Lowstand alluvial bypass systems: Incised vs. unincised

Henry W. Posamentier

ABSTRACT

Alluvial systems ranging in age from Miocene to late Pleistocene are observed beneath the southern Java Sea Shelf, offshore northwest Java. A combination of seismic reflection attributes, time slices, and horizon slices extracted from three-dimensional seismic volumes have enabled identification of these alluvial systems. The plan-view expression of these systems ranges from low sinuosity to high sinuosity, and incised to unincised. Widths of individual channels range from 100 to 250 m. Meander belt widths range from 2 to 6 km. In some instances, well-developed minor tributary feeder systems can be observed to be associated with major trunk valleys.

Late Pleistocene alluvial systems imaged on the shelf were active during periods of lowered sea level when vast shelf areas were emergent. Of these systems only a select few are characterized by incision. Incision is inferred where trunk channels of fluvial systems are associated with minor, orthogonal, deeply etched tributary channels/valleys. The incised trunk valleys range from 0.5 to 5 km wide and contain channels within them; the incised tributary valleys are an order of magnitude narrower and are characterized by well-developed dendritic drainage patterns. Valley incision, which likely formed within a period of 3–5 k.y., can be traced more than 200 km inboard of the shelf edge.

The presence of numerous unincised alluvial systems on marine shelves of the southern Java Sea suggests that valley incision likely characterizes only the lowest of lowstands. To the extent that the Pleistocene can be used as an analog to older sections, we conclude that unincised lowstand alluvial bypass systems can constitute a more common response to sea level lowering than do incised systems.

INTRODUCTION

An incised valley is said to exist where a river has cut into its flood plain sufficiently so that even when it is at flood stage, flow does not overtop the riverbanks. This leaves the formerly active flood plains abandoned and serving as interfluves. Much has been written

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about incised valley systems (e.g., Shanley and McCabe, 1994; Dalrymple et al., 1994), especially since the popularization of sequence stratigraphic concepts (Posamentier and Vail, 1988). Incised valley systems are most commonly thought to have characterized extensive shelf settings each time a relative sea level fall has occurred (Posamentier and Vail, 1988; Van Wagoner et al., 1990). Incised valleys have been described in all types of physiographic settings ranging from active to passive continental margins as well as interior continental basins (e.g., Dalrymple et al., 1994). A wide range of incised valley dimensions has been documented. Extreme incised valley depths of up to several thousand feet have been described on the margins of basins that have been nearly completely drained by massive sea level fall. Such a situation has been described on the margins of the Mediterranean Sea during the Miocene Messinian event (Montadert et al., 1977). Extreme widths of tens of kilometers have also been described (e.g., Van Wagoner, 1995).

The hallmark of an incised valley, and possibly the least equivocal diagnostic attribute, is the presence of numerous smaller tributary valleys that develop on the abandoned flood plain, now interfluve, feeding the trunk valley. These tributary valleys form in response to drainage of the flood plain and are characterized by longitudinal profiles anchored or adjusted to the level of the channel within the trunk incised valley. The length and breadth of these tributary valleys depend upon the length of time over which this system evolves, as well as on the erodibility of the substrate and the amount of fluvial discharge.

Incised valley systems can be filled with a complex array of depositional systems ranging from open marine to estuarine to fluvial (Zaitlin et al., 1994). Incised valleys can be the sites of numerous stratigraphic discontinuities that punctuate the stratigraphic architecture (Pattison, 1991). These include tidal ravinement surfaces, base of channel local erosional surfaces, and valley within valley widespread erosional surfaces. Incised valleys are not uncommonly the sites of multiple incision events associated with successive sea level falls (Donovan, 1995).

Little consideration has been given to situations where sea level fall has not resulted in fluvial incision; however, only under certain circumstances does sea level fall result in fluvial incision as defined previously. In the following discussion, examples of both incised and unincised lowstand fluvial systems are illustrated, and possible scenarios for the development of each are addressed. In either case, where basin margins are characterized by sea level fall, the bulk of fluvially transported sediment bypasses the coastal plain and alluvial plain, either through incised valleys or through unincised channels superimposed on the old sea floor. Consequently, in either instance, lowstand alluvial bypass systems exist.

This article focuses on Pleistocene and Miocene alluvial systems imaged on three-dimensional (3-D) seismic volumes offshore northwest Java (Figure 1). These systems are imaged using time slices and horizon slices as appropriate. In some instances the alluvial systems are incised, whereas in others they are unincised. A case is made that both types of systems can develop in response to sea level fall.

CAUSES OF VALLEY INCISION

Incised valley formation can occur in at least three principal ways: (1) as a result of sea level or base-level fall, (2) as a result of tectonic tilting of alluvial settings, or (3) as a result of significant decrease in fluvial discharge resulting in formation of underfit streams. In general, each of these processes results in a physiography characterized by channels located within valleys cut into formerly active flood plains, though there can exist subtle differences between systems attributed to each cause. Note also that these processes are not necessarily mutually exclusive. That is, more than one of these factors can be involved at any given time in the formation of incised valleys.

Sea Level Fall

Sea level fall can cause valley incision if during sea level fall a land surface is exposed that is characterized by a significantly steeper gradient than that of the associated alluvial plain (Posamentier et al., 1992; Leeder and Stewart, 1996; Posamentier and Allen, 1999). Helland-Hansen and Gjelberg (1994) suggest that if shoreline trajectories migrate across surfaces steeper than the associated alluvial profile, valley incision occurs. Where shoreline trajectories migrate across surfaces with the same or lower gradient as the alluvial plain, then valley incision does not occur. Consequently, the difference in gradient between the alluvial plain and the adjacent shelf is critical in determining whether a river will respond to sea level fall by forming an incised valley across the shelf or simply flowing across the old sea floor. In either instance, a "lowstand" alluvial system forms. In both instances, most of the

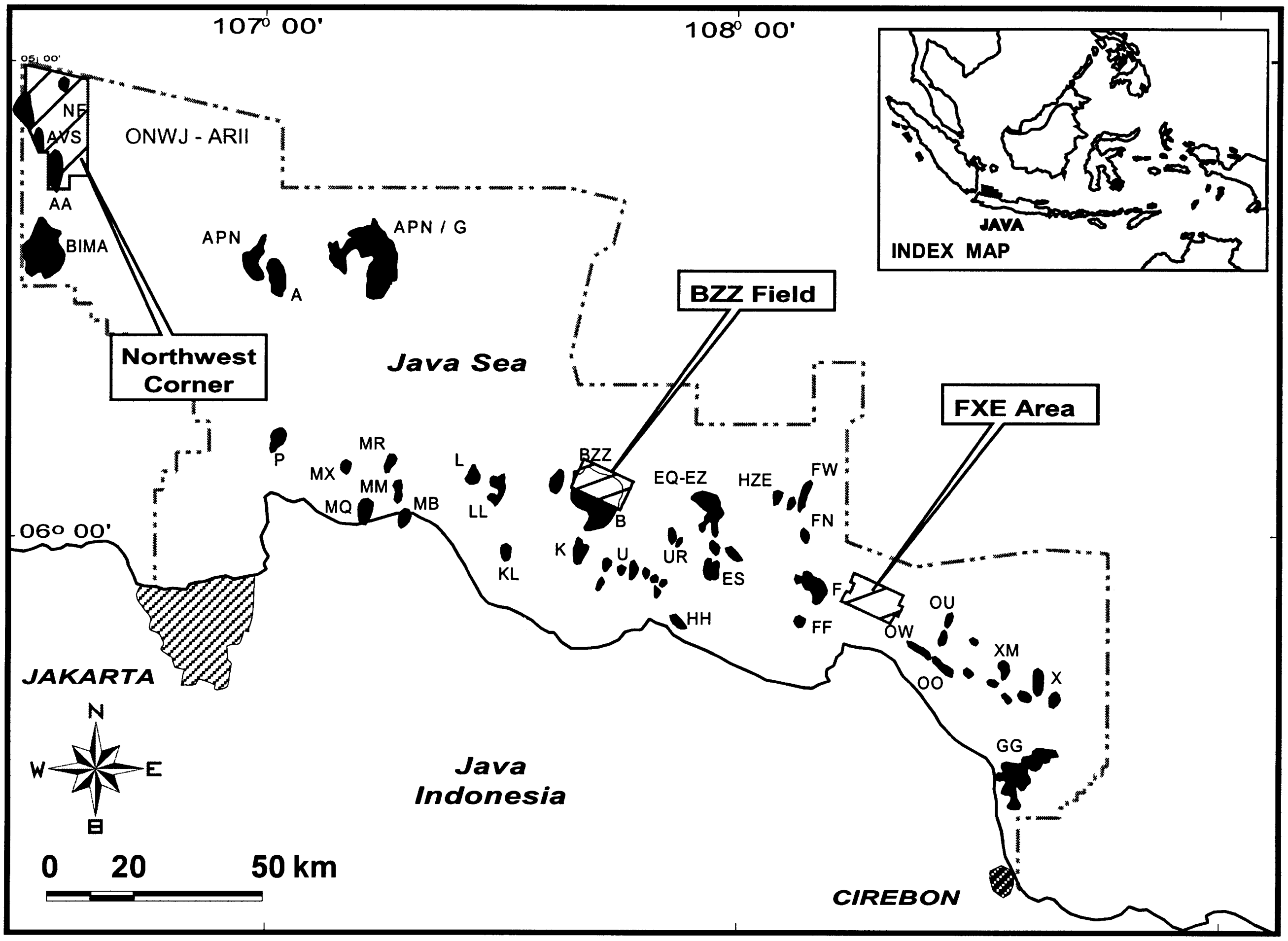


Figure 1. Base map showing study areas offshore northwest Java: Northwest Corner area, BZZ field, and FXE area. The dashed line demarcates the ARCO Indonesia Product Sharing Contract area. Dark-shaded areas offshore indicate oil and/or gas fields, each designated by a letter or letters.

sediment load carried by these systems bypasses the shelf. The only sediments deposited are in the form of fluvial sediments of the associated point bars and flood plains. No significant alluvial aggradation characterizes this period of sea level fall.

Valley incision occurring in response to sea level fall is initiated at river mouths. Downcutting begins there and propagates upstream in the form of knickpoint migration. The extent of upstream migration is primarily a function of the magnitude of sea level fall, duration of the period of sea level fall, erodibility of the substrate, and fluvial discharge. The greater any of these parameters, the greater the extent of upstream migration. Leeder and Stewart (1996) point out that the upstream extension of valley incision also can be limited by avulsion events upstream of the knickpoint, diverting flow away from the valley and across an interfluve. This causes a new knickpoint to form where the mouth of this now-avulsed river reaches the shoreline, and consequently a new incised valley begins to form. The original incised valley would effectively be abandoned in favor of the new incised valley.

Tectonic Tilting and Uplift

Tectonic tilting or uplift can cause accelerated stream flow and consequent erosion and incision. Where alluvial plains are uplifted and tilted at a rate slower than the rate at which associated river systems cut down in response, river entrenchment occurs. In contrast with sea level–induced incision, entrenchment is a type of incision that occurs simultaneously across the entire area where slopes have been increased. Under such circumstances knickpoint migration does not accompany incision. Consequently, incised valleys can characterize extensive areas that are commensurate in size with the area that is uplifted.

Incision because of tilting is most common in tectonically active areas such as rift basins, foreland basins, and leading margins of continents. In certain circumstances, tectonic uplift can sporadically induce incision, punctuating overall basin subsidence. This process could account for some of the long-distance incised valleys that have been observed, including the incised systems of the Albian Muddy and Pennsylvanian Morrow formations of the United States midcontinent. Each system has been documented (Krystinik and Blakeney, 1990; Dolson et al., 1991) as incising into the underlying sea floor and extending tens to hundreds of kilometers upstream. Each is also associated with significant hiatuses at its base (Krystinik and Blakeney, 1990; Dolson et al., 1991).

Underfit Streams

Large fluvial systems characterized by high discharge commonly are characterized by large channels. Where discharge diminishes because of climate change, stream piracy, or some other factor, smaller channels occupy the once-larger channel in an underfit relationship. If the discharge associated with the now smaller channels is insufficient even at flood stage to overtop the banks of the former channel, then an underfit channel is said to exist. Examples of such systems are common at the present time in areas associated with Pleistocene glacial drainage systems. During periods of deglaciation, glacial meltwater systems commonly were characterized by fluvial discharge that were in some instances orders of magnitude greater than at present. These Pleistocene channels today are occupied by fluvial systems that can be markedly underfit. Blum (1990, 1993) and Blum and Valastro (1989) documented alternating periods of aggradation and incision for the Colorado River of Texas during the late Pleistocene and Holocene occurring in response to climatic change and associated changes of vegetative cover.

