MORPHOLOGY AND INTERNAL STRUCTURE OF A RECENT UPPER BENGAL FAN-VALLEY COMPLEX

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ABSTRACT: 3D seismic and multibeam data show that the present seafloor morphology of the entire upper Bengal Fan-valley complex is broadly sinuous and is more than 20 km wide in places, and consists of a highly sinuous channel flanked by a series of several terraces or overbanks on either side all along its length. This morphology is but a surface expression of the underlying internal structure and evolution of several, vertically and laterally stacked valley fills and their flanking overbanks. Each of these valleys consists of underfit sinuous channel fills with development of scrolling, indicative of much lateral channel migration with downstream shifts in their courses in the initial stages of their evolution. The scrolls may be of high seismic amplitudes, sand-prone, or of low seismic amplitudes, mud-prone. In their later stages of evolution, the channels exhibit more aggradation. Cutoffs are more common in the initial stages of sinuous-channel evolution and less common in the later stages. The highly sinuous channel on the present sea floor is also an underfit feature and represents the latest phase of the uppermost valley fill. The various stages of channel evolution are a function of the hydrodynamics of the flows in the channels and sediment grain size supplied.

At the very base of the above mentioned main valley-fill complex, but frequently amalgamated to it, a fan-shaped network of straight to slightly sinuous channels with thin fills, fed by the same canyon as for the overlying valley complex, is present. This basal channel network reflects smaller flows in the very initial stages of avulsion from an older upper fan-valley complex to the east. However, the overlying main valley complex reflects large-volume flows when the avulsion became fully established later and the canyon was entirely feeding it. The innermost terraces on either side of the present sinuous channel on the seafloor resulted from its flanking overbanks over the abandoned channel fills within the uppermost valley of the complex. The more outer terraces formed from the overbanks of successively younger valleys when they abutted against the higher banks of the preceding older and larger valleys.

The recent upper fan-valley complex may have originated during the last glacial stage and continued to evolve mainly until about 6000 years B.P. (Weber et al., 1997; Hübscher et al., 1997). Smaller turbidity flows that could not have generated overbanks may have continued subsequently. However, our cores from the latest upper-fan sinuous channel with brown oxidized muds at the tops show that there is little or no turbidity-current activity in it at present.

KEY WORDS: Bengal Fan, fan valley, sinuous channel, morphology, internal structure, lateral migration, aggradation, cutoffs

INTRODUCTION

In recent years, many hydrocarbon discoveries have been made in deep-water sinuous-channel reservoir systems from Cenozoic stratigraphic intervals along several passive margins around the world ocean (e.g., Kolla et al., 2001; Abreu et al., 2003; Bastia, 2004; Mayall et al., 2006; Ardill et al., 2005; Kolla et al., 2007). Several of these discoveries have been developed into producing fields. For efficient field production, it is critical to have a detailed and precise understanding of the reservoir lithological distributions and architectures of deep-water sinuous-channel systems at exploration depths and their evolution. Such detailed understanding can be obtained from as many of the following studies as possible and their integration: (1) high-resolution 3D seismic imaging of the stratigraphic targets within the hydrocarbon fields, supplemented by cores, logs, and production histories (e.g., Porter et al. 2006; Abreu et al., 2003; Kolla et al., 2001); (2) very high-resolution 3D seismic studies of shallow subsurface sinuous channel systems in settings similar to those of the discoveries, supplemented by cores (e.g., Posamentier and Kolla, 2003; Kolla et al., 2007; Deptuck et al., 2003; Deptuck et al., 2007); (3) outcrop studies in analog settings (e.g., Abreu et al., 2003; Wynn et al., 2007, and the references therein); (4) experimental, numerical, and theoretical studies on deep-water sinuous-channel systems (e.g., Wynn et al., 2007; Peakall et al., 2007; Islam et al., 2008); and (5) comparative studies of fluvial and deep-water sinuous channel systems (Kolla et al., 2007; Peakall et al., 2007; Islam et al., 2008). More studies of this type help to increase understanding of architectures of sinuous-channel reservoirs. The present study deals mainly with a high-resolution 3D seismic and multibeam data sets of the most recent, what Curry et al. (2003) referred to as, upper Bengal Fan “valley” (or “channel”), from the sea floor to about 400 m subsurface (Figs. 1A, 1B). Curry et al. (2003) used both the terms “valley” and “channel” interchangeably to describe this geomorphic feature. In other fans, previous authors used either “valley” or “channel” or both for the same upper-fan feature (e.g., Damuth and Kumar, 1975; Normark, 1978; Kolla and Coumes, 1987). In our paper, we make a distinction between “valley” and “channel,” although qualitatively (Wescott, 1997); we use the term “valley” for large and wide
(kilometers) features and “channel” for small and narrow (a few tens to several hundreds of meters or less wide) features. However, as will become apparent from our study, the upper Bengal Fan “valley” actually consists of several vertically and laterally stacked, wide valleys, each filled by networks of deposits of highly sinuous narrow channels and is thus a valley–channel complex. For brevity, we refer to the study area as the upper Bengal Fan-valley complex.

