Deep Water Depositional Systems—Ultra-Deep Makassar Strait, Indonesia

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Abstract

The ultra deep environment in the Makassar Strait, offshore eastern Kalimantan, Indonesia is characterized by abundant turbidite, debrite, and sediment wave deposits. Key depositional elements imaged by 3-D seismic data include leveed channels, distributary channels/frontal splays, overbank wedges (levees), overbank splays/sediment waves, bottom-current sediment waves, debris flow sheets and debris flow lobes. These elements are systematically deposited within the context of a deep-water depositional sequence in the following order: 1) debris flow sheets/lobes at the base, 2) distributary channels or frontal splays, 3) single, prominent leveed channels, capped by 4) less widespread debris flow sheets or lobes.

Leveed channels of inferred Miocene to Pleistocene age are common in the stratigraphic record of the ultra-deep (i.e., greater than 2000 m water depth) Makassar Strait. These channels are characterized by moderate to high sinuosity and range in width from less than 250 m up to one km, and are associated with overbank wedges approximately one order of magnitude wider. Overbank wedges are characterized by abundant sediment waves. These sediment waves commonly are best developed on outer bends of channel meanders. Sea-floor irregularities have a marked impact on channel pattern as well as stratigraphic architecture. One prominent channel is characterized by a dramatic increase in sinuosity and decrease in channel width just down-system from a toe-thrust ridge across which it flows.

Leveed channels commonly feed as well as overlie distributary channel complexes. Distributary channel complexes can attain widths of greater than 10 km and thicknesses exceeding 80 m. Frontal splays appear to be channelized throughout, nearly to their distal extremities.

Debris flow deposits, in the form of sheets, lobes, and channel fill, are common in the study area. Amalgamated debris flow sheets reach thicknesses up to 150 m and widths greater than 20 km. The base of debris flow sheets are characterized by scour and exhibit deep (up to 30 m) and long (greater than 20 km) parallel grooves that diverge basinward.

Introduction

The recent explosion of widespread 3-D seismic surveys acquired over vast tracts of deep-water environments has led to major advances in the understanding of deep-water depositional systems (e.g., Beaubouef *et al*., 1998; Friedmann and Beaubouef, 1999; O'Byrne *et al*., 1999; Pirmez *et al*., this volume). Deep-water depositional elements can be imaged, mapped, and interpreted through the analysis of time slices, horizon slices, and interval attributes, using a variety of data types ranging from full migration stack to combinations of near and far offsets to coherence volumes. Co-rendering of various seismic attributes can further shed light on the morphology and stratigraphic architecture of such features.

The inherent advantage of 3-D seismic volumes over conventional 2-D seismic profiles rests in the map view displays uniquely afforded by 3-D coverage. Map views potentially provide images that illustrate the "lay of the land," or the paleo-geomorphology. Such images can then be integrated with analysis of strategically located profiles to produce comprehensive geological and stratigraphic models. This blend of seismic geomorphology and seismic stratigraphy constitutes a powerful combination of disciplines resulting in quantum advances in the understanding of depositional systems.

The study area lies offshore eastern Kalimantan, Indonesia, at water depths greater than 2000 m (Fig. 1). The physiographic setting is at the base of the slope and beyond. The western side of the data set covers the most distal toe thrust ridges associated with the prograding continental shelf margin. Much of the area covered can be characterized as a broad, relatively flat surface dipping gently basinward at a slope of 0.6°. The high-quality 3-D seismic volume was acquired by Western-Geco in 1999 with a bin spacing of 12.5 m. The peak frequency in the shallow part of the section is approximately 60 Hz, suggesting a vertical resolution of approximately 3 m. The total area covered was approximately 2100 km^2. For this study, the full migration volume was used exclusively.

The primary focus of this study is a leveed channel with its associated deposits observed just below (c. 100 m) the sea floor. The presentation format we will follow in this report is geared to the depositional elements observed. The depositional element approach to analysis of deep-water systems was pioneered by Normark and Mutti (1991) and affords a way to simplify a relatively complex depositional environment. A variety of deep-water depositional elements have been described using 3-D seismic data in a variety of slope and basin settings. This study focuses on some of these elements, notably 1) leveed channels, 2) overbank wedges with associated overbank splay deposits in the form of sediment waves, 3) frontal splays, taking the form of distributary channel complexes, and 4) debris flow sheets and wedges. We present observations relevant to each of these elements and subsequently interpret within the context of deep-water depositional processes.

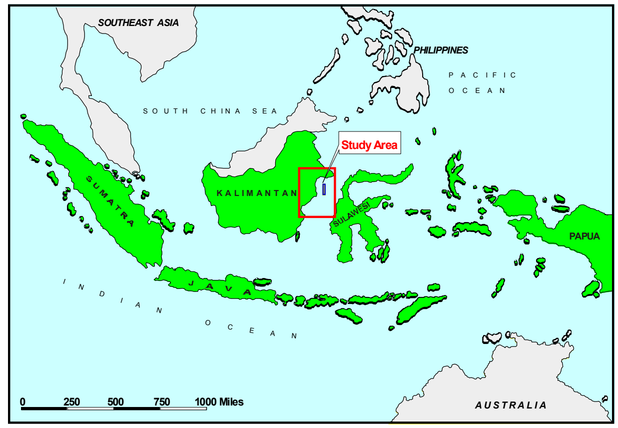

Figure 1. Location map of study area.

