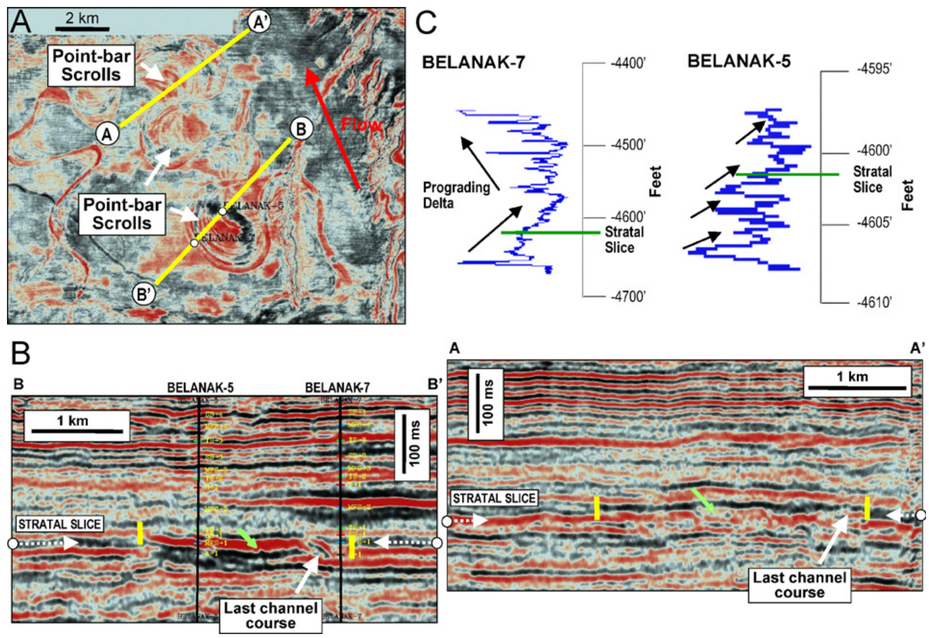

Fig. 2. Amplitude stratal slice (A) showing two fluvial sinuous channels from Miocene stratigraphic interval (exploration depth), Natuna Basin, offshore Indonesia (Wongsosantiko and Wirojudo, 1984). The sinuous channel in the center of the slice shows high seismic-amplitude point-bar scrolls. Two seismic cross sections (B) from two sinuous loops of this channel, with well locations on one section and corresponding well logs (C) are shown. White dashed arrows in seismic sections indicate the position of slice (A). In seismic sections, reflections corresponding to point-bar scrolls (indicated by a green arrow and bracketed by yellow markers) are either continuous, shingled or off-setting, and are one seismic phase thick, with flat tops. Last channel course towards the end of lateral migration is indicated by white arrow on the seismic section. Deflections to the left in gamma well logs (modified from Walker, 2003) indicate sandier intervals, and deflections to the right indicate more shale-rich intervals. The logs show fining upward intervals corresponding to point bars.

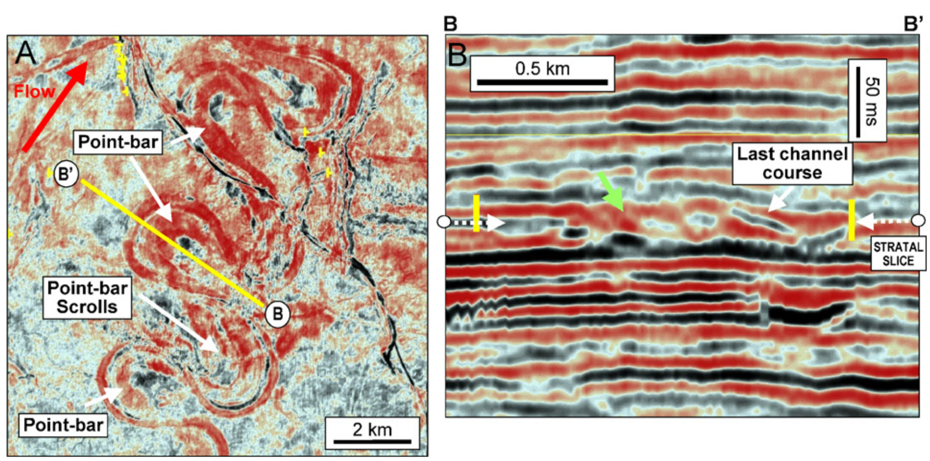

Fig. 3. Amplitude stratal slice (A) from Miocene stratigraphic interval, Natuna Basin, showing high channel sinuosity and high seismic-amplitude point-bar scrolls in a fluvial system. A seismic profile across one sinuous loop (B) shows shingled off-lapping reflections (indicated by a green arrow and bracketed by yellow markers) with about one seismic phase thick and a flat top. Dashed white arrows indicate location of slice (A).

1–2 km wide and one seismic phase (loop) thick, and their tops from the convex to the concave (inner to outer) banks of meander loops are flat. A clear erosive event is evident only at the location of the last channel course in the meander belt. In seismic sections, in some cases, off-lapping reflections may be separable by as much as about 80 m lateral distance, and dip in the direction of channel shifts, whereas in other cases they are not separable. The off-lapping reflections are not concave upward and do not appear to represent significant erosive events, but rather boundaries of clusters of scroll bars or accretionary surfaces. Generally, the seismic reflection facies in sections corroborate the amplitude slices to indicate continuous channel migration and accretion.

Amplitude slices of some fluvial point-bars, presented by Isa et al. (1992), Hardage et al. (1994), Posamentier (2001), Miall (2002), Carter (2003) and Feldman and Maynard (2005), also exhibit scroll-bar patterns within meander

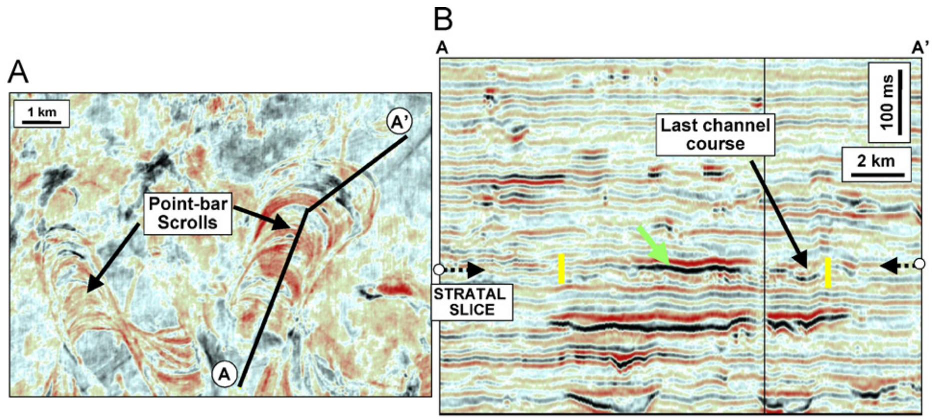

Fig. 4. (A) Amplitude stratal slice from a Pliocene interval, Natuna Basin, showing high channel sinuosity and high seismic-amplitude point-bar scrolls in a fluvial system. (B) A seismic profile across a sinuous loop shows the point bar to be one reflection thick (indicated by a green arrow and bracketed by yellow markers) with no 'shingles' but with a relatively flat to undulating top. Black dashed arrows on seismic section (B) show the location of stratal slice (A).

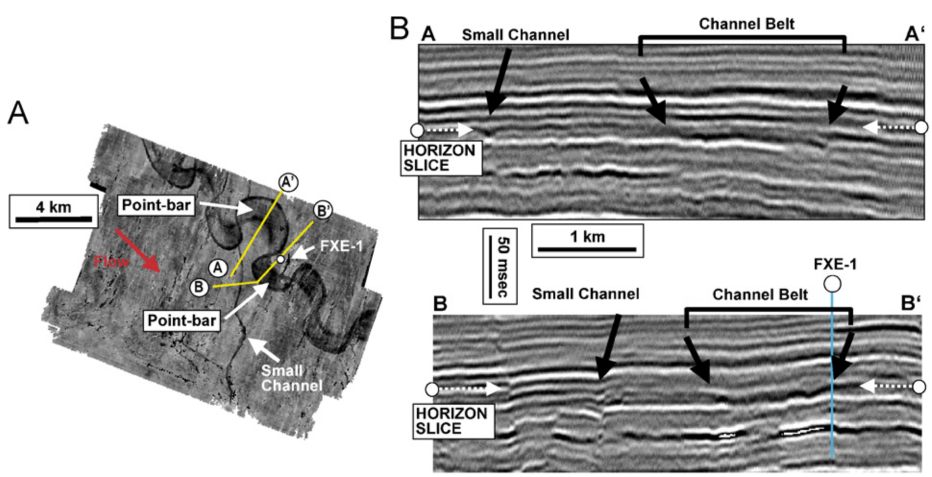

Fig. 5. (A) Horizon amplitude slice of a fluvial sinuous channel complex from a Miocene shelf section of a hydrocarbon field, offshore northwestern Java, showing high-amplitude point-bar facies with no visible scrolls. Initial and final channel courses can be continuously traced all along the channel length more easily in this example than in others. (B) Seismic profiles show point-bar facies (indicated by black arrows) to be one seismic phase thick with no 'shingles', but with relatively flat reflections. Dashed white arrows locate position of stratal slice.

bends. Not all these studies have, however, shown seismic sections across the scroll bars of sinuous loops and discussed the internal architecture as seen in cross section. Where sections are presented in these studies, scroll bars may or may not show up as shingled reflections and are about one seismic phase thick, as noted in the present study.