Most of the Bengal Fan is located along the passive eastern Indian margin in the Bay of Bengal. With the exception of parts of the fan located near the Bangladesh–Burmese margin, the fan is largely undeformed. The upper Bengal Fan-valley complex is part of the upper Quaternary valley–channel system, mapped by Curray et al. (2003) (Fig. 1A), utilizing widely spaced seismic lines. This fan-valley complex is located in the present water depths of about 1600 to 2300 meters, directly downdip of the canyon, “Swatch of No Ground”, that fed the Ganges–Brahmaputra river sediments to it and farther downdip to the long north–south-running channel systems in the middle and lower fan regions (Fig. 1A; Curray et al., 2003). The main factors affecting the development of this fan in general and the upper fan-valley complex in particular are: climate, high hinterland and geology of the source area, very large sediment supply, fine-grained sediment type, connectivity of the canyon to the river confluence during sea-level changes, and bathymetric (including water depths, gradients) and structural setting. Because of the lack of any significant deformation, the internal architecture of the Bengal Fan-valley complex is undisturbed, reflecting original depositional–erosional processes, and is ideally suited for detailed reservoir architectural studies of deep-water sinuous-channel systems. Parts of the downdip extension of the present upper-fan-valley channel into the middle and lower fan regions have been studied in some detail by Weber et al. (1997), Hübischer et al. (1997), and Moe et al. (2001). Weber et al. (1997), and Hübischer et al. (1997) suggested from their core studies that the recent fan-valley–channel complex, initiated sometime during the last glacial, continued to evolve mainly until about 6000 years B.P. However, the cores reported by these authors were too short to give a more definitive age for the initiation of this fan-valley complex.

The objectives of the present study are to better understand the morphology, internal architecture, and evolution of the recent upper Bengal Fan-valley complex and gain insights into the lithology distributions, geometries, and architectures of sinuous-channel reservoir systems, applicable to similar depositional systems at exploration depths.
DATA TYPES AND METHODOLOGY

Three types of data are included in this study: (1) multibeam data of the seafloor; (2) 3D seismic data of the shallow sub-seafloor and seafloor (Figs. 1A, 1B); and (3) A preliminary study of 14 piston cores (each less than 5 meters long), taken along four traverses from sub-environments (present channel thalweg and flanking terraces or overbanks) of the upper-fan valley complex from updip to downdip (Fig. 1B). Multibeam data in the study area provide a terrain grid with 75 m horizontal spacing and ± 1 m vertical spacing. The 3D seismic grid has an inline spacing of 25 m and a cross-line spacing of 12.5 m, with a vertical sampling rate of 4 ms. From the shallow subsurface depths (300 to 500 milliseconds) to the seafloor of the study area, the seismic data consist of peak frequencies of 90 to 100 Hz. Assuming acoustic velocities of 1500 to 1800 m in the shallow subsurface of the Bengal Fan, these frequencies would give a vertical resolution of 3 to 5 m within the sediment column. This resolution is significantly higher than that of the high-resolution data of the deeper field targets in exploration (e.g., Abreu et al. 2003). This resolution, combined with the pristine, original depositional setting of the Bengal Fan valley complex, provides an excellent opportunity to obtain very high-quality geomorphic images and unparalleled architectural details of sinuous-channel reservoir systems within the fan-valley complex.

Using every other twentieth cross-line, a plane was constructed above the present channel floor at the level of its flanking innermost overbanks. This plane above the present channel cuts out the higher, outer overbanks outside the innermost overbanks and does not therefore include them. The plane dips south with increasing water depths of the channel and associated innermost overbanks. Flattened time slices were made in the workstation parallel to this plane, and the images thus obtained were examined.

A visual examination of cores, supplemented by examination of smear slides, was made to ascertain the types of lithologies in the surface and near-surface sediments within the channel thalweg and on the flanking terraces (overbanks).

MORPHOLOGY, INTERNAL STRUCTURE, AND EVOLUTION OF THE RECENT BENGAL FAN VALLEY COMPLEX

Seafloor Morphology and Surface (and Near-Surface) Sediment Lithology

The seafloor of the upper Bengal Fan valley complex consists of a highly sinuous channel system, flanked on both sides by a series of terraces or levee-overbanks (Figs. 1B, 2). The outer boundaries of the terraces mimic somewhat fault traces on seismic lines. The high sinuosity of the channel is apparently superposed on a more regional set of broad sinuous curvatures of the morphology of the entire terraced fan-valley complex. Although terraces are present all along the channel on both sides, each terrace, with maximum widths from a few hundred meters to several kilometers, is somewhat limited in areal extent (Figs. 1B, 2).

Although the water depths of the channel axis (measured at straight 10 km segments of the channel) vary locally erratically due to differential sedimentation, they gradually increase from proximal (in excess of 1900 m depth) to distal (2300 m depth) ends of the channel in the study area (Fig. 3). The sinuosity of the channel, measured at 30 km segments, with distance shows that the sinuosity is generally higher than 1.5, reaching values as high as 2.5 to 3.0 in places, similar to or higher than those of the channels from other major fans of the world ocean (e.g., Clark and Pickering, 1996; Flood and Damuth, 1987; Pirmez and Flood, 1995; Babonneau et al., 2002) (Fig. 4). The sinuosity measured at 10 km and 20 km segments shows more variability than at 30 km segments. The longer-distance segments average out the sinuosity variations measured at shorter-distance segments.

The dimensions of the present sinuous channel on the seafloor within the 3D seismic grid area were measured along seventeen selected traverses that are oriented transverse to the channel axis, with each traverse crossing only one sinuous loop. Each of these traverses crosses from a clearly defined innermost terrace (interpreted to consist of overbank deposits) adjacent to one side of the channel to a corresponding terrace on the other side of the channel. The widths of the sinuous channel floor (from the base of one bank to another; thalweg widths of Deptuck et al., 2003) vary from about 200 to 400 m; the widths of channels from one levee to another levee (bankfull widths of Pirmez and Flood, 1995) vary from 400 to 800 m; and the channel relief (from levee tops to the deepest part of the channel) varies from 18 to 30 m (Table 1).