Observations

Leveed Channels

Channels with associated levee deposits are observed at many levels within the stratigraphic section. Figure 2 illustrates a channel-levee complex near the sea floor, presumably of Pleistocene age. This channel is notable for the abrupt change of channel pattern that can be observed just basinward of a steep (>7° slope), albeit short, slope. Over a short distance, the channel width decreases from one km to less than 250 m. This change is accompanied by a marked increase in sinuosity.

Seismic profiles across the high-sinuosity section of the channel reveal a pattern of meander growth and channel migration through time (Fig. 3). The channel path tends to migrate toward the outer bend of the meander; there is both a lateral as well as vertical component of channel migration. Vertical aggradation characterizes the later stages of channel axis migration. Horizontal time slices through this channel levee complex reveal a pattern of down-system meander loop migration. This pattern of channel axis migration is remarkably similar to meander patterns that characterize fluvial systems.

Similar high-sinuosity channels can be observed at depth (Fig. 4). These channels average 250 m in width and extend across the study area. Seismic profiles (Fig. 5) suggest the presence of levees flanking these channels.

Overbank Wedges – Levees

The height of the levees bordering the channel diminishes progressively down system. From a height of greater than 50 m proximally, the levee height gradually decreases over a distance of 150 km to heights that cannot be imaged by the seismic data distally. The seismic facies that

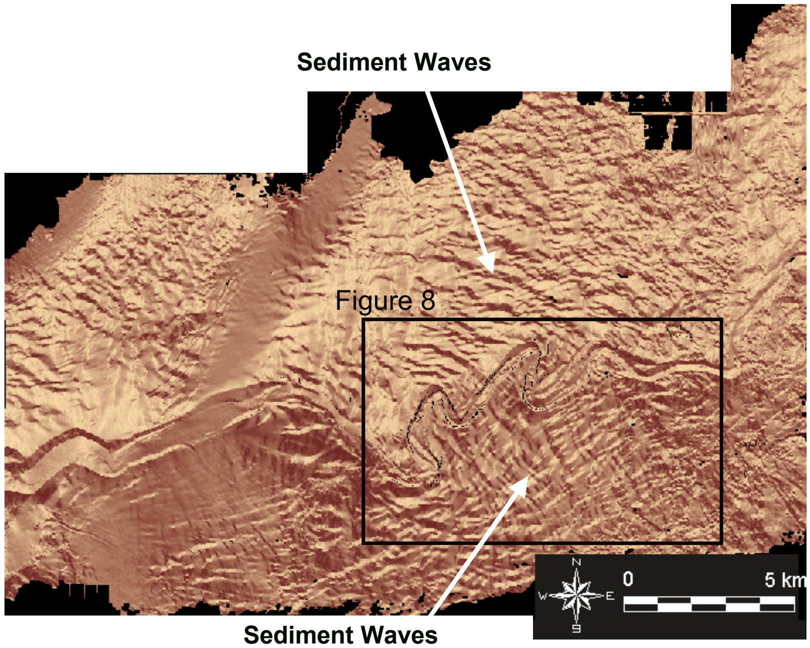

Figure 2. Azimuth map of the upper surface of a Pleistocene deep-water channel levee complex. The overbank surface is characterized by extensive sediment wave development. Note that the long axes of these sediment waves seem oriented normal to the inferred direction of down-system flow.