3.1.2. Lithologic characteristics of fluvial point-bar deposits

We summarize here lithological information from studies of outcrop and modern fluvial environments, as given in Miall (1996), and from 3D seismic subsurface examples calibrated by drilling (e.g. Burnett, 1996; Carter, 2003; Feldman and Maynard, 2005). Fining-upwards sequences are typical of the central portions of fluvial point-bar deposits. Elsewhere on point-bars, blocky or even coarsening-upwards sequences may be common (e.g. Jackson, 1976; Miall, 1996). In one of our examples (Fig. 2), well logs show fining-upwards character at two locations across a point-bar. Sedimentary structures in point-bar deposits include trough and planar cross bedding, rippled and plane beds; thus, tractive sedimentary structures are common. Although point-bar deposits can form excellent hydrocarbon reservoirs, lithologies may actually vary from gravels to sands to silts and clays from base to top, depending on the type of sediment fed into the fluvial system (Tyler, 1988; Miall, 1996). In outcrops, gross point-bar strata off-lap and dip towards cut banks. Dips of these strata vary between 5° and 20° in coarse to fine-grained systems (Miall, 1996). In mixed sediment-load systems, they range from 5° to 12°. In relatively coarse-grained systems, shale beds are generally thin, but in fine-grained systems, their thickness may be considerable (Reineck and Singh, 1990). In any case, sand-shale bed separations in fluvial point-bar deposits are so closely spaced that they are not resolvable on normal 3D seismic.

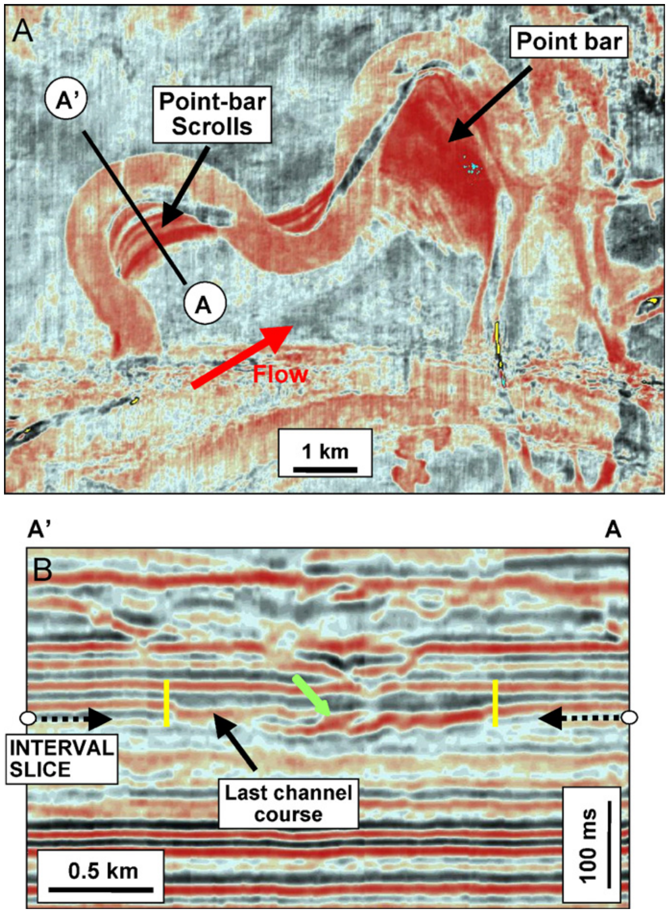

Fig. 6. (A) Amplitude stratal slice from a late Pleistocene interval, Natuna Basin, showing high-amplitude point-bar scrolls in a fluvial sinuous channel loop. Seismic amplitudes of the last-phase channel course are not as strong as those of the point-bar. A seismic profile (B) across one of the loops shows shingled off-lapping high-amplitude reflections (indicated by a green arrow and bracketed by yellow markers) of one seismic phase thick, corresponding to the point-bar scrolls. Dashed black arrows show location of stratal slice.

Ideally, point-bar deposits are expected to show up as relatively continuous reflections (Figs. 2B, 4B, 5B). However, clusters of accretionary surfaces (e.g. sand and shale bed separations, boundaries of grain size changes) may show up as off-lapping or shingled reflections (Figs. 2B, 3B, 6B). Thicknesses of point-bar deposits in a given meander loop are usually <20–30 m, resulting in one seismic phase thickness as observed. There is seismically no perceptible aggradation of point-bar deposits observed from the inner to outer bank of a meander loop.

3.1.3. Processes/controls

Much has been published on the processes/controls affecting sinuosity of fluvial channels. We briefly summarize here the factors controlling evolution of fluvial channel sinuosity as discussed by Schumm (1981, 1985), Schumm et al. (1987), Miall (1996), Ethridge and Schumm (2007) and others. Flow volume and velocity (stream power), effects of channel curvatures on flows, valley or flood-plain gradients, sediment load and grain size, channel bank cohesiveness and initial morphologies of channels/valleys (e.g. width and width to depth ratios) are the primary controlling factors of sinuosity evolution. Not all these factors are, however, completely independent of each other. Very steep or very flat gradients, very high stream power and high bed load to total sediment load ratios, lack of cohesive silts/clays or great abundance of them in flows, and very high or very low width to depth ratios of initial channel/valley systems do not favor evolution of increased sinuosity, but moderate values of these various factors do. Threshold values of various factors, below or above which sinuosity is favored, depend on each fluvial system. Helicoidal circulation and asymmetry in flow strength across sinuous river channels are also considered to be important in eroding on the concave sides and depositing on the convex sides of meander loops, and thus increasing channel sinuosity. Base level (sea level), shoreline position (Posamentier and Vail, 1988) and channel depths affect the thickness of point-bar deposits. Active subsidence may influence channel depths and thus also the thickness of point-bar deposits.

We do not have data relating to controlling factors for the fluvial examples described, not even initial valley gradients because of later deformation in many cases. Well logs in the described example (Fig. 2) do not have any corresponding cores for the interval of interest, but from general log character and very high channel sinuosities, we infer that suspended to mixed load was perhaps the primary sediment type fed to the fluvial channels discussed in our seismic examples (Schumm, 1977). We assume that suitable threshold values of other necessary factors did exist to cause the observed high sinuosities.

3.2. Deep-water channels

3.2.1. Morphologic and internal characteristics from seismic

Several examples of deep-water sinuous channel complexes from the shallow subsurface and one from exploration (deeper subsurface) depths are presented here (Figs. 7–15). They show characteristics common to all sinuous channels, but also some variability, and together provide a more complete picture of sinuous deep-water channel characteristics and architectures.

Typically, many sinuous channel complexes, and associated banks and overbanks, are housed within larger channels/valleys, flanked by large overbanks (Figs. 7–9, 12–15). These larger channels/valleys are designated as master valleys, and their overbanks as master overbanks (outer overbanks or outer levees). The overbanks associated with the network of sinuous channels within master valleys are labeled as secondary (inner) overbanks (or levees) (Posamentier and Kolla, 2003; Deptuck et al., 2003; Figs. 7, 8, 14). Secondary overbanks associated with the upper or top portions of sinuous channel growth may extend beyond the confines of the master valley and overlie the master overbanks, because most of the valley was filled