Sediment waves oriented subparallel to the trends of the valley complex are found on the flanks of the outermost overbanks and are especially common to the concave sides of the broad curvatures of the complex (Fig. 1B).

As will become apparent in the following pages, the entire seafloor morphology of the present fan-valley complex is but a surface expression of the internal structure and evolution of the underlying fill until about 6000 years B.P. The sinuous channel on the seafloor represents the latest phase of the evolution of much wider, underlying subsurface valley fills in the upper Bengal Fan (Figs. 1B, 2A, B).

Cores taken in all four traverses from the floor of the channel thalweg (from north to south, cores 375, 376, 381, 265, and 259) commonly have relatively coarse, thick (several tens of centimeters to a meter or more thick) turbidite beds as well as some thin laminae (Fig. 5; Reliance Industries Ltd. Report). Cores from terraces and overbanks on either side of the recent channel (from north to south, cores 379, 380, and 382; 385, 266, and 264; and 257, 258, 260, and 261) consist of thinner coarse-grained beds than in the channel-floor cores. Cores from the outermost overbank (core 264) or from the back sides of the outermost levees (cores 379, 257) have mostly muds (Fig. 5). As will be shown later, overbank spilling of turbidity currents from the recent highly sinuous channel did not significantly extend beyond the limits of the innermost overbanks closest to the channel. Generally, the relatively coarse-grained sediments in the cores are actually fine-grained sands and coarse silts, composed of quartz, feldspar, and mica as well as shell fragments. The very top of each core consists of oxidized brownish-colored mud and is probably indicative of the nature of the present water-sediment interface.

The coarse-grained beds in the cores suggest turbidity-current activity during their deposition. However, the intervals of fine oxidized mud at the core tops suggest that turbidity-current activity has ceased at present. The study by Weber et al. (1997), on the sediments from the innermost overbank of the recent middle-fan channel, which is the downdip extension of our upper-fan sinuous channel, concluded that turbidity-current activity capable of producing overbanks lasted until about 6000 years BP. They inferred from this that the canyon became disconnected from the river confluence at this time. However, the study by Kuehl et al. (1997) on the shelf off the Ganges-Brahmaputra Delta mouth extending to the head of the canyon, the Swatch of No Ground, and investigations by Kottke et al. (2003) and Michels et al. (2003) in the same upper canyon as far...
Fig. 2.—A) A magnified portion of multibeam map, with the present sinuous channel C and flanking terraces RT, LT1, LT2, and LT3 and seismic line A–A' (Fig. 2B) location shown. B) 3D seismic line A–A' (location in Figs. 1B and 2A) showing sectionally the present sinuous channel C and flanking RT, LT1 LT2, and LT3 terraces and subsurface valley fills. Vertical scale bar on this and other figures with seismic sections is 100 ms two-way travel time, equivalent to 85 meters.
Fig. 3.—Channel depth from sea surface, measured at every 10 km straight segment starting at the origin updip.

Fig. 4.—Sinuosity at 10 km, 20 km, and 30 km straight segments versus distance.
as 600 m water depth, suggest that sediments are being actively transported by turbidity currents down to these depths. However, interval of the oxidized mud in our core tops shows that no turbidity-current activity is presently occurring in the upper fan channel downdip of the canyon. These interpretations do not rule out the possibility that there may have been some sediment transport into the upper fan channel and beyond into deep waters by turbidity flows for some time after 6000 years B.P., but without the ability of overbank spilling.

Internal Structure and Evolution

Upper Stratigraphic Bengal Fan Valley Complex.—

The main fan-valley complex appears to consist of several valley-scale fills, kilometers-wide and hundreds of milliseconds thick. Because the upper stratigraphic valley complex just below the present channel preserves the original depositional–erosional regime better, we discuss here its internal structure in some detail along two typical transect lines A–A' and B–B' from updip and downdip portions of the 3D seismic grid, respectively (Figs. 1B, 2, 6A, 6B, 7A, 7B, 7C). Looking downstream of the present channel, the terraces (T, levee–overbanks) to the left or to the east are prefixed with “L” and the ones to the right or to the west are prefixed with “R.” Generally the major levee–overbanks and terraces to the right (west) of the channel appear to be higher than those to the left (east), as would be expected in the northern

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Table 1.—Recent channel characteristics—relief and widths.