Where an underfit channel occupies a larger channel, the larger channel becomes a valley that has the characteristics of incision as described previously (i.e., tributary incised valleys develop). These systems, like those that develop in response to tectonic tilting, develop the attributes of incision over their whole length simultaneously and therefore can be described as entrenched. The degree of entrenchment or incision diminishes downsystem, approaching zero incision at the point where the system reaches its end (i.e., the mouth of the river).

EXAMPLES OF SHELF ALLUVIAL SYSTEMS

Incised valleys have been the subject of numerous studies in recent years (Dalrymple et al., 1994). Such systems have been thought to be the most common response to sea level fall (Posamentier and Vail, 1988; Van Wagoner et al., 1990). Studies of incised valleys largely have been based on outcrop, well-log, and core data. Incised valley recognition has been based largely on the presence of multistory channel fill, the presence of a significant time break at the channel base, or the absence of a transitional facies between the channel/valley fill and the underlying substrate. Arguably, however, the most unequivocal evidence for the existence of incised valleys, the presence of small subordinate tributary valleys to the principal trunk valley (Posamentier, 1998; Posamentier and Allen, 1999), has not been commonly used. Unfortunately, the presence of coeval incised tributary valleys cannot commonly be recognized because of the discontinuous nature of most forms of data other than 3-D seismic data.

Lowstand unincised alluvial bypass systems, in contrast with incised valleys, have not been well documented. This is likely because (1) they are difficult to distinguish from highstand alluvial systems and (2) in mid- to outer-shelf environments, a niche commonly occupied by lowstand depositional elements, their presence has not been anticipated, so unincised alluvial systems consequently are mistaken for incised valleys. The following examples illustrate both incised and unincised systems and rely strongly on the interpretation of 3-D seismic data. The type of incised valleys presented here are those thought to be associated with sea level change rather than misfit streams or tectonic tilting.

Pleistocene Section of Offshore Java

Observations: Seismic

The Pleistocene section offshore northwestern Java is characterized by a variety of alluvial systems that are clearly imaged on 3-D seismic data. These alluvial systems range from high-sinuosity to low-sinuosity to braided channels. In some instances, these alluvial systems clearly are associated with small tributary valleys, whereas in other instances they clearly are not. The area shown in Figure 2 is covered by a mosaic of three

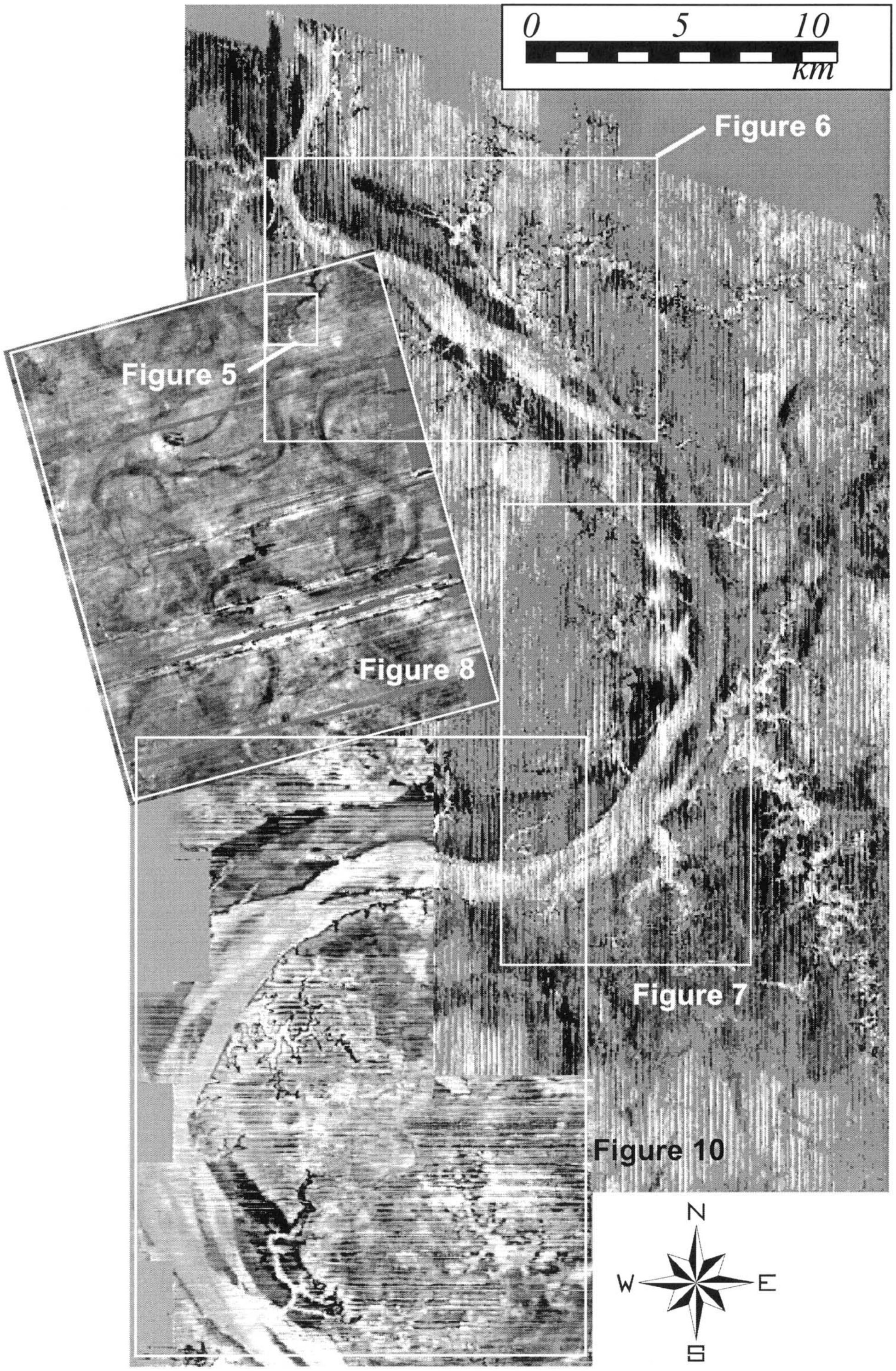


Figure 2. Mosaic of time slices in the Northwest Corner area at approximately 72 m subsea. The principal trunk incised valley can be observed on all three data sets. This valley system is characterized by short incised dendritic tributary valleys and crosscut unincised lowstand alluvial deposits. The length of the valley shown here is approximately 90 km, and flow is interpreted to be southward. The southward flow direction is inferred on the basis of the fact that the river system appears to widen toward the south.

3-D seismic volumes that illustrate both types of fluvial systems. The mosaic comprises three time slice images at approximately the same level. Time slices constitute seismic amplitude extractions at specific depths (in time) below the sea surface. Light areas correspond to areas where the time slice crosses positive wavelet excursions along seismic traces, whereas dark areas correspond to areas where the time slice crosses negative wavelet excursions along seismic traces. Although these seismic data were acquired for deep targets, sufficient resolution is available at shallow levels to allow for imaging of shallow buried depositional and erosional features. The seismic data used were a full stack migrated volume.

Several key time slices from one of the 3-D volumes are shown in Figure 3. These time slices illustrate the geomorphologic evolution of the late Pleistocene section under the southern Java Sea Shelf. A prominent channel system can be observed on all the slices. The channel appears to lie within a valley, which, in

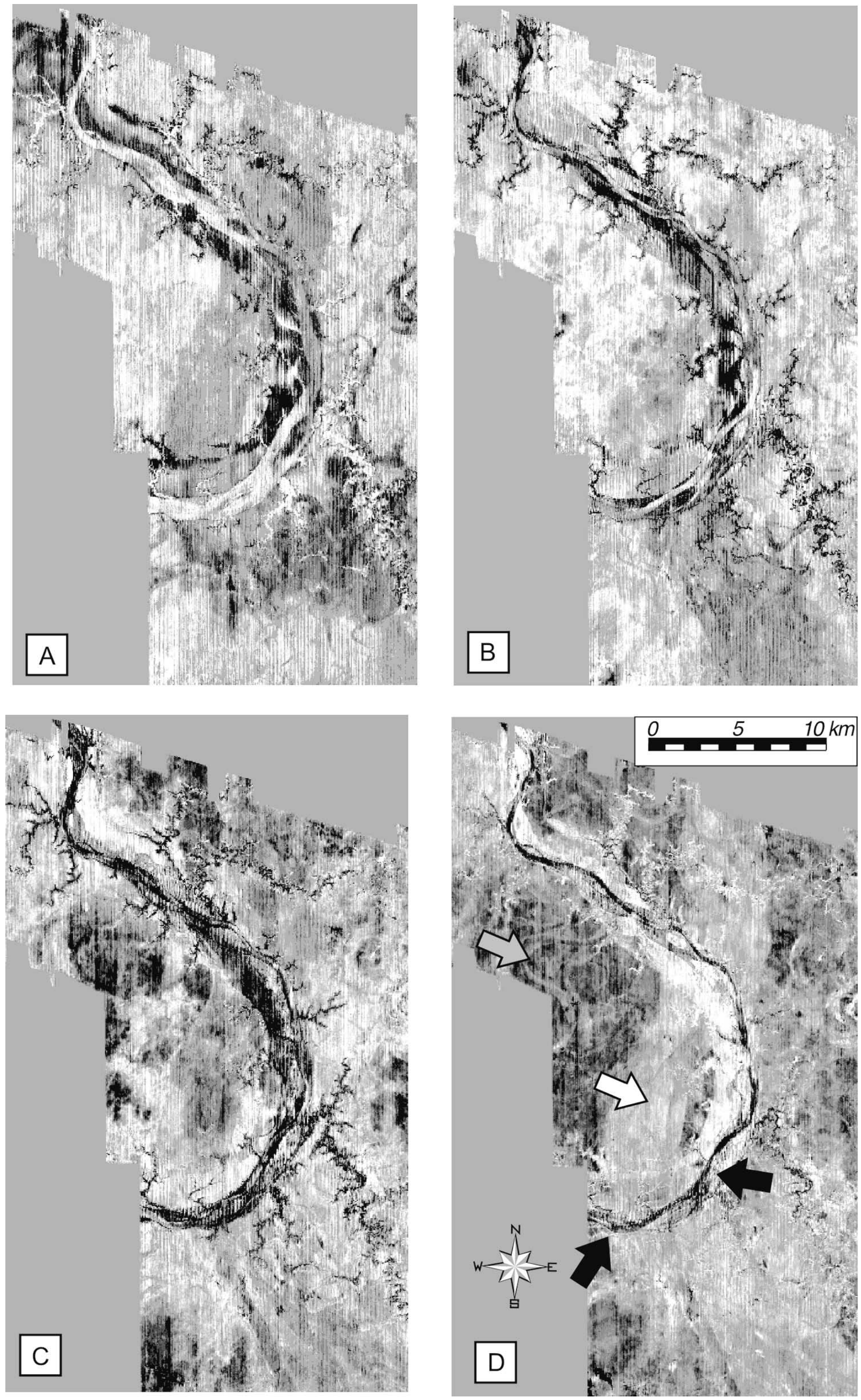


Figure 3. A succession of four time slices through the seismic volume located at the eastern side of the mosaic shown in Figure 2. The time slices shown are at 68 ms (A), 84 ms (B), 96 ms (C), and 108 ms (D) subsea. Note the unincised alluvial systems indicated by arrows. The trunk incised valley appears to be deflected southward (indicated by black arrows) where it crosses a buried 4–5 km–wide unincised channel belt (indicated by the white arrow; compare with Figure 2). The unincised alluvial system indicated by the gray arrow is shown also in Figure 8.

turn, appears to be associated with numerous subordinate tributary valleys (Figure 3). The small tributary valleys are characterized by a dendritic drainage pattern and in most instances extend only short distances away from the trunk system. The maximum length of such tributary valleys is 15–20 km. A detailed section across one of these valleys is shown in Figure 4, and a map of the relief of this small tributary system is shown in Figure 5. The width of the principal trunk valley is approximately 3–4 km in the north, widening to 5 km in the south, and the depth is 14–16 m to the top of the alluvial fill (Figures 4, 5) in the north deepening to 41 m in the south (see discussion immediately following). The width:thickness aspect ratio is approximately 175:1 (assuming that the depth of the valley includes 14–16 m relief to the top of the alluvial fill, plus another 5 m of alluvial fill) in the north, and 120:1 in the south. A single channel that bifurcates in places and is characterized by low sinuosity dominates the trunk system. Upon closer inspection lateral accretion with associated meander scroll bars can be recognized within the incised valley (Figure 6). Meander scroll bars are arcuate bar-form deposits that are associated with meander loop migration. This river system seems to be fully confined by valley walls as illustrated in Figure 7. The trunk valley can be mapped for a total distance of 90 km. This area lies approximately 110 km from the closest shelf-slope break to the south-southwest, resulting in a presumed total valley length of at least approximately 200 km.