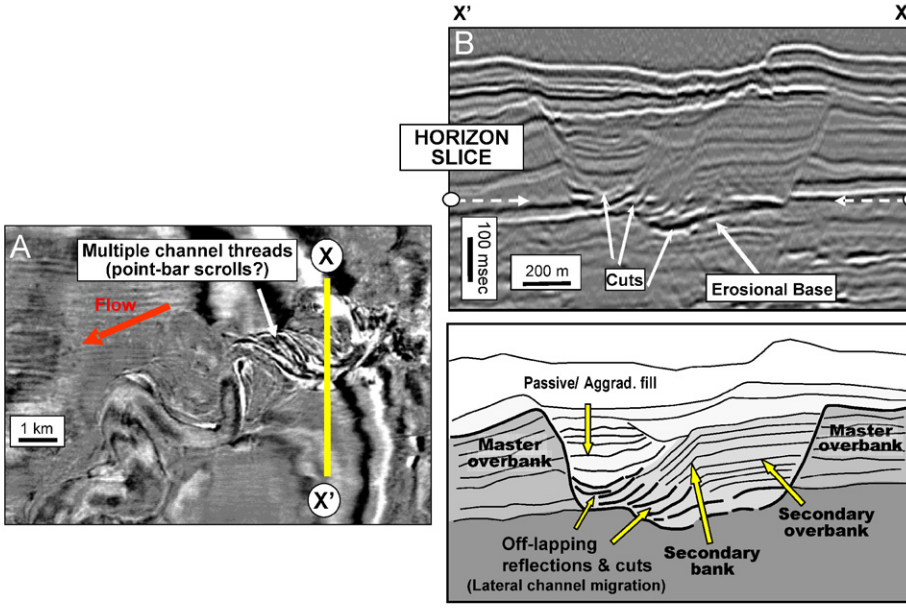

Fig. 7. (A) Amplitude horizon slice from the lower part of a Pleistocene deep-water sinuous channel complex, offshore Nigeria. Multiple thread-like features resembling point-bar scrolls within a sinuous loop of the channel are apparent. (B) Seismic profile across a meander loop shows high-amplitude shingled off-setting (somewhat curved) reflections, corresponding to the multiple threads. Dashed white arrows indicate location of stratal slice. The high-amplitude reflections in (A) and (B) indicate lateral and downstream (red arrow shows flow direction) and continuous channel migration (or shifts) as well as some aggradation. Lateral migrations, consisting of subtle cuts and fills, are most significant in the lower part of the valley fill. The upper part of the channel complex appears to be primarily an aggradational deposit. This sinuous channel complex, and associated banks and overbanks, are housed in a larger master valley, flanked by master (outer) overbanks. Overbanks and banks associated with sinuous channels within the master valley are called secondary (inner) overbanks and banks, respectively.

and channelized flows could no longer be contained (e.g. Fig. 14). Sinuous channels, with or without their associated overbanks, within larger channels/valleys/canyons, have also been found to be common in many other deep-water depositional systems in subsurface and in outcrop (e.g. Sikkima and Wojcik, 2000; Wonham et al., 2000; Kolla et al., 2001; Deptuck et al., 2003; Ardill et al., 2005; Cronin et al., 2005).

Seismic facies of sinuous channel-floor deposits, from bases to tops of complexes in our examples, are generally of high amplitude, discontinuous reflections, whereas many of the associated banks and overbanks have relatively low amplitude, continuous reflections. Horizon slices of sinuous channel-floor facies in basal portions of channel complexes show high-amplitude, multiple sinuous threads (or thread-like features) (Figs. 7–9) or multiple sinuous bands (Figs. 10–12-I). Deptuck et al. (2003) noted development of similar features in basal portions of a channel complex (labeled Phase 1 deposits in Fig. 14) from offshore Nigeria. In this case, multiple sinuous thread-like features have been reported to be intercalated with slumps and chaotic facies, and cannot be traced continuously all along the master valley. In a deeper subsurface example (Fig. 15), similar features are present in slices from the basal portions of a sinuous channel complex (not shown here), although their seismic resolution is not as clear as the shallow subsurface examples. Multiple sinuous threads or bands in our examples are very closely spaced and resemble fluvial scroll bars; they are interpreted to be due to relatively continuous lateral channel shifts or migrations that occurred during the evolution of sinuous loops. Because of the dominance of lateral shifting of channels in basal portions, even one horizon slice can reveal multiple channel courses (threads). Also, one bundle of multiple channel threads/bands may be separated from another similar bundle by a significant distance (Figs. 7–12-I) and may reflect more discrete lateral channel shifts or abrupt jumps, interrupting relatively continuous migrations. Successive continuous and discrete channel shifts frequently display both downstream ‘sweep’ and lateral ‘swing’ components. Basal sinuous channel belts in meander loops of examples given here are 1 to >2 km wide and are frequently multiple seismic phases thick.

In seismic sections, facies corresponding to multiple-threaded channel features in basal portions of sinuous channel complexes may be in the form of off-setting, on-lapping or shingled relatively discontinuous reflections (Figs. 7–12-I, 13, 15; Mitchum, 1977). Spacing between consecutive reflections may be >40–50 m. Dip angles of off-setting reflections measured in one example (Fig. 11) are in the range of 4°–6°. Both off-setting and on-lapping reflections are frequently interrupted by significant cuts and indications of small unconformities separating them. Multiple thread-like channel features seen on horizon slices thus seem to consist of closely spaced, laterally shifting, cuts and fills in seismic sections (Figs. 7–9, 11, 12-I, 13).

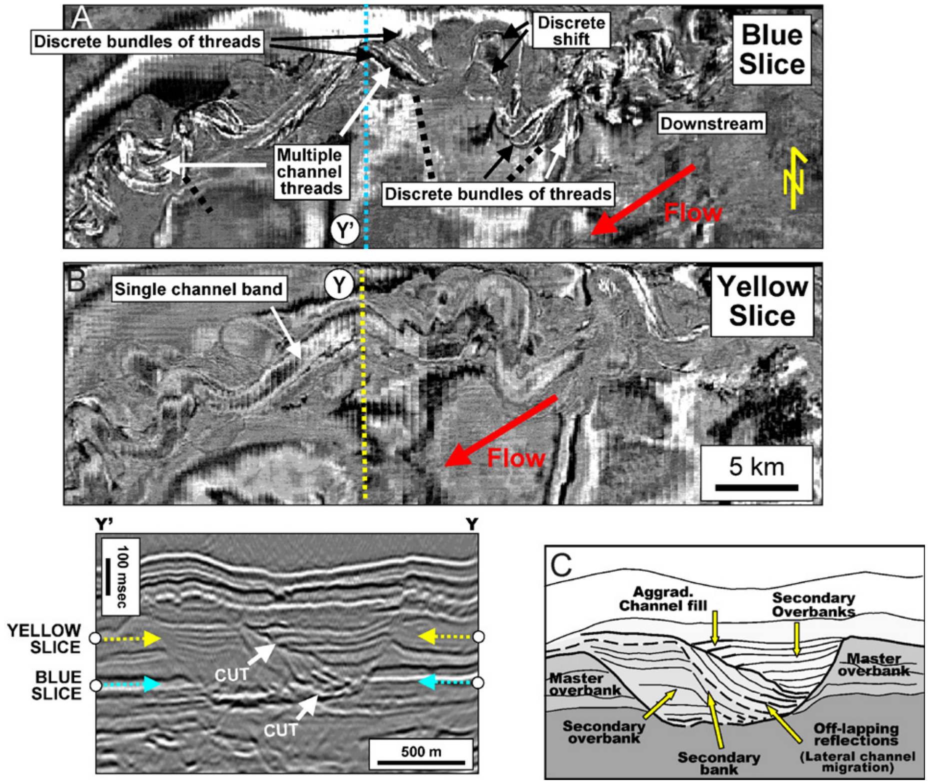

Fig. 8. Two amplitude horizon slices, (A) and (B), of the same gross channel complex as in Fig. 7, and a seismic profile (C). The blue and yellow dashed lines on the profile locate the positions of A and B slices, respectively. The slice (A) from the lower part of the channel complex with multiple thread-like features (scroll bars), and a seismic profile (C) with off-setting shingled reflections, show lateral continuous and discrete migrations (shifts) and some aggradation. The slice (B) from the upper part of the channel complex largely displays a single band-like or thread-like feature (channel), instead of the multiple threads visible in the lower slice. The seismic profile (C) shows significant channel fill aggradation with some lateral migration for the upper interval. Both the lower and upper channel intervals are housed in a master valley flanked by master overbanks (as explained in Fig. 7). Red arrows on slices indicate paleo-flow direction.

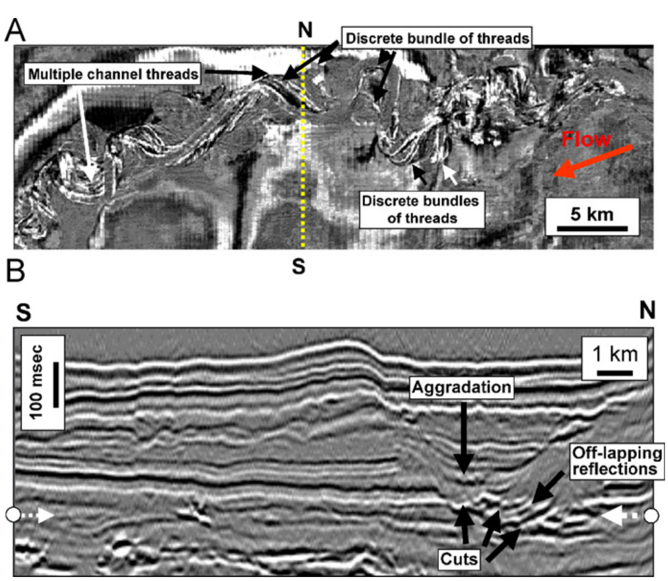

Fig. 9. (A) Horizon amplitude slice from the same channel complex as in Fig. 8. (B) A profile across one loop displays clear, discrete (punctuated) and continuous migrations (shifts). Significant unconformable cuts corresponding to discrete channel shifts are apparent in the profile. White dashed arrows on profile indicate the location of slice.