<table>
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Fig. 5.—Core lithologs from the upper Bengal Fan sinuous channel and flanking overbanks and terraces. From north to south, the cores consist of four traverses: (I) 375 and 376 from channel floor (thalweg); (II) 379, 380, and 382 from terraces (overbanks), and 381 from channel thalweg; (III) 385 from sediment waves, 266 and 264 from terraces (overbanks), and 265 from channel thalweg; (IV) 257, 258, 260, and 261 from terraces (overbanks), and 259 from channel thalweg (modified from Reliance Industries Ltd. internal report, 2009).
Fig. 6 (above and on following page) — A) Seismic section A–A’ with locations of time slices S6, S5, S4, S3, S2, and S1 consecutively from bottom upwards and time slices S6, S5, and S4. Location of line A–A’ is shown in Figs. 1B and 2A, and on the slices. Terraces on the seafloor (T1, T2, etc.) and channels in the subsurface (1, 2, etc.) on either side of the present sinuous channel C are prefixed “R” or “L,” depending on their location to the right (west) or left (east) of it, respectively, looking downstream (see also text). Examples of overbanks flanking the underfit channels (C.O.) and valleys (V.O.) are shown. Vertical scale bar on this and other figures that follow are in milliseconds of two-way travel time. B) Seismic section as in Part A and time slices, S3, S2, and S1 above those in Part A. Labeling of the various features is explained in the text and in the caption for Part A).
Fig. 7 (and on following two pages). — A) A seismic section B–B’ and an enlarged portion of multibeam map with the location of the section shown. Location of slices shown in Figs. 7B and 7C are indicated on the section. Terraces are labeled similarly to those in Figs. 6A and 6B. B) Seismic section B–B’ (location shown in Figs. 1B and Part A) and flattened time slices S5 and S4 from bottom upwards in the section. Labeling of terraces, overbanks, and subsurface channels are as in Fig. 6A and 6B. Terrace RT4 appears covered by terrace RT3 just at the seafloor. Examples of overbanks flanking valleys (V.O.) and underfit channels (C.O.) are shown. C) Seismic section B–B’ and time slices (S3, S2, and S1) above those of Part B in the section. Labeling of the various features is as in Part B.
hemisphere. Similarly to the terraces, the channels (numbered) in the subsurface to the left (east) of the present channel are designated with “L” and the ones to the right (west) with “R”. From the crosscutting relationships both in the seismic sectional-view and plan-view images of time slices (Figs. 6A, 6B, 7A, 7B, 7C), it is apparent that the sinuous channel loops are successively younger from outer limits of both east and west sides of the valley-complex fill towards the present channel C.

Updp: A seismic section and six seismic time slices, 6, 5, 4, 3, 2, 1, from the bottom upwards in the section are shown (Figs. 6A, 6B). To the west of the present channel, there is only one sinuous loop, R1, in the time slices shown here. R1 and L1 appear to be two contemporaneous loops of the same channel. The present channel course is itself a later cutoff from these two sinuous loops and is less sinuous close to the section location.

Each sinuous loop is highly scrolled, especially in the bottom slices (Fig. 6A). This scrolling depends, to a great extent, on where the time slice intersects a channel that in part depends on its depth in the vertical section. The scrolls may consist of high-seismic-amplitude reflections (with bright and strong colors) or may be of low-amplitude reflections (pale colors), and exhibit lateral swings as well as downstream shifts of channel courses. The high-amplitude-reflection scrolls correspond to the lower banks and thalweg floors (channel-floor scrolls, Fig. 6A) of laterally migrated channels. Sectionally, these reflections dip and offlap in the direction of migration. The low-amplitude-reflection scrolls correspond to the upper portions of laterally migrated banks of the channels (bank scrolls, Figs. 6A, 6B). Sectionally, these reflections also dip and offlap, similar to those of the channel floor. The channel and bank-overbank migrations are suggestive of hydrodynamically active turbulent currents in the channels, as discussed by Kolla et al. (2007) and Kneller (2003). The high-amplitude scrolls resulting from channel thalweg and lower-bank migrations are inferred to be sand-prone. However, although the low-amplitude scrolls resulting from channel upper-bank migrations appear to be very similar to the high-amplitude scrolls and are due to the same channel migrations, they are expected to be sand-poor.

In the upper slices (i.e., later stages of channel evolution), the scrolls and downstream shifts, although not as prominent, are still present, indicating some lateral migration at that time also (Fig. 6A, 6B). However, in the upper-interval slices, lateral channel migration has slowed down considerably and channel aggradation has become more significant than in the lower interval. The fill deposited during the aggradational stage appears to be also of somewhat lower seismic amplitudes and are probably not as much sand-prone as the high-amplitude fill deposited in the high-lateral-migration stage. In the initial stages of aggradation, the images in the slices display sharply defined, somewhat narrow channel courses, compared to the final stages of channel fill when the courses are wide and vaguely defined. The sharp aggradational channel courses in the lower fills are inferred to be due to more weakly depositing turbidity currents in the channels, compared to their respective laterally scrolled channel courses below (Kolla et al., 2007). However, the wide, vaguely defined channel courses in the uppermost fills are not due to channelized flows as such but are likely due to overbank fills from turbidity currents flowing through later nearby channels or valleys. Depending upon the overbank seismic reflections in sections being continuous or wedging away from channels or valleys, and their terminations, the turbidity flows are related to the respective features in our interpretations. Also, the overbanks resulting from the overbank flows of channels are relatively thin and small in height, and are similar to those flanking the present channel on the present seafloor (described above), and those resulting from the flows of large valleys are significantly higher and thicker.

The boundaries of some sinuous-channel outer loops (as seen in different seismic slices from the bottom upwards in the section) align along lines (mimicking faults) in seismic sections with the outer limits of terraces on the seafloor. Based on this alignment and on relative channel chronologies, several valley-scale fill sequences, 1, 2, and 3, are distinguished in the upper stratigraphic valley complex (Figs. 6A, 6B). The youngest valley fill, 1, includes L1 and R1 sinuous loops and the latest channel, C. Within this sequence, the extreme outer limits of sinuous channel loops, L1 and R1, are aligned with the outer limits of LT1 and RT terraces, respectively. These terraces are clearly due to overbank spilling from the latest channel, C, onto the abandoned loops of the L1 and R1 fill (Figs. 6A, 6B). The areal extent of these terraces on the seafloor (Fig. 2) appears to be related to (1) the areal distribution of the abandoned sinuous-channel loop (L1 and R1) fill and (2) the extent of overbank fill from the latest channel, C, which is in turn dependent upon the dimensions of valley 1 (Figs. 6A, 6B). The width of this valley at the location of the sectional view (Fig. 6A) is about 4 km. The thalweg widths of sinuous channels L1 and R1 are, however, comparable to those of the present channel, i.e., a few hundred meters (Table 1). Thus, these highly sinuous channels are underfit features within the valley 1. The overbanks flanking valley 1 are higher than those flanking the underfit channels. It is possible, however, that the underfit channels might have modified somewhat the dimensions of valley 1 during their extensive lateral migrations within it.