Other channel systems also can be recognized within the slices through these 3-D seismic volumes (e.g., Figure 8). Channel systems such as those shown in Figure 8 commonly are imaged only on 2–4 successive time slices over an interval of 2–8 ms (approximately 2–6 m), in contrast with the system described previously (Figures 2, 3), which can be observed on time slices from near the sea floor down to 120 ms subsea (approximately 26–96 m subsea). This suggests, as one would expect, that channels with limited vertical seismic expression also are characterized by significantly less vertical expression. Channel systems

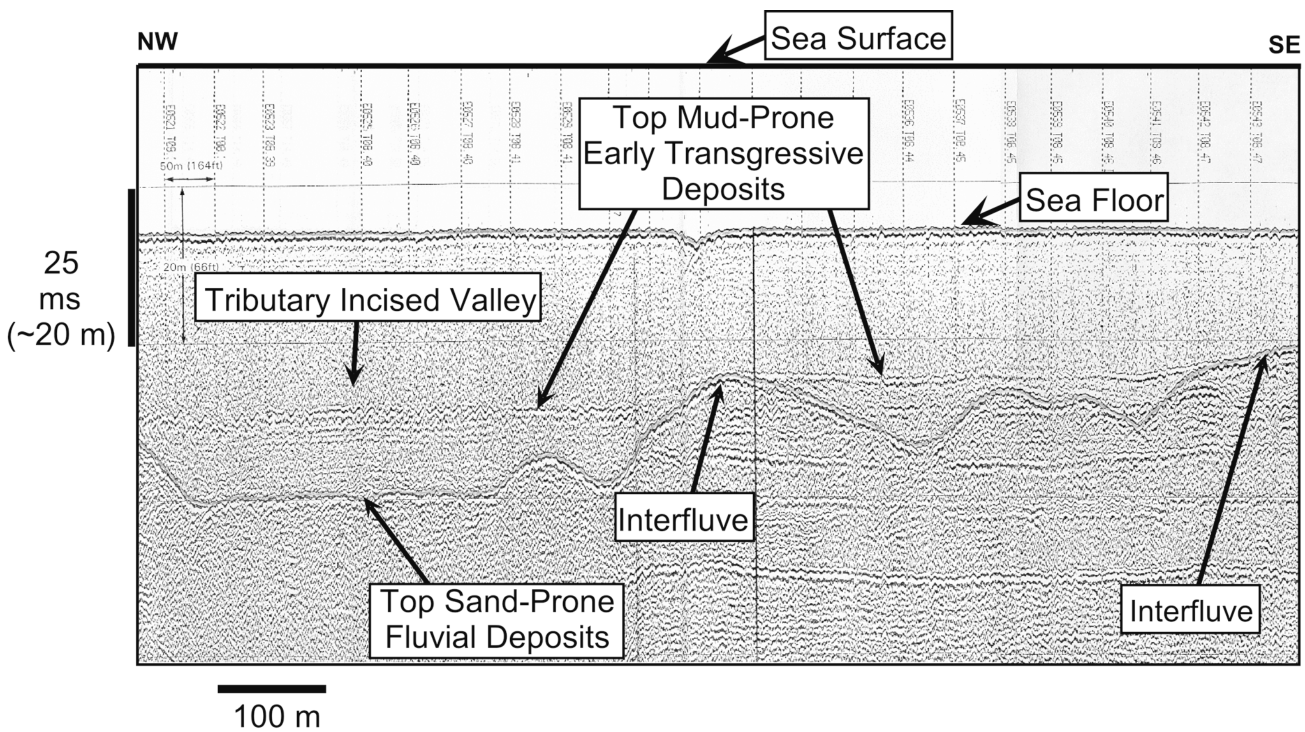
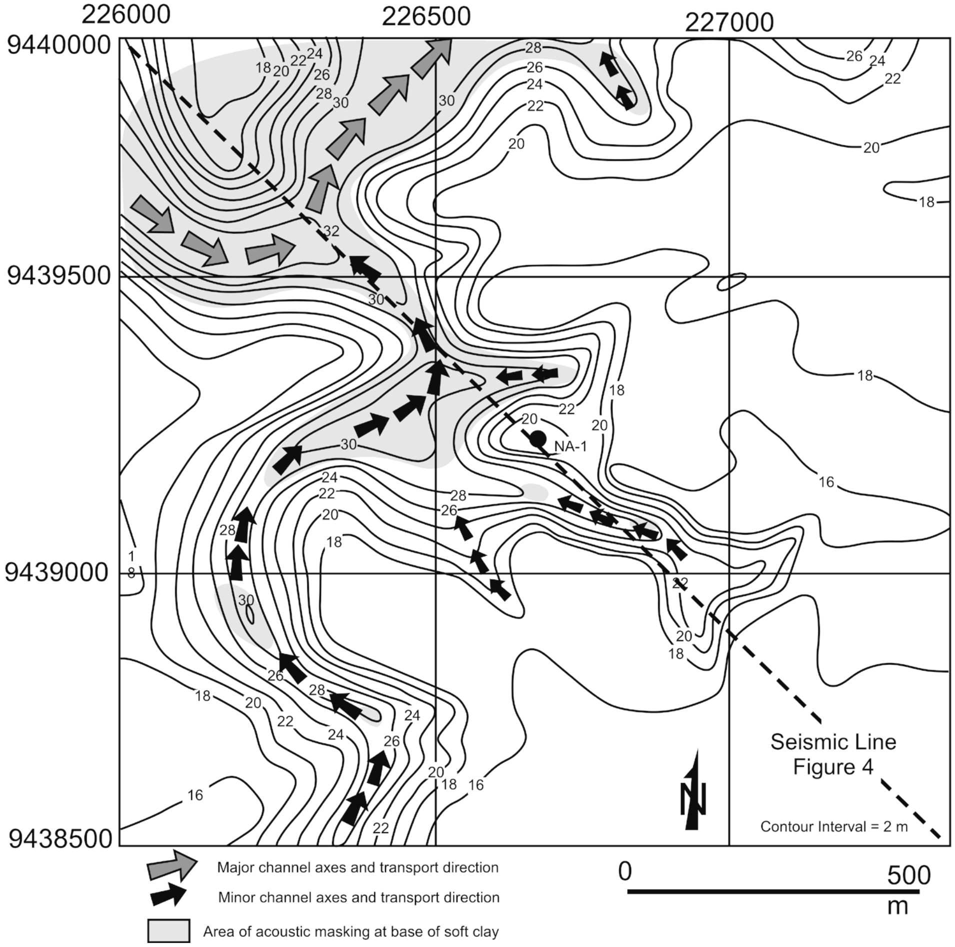


Figure 4. High-resolution, shallow-penetration 280 J boomer seismic profile across small tributary incised valley (location shown in Figures 2, 5). The flat-floored part of this tributary incised valley indicates that at this location flood-plain aggradation had occurred. The presence of sand within the flood-plain section is inferred by the apparent acoustic opacity of these fill deposits as well as the presence of sand in the platform boring shown in Figure 11. Compare the acoustic penetration there with the acoustic penetration below the incised valleys on the southeast end of this seismic section. Note the seismic reflection demarcating the interpreted transgressive mud-filled part of the incised valley. These deposits appear to have filled the valley to its top; they have essentially "healed" the originally irregular topography of the valley system (R. Mueller, D. Syam, and M. Herianto, 1995, unpublished data).

Figure 5. Contour map depicting the relief associated with the incised tributary valley, based on interpretation of a grid of high-resolution, shallow-penetration 280 J boomer seismic profiles, spaced at 175 m east to west, and 300 m north to south (location shown in Figure 2). Arrows indicate local direction of sediment transport. The contours indicate sub–sea-floor depths. Note the relatively flat floor (gray arrows) and compare with Figure 4. The depth to the tops of the interfluves locally is 16–18 m, which corresponds to the inferred Holocene drape section (compare with Figures 4, 11) (R. Mueller, D. Syam, and M. Herianto, 1995, unpublished data).



such as these appear to have no small tributary systems associated with them, nor do they seem confined to valleys (Figure 8). In fact, the trunk channel with the associated tributaries described previously appears to cut through the more subtly expressed channel systems such as the systems shown in Figure 8. Note the presence of the deeply incised trunk valley with one of its tributaries located in the upper right corner of the time slice shown on Figure 8 (compare with Figure 2)

Another channel fairway with limited vertical expression crosses the principal trunk system described previously and is indicated with an arrow in Figure 3D. This system is up to 5 km wide and appears to be characterized by a low-sinuosity, possibly braided channel pattern. Note that the trunk incised valley system appears to be deflected south-southeastward where it crosses the low-sinuosity channel complex in the central part of the study area (Figure 2). This apparent pathway deflection may be related to the effect of differential compaction between the channel fairway and the surrounding mud-prone flood plain, producing an alluvial ridge.

In other areas of the southern Java Sea, similar Pleistocene incised valley systems cutting through unincised channel systems can be observed. Figure 9 illustrates one such trunk valley system with tributaries, which can be observed in the BZZ field area (Figure 1). This system is notable for its significantly narrower width and significantly greater sinuosity than the system observed in the Northwest Corner area (Figure 1). This valley seems to have inherited and preserved a meander pattern that existed prior to incision and valley formation. Note also that this valley is not associated with as many tributary valleys as that shown in Figure 2.

Observations: Lithology

Direct determination of the lithology of the trunk valley shown in Figures 2 and 3 is based on the results of a platform boring in the southern part of the study area (B. P. Mandidjaja and P. Somehsa, 1995, unpublished data) (Figures 10C, 11). This boring, located near the eastern edge of the trunk valley, suggests that the depth to the top of the alluvial fill is 38 m below the sea floor.

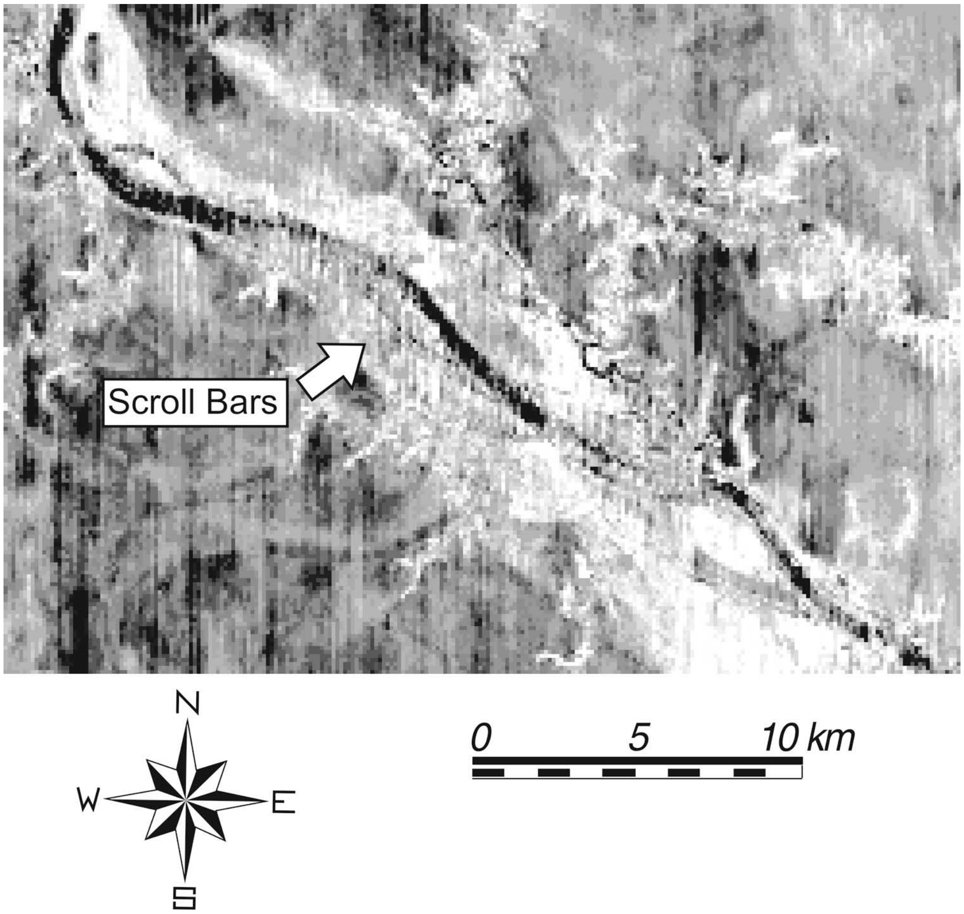


Figure 6. Detail of incised valley fluvial geomorphology at time slice 112 ms subsea (~90 m subsea) (location shown in Figure 2). Note the channel with associated scroll bars.