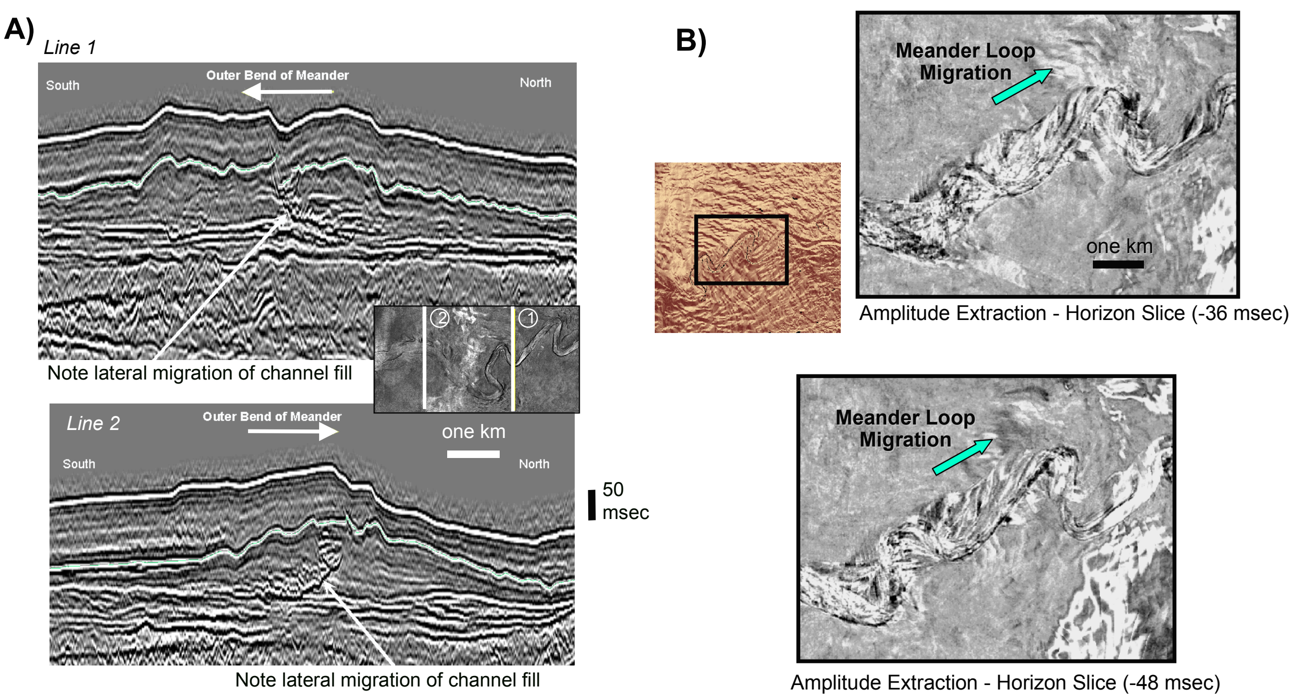

Figure 3. (A) Seismic traverses across leveed channel illustrating channel axis migration. Note the high-amplitude reflections, which suggest the presence of sand, define migration of the channel fill toward the outer bends of associated meanders. The latter stage of channel evolution seems markedly more aggradational. (B) Seismic time slices through the leveed channel clearly indicating a down-system migration of meander loops and associated point bar-like features.

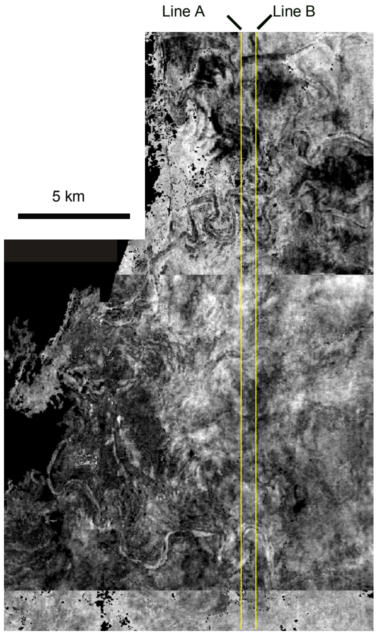

Figure 4. Mosaic of horizon slices and interval attributes illustrating a number of high-sinuosity Mio-Pliocene meandering complexes.

characterizes the overbank wedges can be described as nearly transparent, with predominantly low-amplitude continuous seismic reflections. There are no lateral breaches (i.e., crevasses) of the levee observed along the entire length studied. Abundant linear ridges or sediment waves are observed at the tops of the overbank wedges (Fig. 6). These waves are oriented normal to the direction of inferred overbank flow. Individual waves are up to 2 km long and 20 m high and are distributed in fields with a typical wavelength of c. 200 m.

They are best developed on overbank areas located along outer bends of the meandering channel. The well-developed sediment waves commonly cover areas of 4 km by 4 km.

Figure 7 illustrates two seismic profiles oriented normal to one such sediment wave field. The profile in Figure 7B clearly illustrates the asymmetry of wave development, being better developed in the area on the outer meander bend of the channel. Note the apparent sediment waves that characterized the internal architecture of the overbank wedge.

Two populations of sediment waves can be observed atop the overbank wedges. The two populations appear to be oriented normal to each other (Fig. 8). One set of waves, as described above, appears to be oriented normal to the direction of channel overbank flow, whereas the other appears to bear no relationship with this flow direction. This phenomenon is best developed along the southern overbank wedge.

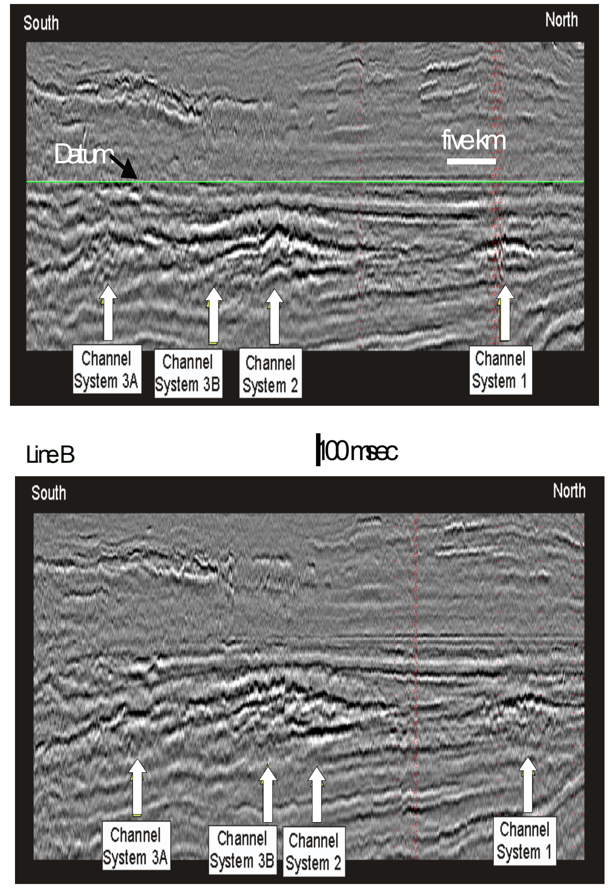

Figure 5. Seismic profiles oriented transverse to the Mio-Pliocene meandering channels shown in Figure 4. Note that these channel complexes seem associated with constructional levees. These channels are not coeval; rather they are progressively younger towards the south.