These cuts may have been focused more on the outer banks of sinuous channels. However, at least some of them appear to have been more channel-wide and have affected the underlying reflection facies of the fill deposited earlier. Concave upward shapes of some off-lapping and on-lapping reflections (e.g. Fig. 7) may be indicative of subtle cuts within fill facies. From inner to outer ends of sinuous loops, fill facies commonly appear to show some aggradation, although lateral channel shifts (migrations) are much more significant. Basal portions of sinuous channel complexes commonly overlie erosional bases of master channels/valleys (Figs. 7–15).

In contrast to the multiple threaded and laterally shifted sinuous channels in basal portions, fills in the upper sections of channel complexes are mainly aggradational with some lateral shifting. Horizon slices across these upper complexes may commonly show a single sinuous channel thread or band (Figs. 8 and 12-II), not multiple channel threads (or bands) as in basal sections. However, a series of successive horizon slices, at different levels from bases to tops of aggrading channel complexes, do frequently show narrow channels (or bands) with increasing or differing sinuosities (Fig. 14). Lateral and down-system, continuous and discrete (abrupt jump) migrations are also apparent

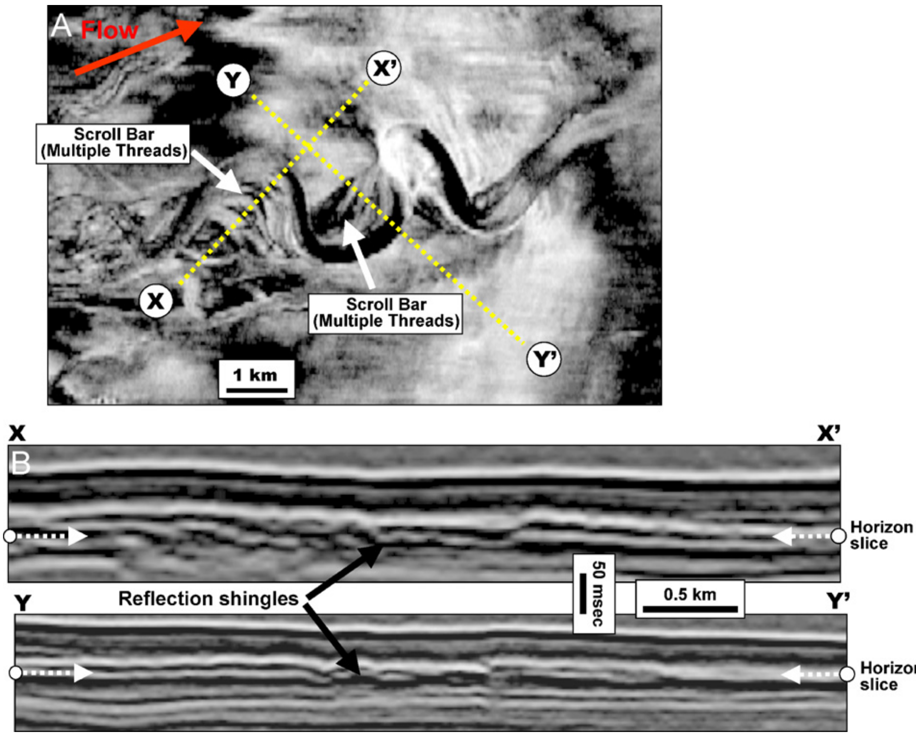

Fig. 10. Horizon amplitude slice (A) with two seismic profiles (B) across two sinuous loops. Multiple threads resembling scroll bars with a tendency for downsystem (red arrow indicates flow direction) and lateral migration are evident. Seismic profiles (B) show shingled, off-setting and discontinuous reflections corresponding to this lateral migration.

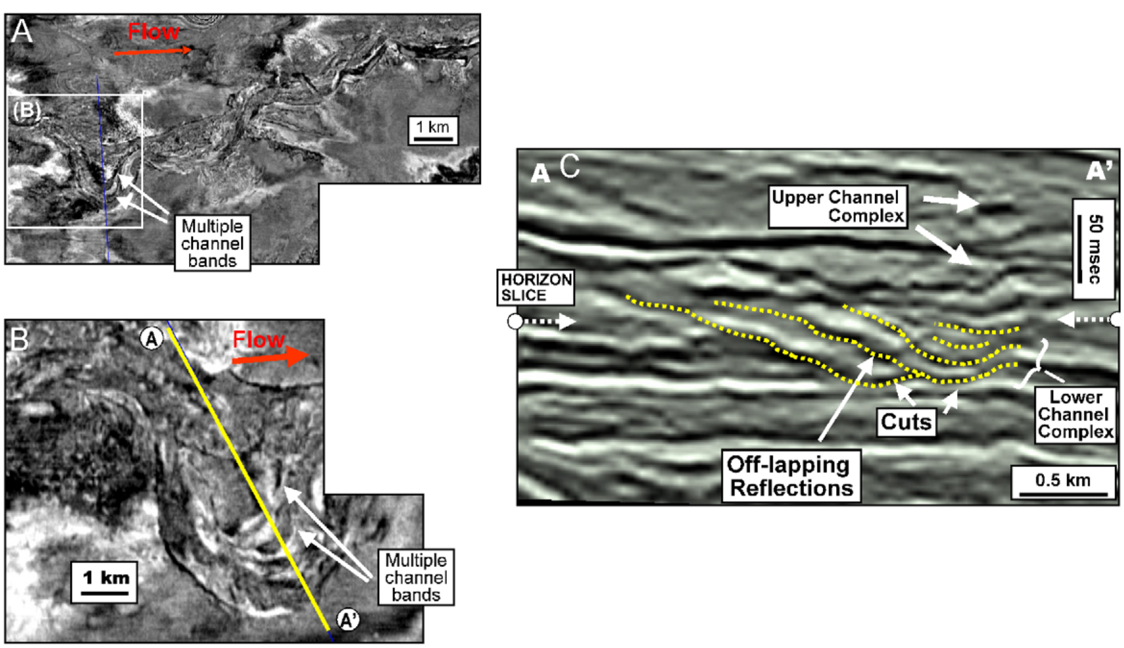

Fig. 11. Two horizon slices (A) and (B) from the lower part of sinuous channel complex, Gulf Mexico, and a seismic line (C) across a loop. Closely-spaced or amalgamated multiple channel bands or threads on slices (A) and (B), and corresponding off-setting shingled reflections (highlighted) with subtle cuts on seismic profile (C), suggest downstream (red arrow) and lateral channel migration and shifting.

(Deptuck et al., 2003). As lateral channel shifting increases in relation to vertical aggradation, even a single horizon slice might unravel more than one thread or band.

In seismic sections across sinuous loops, a significant unconformity surface or cut apparently separates the basal, mainly laterally shifted channel complexes from the upper,