The time slice at that approximate level is shown in Figure 10D. At this level, fine sands are encountered in the borehole. The sand-rich section, which is inferred to constitute the alluvial fill within the incised valley, is 13 m thick. The base of the sand-rich section is characterized by a cemented zone and sharply overlies a very stiff to hard clay. The 38 m section overlying the top of the alluvial fill can be subdivided into two discrete sections on the basis of lithology. A significant contact separating very soft clay from very stiff clay is encountered at a depth of 13 m below the sea floor. The very soft clay, with water content that ranges from 75 to nearly 100%, abruptly overlies the very stiff clay, with water content that ranges from 25 to 50%. Shell fragments are observed in both sections. The time slice at the contact between the very soft and very stiff clay is shown in Figure 10B. The time slice just below the sea floor is shown in Figure 10A.

Interpretation: Incised Valleys

The systems comprising trunk valleys associated with small tributary systems are interpreted as incised valleys. The trunk valley shown in Figure 3A, approximately 3–5 km wide and based on the channel pattern, the presence of meander scrolls and point bar development, and the presence of numerous subordinate tributary systems, was cut by fluvial processes. The channel has acted to both deepen and widen the valley, sweeping from one side to the other as it downcut. Terraces likely formed during the period of downcutting (Figure 10C, D). These terraces appear to have been abandoned by continued sea level fall toward the end of the period of valley incision as evidenced by the small tributaries etched into these terraces locally (e.g., Figure 10D). The presence of a flood plain within the deepest parts of the incised valley, below the terraces, suggests that after downcutting had ceased, alluvial aggradation had occurred prior to eventual abandonment (Figure 6).

The incised valley illustrated in Figure 9 is considerably narrower than that shown in Figure 2. This could be because of differences in substrate erodibility and/or channel discharge and/or length of time during which lateral cutting occurred. The system shown in Figures 2 and 3 lies approximately 150–200 km from the paleoshoreline, whereas the system shown in

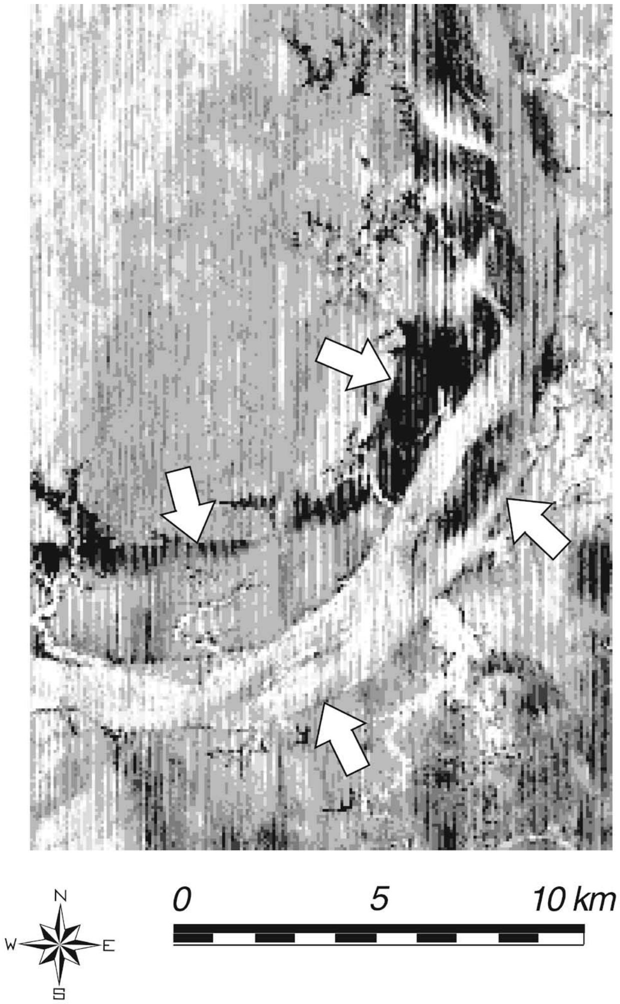


Figure 7. Detail of incised valley fluvial geomorphology at time slice 68 ms subsea (~54 m subsea) (location shown in Figure 2). Note the lateral extent of the incised valley (arrows indicate incised valley walls) and the presence of an incised alluvial terrace within the valley on its northern side.

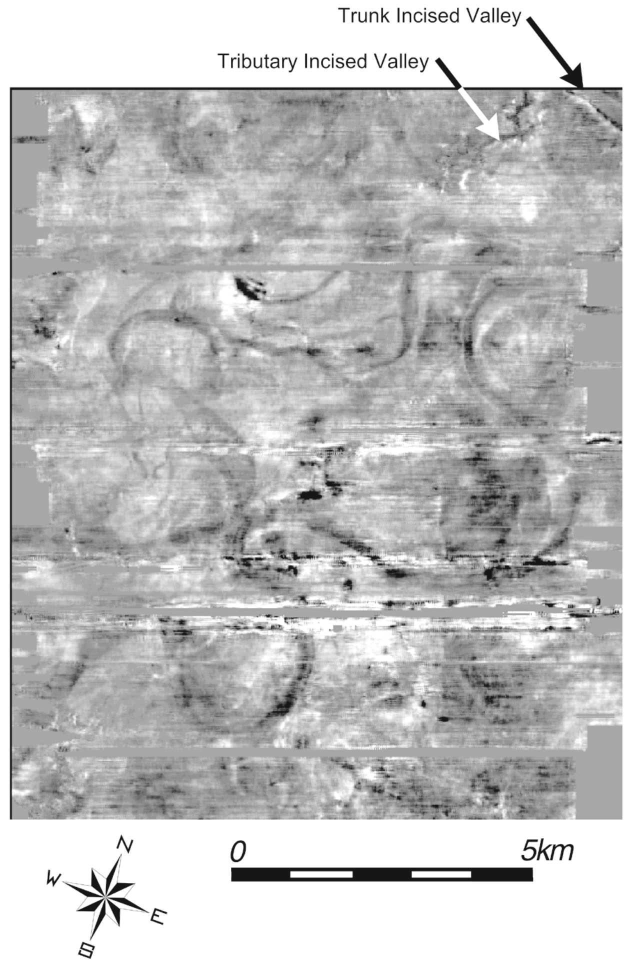


Figure 8. Detail of unincised alluvial geomorphology at time slice 112 ms subsea (location shown in Figure 2). Note the numerous meandering channels and that no incised tributary valleys are associated with these channels.

Figure 9 lies approximately 250–300 km from the paleoshoreline. The two systems are possibly of different ages; the system shown in Figures 2 and 3 seems to be of latest Pleistocene age, probably associated with the sea level lowstand at 18 ka, whereas that shown in Figure 9 is somewhat older, possibly associated with the sea level lowstand at 160 ka. This age interpretation is based on the observation from high-resolution site survey seismic data in the Northwest Corner area (Figure 4) that a seismically uniform, nearly transparent section immediately overlies the trunk valley incision. This uniform, nearly transparent section is inferred to comprise hemipelagic mudstone of Holocene age. In contrast, the incised valley shown in Figure 9 is overlain by a complex section of varying acoustic impedance, suggesting a stratigraphic history that was likely too complex to have developed during the latest Pleistocene and Holocene and thus is assigned to the next oldest significant lowstand of sea level at 160 ka. Nonetheless, in each instance, the principal trunk channel seems to have stabilized in an incised position, ceased downcutting, and begun to form a flood plain within the incised valley.

The fill of the incised valley as observed in the platform boring (Figure 11) is interpreted to be subdivided into a lowstand alluvial and a transgressive open marine component. The net sand within the incised valley fill is 25%. The alluvial component is sand rich and seismically is characterized by channel bars, point bars with scroll bars, alluvial terraces, and well-defined channels. The open-marine component consists of clay with scattered shell fragments. This section of the valley fill is interpreted as having been deposited during the period of rapid transgression that characterized