Frontal Splays – Distributary Channel Complexes

On the eastern side of the study area, approximately where the levee height diminishes to a thickness below seismic resolution (i.e., less than 3 m), the single leveed channel gives way to a broad fan-shaped splay. This is most apparent on the reflection amplitude map of the top of the leveed channel complex (Fig. 9). This feature is characterized by markedly higher reflection amplitude than the adjacent overbank wedge deposits. The thickness of the splay deposits reaches 40 m in places. The edges of the high-amplitude field are characterized by a fringe-like pattern extending out like fingers into adjacent low-amplitude areas. The seismic facies of these deposits are characterized by high-amplitude continuous to discontinuous seismic reflections.

A similar splay complex can be observed underlying the channel levee complex in the central part of the study area.

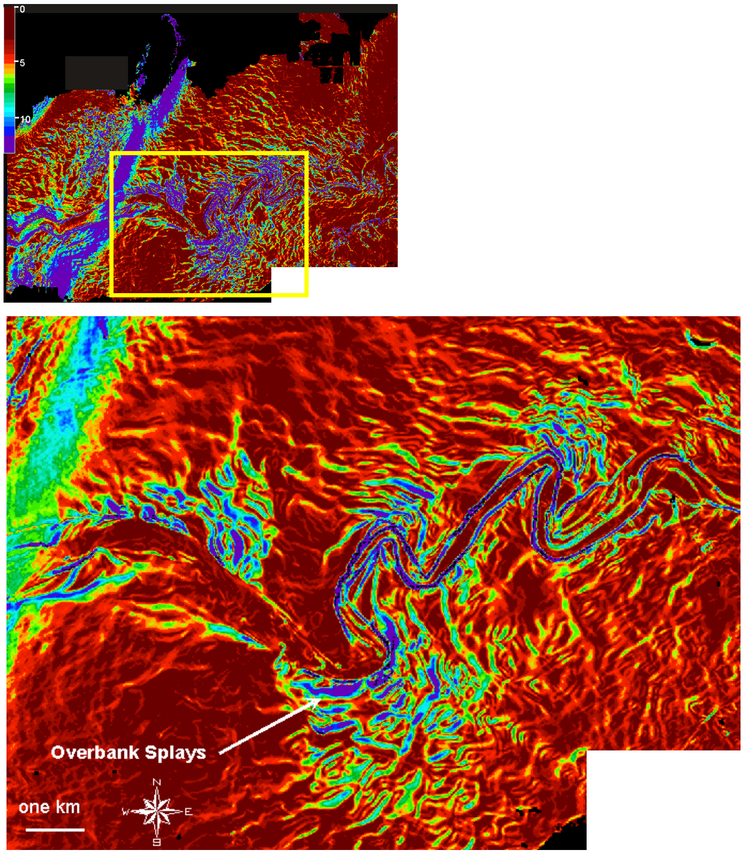

Figure 6. Dip map of the top of leveed channel system shown in Figure 2; the sediment waves are clearly imaged. These waves are best developed on overbank areas closest to outer channel bends.

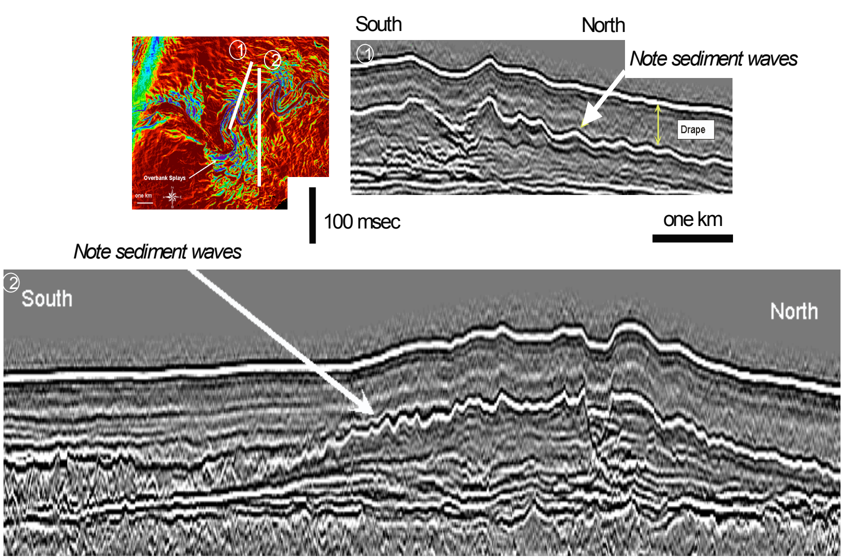

Figure 7. Two seismic profiles illustrating sediment waves. Note that the sediment waves are better developed on overbank areas proximal to outer bends of the meandering channel with minimal development on areas proximal to inner meander bends (compare with Fig. 6). Note also the presence of sediment waves internal to the overbank wedges suggesting that sediment waves are an integral part of levee construction.