The eastern boundary of valley 2 is defined by the alignment of the outer loop of channel L3 in different slices with the outer limit of terrace LT2 in the seismic section (Figs. 6A, 6B). However, the original boundary of this valley to the west may have been eroded when valley 1 formed later. The western boundaries of valleys 1 and 2 may thus have coincided. However, to start with, valley 2 was probably wider than valley 1. During the formation of valley 1, some of the valley 2 fill may also have been eroded. Overbank deposition (VO, resulting in continuous reflections on the seismic section) from valley 1 clearly occurred on the abandoned sinuous channel loops L2 and L3 of valley fill 2 and resulted in the formation of terrace LT2 (Figs. 6A, 6B). In the images of upper slices of the subsurface, the sinuous loops of L2 and L3 are wide and are vaguely defined because of this overbank-spilled fill from valley 1. The fill imaged in the slices of this valley is also due to underfit channels as in the fill of valley 1. Cutoffs and high lateral scrolling in the initial stages of underfit-channel evolution and aggradation in the later stages in the valley 2 fill are also similar (Figs. 6A, 6B). At least, another valley, 3, is distinguished by the alignment of the outer limit of sinuous loop L6 in different slices and the outer boundary of the terrace LT3 in the seismic section (Figs. 6A, 6B). Again, due to later erosion during the formation of valleys 2 and 1, the western boundary of valley 3 cannot be distinguished separately from the western boundaries of valleys 2 and 1. Much of valley 3 fill, deposited by underfit, highly scrolled sinuous channels, appears to have been later eroded during the formation of valley 2. The fill of the sinuous loops of L4, L5, and L6 of valley 3 was covered in part during the later stages by overbank-spilled sediments from valley 2, resulting in the formation of terrace LT3. The areal extent of this terrace is dependent upon the distribution of subsurface abandoned sinuous channel fills of L4, L5, and L6, the width of valley 3, and the extent of the cover from the spread of overbank spill of the valley 2 flows. The larger number and widths of the terraces east of the present channel suggest that valleys 3, 2, and 1 consecutively shifted away from that direction toward the west. It is apparent that the overbank flows from the
present channel, C, did not reach significantly beyond terraces LT1 and RT1. Similarly, the overflows from valleys 1 and 2 did not spread significantly beyond terraces LT2 and LT3, respectively (Figs. 6A, 6B).

Down Dip: As in the updip area, in the time slices and section shown for the upper stratigraphic valley complex in the downdip area, sinuous channels to the east of the present channel are designated L1, L2, and L3, and those to the west, R1, R2, R3, and R4 (Figs. 7A, B, C). The terraces on the seafloor in the downdip area are similarly designated LT1, LT2, LT3, and LT4, and RT1, RT2, RT3, and RT4 to the east and west of the present channel, respectively (Figs. 7A, B, C). This nomenclature does not imply the same numbered or labeled channels, and terraces here and in the updip are necessarily continuous. However, the channel dimensions, and the lateral scrolling and apparent cutoffs due to lateral migrations in the initial stages, the aggradation in the later stages of channel evolution, and the corresponding seismic-amplitude characteristics in the downdip area are similar to those in the updip area (Figs. 7B, 7C).

In the downdip area also, it is also possible to distinguish three valleys, 1, 2, 3, in the upper part of the valley complex (Figs. 7B, 7C). Valley 1 is about 7 km wide, and its fill is due to underfit (200 to 400 m wide) sinuous-channel deposits, similar to the up-dip area. The initial much lateral scrolling and the final dominant aggradation of channels, L1, R1, and R2 are best preserved in this youngest valley fill (Figs. 7B, 7C). The present channel (C) is but the latest phase of this valley fill. The overbank fill of this latest channel phase overlying the L1, R1, and R2 channel fill resulted in terraces LT1 and RT1 (Figs. 7A, B, C). The outer limits of sinuous-channel loops L1 and R2 in different slices in the subsurface are aligned with the outer limits of these terraces on the seafloor. The extent of these terraces defines the valley 1 width at its top. The overbank cover from the latest channel did not extend significantly beyond terraces LT1 and RT1. Valley 1 is interpreted to have been formed by the erosion of much of valley fill 2 by larger-volume flows than those responsible for the underfit channels L1, R1, and R2 that later filled the same valley. The still-preserved fill in valley 2 is interpreted to be due to L2 and R3 sinuous channels. The overbank-spill deposits from the flow that created valley 1 accumulated to form terraces LT2 and RT2. The outer limits of sinuous-channel loops L2 and R3 in different slices are aligned with the outer limits of these terraces and define the dimensions of valley 2 that formed subsequent to valley 3. Time slices shown here (Figs. 7B, 7C) do not show all of the sinuous-channel fill of valley 3, except L3 and R4. Again, the overbank spills from the flows that created valley 2 are interpreted to have resulted in terraces LT3 and RT3. Towards the east, the width of valley 3 is defined by the alignment of the outer limit of sinuous-channel loop L3 in different slices with the outer limit of LT3 on the seafloor, and towards the west it is defined by the alignment of the outer limit of sinuous loop R4 with the outer limit of RT3 just below the seafloor (Figs. 7B, 7C). The flows that created valley 3 resulted in terraces LT4 and RT4. Terrace RT4, to the west, was overwhelmed and covered by the overbank flows (RT3) from valley 2 that reached beyond the original bank of valley 3 (Figs. 7B, 7C). However, on the east side, the overbank flows from valley 2 apparently did not reach beyond the bank limits of valley 3 (Figs. 7B, 7C). All of the fill preserved in valleys 2 and 3 was deposited by underfit sinuous-channel flows as in valley 1, unlike the large-volume flows that created the valleys themselves. In both the downdip and updip locations, the successively older valleys, 1, 2, and 3, and their associated overbanks are larger (wider) and higher, respectively. It may seem simple to subdivide the upper valley fill into individual sections and corresponding time-slice images. However, because of the complications of differential cutting and subsequent filling and amalgamation of sequences, it is not practical to map each individual valley sequence separately from updip to downdip.