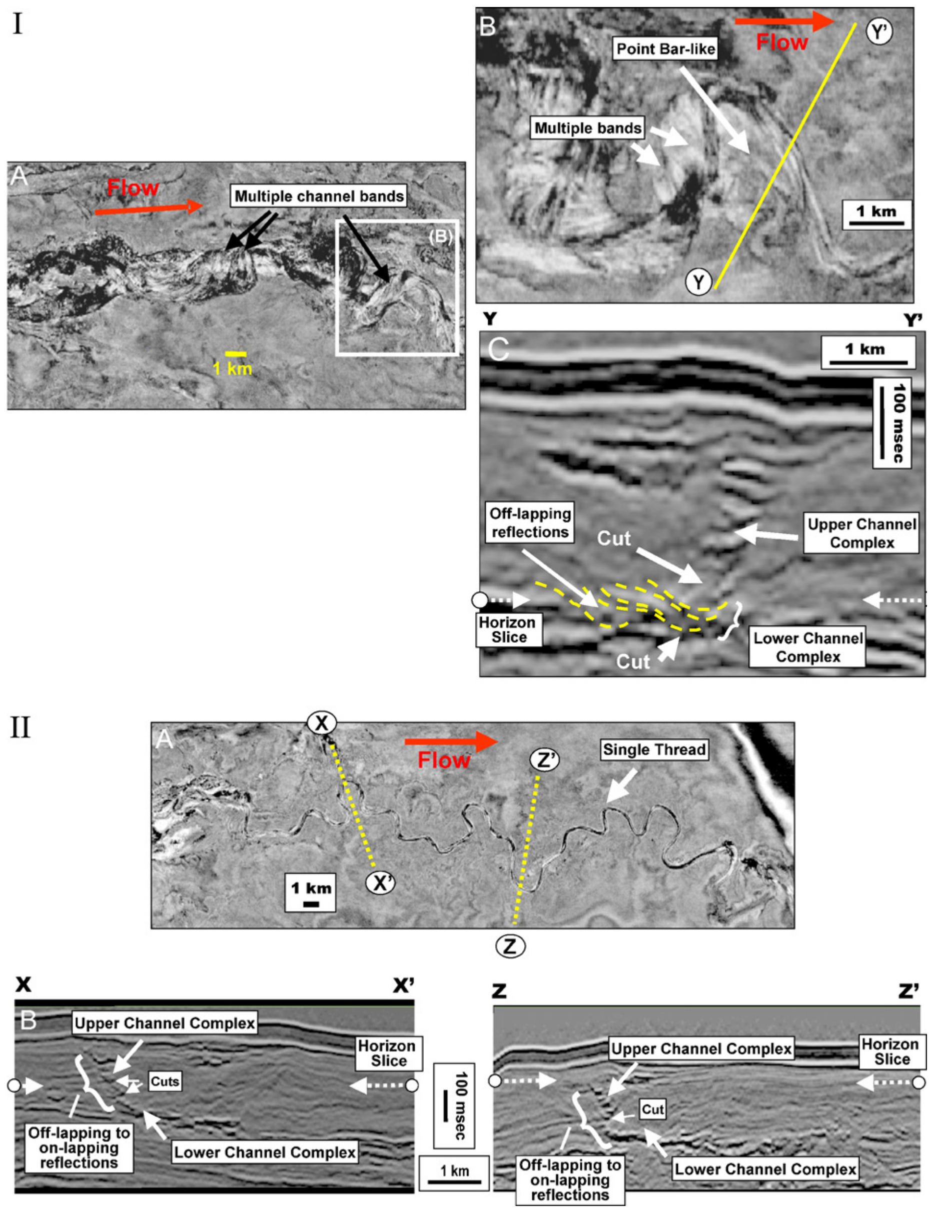

Fig. 12. I. Horizon amplitude slices (A) and (B) from the lower part of a sinuous channel complex, Gulf of Mexico, with a seismic line (C) across a loop. Multiple thread or band-like features in the slices show downsystem (red arrow) and lateral migration with corresponding off-setting reflections (highlighted) in the seismic profile (B). As the channel migrated (or shifted), associated banks, and possibly overbanks, also migrated similar to the ones shown in Fig. 7(B). II. Horizon amplitude slice (A) from the upper aggrading part of the same sinuous channel complex as in A, with seismic profiles (B) across two loops. A single thread-like channel feature is evident in the slice. Dominantly on-lapping and some off-lapping reflections with subtle cuts characterize the aggradational fill in the profiles.

mainly vertically aggrading complexes (Figs. 8, 9, 12-II, 13–15). Furthermore, in two examples (Figs. 12-II and 15), more lateral shifting in the lower parts and more vertical aggradation in the upper parts of a generally aggrading channel complex, separated by a possible unconformity surface, can also be distinguished.

Distinct or discrete cuts with subsequent fills characterize aggrading channel complexes (Figs. 12-II and 14). The fill reflections within these cuts appear to be laterally off-lapping, on-lapping or even converging (Figs. 12-II, 13–15). Some of the off-lapping or on-lapping reflections have concave upward shapes, suggesting subtle cuts within fill facies. Upper, aggrading channel complexes are commonly narrower, but are significantly thicker than basal complexes with lateral channel shifts (Figs. 12-II–14 and, to some extent, Fig. 15). Depositional topographies in basal portions appear to have at least partially influenced the locations and sinuosities of overlying aggrading channel complexes.

Fig. 16 schematically summarizes, in cross sections, the observations made so far on deep-water sinuous channel complexes from the examples discussed. An entire sinuous channel complex, especially the lower part, is usually housed within the confines of a master channel/valley/canyon.

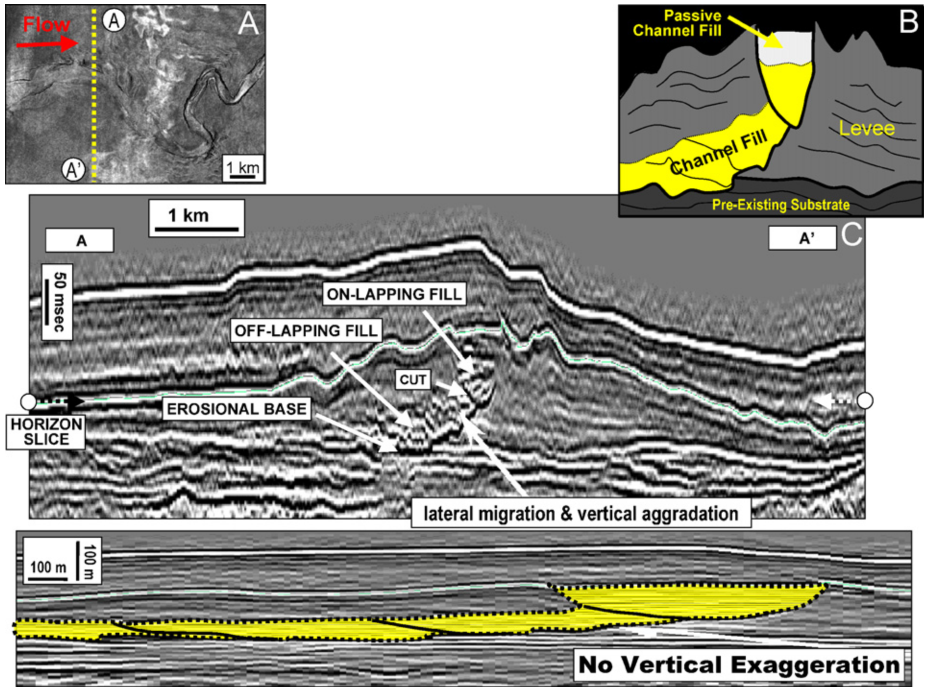

Fig. 13. Horizon amplitude slice (A) from the top of a leveed channel offshore eastern Borneo, Kalimantan, and a seismic profile (B) (in vertically exaggerated as well as 1 to 1 scales) across a sinuous loop of the channel. The slice displays a single sinuous channel band at the top of an aggrading complex. The seismic section shows lateral migration, with off-lapping reflections, in the lower part, and vertical aggradation, with on-lapping reflections, in the upper part. Both the lower and upper channel facies are characterized by cut and fill architecture.

Laterally migrating channel complexes in basal portions of the fill are about one to three seismic phases or more thick, and may be flat or more commonly slightly aggrading, from the inner to the outer banks of the meander loops (Figs. 7–13, 15, 16-II, I and II). These dominantly laterally migrating channel facies may be followed by thicker, increasingly vertically aggrading sinuous channel complexes with varying degrees of lateral migration (Figs. 8, 12-II, 13–15, 16, III and IV). These differing sinuous channel styles may be separated by significant cuts (Fig. 16). Lateral migrations and vertical aggradations may be either continuous or discrete and are due to cuts and fills of various magnitudes. The fill facies may have off-lapping, on-lapping or even converging strata within the cuts.

3.2.2. *Similarities and complexities in thick exploration (deeper subsurface) sinuous channel complexes*

Ardill et al. (2005) reported laterally migrating, amalgamated, and low to moderately sinuous channels in the lower part, and more vertically aggrading, highly sinuous channels in the upper part of Pliocene slope channel complexes of the Zafiro Field, deep-water off Equatorial Guinea. These styles of sinuous channel stacking in the Zafiro Field channel complex are broadly similar to many examples discussed here. However, it is apparent from studies here and elsewhere (e.g. Kolla et al., 2001) that not all sinuous loops along the length of a channel have similar architectures and evolve the same way at any one time. Laterally migrated channels may also occur in the upper parts of channel complexes, not necessarily in the basal parts only (Abreu et al., 2003; Samuel et al., 2003). In some cases, high sinuosities are thought to have been created at the very inception of channel formation due to topographic and/or structural controls, without the necessity of successive lateral shifts, while in others, lateral migrations have not always led to increased sinuosities (Mayall and Stewart, 2000; Kolla et al., 2001).