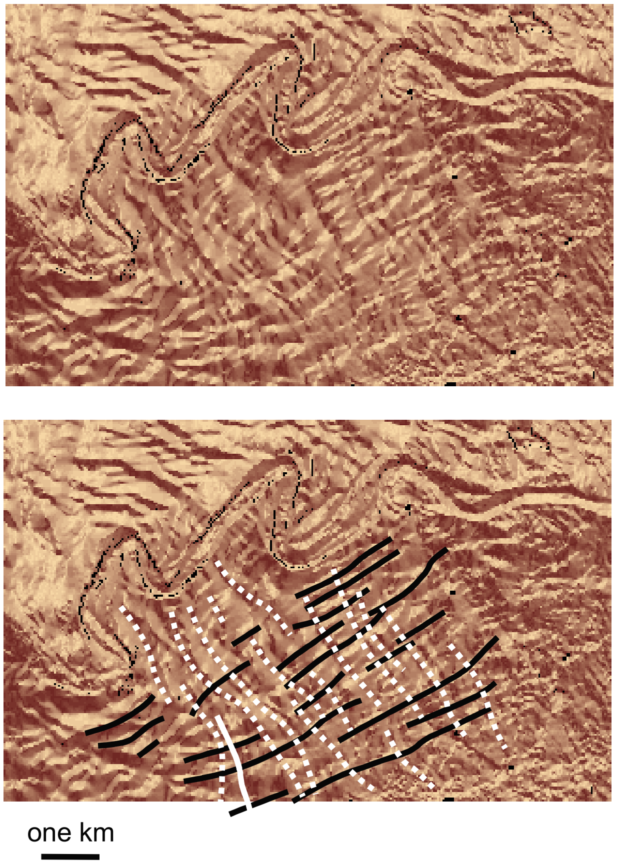

Figure 8. Azimuth map of top of leveed channel system showing two populations of sediment waves oriented normal to each other. Those indicated by solid lines are inferred to be related to overbank turbidity flow, whereas those indicated by dashed lines are inferred to be related to bottom currents. Location of this area is shown on Figure 2.

Inclined time slices through this stratigraphic unit reveal the presence of a distributary channel complex immediately underlying the leveed channel deposits (Fig. 10). The distributary channels are 250 m wide or less with channel bifurcation nodes spaced at approximately 2-5 km. This splay complex is characterized by a high-amplitude continuous to discontinuous seismic reflections, up to 80 m thick.

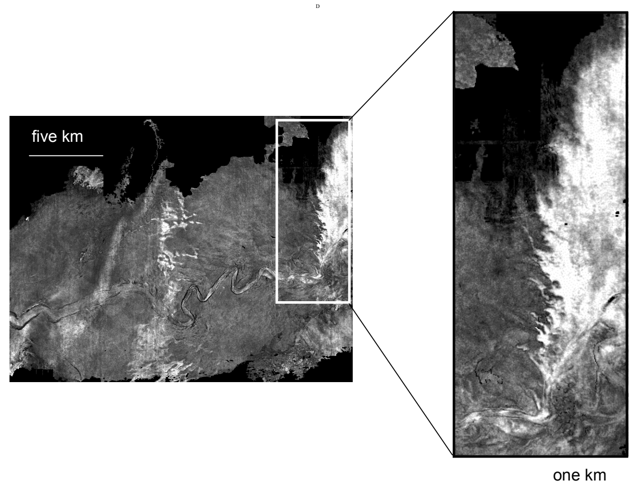

Figure 9. Reflection amplitude map of deep-water channel levee complex. Note the frontal splay in the eastern part of the study area. Note also the apparent channeling characterizing the distal extremities of the splay complex. Whereas no individual channels can be observed within this feature, a pattern of distributary channels is nonetheless inferred to exist here.

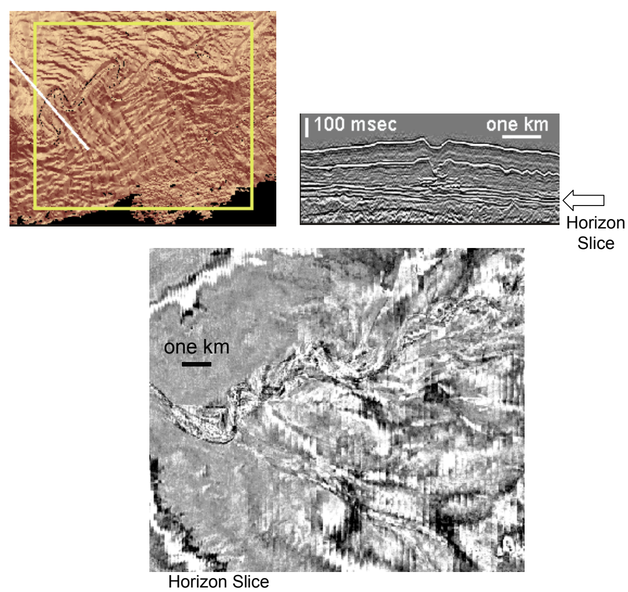

Figure 10. Frontal splay deposits underlying the channel-levee complex. Note the distributary channel pattern of these deposits.

Debris Flow Units

Seismic stratigraphic units characterized by chaotic to transparent seismic facies are common within the near surface section of the study area (Fig. 11). These units range in thickness up to 150 m, though the average is closer to 75 m. Spatially, these units take the form of widespread sheets, narrower tongues, and still narrower channel fills. In each instance they overlie a pavement characterized by prominent grooves and striations which completely blanket these basal surfaces (Fig. 12). Grooves up to 30 m deep, one km wide, and 20 km long have been observed.