Channel cutoffs and their timing: Occurrence of cutoffs in the sinuous channels in the Bengal Fan valley has been mentioned above. However, because of multiple episodes of valley erosion and filling, it is not clear, from the examples given above, how common the cutoffs are in the channels in each valley fill. The time slices from the uppermost part of the upper valley complex shown in Figs. 8A and 8B show that during the initial stages of any valley fill when the lateral channel migration (scrolling) and downstream drifts are prevalent, the cutoffs are very common. In the later stages of the fill, however, when channel aggradation becomes dominant, the cutoffs appear to be less common.

Hydrodynamically active turbidity flows during lateral migration and scrolling, and less active, waning depositing flows during aggradation, are the most important factors for frequent cutoffs in the former case and their decreasing frequency in the latter case (Kolla et al., 2007). It is relevant to note that some earlier studies (e.g., Kolla et al., 2001; Posamentier and Kolla, 2003), based on the data available at the time, generalized that cutoffs may not be common in deep-water sinuous channels. The present study shows that this may be true in highly aggrading but not in strongly laterally migrating sinuous channels.

Middle and Lower Stratigraphic Valley Complex.—

Two time slices from typical middle and lower stratigraphic parts of the valley-fill complex show that they consist of networks of many highly scrolled, underfit sinuous-channel loops with high lateral swings as well as downstream shifts of channel courses, as in the upper part of the complex (Figs. 9A, 9B). The middle and lower parts of valley-fill complex can also be subdivided, perhaps into several valley fills.

Most Basal Part of the Valley Complex.—

At the very base of the Bengal Fan valley-fill complex discussed above, a network of slightly sinuous to straight channels with thin fills is present (Figs. 10A, 10B). Within the limitations of our 3D seismic grid, all of these channels in the network appear to have emanated from a single updip valley of about 1.5 km width. This valley is generally the same sediment pathway as that of the overlying main valley complex. Each of the basal channels is flanked by small overbanks (Figs. 10A, 10B), unlike the overlying main valley–channel complex, with large overbanks. This basal channel network developed by a series of avulsions from one updip channel and expanded downdip into a fan-shaped body (Figs. 10A, 10B). In places, channels in this network appear to have only slightly migrated laterally (Figs. 10A, 10B). Updip, this network of channels forms the most basal part of the overlying, wide, main valley-fill complex, amalgamated to it. Some of the channels in the expanding network downdip form part of the basal main valley complex as in the updip, and some are subdivided into several valley fills.
Fig. 8.—A) A seismic section E–E’ and time slices S4, S3, S2, and S1 from the topmost part of upper valley complex showing the common occurrence of channel cutoffs in the lower slice 4 with high lateral channel migration and no rare cutoffs in the upper slices, 3, 2, 1, with much channel aggradation. C is the present channel position. B) A seismic section F–F’ and time slices S3, S2, and S1 from the channel aggradational portion of the topmost part of upper valley complex showing the rarity of cutoffs. C is the present channel. Once channel C reached its position through much lateral migration as in slice 3, it stayed in almost the same place through much aggradation except close to the seafloor with one cutoff (slices 2 and 3).
Fig. 9. — A) A seismic section C–C’ and a flattened time slice from the middle part of the valley complex. The present sinuous channel, C, and examples of underfit channels (C.O.) and valley (V.O.) overbanks are marked on the section. B) A seismic section D–D’ and a flattened time slice from the lower part of the valley complex. The present sinuous channel, C, and examples of overbanks flanking the valleys (V.O.) and underfit channels (C.O.) are noted.
MORPHOLOGY AND INTERNAL STRUCTURE OF A RECENT UPPER BENGAL FAN-VALLEY COMPLEX

Fig. 9 (continued) —
Fig. 10 (and on facing page).—A) A fan-shaped network of channel pattern at the very base of the main valley complex with locations of seismic lines I (updip) and II (downdip) shown here and in Part B, respectively. Two time slices, S2 and S1, marked on seismic line I are also shown. B) Seismic line II (location shown in Part A) and a time slice (location on seismic line II) from the downdip part of the channel network at the base of the main valley complex. Several channels 1, 2, 3, 4, and 5 (Part A) are marked on the time slice, on the seismic line, and on the channel-network map in Part A.
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Fig. 10 (continued) —
areas (Fig. 10A). From this we infer that when the avulsion began from the older fan-valley complex to the present site, the flow volumes were too small to carve out a large valley. This incipient valley created downdip a fanlike body containing several avulsed small channels (Fig. 10A, 10B). Small valley or channel widths, and perhaps short duration of the flows in the channels at this time, were not conducive to widespread lateral channel migration and to evolution of high sinuosity (Kolla et al., 2007). The gradients of the seafloor in the initial stages also may not have been very favorable for development of high sinuosity.