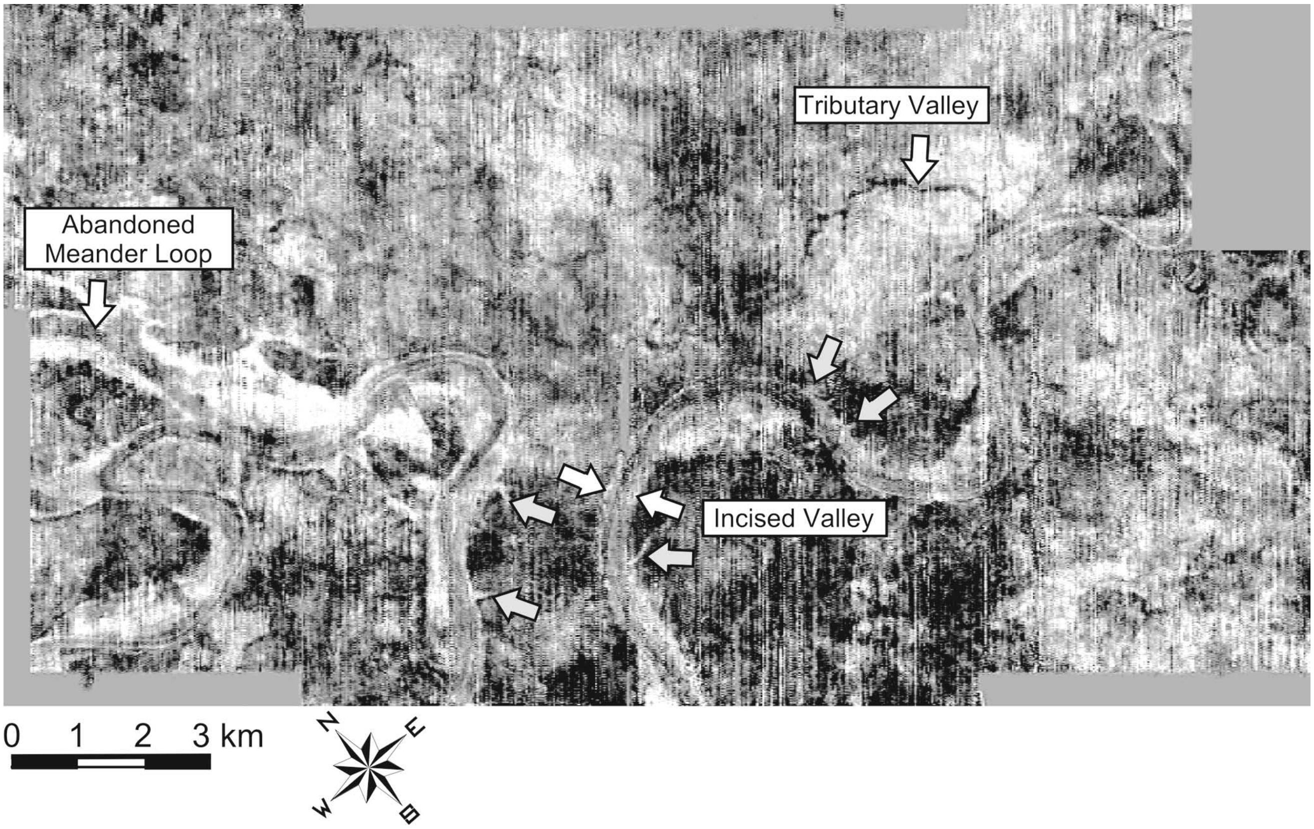


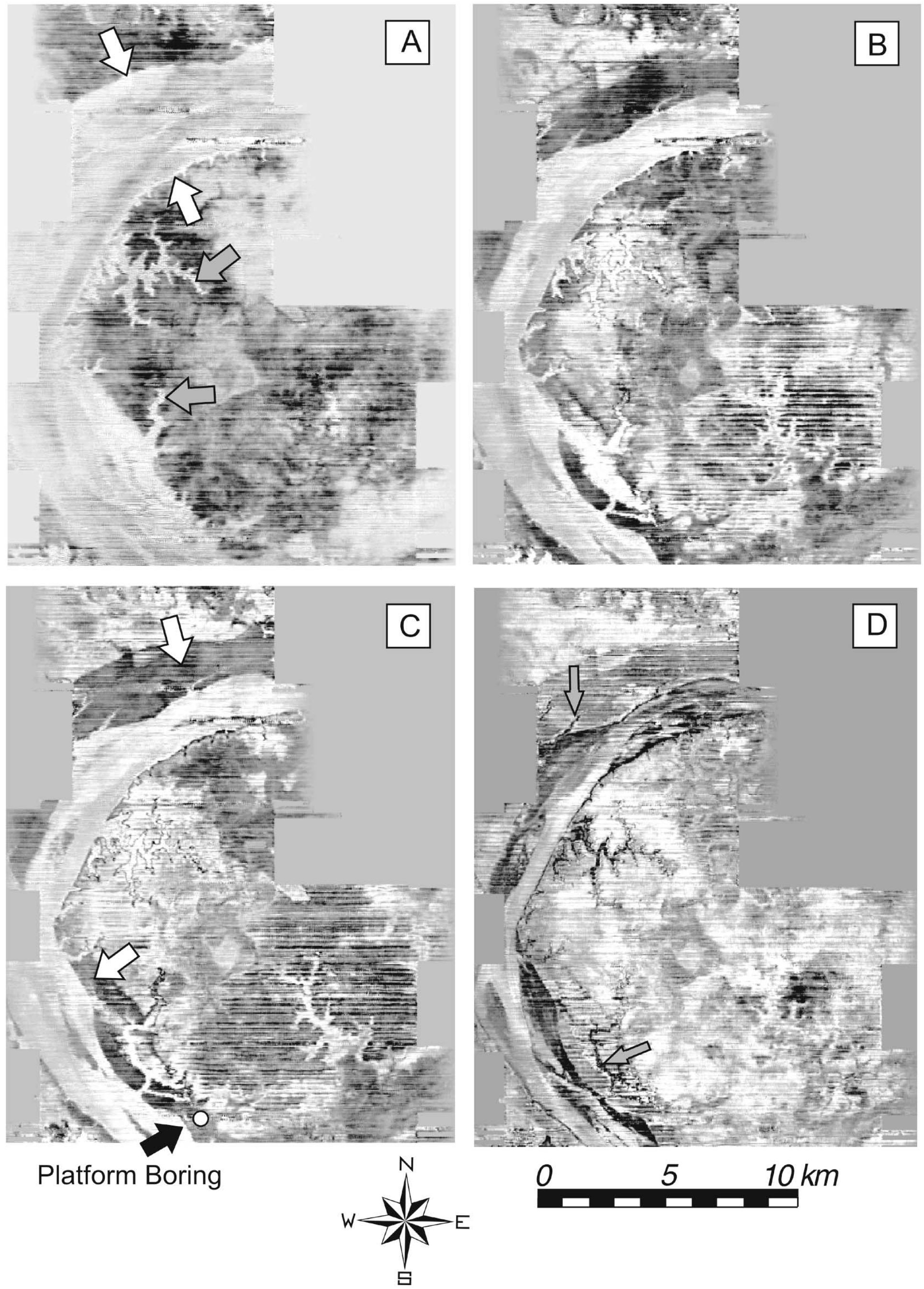
Figure 9. Time slice 156 ms subsea from the 3-D seismic volume at the BZZ area (location shown in Figure 1). The incised valley here is significantly narrower than that shown in the Northwest Corner area (Figures 2, 3). Numerous small tributary valleys are present (indicated by gray arrows); one longer one is indicated with a white arrow. Note that the incised valley has retained the meander pattern inherited from the time when this river was not incised and had flowed across a broad flood plain.

most continental shelf areas between 14 and 10 ka. The process of fill is believed to be similar to that suggested by Posamentier et al. (1998), as shown schematically in Figure 12. The fine-grained valley fill is inferred to have been swept into the valley subsequent to marine transgression, eventually completely filling the relief associated with the valley incision. This was followed by deposition of an approximately 16 m hemipelagic drape deposit during the Holocene. Figure 4 shows one of the tributaries to the principal trunk valley filled to the top with a seismic unit inferred to be of the same origin as the very stiff clay penetrated by the platform boring. Note the different level at which the top of this fill is encountered on this seismic profile, suggesting that the top of the fill was controlled by the height of the nearby valley wall. Above this seismic unit, the seismic facies is essentially acoustically transparent, consistent with a section of homogenous soft clay characterized by extremely high water content (i.e., the very soft clay unit encountered in the uppermost 13 m of the platform boring). The marked contrast in water content at that level suggests the presence of a time gap separating late Pleistocene from Holocene sediments.

The small tributary valleys that feed the principal trunk valley formed in response to draining of interfluve areas (Leeder and Stewart, 1996). Note that these tributary systems do not exhibit significant flood-plain development, suggesting that the channels within these valleys had not done significant lateral cutting. Some of these tributary channels apparently had not downcut to the level of the trunk valley before they were abandoned. The heads of these valleys are defined by knickpoints.

Figure 13 illustrates a modern subaerial incised valley from Alberta, Canada. This system likely represents an underfit stream occupying a much larger former channel that formed during the late Pleistocene by glacial meltwater runoff. Note the numerous small tributary channels feeding the trunk valley. Note also the scroll bars characterizing the valley-restricted narrow flood plain. Notably, despite the very different cause of incision here compared with the incised valley offshore northwestern Java (Figures 2, 3, 9), the

Figure 10. Detail of incised valley fluvial geomorphology at time slices 36 ms (A), 54 ms (B), 60 ms (C), and 82 ms subsea (location shown in Figure 2). The shallowest slice clearly shows the lateral extent of the incised valley (white arrows) and the numerous incised tributary valleys (gray arrows), commonly characterized by a dendritic drainage pattern. Alluvial terraces become apparent at deeper sections (shown by white arrows in C). Incision of these terraces is also apparent (shown by gray arrows in D).



morphologies are nonetheless strikingly similar. This underlines the general similarity of morphology of all incised valleys, regardless of origin.

Interpretation: Unincised Lowstand Alluvial Channel Systems

Abundant channels without tributaries are observed on the interfluves on either bank of the incised valleys shown, for example, in Figures 3 and 8. Commonly, these channels are imaged on only a few successive slices, suggesting that their depth and fill thickness is significantly less than in the incised valley systems previously described. These systems developed on the southern Java Sea Shelf during times when sea level was lower than today in this area (water depths today range from 23 to 56 m) and therefore constitute lowstand deposits. Thus the channels shown in Figure 3 likely developed during the lowstands between 105 and 20 ka. During these times, the entire shelf was not fully subaerially exposed, and lowstand fluvial systems did not incise (Posamentier and Allen, 1999) (Figure 14). Full exposure occurred probably only for brief periods such as that between 20 and 16 ka, when sea level

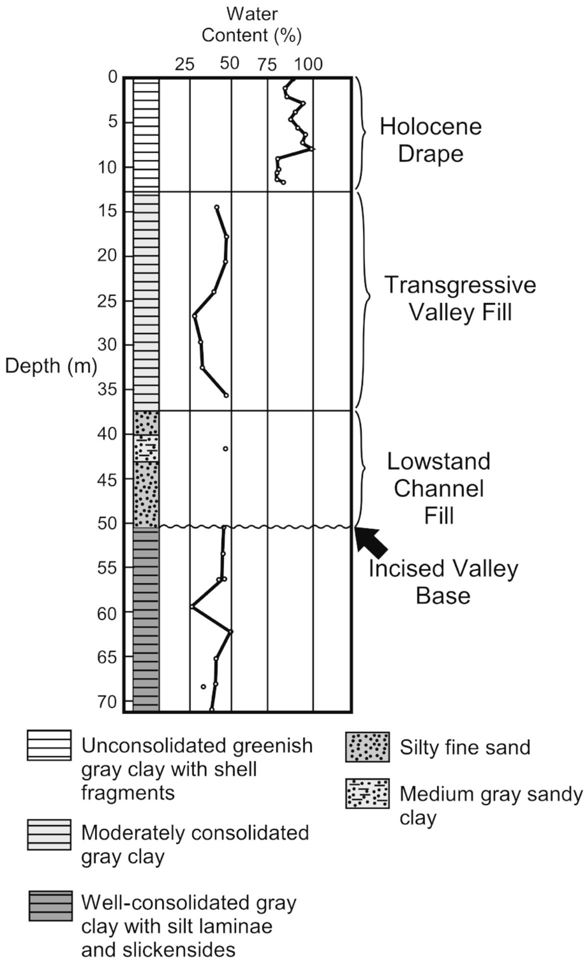


Figure 11. Log of platform boring located just within incised valley (location shown in Figure 10C). This boring penetrates muddy transgressive valley fill and sandy lowstand channel fill within the valley (compare with Figure 4). Note that the interpreted fluvial deposits are encountered within a raised alluvial terrace. The inferred Holocene drape is characterized by sediments with markedly greater water content than the transgressive valley-fill sediments it sharply overlies. This sharp contact defines a boundary inferred to separate late Pleistocene from Holocene deposits. (B. P. Mandidjaja and P. Somehsa, 1995, unpublished data).

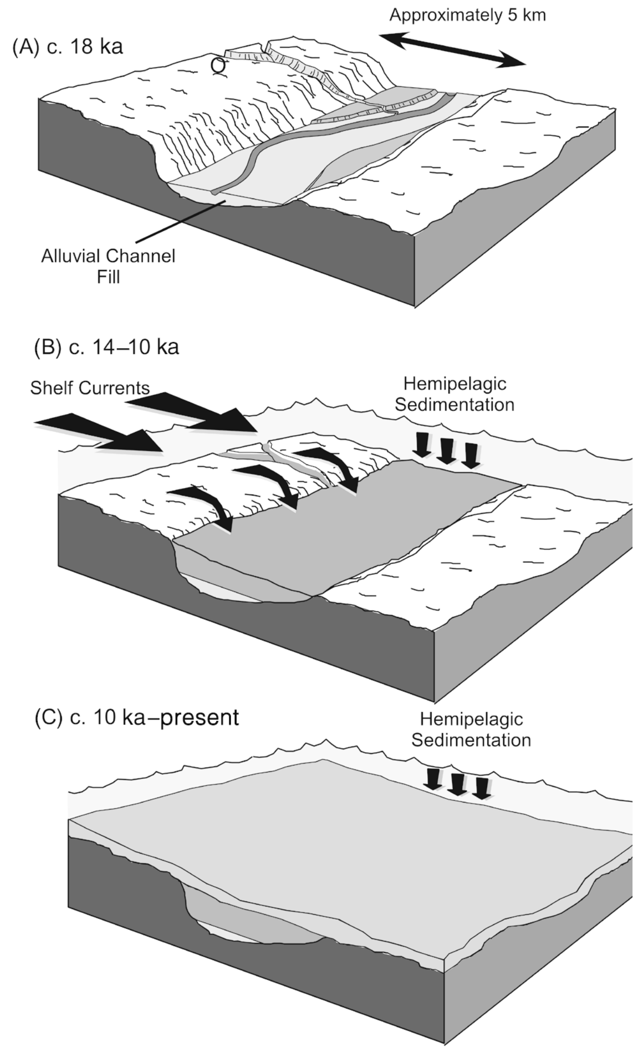


Figure 12. Schematic depiction of the evolution of incised valley fill in the Northwest Corner area from the time of maximum sea level lowstand, characterized by fluvial deposition (A), through the time of rapid transgression and filling by traction and hemipelagic sedimentation (B), and finally the time of sea level highstand and deposition of hemipelagic drape over the entire area (C).

dropped below the –110 m mark, a level that corresponds to the approximate water depth at the shelf edge.

Figure 15 illustrates the late Pleistocene lowstand depositional systems evolution of the Northwest Corner area. Highstand marine shelf conditions (not shown in Figure 15) are followed by early lowstand unincised fluvial systems (Figure 15A, B), followed by late lowstand incised valley formation and interfluve development (Figure 15C). Note that the meander pattern of the main trunk valley represents an inherited (i.e., relict) map pattern of the preincision channel. This inherited map-pattern phenomenon is especially apparent for the incised valley shown in Figure 9.

Miocene Section of Offshore Java

Observations

Figure 16 illustrates a horizon slice through the Miocene shelf section in the FXE area offshore northwestern Java (Figure 1). Two channels are shown: a high-sinuosity channel trending northwest-southeast

Figure 13. Aerial photograph of the Red Deer River, Alberta, Canada, illustrating a modern incised valley. This valley likely formed as a result of deep channel cutting caused by fluvial discharge that was orders of magnitude higher than today as a result of rapid glacial melting during the late Pleistocene. Subsequent occupation of the deep channel by a significantly smaller (i.e., underfit) river results in the development of an incised valley. Note the numerous small incised tributary valleys (compare with Figures 2, 3, 10). Note also the scroll bars associated with the meandering river confined to the incised valley (compare with Figure 6).

and a low-sinuosity channel trending north-south. Although both channels are imaged at the same horizon, they crosscut each other and are not exactly the same age. The high-sinuosity channel is characterized by meanders with a radius of approximately 2 km. Closer inspection of the seismic data across the meanders reveals the presence of scroll bars that appear to be truncated on their northwest limits and tangential on their southwest limit (just north-northwest of the FXE-1 well). The low-sinuosity channel is characterized by a meander radius of less than 250 m. Where the two channels cross, the low-sinuosity channel seems to be deflected by the meanders of the high-sinuosity channel.