Figure 13 illustrates a debris flow unit confined to a channel. The channel is characterized by low sinuosity and the channel floor is characterized by a parallel to divergent groove pattern. Divergence of grooves is a common aspect of these basal pavements

Discussion

Deep-water depositional sequences

The deep-water deposits observed in this area seem to be characterized by a vertical succession consisting of an extensive debris flow deposits at the base, overlain by frontal splay deposits, channel-levee deposits, and ultimately capped in places by less extensive debris flow deposits. This succession within a single depositional sequence could be related to cycles of sea-level change (Fig. 14). As relative sea level falls, the progressive removal of up to 125 m of water can lead to outer shelf and slope instability bescause of increased pore pressure due to hydrate disassociation (Paull *et al*., 1991; Haq, 1993; Posamentier and Allen, 1999). Such instability would give rise to slope failure and debris flow delivery of sediment to the lower slope and basin floor. With continued sea-level fall, forced regression on the shelf (Posamentier *et al*., 1992) can facilitate migration of the depocenter to the shelf edge. At that point sediments from the hinterlands can be delivered via mass flow either directly to the deep water by way of hyperpycnal flow, or indirectly by way of deposition at the shelf edge and subsequent remobilization by slope failure.

Subsequently, when sea level stabilizes at a lowstand position and then slowly rises, previous bypass conduits such as incised valleys and canyons become sites of sedimentation. This process results in a reduction of sand to mud ratio delivered to the shelf edge. Consequently, the sediment delivered to deep-water environments outboard of the shelf-slope break are depleted of sand, tending to lead to the construction of leveed channels rather than the more sand rich frontal splays. Ultimately, when sea-level rise results in shelf inundation, the sediment supply from the hinterlands no longer reaches the staging area at the shelf edge. During this final sea-level rise, pore pressure equilibrium conditions are again disrupted by loading the outer shelf and upper slope with a layer of water up to 125 m thick and slope instability can again be induced. This instability can lead to reactivation of debris flow processes, capping the sequence succession.

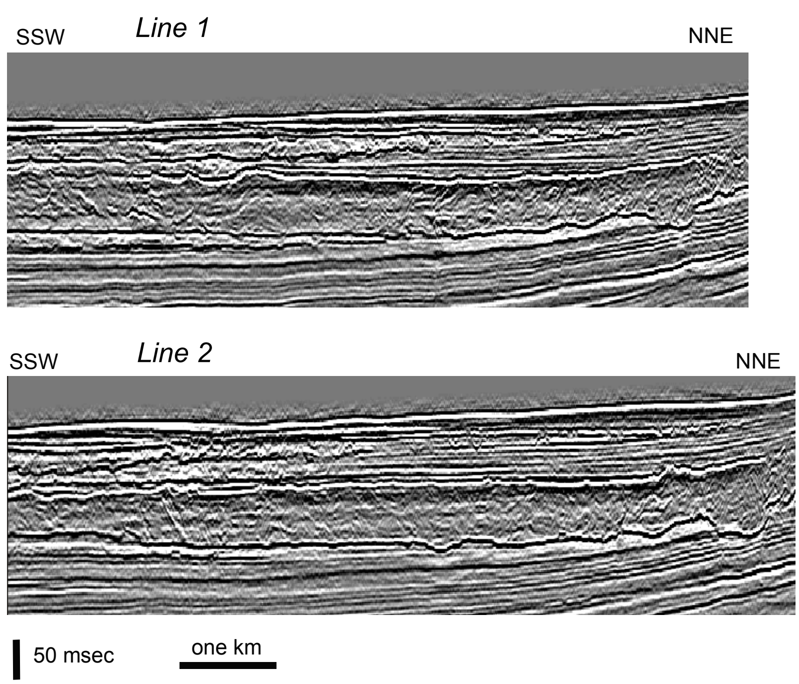

Figure 11. Seismic traverses across a widespread debris flow sheet. These deposits are characterized seismically by chaotic to transparent seismic reflections. Marked erosion characterizes the base of these deposits (see Fig. 12 for location of these profiles).

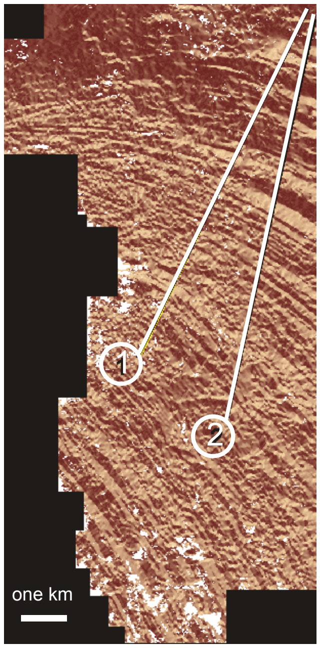

Figure 12. Azimuth map of the reflection at the base of the debris flow sheet shown in Figure 11. Note the markedly grooved and striated pavement across which the debris flow has apparently traveled. One such groove measures c. 30 m deep, one km wide, and 20 km long.