**Summary of the Evolution of the Fan-Valley Complex.**—

When the avulsion from the older eastern fan-valley complex to the site of the present valley complex commenced, only relatively small-volume sediment gravity flows trickled into it and built the most basal part of the present fan-valley complex, as discussed above. The avulsion became fully established during the evolution of the main fan-valley complex overlying the basal channel network, and the flows from the canyon were entirely feeding it during this time. The main valley complex was built through multiple episodes of large-scale valley erosion by large-volume flows and subsequent fill by underfit flows (Figs. 6A, 6B, 7B, 7C, 11), as discussed above for the upper part of the valley-fill complex. These flows were also probably of longer duration, compared to the very initial flows that caused the basal channel network. The morphology of the fan-valley complex on the seafloor is the result of the evolution of this main fan-valley complex. The present channel represents the latest phase of the fan-valley fill, and its characteristics are clearly the consequence of the evolution of the uppermost part of the valley complex, which in turn is dependent on the building of successive underlying valley fills. The present channel is an underfit channel similar to the other underfit channels in the underlying valley fills, and its sinuosity development is also similar, resulting from the initial stage of high lateral migration and the late stage of aggradation.

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**Fig. 11.**—Generalized schematic drawing showing the mode of evolution of a fan-valley complex as proposed in our study. I: A valley flanked by overbanks (VO-I) formed through erosion by large-volume flows. II: The valley becomes infilled by a network of sinuous-channel deposits through underfit flows; these underfit channels migrated laterally in the initial stages and aggraded in the final stages of their evolution; C = channel, CO = channel overbank. III: A second valley, flanked by overbanks (VO-II), formed through erosion of the first valley infill by flows larger in volume than the underfit flows responsible for the infill of the first valley. IV: The second valley is infilled by a network of sinuous-channel deposits through underfit flows, as in the case of the first valley. The overbanks from the second valley abut against the higher banks or overbanks (VO-I) of the first valley and form terraces. The overbanks (CO) from the latest underfit channel of the second valley form the innermost terraces, abutting against the banks or overbanks VO-II. High-amplitude-reflection packages are sand-prone.
Terraces: Several processes have been proposed and discussed in the past to explain the formation of terraces in the submarine valleys. These are: valley incision, slumping, sliding, and faulting, inner levees (overbanks) etc. (see Babonneau et al., 2004, and the references therein). In the Bengal Fan valley complex, the terrace development is clearly due to inner overbank deposition on the abandoned channel fills below. The innermost terraces in the Bengal Fan valley are due to overbank cover from the present channel over the abandoned sinuous-channel fill within valley 1 (C.O., Figs. 6A, 6B, 7B, 7C, 11). However, the outer terraces of the fan-valley complex are the result of overbank deposits (V.O., VO-I, VO-II, Figs. 6A, 6B, 7A, 7B, 7C, 11) from large-volume flows while they carved out the various valleys. The several terraces present on the seafloor on either side of the fan-valley complex at present are largely the result of inner-overbank development during the several episodes in the evolution of the upper stratigraphic fan-valley complex. The overbanks that would have developed into terraces during the formation of lower and middle stratigraphic fan-valley complexes were overwhelmed and covered by the overbank spills from later, larger flows, especially from the flows during the initial stages of development of the upper stratigraphic valley-complex sequence (Figs. 7A, B, C). However, these older overbanks and would-have-been terraces are expressed sometimes as breaks in the gradients on the outermost overbank of the valley complex on the present sea floor towards the west (Figs. 7A, 7B, 7C). To the east of the present valley complex, the overbanks were generally short during the development of older complexes, because of the topographic high of the west overbank of the older fan-valley complex at that time. During the evolution of the upper stratigraphic valley complex, successively lesser-volume flows after the initial, very large-volume flows probably favored the formation of terraces (overbanks) abutting the preceding higher overbanks or banks. These terraces are now exposed on the sea floor.

Increase in the number of terraces and overbanks, and distance between them on one side or the other of the present channel (Figs. 2B, 6A, 6B), are suggestive of the floors of the underlying valleys shifting away from that side. Such shifting of valley floors and associated overbanks from place to place may have resulted in broad curvatures of the entire morphology of the fan-valley complex now observed.

The processes of terrace formation discussed here are similar to the mechanisms proposed by Hübscher et al. (1997) for the Bengal Fan and Babonneau et al. (2004) for the Zaire Fan valleys. Other authors (Deptuck et al., 2003; Posamentier and Kolla, 2003) attributed similar features in inner-overbank formation by underfit channels within wider valleys or channels. However, the 3D seismic data in the present study show many details of the origin of terraces with several episodes of formation of valleys and associated overbanks.

Sylvestre et al. (2010) proposed a geometric model in which incision, migration, and aggradation of a single channel form over time can result in apparently complex channel systems with terraces. These authors argued that the development of such complex systems does not require large temporal variations in flow magnitudes of the types proposed in our study (see also Kolla et al., 2001; Deptuck et al., 2003; Kolla et al., 2007). We believe that this model is applicable to some complexes, but smaller sinuous-channel systems than the one discussed here. This model cannot explain the large differences in the widths of sinuous channels and valleys, and the heights, thicknesses, and extents of their flanking overbanks, and the several vertically stacked valleys and terraces interpreted in our study. However, once formed, the processes of infilling a valley by sinuous-channel network as discussed in our study does include several aspects of the model.