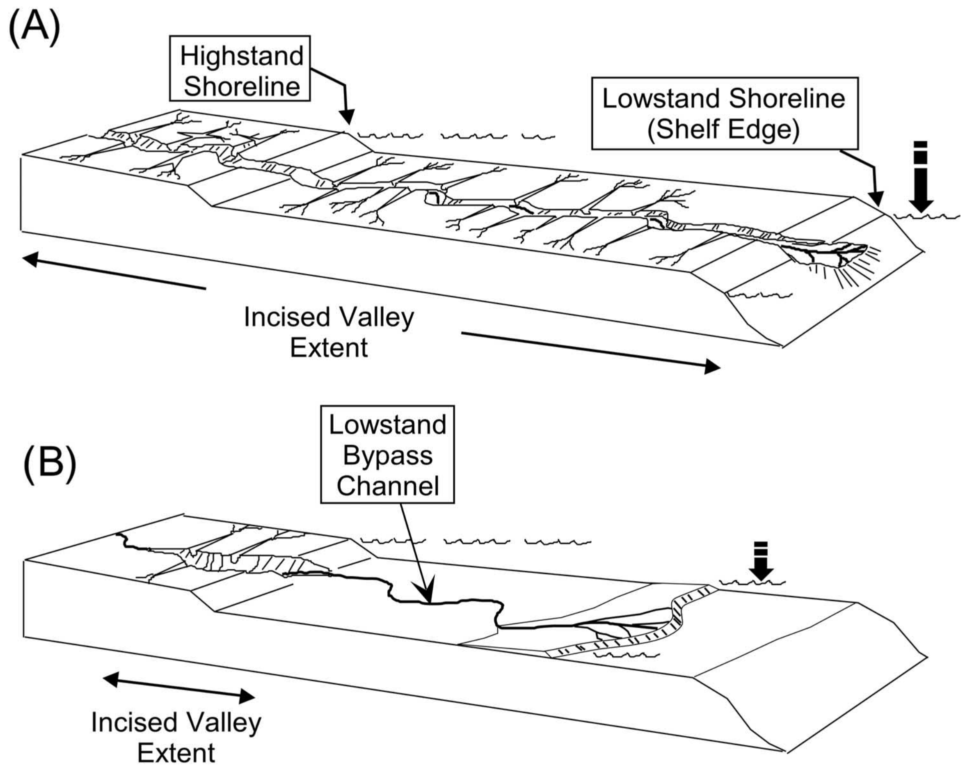


Figure 14. Schematic depiction of (A) incised valley formed where sea level fall fully exposes the shelf, and (B) lowstand alluvial bypass channel system where sea level fall does not fully expose the shelf. Note that in (B) there would be limited incised valley development through the coastal prism (Posamentier and Allen, 1999).

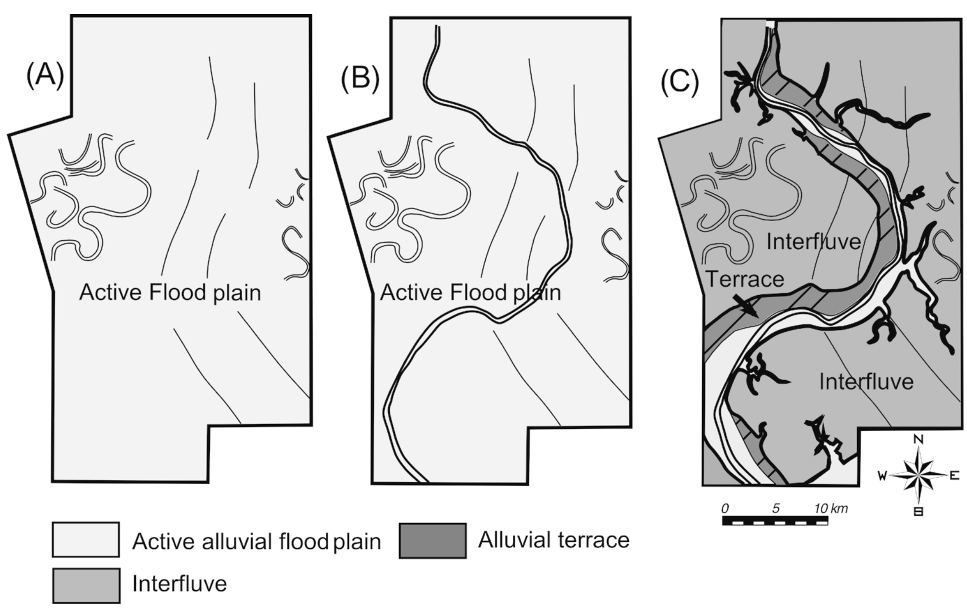


Figure 15. Schematic depiction of geomorphological evolution of the Northwest Corner area from early (A and B) to late (C) lowstand time. During early lowstand time, unincised alluvial systems are established on the former sea floor. High-sinuosity channels characterize these systems. The last such channel that existed just prior to incision (C) is shown in (B). This channel pattern is then modified by incision during lowest sea level stand. The active flood plain, which covers the entire study area during (A) and (B), is reduced in size to the confines of the incised valley. The remaining upland area constitutes an interfluve. Note the numerous incised tributary valleys and the alluvial terraces that form at this time (C).

Four wells penetrate this section, and their locations are shown in Figure 16. The well-log cross section based on these wells (Figure 17) includes only one well that penetrates the meandering channel. The section in that well (well FXE-1) that corresponds to the meandering channel fill is approximately 4.25 m (14 ft) thick. The width:thickness aspect ratio of this system is approximately 940:1,

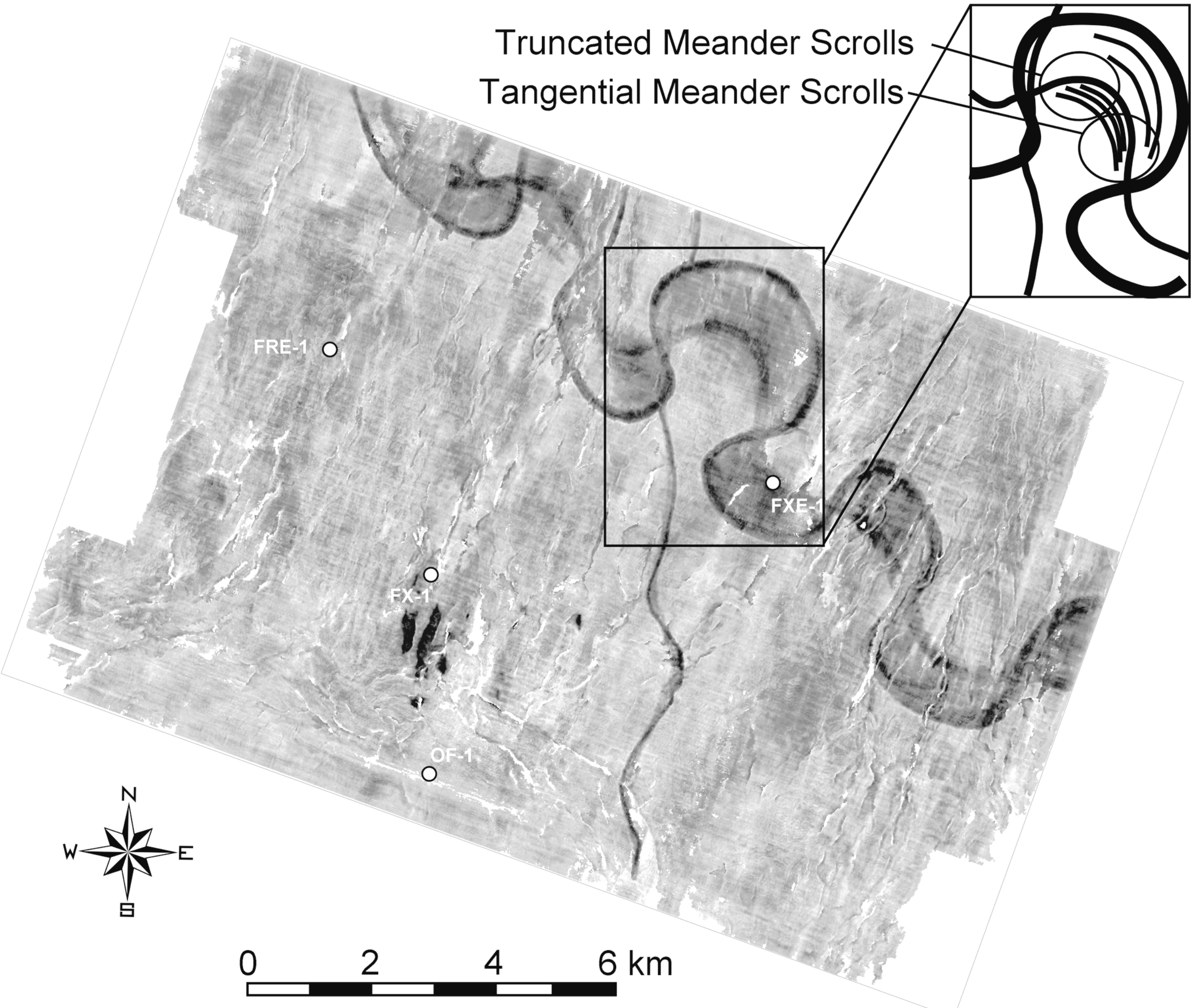


Figure 16. Seismic horizon slice through 3-D seismic volume at FXE area. Two channels can be observed. The high-sinuosity channel flow direction is to the southeast, and the low-sinuosity channel flow direction is to the south. Note the scroll bars in the meander loop just to the north of well FXE-1; they appear to be truncated to the northwest and tangential to the southeast.

assuming a meander belt width of 4 km. The gamma-ray log response appears to be "cleaning" upward; however, the presence of glauconite in the section may be masking what otherwise might be a "muddying"-upward lithology. This interpretation is supported by the resistivity log expression of this same section, which suggests a fining-upward lithology. In wells FRE-1, OF-1, and FXE-1, a calcite-cemented zone is present at this level. Note that this calcite-cemented zone overlies the channel fill in well FXE-1. Of significance in this area is the absence of any precursor deltaic deposits underlying the meander channel or at the correlative level in each of the other wells. Based on biostratigraphic analyses, the section bracketing the meandering channel deposits corresponds to an open-marine, middle neritic environment (R. Meyrick, 1999, personal communication).

Interpretation

The two channels observed in this Miocene section appear to have been established directly on the paleo–sea floor. The absence of any subjacent precursor deltaic deposits associated with these channel features suggests a depositional systems "disconnect," such as would have developed in response to a rapid sea level fall. During such times of forced regression (Posamentier et al., 1992), rapid seaward shift of the shoreline

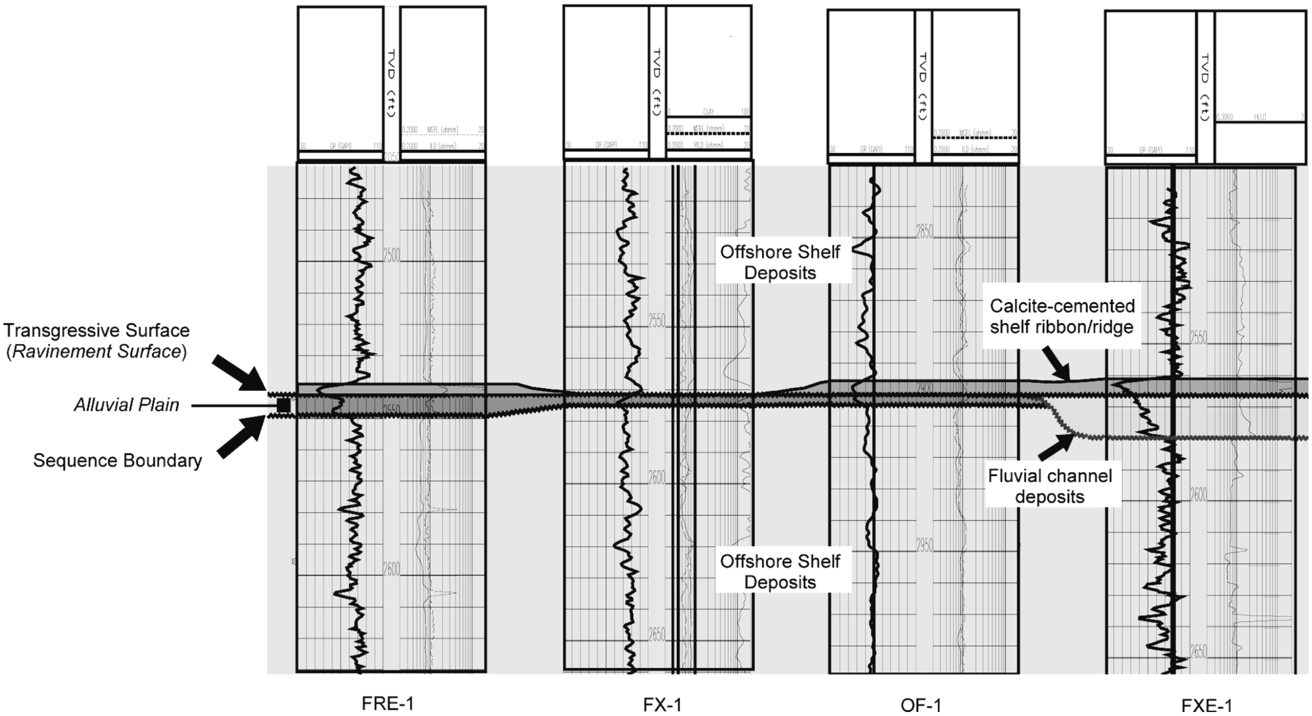


Figure 17. Well-log cross section from FXE area showing unincised lowstand alluvial system and associated flood plain embedded within offshore shelf sediments. A thin calcite-cemented zone inferred to consist of shell fragments in a siliciclastic sand matrix overlies the alluvial deposits.

can limit the extent of deltaic deposition such that river systems extend themselves directly onto the now freshly exposed sea floor. Subsequent transgression across the alluvial plain explains the apparent embedding of the alluvial system within an otherwise open-marine shelf section (Figure 17).