It is also evident from previous studies that in thick, deeper (exploration) subsurface sinuous channel complexes, laterally shifting and vertically aggrading channel styles may occur in a variety of combinations, amalgamated or separated by erosional cuts or thick shales; their thickness and sequential development may be complex and vary from the schematic shown in Fig. 16 (Mayall and Stewart, 2000; Kolla et al., 2001; Mayall and O'Byrne, 2002; Mayall et al., 2006). However, styles of channel stacking, as depicted in Fig. 16, can still provide insights into the understanding of architecture of thick sinuous channel complexes in the deeper subsurface. Fig. 17, with interpretations modified from Kolla et al. (2001), illustrates this point.

The sinuous channel complex image in Fig. 17 is based on 35 Hz peak frequency data, unlike shallow subsurface examples of high-frequency data. This channel complex appears to consist of two groups of sinuous channel loops: 1A and 1, and 2 + 2A, 2B and 2C (Kolla et al., 2001). From intersecting relationships in the strat-amplitude plan-view

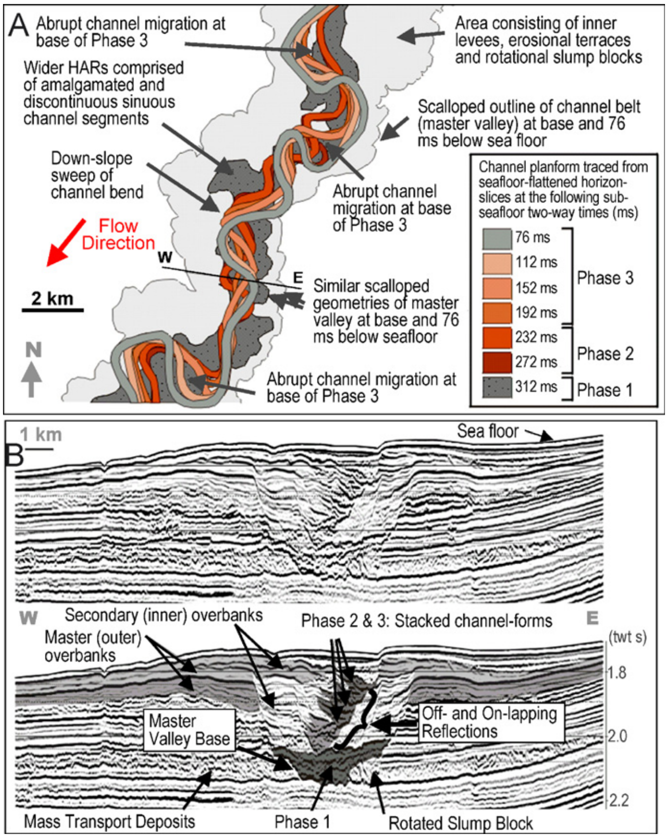

Fig. 14. A drawing of planform geometry of stacked sinuous channel-axis deposits (A) (with high-amplitude reflection facies) every 36–40 ms below the flattened seafloor, and a seismic profile (B) across a sinuous loop of a channel complex from offshore, Nigeria (modified from Deptuck et al., 2003). These deposits consist of 1, 2, and 3 phases and are housed in a master valley flanked by master (outer) overbanks. Scalloped geometries at 76 ms below seafloor, and at the base of the erosional fairway, define the widths of the master valley (see text) at these levels. Downslope sweeps and lateral relatively continuous and abrupt migrations from deeper to shallower levels are evident in phase 2 and 3 aggradational deposits (A). Cuts, and off- and on-lapping reflections within cuts, characterize the deposits (B).

image (Fig. 17), loop 1A may be interpreted to have evolved first, followed by loop 1; and then loop 2 + 2A followed successively by 2B and 2C. After the evolution of loop 1, there may have been a cutoff that initiated loop 2. An alternative interpretation is that sinuous loops evolved gradually from 2 + 2A to 2B, 2C, 1A and finally to 1. In any case, because the total channel sequence is thick (especially to the right of the seismic section, 2 + 2A in Fig. 17), and because the same sinuous loop is apparent in more than one strat-amp image (Kolla et al., 2001), each loop is interpreted to consist of vertical aggradations at each channel location (2 + 2A, 2B, 2C, 1A, 1) and each channel discretely shifted laterally to the left of the preceding one (Kolla et al., 2001). This series of channel shifts or migrations is thought to be similar to the thicker lateral channel shifts sketched in Fig. 16B-II. The sketch in Fig. 16B-I approximates lateral shifts and migrations with less thick deposits from shallow subsurface examples discussed.

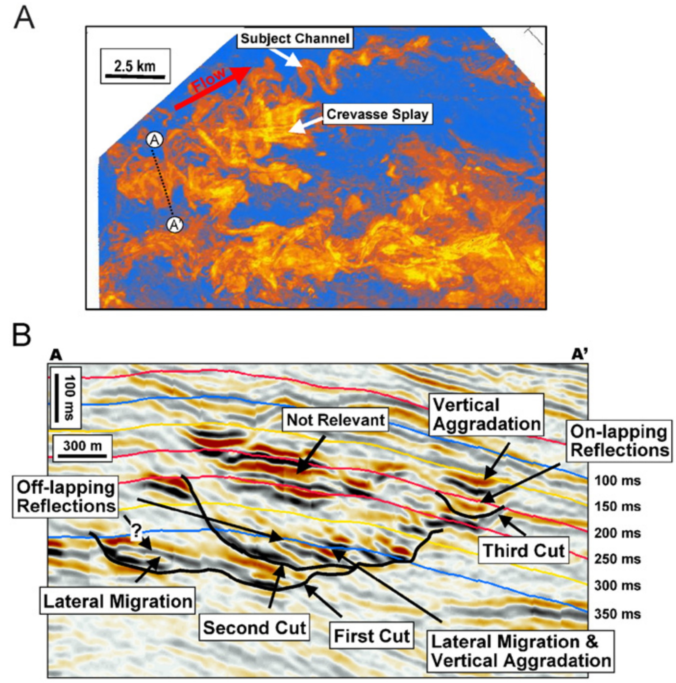

Fig. 15. A composite interval amplitude map (A) of Pliocene sinuous channel complexes, offshore east coast of India (Bastia, 2004). A typical seismic profile (B) across a loop of one sinuous channel complex (subject channel in (A)) depicts the channel architecture and evolution in sectional view. Laterally shifting channel complex in the lower part, laterally shifting and vertically aggrading channel complex in the middle part, and vertically aggrading channel complex in the topmost part, are distinguished in the profile (B). Several amplitude maps corresponding to intervals in the profile were generated to document these differing styles of channel stacking in plan-view images, but are not shown here.

3.2.3. Lithological characteristics

None of the shallow subsurface examples discussed here have been drilled. However, several sinuous channel complexes from exploration depths, especially from offshore areas of Angola, Equatorial Guinea, India etc. have been drilled. From published information, it is apparent that high-amplitude seismic reflections, defining sinuous channel geo-bodies in these examples, usually appear to be good indicators for sand-prone lithologies (e.g. Roberts and Compani, 1996; Sikkima and Wojcik, 2000; Shanmugam, 2000; Mayall and O'Byrne, 2002; Navarre et al., 2002; Abreu et al., 2003; Bastia, 2004; Ardill et al., 2005). Thick- and thin-bedded sands (high-density turbidites/sandy debris flows and low-density turbidites, respectively), reworked in places by bottom currents, were reported in these sinuous channel complexes (e.g. Shanmugam, 2000; Mayall and O'Byrne, 2002; Ardill et al., 2005). High-amplitude seismic facies in sinuous channels from the shallow subsurface discussed here are also likely to be sand-prone. It is of interest to note that Ardill et al. (2005) reported thick amalgamated coarse sand lithologies in the basal, laterally migrating sinuous channel complex and inter-bedded sands in the upper parts of the vertically aggrading, highly sinuous channel complex in the Zafiro Field, off Equatorial Guinea. However, in other areas drilled, published data are not sufficient to show lithological differences between laterally migrating and vertically aggrading sinuous channel complexes.

Off-lapping, laterally accreted strata filling erosional cuts, interpreted as deposits of lateral channel migrations, have been reported in outcrops by several authors (e.g. Elliot, 2000; Abreu et al., 2003; Pyles et al., 2006). The extents of such off-lap strata observed in outcrops are very limited, compared to the widths of channel off-lap fill reflection facies seen in seismic. However, as noted by Deptuck et al. (2003), such off-lap strata in outcrops may be overlain by laterally shifting and vertically aggrading cuts and fills with on-lapping and converging strata, all within a larger erosional cut and together forming a channel complex of significant vertical extent. These observations are very similar to migrations and aggradations of channels noted in the seismic examples discussed here (Figs. 9–11, 15 and 16B).