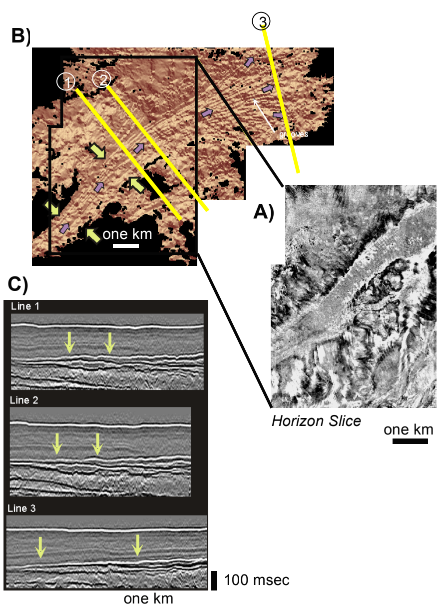

Figure 13. (A) Seismic time slice across a debris flow channel. Note the low sinuosity that characterizes this feature. (B) Azimuth map on the reflection at the base of this debris flow. Note again the markedly grooved and striated nature of this surface. Note also the tendency towards divergence of these grooves down-system. (C) A succession of seismic traverses across the debris flow channel.

Leveed Channels and Frontal Splays

The channel-levee complex described above is characterized by a channel one km wide with low sinuosity abruptly changing to a channel less than 250 m wide with high sinuosity. This marked change in channel pattern, observed immediately down system of a short steep slope, can be partially explained by analogy with fluvial systems. As Schumm (1993) observed, fluvial channels can adjust for steepened gradients either by lengthening their courses through increased sinuosity, thereby effectively lessening the flow gradient, or by accelerating their flow and incising into the substrate so as to re-establish an equilibrium or graded profile or both. The leveed channel observed here seems to respond to the steeper gradient and accelerated flow by increasing sinuosity and deepening of the channel (relative to its width). Both constitute responses to accelerated flow velocity.

Seismic horizon slices clearly illustrate the process of channel meander evolution. Figure 4 suggests a downdip migration of meander loops through time. Likewise, seismic profiles across the leveed channel illustrate meander migration toward the outer bends of the meandering channel. This meander evolution is associated with development of features that have some similarity to fluvial point bars. These features are characterized by lateral accretion, which, similar to fluvial point bars, results in expansion and down drift migration of meander loops. In contrast with fluvial point bars, however, little vertical aggradation in the core of the meander loop occurs. The sand prone extent of the channel fill is inferred to be associated with high-amplitude discontinuous reflections, which are observed within the channel axis.

The levees on either side of the channel are progressively lower in a down system direction. At the point near to where the levees approach the limits of seismic resolution, the single leveed channel gives way to a frontal splay complex (Fig. 9). The reflection amplitude associated with the frontal splay is equivalent to the reflection amplitude of the leveed channel fill, suggesting a similar sand-rich lithology. No channel details can be observed within the frontal splay, but the fringe-like margin of this feature suggests the presence of channels all the way to the fingertips of the frontal splay. This, in turn, suggests that the splay itself comprises a complex of distributary channels that are below seismic resolution; i.e., less than 3 m deep. A similar splay complex is observed underlying the leveed channel (Fig. 10), although in this instance a distributary channel pattern is clearly evident. Frontal splays likely consist of widespread shallow channel deposits characterized by amalgamated sheet-like turbidites.