The presence of a calcite-cemented zone at the top of the alluvial section is likely associated with the deposition of abundant shell fragments on the transgressive surface forming the upper boundary of the alluvial plain deposits. Although no core data are available from this section locally, similar calcite-cemented zones are observed elsewhere within the Miocene section offshore northwest Java. In most instances, where conventional core data are available, calcite-cemented zones are characterized by shell fragments in a siliciclastic sandstone matrix (H. W. Posamentier, 1998, unpublished data).

This section is interpreted as constituting an unincised lowstand alluvial bypass system. Conspicuous by their absence are any incised tributary valleys, such as those observed within the Pleistocene section (Figures 2, 9). This Miocene alluvial system was emplaced on the exposed sea floor during a rapid sea level fall and flowed toward the southeast as indicated by the truncation of meander scroll bars to the northwest. The high-sinuosity channel was established first, followed by infilling, abandonment, and eventual establishment of the low-sinuosity channel, which flowed toward the south. The timing of these channels is suggested by the deflection of the path of the low-sinuosity channel by the meander scrolls of the high-sinuosity channel. Note that between the time of formation of the high-sinuosity channel and the low-sinuosity channel, slight tectonic tilting must have occurred. This is evidenced by the fact that the direction of the paleoslope shifted from southeast to south (as indicated by the direction of channel paleoflow) during this time. Deposition of both channels in addition to the tectonic tilting event is interpreted to have occurred during a single lowstand period.

No true incised valleys have been observed on the 3-D seismic data in the Miocene section of the FXE area. This could be a result of (1) inadequate seismic coverage, that is, incised valleys may exist but not in the area of seismic control, or seismic data quality is insufficient to image any incised valley systems; or (2) the shelf in this basin being not fully emergent during the Miocene, that is, the amplitude of sea level change was insufficient to expose the shelf relative to the highstand water depth at the outer shelf. The second scenario is favored in light of the high-quality seismic data available here (peak frequency > 50 Hz), although the existence of incised valleys outside the area of data coverage cannot be ruled out. This scenario would be consistent with the conclusions drawn from the Northwest Corner area regarding the development of alluvial systems only during the lowest of sea level lowstands.

DISCUSSION

Both incised and unincised lowstand alluvial bypass systems are observed offshore northwest Java. The Pleistocene section, in particular, yields valuable insights to the process of lowstand depositional-system evolution. Four significant conclusions can be drawn from this analysis that can have implications beyond this study area and may be relevant to other time intervals as well: (1) despite the fact that multiple high-amplitude sea level falls characterize the Pleistocene epoch, lowstand deposition in this area is expressed most commonly as unincised alluvial systems rather than incised valley systems in this area; (2) the incised valley system observed in Figure 2 suggests that knick-point migration has propagated upsystem more than 200 km in a relatively short period of time; (3) from the perspective of areal coverage, incised valleys in this area cover only a small part of the landscape; and (4) the presence of abundant indications of primary fluvial geomorphologic features, such as point bars, channel bars, and alluvial terraces, suggests that under certain circumstances such as those that prevailed on the northwest Java shelf, such primary features can have excellent preservation potential. These conclusions are discussed in detail in the following sections.

Unincised vs. Incised Alluvial Systems Offshore Northwest Java

Abundant evidence from 3-D seismic data volumes suggests that both unincised and incised alluvial systems characterize the Pleistocene shelf section offshore Northwest Java. In the Northwest Corner area (Figure 1) within a section that likely is of late Pleistocene age, an incised valley is observed to crosscut nonincised alluvial systems (Figure 2). The modern water depth at that location is a relatively uniform 20–22 m. One may fairly assume that similar water depths characterized earlier Pleistocene highstands. Following on this, it is also reasonable, therefore, to assume that to have established any alluvial systems in this area, sea level must have fallen more than 21 m, so as to subaerially expose the shelf in this location.

Pleistocene sea level curves suggest that there are numerous periods of relative sea level lowstand (Figure 18) during which sea level was sufficiently low to at least partially expose extensive shelf areas offshore Java, including the areas studied. However, to fully expose the shelf, sea level would have to have fallen in excess of 110–120 m (the current water depth at the shelf edge). Full exposure of the shelf is required for the formation of long-distance incised valleys related

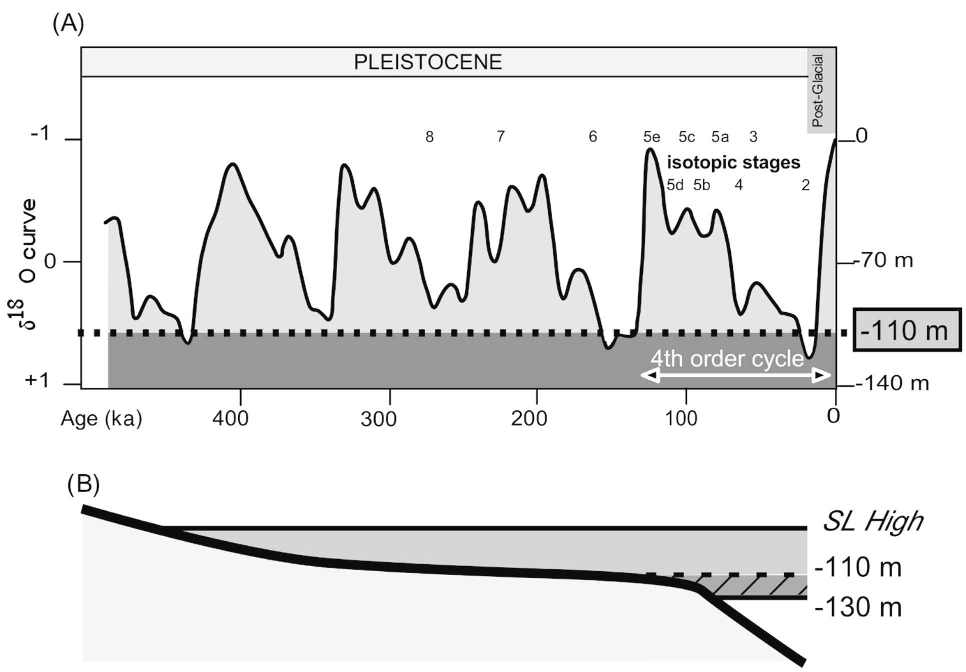


Figure 18. (A) Late Pleistocene to Holocene sea level curve based on oxygen isotope data (Bard et al., 1990). The water depth of −110 m has been identified as a threshold level, below which the continental shelf would be fully exposed (B). If sea level fall is less than 110 m, then unincised lowstand alluvial channel systems form; if sea level fall exceeds 110 m, then incised valleys form.

to sea level fall, because the relatively steep outer shelf and upper slope would then be exposed (Figure 14A; note that limited incised valley formation can develop with a smaller sea level fall that does not fully expose the shelf, if a coastal prism is present, Figure 14B). This steep gradient, in turn, would cause rivers to incise as a result of accelerated flow, causing a knickpoint to migrate upstream; however, such high-amplitude sea level falls were not common and, in fact, where they did occur were short lived during the late Pleistocene. The observation from the seismic data, that incised valleys seem to be the exception rather than the rule for the Pleistocene section, is consistent with the hypothesis that to develop an incised valley by sea level lowering, the shelf must be fully exposed. If the shelf is only partially exposed, unincised alluvial systems develop.

During much of the Pleistocene, periods of sea level highstand were short, averaging 10–15 k.y. During these times of highstand, continental shelves offshore Java, as they were around the world, were submerged by as much as 120 m of water. The short duration of highstands coupled by this significant shelf submergence meant that much of each period of sea level fall was spent progressively exposing the shelf, without ever fully exposing the entire shelf. As previously discussed, only the lowest of lowstands of sea level would result in full exposure of the shelf and partial exposure of the upper slope. Consequently, although most of the Pleistocene can be considered lowstand time, as Figure 14 illustrates, widespread incised valleys would not necessarily form with each successive lowstand period. As shown in Figure 18, widespread incised valley formation during the past 400 k.y. would have been restricted to only those short periods when sea level fall exceeded 110 to 120 m. We can take this line of thinking a step further and speculate what might happen if sea level highstands were considerably longer. In such circumstances, highstand sedimentation could fill a significant part of the shelf accommodation (assuming the same accommodation scenario), such that when sea level fall began, a significantly diminished water depth would be present (Figure 19). To fully expose

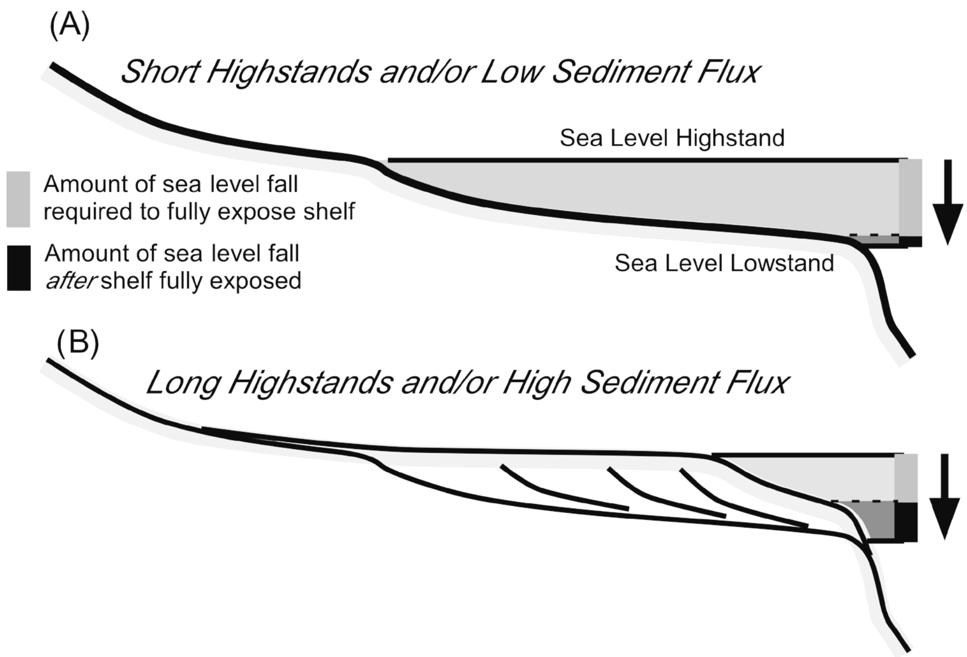


Figure 19. Schematic profiles across a continental shelf illustrating (A) short highstands and/or low sediment flux, and (B) long highstands and/or high sediment flux. In the scenario in (A), available highstand accommodation is not filled before the initiation of sea level fall, and the amount of sea level fall required to fully expose the shelf is high, whereas the amount of remaining sea level fall after the shelf is fully exposed is low. In the scenario in (B), much of the available shelf accommodation is filled prior to the initiation of sea level fall, and the amount of sea level fall required to fully expose the shelf is low compared with the situation depicted in (A). At the same time, in (B), the amount of sea level fall after the shelf has been fully exposed is comparatively high. Consequently, the scenario in (A) favors the development of unincised lowstand alluvial bypass channels vs. incised valleys, whereas the scenario in (B) favors the development of incised valleys vs. unincised lowstand alluvial bypass channels (compare with Figure 20).

this now-shallower shelf, less of a sea level fall would be required. Figure 20 illustrates a hypothetical sea level scenario of prolonged sea level highstand, and following on that, the lower sea level fall threshold required to induce widespread valley incision (compare with Figure 19). Note also, that given a moderated sea level fall threshold, the duration of valley incision would be longer. Consequently, not only would upstream response to sea level fall be facilitated, but so too would incised valley widening.