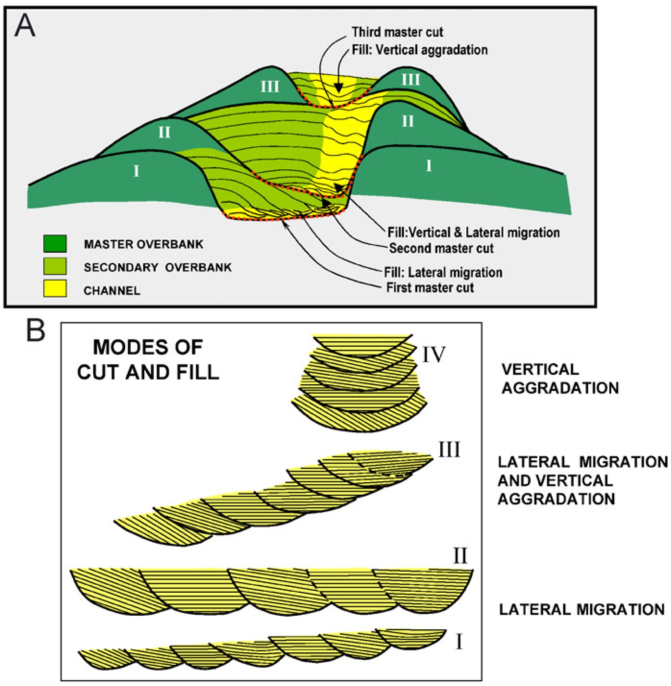

Fig. 16. Generalized schematic drawings in sections across sinuous loops summarizing the observations made from several examples: (A) laterally shifting channel complex in the lower part, increasingly vertically aggrading channel complexes in the upper part, and associated overbanks (secondary overbanks) housed in master channels/valleys flanked by master over banks; (B) details of channel architectures in laterally shifted channel complexes (I and II) and laterally migrating to vertically aggrading channel complexes (III and IV).

3.2.4. Summary of similarities and differences in internal characteristics of fluvial and deep-water sinuous channels relevant to unraveling their modes of evolution

Migrations or shifts in fluvial sinuous channels with point-bar scrolls, as imaged in 3D seismic slices and aerial photos, are usually laterally continuous, except when cutoffs and avulsions occur. These lateral migrations usually have a downstream component. Lateral accretionary point-bar deposits, resulting from lateral migrations, are commonly a single seismic phase (loop) thick, with seismically flat tops. Migrations occur as a consequence of relatively continuous erosion on the concave (outer) bank and deposition on the convex (inner) bank. Most cutting and migration usually occur during flood episodes and soon after. Migrated inner banks are commonly sand-prone. Lateral accretionary deposits show up as scroll bars or as high-amplitude patches filling meander loops on 3D seismic amplitude attribute slices and as scroll bars in aerial photos. In seismic sections with normal 3D seismic frequencies, scroll bars may show up as subtle, off-lapping, reflection shingles or as a single composite reflection, and in outcrops as off-lapping strata. Fining upwards sand sequences with tractive sedimentary structures are common

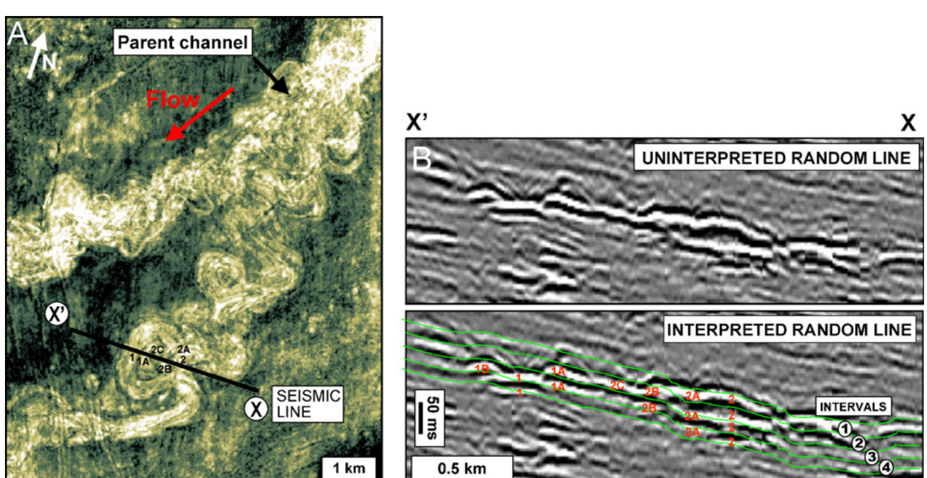

Fig. 17. A sinuous channel complex example from exploration depths (Early Miocene stratigraphic interval) off Angola, modified from Kolla et al. (2001). The sinuous channel complex in plan-view (A) represents a composite amplitude image of all seismic facies within intervals 4, 3, 2, and 1 shown in the sectional view (B). Amplitude images within individual intervals 4, 3, 2, and 1 have been shown by Kolla et al. (2001) to document successive channel aggradations and lateral shifts, 1A, 1 and 2 + 2A, 2B, 2C, but are not reproduced here.

in point-bar deposits, although blocky or even coarsening upwards sequences may also be present.

In deep-water sinuous channels with or without point-bar scroll-like features, migrations or shifts may be lateral, either continuous or discrete, and laterally migrating to vertically aggrading, either continuous or discrete, and are single to multiple seismic phases thick. Lateral migrations in deep-water channels are more resolvable in seismic compared to point-bar migrations in fluvial channels. Even the most laterally migrated sequence in a deep-water channel may be commonly aggrading, however slightly, from the convex (inner) to the concave (outer) bank of the meander loop. Lateral migrations in deep-water channels may or may not have a downstream component (see also Kolla et al., 2001). Lateral migrations and vertical aggradations can occur as a consequence of relatively continuous erosion, discrete cuts, or less deposition on the concave (outer) bank and more deposition on the convex (inner) bank (Imran et al., 1999); or as a result of episodes of distinct and discrete channel-wide cuts and fills. On 3D seismic horizon amplitude slices, sequences resulting from lateral migrations and shifts show up as multiple sinuous channel threads or scroll bar-like features, and those from vertical aggradations as single threads or bands. On seismic sections and in outcrops of deep-water sinuous channels, both laterally migrating and vertically aggrading sequences might appear as off-lapping and on-lapping reflection shingles or strata, often filling closely spaced, subtle or discrete cuts. Blocky, fining or coarsening upwards, massive, inter-bedded, graded or laminated sands, with or without common tractive sedimentary structures, characterize the channel deposits. Inner channel banks that migrate with lateral channel shifts may or may not be of high amplitude and may or may not be sand-prone in deep-water channels.

4. Factors and processes controlling sinuosity evolution of deep-water channels

Factors considered to be generally important in controlling overall deep-water channel sinuosity evolution are: (1) seafloor gradients and topography (including also structural features); (2) current flows: point vs. line source, turbidity currents (more important) vs. debris flows; (3) catastrophic vs. steady turbidity currents; (4) flow velocities, frequencies, volumes and sediment concentration, and flow density differences with ambient water; (5) sediment grain size; (6) types of secondary circulations within channels; (7) effects of channel curvature (centrifugal forces) and Coriolis force on flows; (8) width to depth ratios and shapes of initial channels/valleys, bank cohesiveness, slumping and channel plugging; (9) effects of sea- and base-level changes.

Unique properties of sediment gravity flows and fluvial currents and their similarities and differences (e.g. Imran et al., 1999; Shanmugam, 2000; Kolla et al., 2001 and others) can explain their respective channel behaviors:

River currents are fluid gravity flows. Both traction and suspended modes of sediment transport are important in fluvial currents. Density differences between river currents and the ambient fluid (air) are very significant and entrainment of ambient fluid (air) into river currents is negligible, although flow thickness along a river course may increase from additional runoffs. Effects of centrifugal forces on flows at curves in river courses are significant, but effects of Coriolis force may be negligible. Helicoidal circulation and asymmetry in strength are characteristic of flows across river channels. Catastrophic currents may be common during floods and most erosional cutting occurs on outer banks during that time. At all other times steady flows are typical. For a given channel depth, a stationary sea level usually limits point-bar thickness.

Turbidity currents are sediment gravity flows. Suspended sediment transport is more important and traction transport is less important than in river currents. Density differences between sediment gravity flows and ambient fluid (water) are much smaller and entrainment of ambient fluid (water) into flows is very significant. Effects of both Coriolis and centrifugal forces on flows are very marked. Helicoidal circulations and flow asymmetry may exist across channel widths (Kassem and Imran, 2004; Das et al., 2004; Corney et al., 2006; Peakall et al., this volume). Catastrophic currents are more common; however, steady or quasi-steady currents may also frequently occur. Sea level does not have as much limiting effect on flows in influencing vertical aggradation in deep-water channels as in fluvial channels.