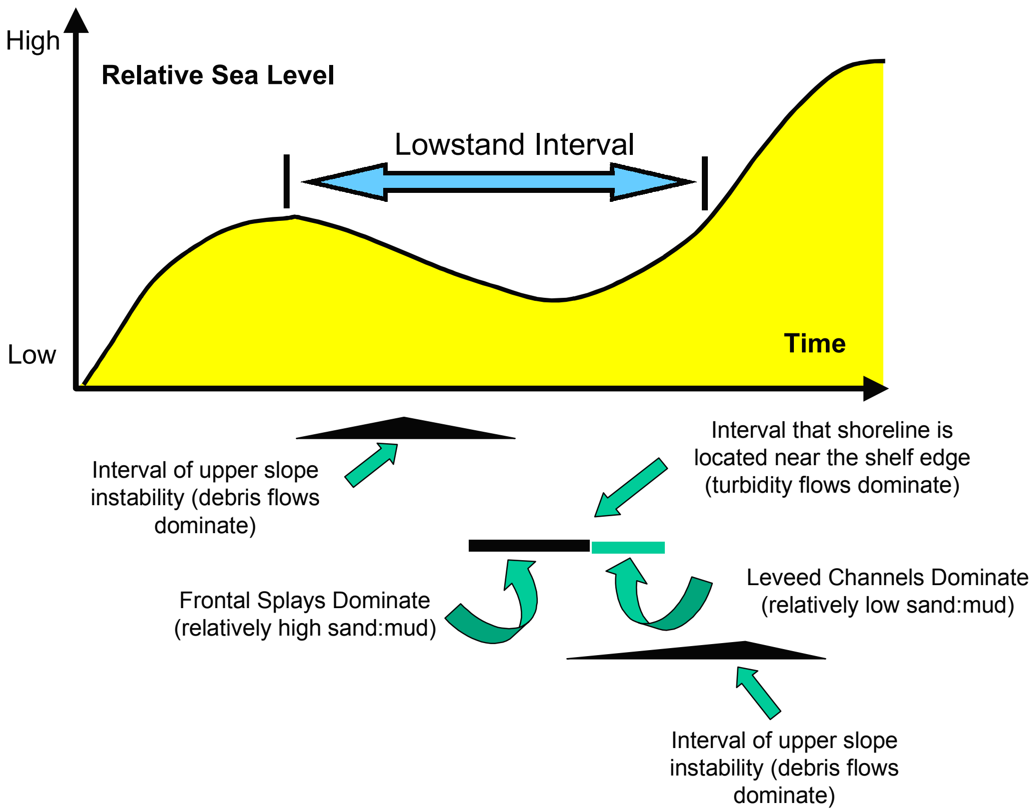

Figure 14. Schematic showing the relationship between relative sea level and type of dominant mass flow process. At the onset of relative sea-level fall, outer shelf and upper slope instability is induced by stripping off up to 100 m of water. This instability leads to the dominance of the debris flow process at this time. When the depocenter reaches the shelf edge later in the sea-level cycle, sand prone sediments are delivered to the deep water either directly from the hinterlands by hyperpycnal flows associated with river flow, or by deposition and remobilization of shelf edge deposits by mass flow, dominated by turbidity currents. These relatively sand-prone flows favor development of frontal splays characterized by distributary channel complexes. When sea level rises, flows are characterized by a decreased sand:mud ratio, favoring the formation of leveed channels. Finally, after the depocenter migrates back to the middle to inner shelf, outer shelf and upper slope instability associated with the loading of the shelf by upwards of 100 m of water again leads to the dominance of the debris flow process at this time.

Overbank Splays and Sediment Waves

Overbank areas on either side of the leveed channel are characterized by the presence of abundant ridge-form features inferred to be sediment waves. These deposits are oriented normal to the inferred direction of overbank flow. The sediment waves are best developed on overbank areas adjacent to outer meander bends (Fig. 6). Presumably this is caused by stripping of the upper parts of turbidity flows as the flow encounters a bend in the channel. The lower, higher-density component of the flow remains confined by the levee walls, but the higher, lower-density component of the flow escapes the confines of the channel to be deposited as waves atop the overbank. These overbank splay deposits likely comprise thin-bedded, low-density turbidites. The presence of sediment waves within the overbank wedges suggests that sediment wave formation is an integral part of the construction of the levee. Clusters of prominent sediment waves up to 4 km by 4 km in area are observed at each meander bend.

Figure 8 illustrates two populations of sediment waves oriented normal to each other. The waves indicated by solid lines are interpreted to be related to overbank turbidity flows, based on the orientation of their long axes normal to the inferred direction of overbank flow. In contrast, the waves indicated by dashed lines seem to be unrelated to turbidity currents but rather are inferred to be related to ambient bottom currents. These types of flow are, in a sense, competing with each other. The overbank turbidity flows presumably occur sporadically, whereas the ambient bottom currents likely occur on a more regular basis.

Debris Flow Deposits

Debris flow deposits are extensive with individual units covering areas greater than 30 km wide, approaching thicknesses of 150 m. The grooved nature of the basal pavements is consistent with a laminar flow process that characterizes debris flow units and is therefore diagnostic of the presence debris flow mass flow deposits. The grooves are inferred to be associated with clasts imbedded within the base of the debris flow. The striated and grooved pavement is akin to a striated bedrock pavement that develops at the base of glaciers. The divergent pattern of these grooves suggests a lateral spreading, perhaps as a "flattening out" of the flow down-system. Such divergence can be observed even at the base of debris flow channels. The debris flow channel (Fig. 13) would likely have been indistinguishable from a turbidity flow channel were it not for the divergent grooved pavement upon which it lies.

Conclusions

3-D seismic data over the ultra deep environment offshore Kalimantan, Indonesia, reveal well-imaged deep-water turbidite and debrite depositional elements. Turbidite depositional elements include leveed channels, overbank splays, and frontal splays. Debrite depositional elements include debris flow sheets, lobes and channel fills. Depositional sequences seem to comprise a stratigraphic succession of extensive debris flow deposits, overlain by frontal splay deposits, leveed channel complexes, and ultimately capped by less extensive debris flow deposits. This succession is inferred to be associated with cycles of sea-level change.

Leveed channels range in width from 250 m up to one km. Both low sinuosity as well as high sinuosity leveed channels are observed. Seismic profiles as well as horizon slices and time slices clearly reveal a pattern of meander loop growth and migration down system. Levee tops are characterized by extensive development of sediment waves. Such sediment waves are best developed in overbank areas just outboard of the outer bends of the leveed channels. Such areas would be the prime location for the process of flow stripping. Overbank wedges are seismically characterized by low amplitude nearly transparent reflection packages. Sand-prone channel fills are characterized by high-amplitude discontinuous to continuous seismic reflections.

Leveed channels both overlie as well as feed frontal splays. Frontal splays appear to be channelized all the way to their distal extremities and likely consist of a network of distributary channels. Leveed channels transition to frontal splays down-system where levee height has decreased to a critical elevation no longer capable of efficiently containing the high-density portion of successive turbidity flows. Frontal splays are characterized seismically by high amplitude continuous to discontinuous reflections.

Debris flow deposits take the form of sheets, lobes, and channel fills. They are characterized seismically by chaotic to transparent reflection packages. The surfaces upon which debris flow units lie are distinctively grooved and striated. Commonly, these grooves are straight, tending to diverge in a basinward direction.

Acknowledgments

The authors thank Schlumberger-Geoquest for permission to publish the data upon which this report is based. We also thank ARCO Indonesia as well as Veritas Exploration Services for permission to publish this report. This paper benefited significantly from an insightful review by C. Pirmez. Finally, the authors wish to express their appreciation to Paul Weimer for the patience he has shown us during the preparation and submission of this paper.

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