Long-Distance Knickpoint Migration

The northern end of the incised valley observed in Figure 2 lies more than 200 km from the nearest shelf edge to the south-southwest in the Sunda Straits area. If the assumption is correct, that incised valley formation was restricted to the period during which sea level fully exposed the entire shelf and the upper part of the slope; then it follows that the duration of incised valley cutting was quite short, on the order of 3000–5000 yr. This implies that knickpoint migration occurred at a rate of approximately 40 m/yr or 40 km/1000 yr. This rate, over geologic time, is nearly instantaneous. Moreover, the absolute distance of knickpoint migration suggests that entire shelf and associated coastal plain areas can readily be incised with even very short-lived sea level falls if the entire shelf and upper slope are subaerially exposed.

Areal Coverage of Incised Valleys

From the perspective of areal coverage, Pleistocene incised valleys in this area cover a small proportion of the landscape. In the area of 3-D seismic data coverage shown in Figure 2, for example, only 20% of the area is covered by the observed incised valley. This percentage of coverage is unrealistically high in light of the fact that other nearby data sets show no incised valleys present at this level at all, an observation that would only serve to lower the percentage of coverage significantly. Although the area covered by 3-D seismic data represents only a statistically insignificant part of the total southern Java Sea Shelf, it does nonetheless represent an unbiased random sample of this area.

Leeder and Stewart (1996) point out that the rate of valley widening is significantly lower than the rate of upstream knickpoint migration. This reflects the contrast between the erosive effectiveness of hillslope diffusion processes of soil creep and rain splash vs. fluvial incision. Leeder and Stewart (1996) also point out that a critical part of valley widening is the formation of slope gullies on the sides of the incised valleys, which leads to the development of new subordinate stream systems incised into the interfluves adjacent to the incised valley.

The significance of this limited areal extent of incised valleys is that although lowstand alluvial deposits are widespread, characterizing interfluve as well as in-

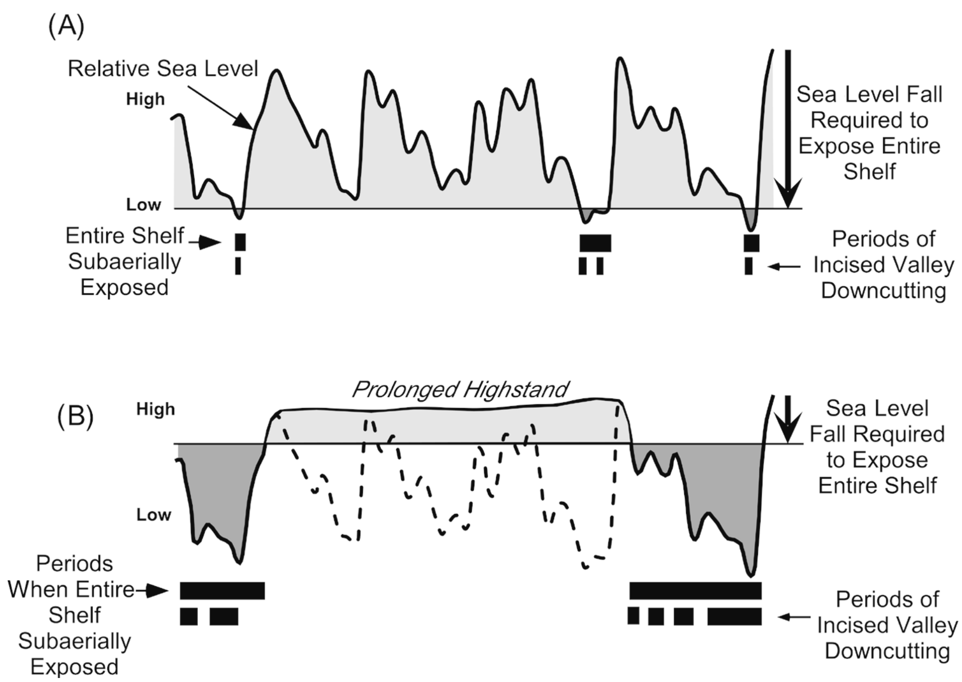


Figure 20. (A) Late Pleistocene to Holocene sea level curve (from Figure 18) showing periods of total shelf exposure and associated periods of incised valley formation. Note that valley downcutting occurs only during the falling segment of the periods of lowest sea level. Valley widening could persist longer. (B) Hypothetical modification of the late Pleistocene–Holocene sea level curve to illustrate the effect of a prolonged period of sea level highstand on the amount of time that the entire shelf would be subaerially exposed and the amount of time during which incised valleys would form.

cised valley settings, the extent of incised valleys alone is relatively quite limited. This areal extent of any given incised valley will be a function, again, of the duration of the period of sea level fall, erodibility of the substrate, and fluvial discharge.

Alluvial Depositional Elements Well Preserved within Incised Valleys

In most instances, incised valleys initially contain continuous fluvial deposits at their base (e.g., Figure 12); however, subsequent to transgression and potential erosion and reworking by tidal and/or wave energy, at best only patches of fluvial deposits commonly are preserved (Allen, 1991; Allen and Posamentier, 1993; Zaitlin et al., 1994). In the Pleistocene section offshore Java, seismic time slices suggest extensive preservation of fluvial deposits within incised valleys. Such features as point-bar deposits, meandering channels, fluvial terraces, and channel bars can be imaged within the valleys directly on the seismic data (Figures 2, 10). This strongly suggests that fluvial depositional elements are well preserved in this system. The reason for this excellent preservation is suggested to be twofold. First, rapid transgression, which likely characterized the period between the lowest sea level position approximately 16 k.y. ago and the early Holocene approximately 10 k.y. ago, may have caused any high-energy environment located in the area of the coastline to rapidly pass across the area, therefore minimizing the impact of potential erosion. Second, if the environmental energy associated with the transgressing coastline (i.e., waves and tides) were low, the preservation potential of the incised valley fluvial deposits would be high. In the southern Java Sea, wave energy is low for two principal reasons: (1) this area lies in the zone of equatorial convergence, and wind patterns are inconsistent and generally light; and (2) with an island arc to the south and the Sunda shield to the north, wave fetch is restricted. If rapid transgression occurs in conjunction with the presence of low environmental energy, then the likelihood of preservation of primary alluvial deposits is compounded.

EXPLORATION SIGNIFICANCE

The incised valley play type has received much attention in recent years (Dalrymple et al., 1992, 1994; Zaitlin et al., 1994). Though there are some similarities between the incised valley play and simple fluvial or distributary channel fill, they are inherently different play types. Generally, the incised valley is a significantly more complex system potentially containing depositional environments that can range from alluvial to open marine (Figure 12). In contrast, fluvial and distributary channel systems tend to have a simpler stratigraphic architecture. Moreover, though each of these play types is associated with channel-related processes, the aspect ratio commonly is significantly greater for alluvial systems than for incised valleys (see previous discussion). The areal extent of the incised valley, the architecture of the fill, and the depositional environment and associated reservoir attributes of that fill are all critical issues surrounding the incised valley fill play type. In some instances, the fill of an incised valley can be mistaken for that of a fluvial or distributary channel and vice versa, yet the strategies one would employ to explore for and exploit oil and gas fields within these play types could be radically different. Consequently, it is of great value to exploration geologists to be able to (1) distinguish between these play types, (2) be aware of the distinguishing attributes of each, and (3) know what constitutes reasonable dimensions for each type of system.

This article presents documented examples of both incised and unincised lowstand alluvial deposits. Analyses of Miocene and Pleistocene examples from offshore northwest Java illustrate that lowstand unincised alluvial deposits can be ubiquitous especially in midshelf settings, whereas lowstand incised systems are isolated and of relatively small areal extent. The incised valleys (e.g., Figure 2) have a significantly lower aspect ratio (175:1 and 120:1) than the lowstand bypass channel systems (e.g., Figure 16; 940:1). Given a sea level history such as that which characterized the late Pleistocene (i.e., high amplitude and high frequency) and a shelf depositional environment such as encountered offshore Java, the key exploration insights are that (1) unincised lowstand alluvial deposits would be encountered far more commonly than incised lowstand valley-fill deposits; (2) the potential landward extension of the incised valley play type may exceed 200 km or more inboard of the shelf edge, even with very short intervals of sea level lowstand; and (3) under the right environmental conditions, nearly complete preservation of alluvial deposits within incised valleys can occur. In this environmental setting of low wave energy, predominantly alluvial and open-marine deposits are preserved within the incised valleys.

In light of the abundance of unincised lowstand alluvial deposits observed here, it is suggested that this play type should be relatively common in the rock record; however, review of the literature reveals a virtual absence of documented unincised lowstand alluvial deposits. Whether these deposits have been overlooked or misinterpreted because of inadequate well spacing, lack of high-resolution 3-D seismic data, or overlooked horizon slice imagery is not clear. At the least, their clear underrepresentation in the literature should prompt a reevaluation of previously interpreted incised valley systems, and a closer look at lowstand deltaic or shoreface systems that seem to lack fluvial feeder channels. Unincised lowstand alluvial deposits should be especially common in shallow marine basins with gentle ramp margins, such as intracratonic basins and shallow foreland basins. Such basins commonly lack a necessary high-gradient sea floor such as encountered at the outer shelf or upper slope on passive continental margins, which is required to induce valley incision. Where bona fide long-distance incised valleys are observed in such basins, a dominant factor of tectonics rather than sea level change should be considered.

The fact that not all lowstands of sea level result in valley incision has implications for deep-water deposition seaward of the shelf edge. If sea level falls do not fully expose the shelf (i.e., the outer shelf remains submerged), as inferred from the presence of shelfal nonincised lowstand alluvial systems (see previous discussion), then during these lowstands, depocenters do not reach the shelf edge. The shelf edge serves as the staging area for deep-water sedimentation, that is, those areas where sediment is either temporarily stored for later delivery to the deep water, or delivered directly to the deep water via density underflows from river mouths. Consequently, if depocenters do not reach shelf-edge staging areas during periods of sea level lowstand, then such lowstands would not be associated with widespread deep-water sedimentation. As discussed here, the occurrence of sea level fall that fully exposes the shelf is relatively uncommon (see Figures 18, 20A), and therefore it can be concluded that at least for the study area most periods of lowstand did not result in periods of active deep-water sedimentation. The extent to which this conclusion can be extrapolated to other areas and other stratigraphic intervals is uncertain. Other factors such as the duration of previous highstands and rates of sediment supply must also be considered. Nonetheless, the conclusions of this article suggest that care should be taken before making a one-to-one correlation between all sea level lowstands and the incidence of periods of active deep-water sedimentation.

CONCLUSIONS

Analysis of 3-D seismic data reveals the presence of both incised valley and unincised alluvial bypass systems within the Miocene and Pleistocene section of offshore northwest Java. Unincised alluvial deposits have a high width:thickness aspect ratio compared with incised valleys. Time slices and horizon slices show that unincised lowstand channels are common across the study area within the Pleistocene as well as the Miocene. Both incised and unincised systems are observed to lie embedded within offshore marine muds. The data also show that incised valleys are relatively isolated and uncommon; however, those that have been observed are seen to extend significant distances inland, reaching extents in excess of 200 km, with widths reaching 5 km and depths of approximately 14–41 m in the upsystem location. Incised valleys commonly are associated with small subordinate tributary valleys formed in association with drainage of adjacent interfluve areas. Where seismic resolution allows, these features can readily be imaged on time slices and/or horizon slices. The excellent-quality seismic data used in this study enables direct imaging of the physiography of incised valleys within the Pleistocene section and reveals near complete preservation of alluvial depositional elements within the valley, complete with alluvial terraces, channels, channel bars, and point-bar deposits with meander scrolls.

The common presence of unincised lowstand alluvial deposits is in stark contrast to the virtual absence of documented examples in the geologic literature. This study suggests that in tectonically quiescent areas, unequivocal extensive incised valleys form only if sea level fall is sufficient to fully expose the relatively steep gradient outer shelf and upper slope. Because of this, it is suggested that unincised lowstand alluvial deposits are far more common than heretofore realized. A reevaluation of published examples of incised valleys may reveal that some, if not many, are not, in fact, incised systems. Though both serve as conduits for sedimentary bypass, the reservoir architecture can be quite different, having significance for petroleum exploration and development.

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