Observed similarities in morphologies, and to some extent in internal architectures, of fluvial and deep-water sinuous channels discussed here implies that, in both cases, sinuosity enhancement resulted from processes that involved interaction of flows, sediments and alluvial plain or seafloor over a period of time in attempts to build equilibrium profiles. Flat gradients, high width to depth ratios of valleys/channel belts, fine sediment grain sizes, certain degree of bank cohesiveness and presence of secondary circulations were pre-requisites in both systems. Differences in density contrasts of flows and ambient fluids, entrainments of additional fluids into flows, effects of centrifugal and Coriolis forces on flows, frequency, volume and duration of steady vs. catastrophic flows, modes of sediment transport, and effects of sea level changes probably caused the main differences in internal architecture of fluvial and deep-water channels and their evolution.

Within deep-water systems, changes in flow parameters, flow duration and sediment grain size may cause erosion, bypassing and deposition, depending on the preceding equilibrium conditions, and result in channel sinuosities in space and time through various degrees of lateral migrations, aggradations and combinations thereof. Currents that created sinuous channel networks in the present examples were under-fit flows, different from initial, large volume flows and/processes that caused their valley/canyon hosts. Assuming turbidity currents as a mechanism and with the Chezy-type equation as a guide, these under-fit flows can be visualized at different energy levels by varying their suspended sediment concentrations and thicknesses, and valley gradients (Kneller, 2003).

For a particular sediment grain size, increasingly less energetic turbidity flows favor continual deposition and channels vertically aggrade (Fig. 18). In the high-resolution seismic data presented here, dominantly aggraded sinuous channel complexes consist of continuous deposition with subtle and discrete cuts filled with off-lapping, on-lapping or even converging strata (Figs. 12-II–16). Infrequently, increased bursts of energy levels for several short periods that interrupt long periods of low-energy flows are thought to have created cuts towards the concave side of the channel or across the entire channel width. On-lap stratal fill in these cuts was probably by low-energy flows that favored channel-wide deposition, whereas off-lap stratal fill was by slightly higher-energy flows that were more depositional on the inner banks and less depositional, or even slightly erosive, on the outer banks. On the whole, frequent cuts towards outer banks and fill towards inner banks of channels resulted in higher sinuosities.

Coarse sediment grain size favors aggradation whereas fine grain size favors erosion for flows of given energy levels (Kneller, 2003). Flows in deep-water systems, however, generally favor vertical aggradation irrespective of grain size. Increasingly low-energy flows tend to have generally fine sediment grain size and may result in thin and interbedded sands as reported by Ardill et al. (2005). Base level in deep-water systems, much controlled by flow parameters, sediment grain size and evolving valley (seafloor) gradients, is a dynamic variable and does not limit vertical aggradation as much as in fluvial systems.

Flows that have increasingly high energy levels for persistently long periods of time are likely to create significant erosive surfaces (Fig. 18). Large volumes of such high-energy flows result in widespread erosion. However, constant flow energy levels lead to equilibrium conditions and sediment bypassing. Even then, effects of secondary circulation may favor some deposition on the inner bank side with concomitant erosion on the outer bank side of channels, resulting in continuous channel migration towards the outer banks. In channels with lateral migrations, discrete channel cuts and shifts with subsequent fills are typically observed in the examples discussed (Figs. 7–12, 16B-I and II). These cuts were probably due to small, frequent and increased bursts of flow energies for shorter periods of time, but close to equilibrium conditions (Fig. 18), and occurred preferentially towards the concave sides of channels and sometimes across entire channel widths. Fill in these cuts consists of on-lapping or off-lapping strata, deposited by somewhat less-energetic flows, again close to equilibrium conditions, that occurred frequently and lasted for short periods of time. Thus, under conditions of flows not greatly varying from

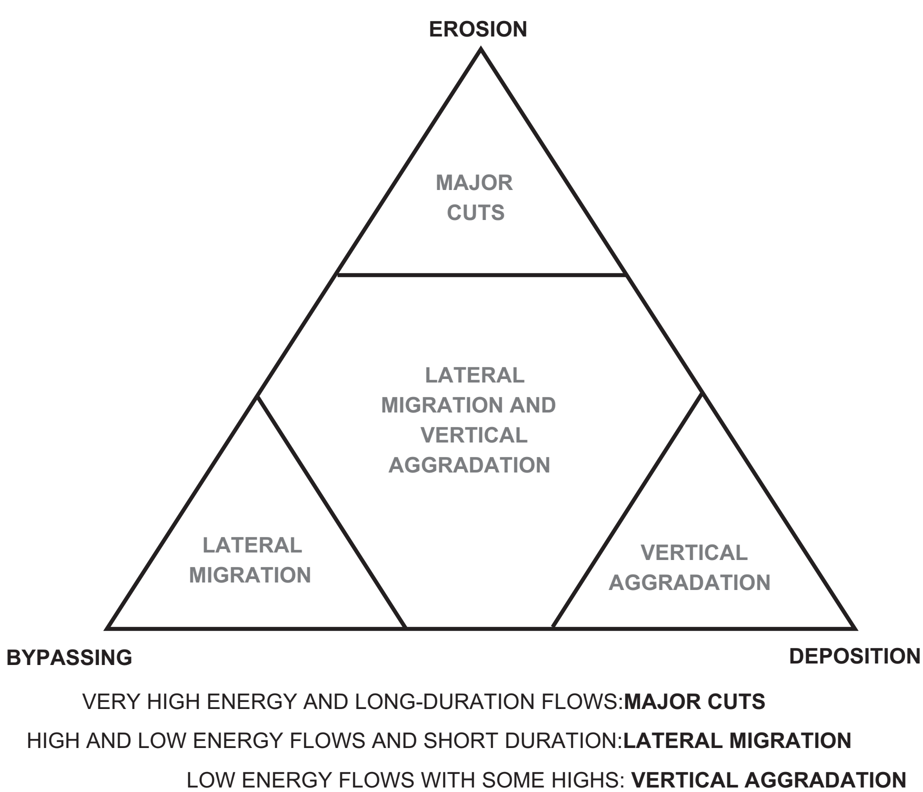

Fig. 18. Triangle diagram showing very qualitatively how different processes, namely erosion, bypassing and deposition, result in lateral migration, lateral migration-to-vertical aggradation and vertical aggradation. Apices of the triangle represent both the highest rates (intensity) and the longest duration of the respective processes.

equilibrium conditions, and only for short periods, lateral channel migrations were developed (Fig. 18). Channel aggradation under bypassing conditions, in spite of variability, is expected to be limited. With energy levels of flows close to equilibrium conditions, lateral migratory deposits are likely to consist of thin- to thick-bedded sands, depending on the availability of sediment grain sizes (Ardill et al., 2005).

Fills with continuously deposited, gently dipping, off-lapping strata in cuts more closely resemble point-bar deposits. Other lateral migratory deposits with discrete cuts and on-lap fills should be considered as laterally stacked channel deposits rather than point-bars. However, in low-resolution seismic data, some of these deposits are likely to be interpreted as point-bar accretionary reflection surfaces.

5. Conclusions

(1) High-resolution 3D seismic data of several examples show that, although there are morphological similarities between fluvial and deep-water sinuous channel systems, there are also significant differences, both in their internal architectures and modes of evolution. Channel migrations or shifts in fluvial systems are laterally continuous with a downstream component, and resulting point-bar deposits are commonly a single seismic phase thick, with seismically flat tops. In deep-water systems, channel shifts or migrations may be lateral, either continuous or discrete, and laterally migrating to vertically aggrading, either continuous or discrete; they are single to multiple seismic phases thick, with or without a downstream component. Even the most laterally migrated sequences are commonly aggrading, to varying degrees, from the convex to the concave side of sinuous loops.

(2) Similarities between fluvial and deep-water sinuous channel systems in examples presented here, imply that in both cases channel shifting and sinuosity enhancement were the result of processes involving interaction of flows, sediments and alluvial plain or seafloor gradients in attempts to build equilibrium profiles over a period of time. Flat gradients, high width to depth ratios of valleys/channel belts, fine sediment grain sizes, certain degree of bank cohesiveness and presence of secondary circulations in the flows were pre-requisites in both systems.

(3) Differences in density contrasts of flows relative to ambient fluids, effects of centrifugal and Coriolis forces on flows, frequency, volume and duration of steady vs. catastrophic flows, modes of sediment transport, and effects of sea level changes appear to have caused the main differences in the internal architectures and lateral migrations/aggradations of fluvial and deep-water channels.

(4) Within deep-water systems, changes in flow parameters and sediment grain size in space and time probably resulted in sinuous channels with varying degrees of cuts, lateral migrations, vertical aggradations and various combinations thereof.

(5) Different styles of internal architecture and their manner of stacking in deep-water sinuous channels, as interpreted from this study, provide insights into the understanding of thick exploration (deeper subsurface) sinuous channel systems with more complex architectures and with less seismic resolution.

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