SIGNIFICANCE OF THE MORPHOLOGY, INTERNAL STRUCTURE, AND EVOLUTION OF THE BENGAL FAN VALLEY COMPLEX TO EXPLORATION

High-resolution 3D seismic and multibeam data on the Bengal Fan valley complex have revealed multiple episodes of valley erosion and fill with associated overbanks. The lower part of each valley fill is generally characterized by erosion–deposition through mainly laterally migrated sinuous channels and the upper part by mainly aggrading sinuous channels. As the channels migrate laterally and shift downstream, their banks and overbanks do the same. In seismic time-slice images, the fill from the laterally migrated channel floors and the lower portions of their banks are characterized by scrolls with high seismic amplitudes that are probably sand-prone whereas the fill from the upper portions of the banks are of low seismic amplitude and may be more mud-prone. Thus, not all scrolls would be sand-prone. Portions of the aggrading channel fills have also high-amplitude reflections. However, significant upper portions of the aggrading channel fills also consist of low seismic amplitudes, although short cores (less than 5 meters long, probably below seismic resolution) from palaeoportions of the present channel did recover frequent fine-grained sand and silt beds. Frequent valley erosion and deposition, and amalgamation of valley fills, tended to reduce somewhat the thickness of low-amplitude deposits resulting from the upper parts of banks and overbanks of laterally migrating and aggrading channels, and preserve preferentially the thickness of high-seismic-amplitude deposits resulting from laterally migrating lower banks and floors of channels in the subsurface. Thus, a high-seismic-amplitude, probably sand-prone valley-fill complex, relatively thick and several kilometers wide, resulting from lateral channel migration was created in the Bengal Fan valley complex.

The insights gained from our study may be useful in understanding better the nature, thickness, extent, and architecture of reservoir lithologies in large, exploration valley- (canyon-) sinuous-channel complexes such as those of offshore Congo–Angola, Equatorial Guinea, and the east coast of India (Krishna–Godavari Basin) (e.g., Kolla et al., 2001; Abreu et al., 2003; Bastia, 2004; Mayall et al., 2006; Ardill et al., 2005; Kolla et al., 2007). In these areas, networks of both the laterally migrated and vertically aggraded sinuous-channel reservoirs of varying thicknesses, stacked in valleys and canyons, similar to those in the Bengal fan valley complex, are the exploration and production targets. The processes of development of thick and wide high-seismic-amplitude sand-prone packages, resulting from lateral channel migration in the Bengal Fan valley complex, are applicable in the above exploration areas. This does not imply that the sinuous-channel reservoir architectures in these exploration areas are necessarily identical to those in the Bengal Fan valley fills. Once the differences in the controlling factors of valley and canyon-fill evolution, such as sediment type and volume, bathymetric (gradients, water depths etc.) and structural settings, continuity of the canyon to the river confluence during sea-level changes, and hydrodynamics of channel systems are taken into account, the similarities and differences in the internal architectures in the exploration areas in relation to those in the Bengal Fan valley and their implications for reservoir prediction can be better understood. Our study gives geologic clues as to why high-seismic-amplitude scroll patterns are sand-prone, but not the exactly looking low-amplitude scroll patterns. This is a warning for hastily interpreting scroll patterns as being sand-prone. It is essential to evaluate
whether the scroll patterns are caused by channel banks or channel floors and whether they are of high or low seismic amplitude. In the Bengal Fan valley complex, the aggrading relatively low-seismic-amplitude sinuous-channel fills are interpreted to be less sand-prone than the laterally migrating high-amplitude sinuous-channel fills. The actual sand-proneness of the laterally migrating or aggrading fills depends on the sediment grain size supplied and hydrodynamics of the channel systems. For example, the highly aggrading as well as laterally migrating channel fills of the Krishna–Godavari Basin have high-seismic-amplitude packages with thick medium sand beds (Bastia, 2004). This is probably due to the fact that sediment with coarser grain size was supplied to the Krishna–Godavari Basin compared to that supplied to Bengal Fan valley. However, details observed in our study on the scroll patterns from lateral channel migration and downstream channel shifts, and the accompanying channel-bank and overbank migration, help to unravel, in detail, the architectures and continuities of the sinuous channel reservoir lithologies at the less seismically resolvable exploration target depths in any system.

CONCLUSIONS

1. The morphology of the upper Bengal Fan valley complex is broadly sinuous, exceeding 20 km wide in places, and consists of a highly sinuous channel flanked on both sides by a series of several terraces or overbanks on the seafloor.

2. The fan-valley morphology is a reflection of the evolution of the subsurface underlying multiple vertically stacked but laterally shifting valley fills and their flanking overbanks or terraces.

3. Each of the valleys in the complex consists of fills of underfit sinuous channels with development of scrolling indicative of much lateral channel migration and downstream channel shifts in the initial stages of their evolution. The scrolls may be of high seismic amplitudes, and sand-prone, or of low seismic amplitudes, and mud-prone. In their later stages of evolution, the channels exhibit more aggradation with relatively low-seismic-amplitude fills, especially in their upper parts. The highly sinuous channel on the present sea floor is also an underfit element, similar in dimensions to the ones in the subsurface, and represents the latest phase of the of the uppermost valley fill.

4. Cutoffs are more common in the initial stages of channel evolution and less common in the final stages.

5. The innermost terraces formed due to the overbanks from the highly sinuous channel on the seafloor whereas the outer and higher terraces resulted from the overbanks of larger valleys in the subsurface.

6. Brown muds at the tops of cores from the sinuous channel on the seafloor show that there is little or no turbidity-current activity in it present.

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