ABSTRACT

Detailed stratigraphic evaluation of 3D seismic data from the Miocene section of the offshore northwest Java shelf reveals the extensive presence of preserved shelf ridges. These features are deposited as long linear bodies ranging from 0.3 to 2.0 km wide, over 20 km long, and up to 17 m high. Upon closer inspection, these features appear to be asymmetric, characteristically sharp-edged and thicker on one side, gradually thinning with an irregular edge on the other side. Possible sand waves, smaller in scale, are observed superimposed upon these ridges and oriented oblique to the long axes of the ridges. Shelf ridge deposits tend to be sand prone and are observed to overlie ravinement surfaces. The ridges appear to be oriented parallel to paleo trunk valleys associated with broad structural embayments. In addition to shelf ridges, shelf ribbons, possibly less than 5 m thick and less than 100 m wide, are also imaged.

Sand ridges are common on modern shelves, but rarely observed in the subsurface or in outcrop. The features observed here represent rare unequivocal examples of preserved ancient shelf ridges. These ridges are thought to have formed as a result of erosion and subsequent reworking of sand-prone delta plain and/or coastal plain deposits by shelf tidal currents that became active immediately after shoreline transgression. They appear to have migrated across the ancient sea floor and represent a significant component of the transgressive systems tract.

These transgressive systems tract deposits have significant exploration potential insofar as they are commonly sand prone and they tend to be encased in shelf mudstone seal facies. Depending upon the degree to which sand is present in inter-ridge locations, these linear sand bodies can comprise potential stratigraphic traps.

INTRODUCTION

Shelf sediments have been the focus of much analysis recently, especially in light of the development of sequence stratigraphic concepts (Plint et al. 1987; Plint, 1988; Posamentier et al., 1988; Swift and Thorne, 1991; Posamentier et al., 1992; Posamentier and Chamberlain, 1993; Snedden et al., 1994; Snedden and Dalrymple, 1999). Ample evidence exists for the presence of sand deposits on modern shelves (Swift and Field, 1981; Stride et al., 1982; Snedden et al., 1994; Snedden and Dalrymple, 1999); however unequivocal documented examples of ancient shelf ridges have been conspicuous by their absence in the recent literature. Whereas sandstones isolated in mid- to outer-shelf settings have been observed and documented, they have most commonly been interpreted to have formed not as shelf ridges but rather as incised valley or lowstand shoreface deposits (e.g., Plint et al., 1987; Posamentier and Chamberlain, 1993). These interpretations reflect the impact of the sequence stratigraphic approach during the past decade. Consistent with this approach, such shelf sands were thought to have been transported onto and across the shelf during low stands of sea level when much of the shelf might have been subaerially exposed. This mechanism afforded a more elegant mechanism for transportation of relatively coarse-grained sediment across a shelf than having sediment transported across a submerged shelf either by traction or suspension, sourced from the shoreline area (Scheihing and Gaynor, 1991).
A hybrid mechanism for developing and subsequently preserving shelf sands involves the reworking of lowstand deposits (shoreface, deltaic, channel fill, etc.) by shelf currents after transgression has occurred. This process is well known in shelf areas influenced by high current energy such as the southern North Sea (Stride et al., 1982), but nonetheless has not been widely embraced as capable of producing depositional elements that have any preservation potential.

This study identifies widespread ancient shelf sand bodies in the late Miocene of offshore northwest Java. These features were first recognized on seismic data and later calibrated with borehole data. Two areas offshore northwest Java where 3D seismic coverage was available, were the focus of this study (Fig. 1). The principal focus area was the area around the FXE-1 well covered by 167 km$^2$ of 3D seismic data. The secondary focus area was the area around the E-Field, covered by 110 km$^2$ of 3D seismic data. The seismic data were sampled at 2 msec intervals and the peak frequencies observed here are in the range of 30-35 Hz at a depth of approximately 800 m.

**REGIONAL SETTING**

This paper focuses on the upper part of the Main Member of the Upper Cibulakan Formation, which comprises a shallow marine siliciclastic succession of middle to upper-Miocene age (Arpandi et al., 1975; Ponto et al., 1987; Reksalegora, 1993; Reksalegora et al., 1996). An overall north-northeast to south-southwest direction of progradation has been observed (Purantoro et al., 1994; Reksalegora et al., 1996). Approximately 60 km to the south-southeast of this area the section thickens into the Cipunegara/E15 trough (Noble et al., 1997) and sandstones are less common. It has been estimated that sandstone reservoirs within this stratigraphic unit contain approximately 75% of all the hydrocarbons discovered to date in ARCO Indonesia’s offshore northwest Java PSC (Atkinson et al., 1993) within a section up to 700 m thick. Over 700 MMBO and 0.7 TCF have been produced from this unit to date.

The study area lies within the southwest-northeast trending Tertiary Offshore Northwest Java Basin. The underlying structural fabric is that of a half-graben, pull-apart extensional basin. Associated faults remained active during upper Cibulakan time, although structural activity was subdued at this time relative to the early Miocene and Oligocene.

**APPROACH**

The initial evaluation of the stratigraphic evolution of the Miocene section was accomplished through detailed analysis of 3D seismic horizon slices and interval attributes. Horizon slices were generated at 2 msec intervals using CGG Petrosystem’s Stratimagic seismic interpretation software. Horizon slicing was accomplished using multiple reference horizons, each having been chosen for its reflection continuity. Successive reference horizons generally were spaced at 100 msec intervals. Each horizon slice represented an amplitude extraction from a level at a fixed interval below the reference horizon. Where features were observed that warranted closer inspection, a variety of additional attributes were generated and analyzed.

Well logs were tied to the seismic slices for the purpose of calibrating the seismic images. Well log tendencies (e.g., fining-upward and coarsening-upward trends) relating to features observed on seismic data were noted. Cores were examined to evaluate the sedimentology of the observed features. Primary as well as secondary sedimentary structures were described, key surfaces were identified, and grain size and mineralogy were recorded.

**SEISMIC OBSERVATIONS**

At a number of levels in each of the two focus areas, long linear features were observed on horizon slices (Fig. 2). These linear features are expressed as bands of alternating light and dark amplitudes, in many instances extending across the data set. The orientation of these bands is quite consistent, ranging from north 20-30 degrees east. In some instances the bands narrow and even appear to pinch out and can appear less as bands than as sharp-edged patches (Fig. 3). The linear bands commonly range in width from under 0.5 km up to 4 km, although in some instances they can be significantly narrower than 0.5 km (Fig. 4). Commonly the bands appear well defined on one side and poorly defined on the other.

Figure 5 illustrates a close-up of the band imaged in Figure 2. This feature was examined in greater detail for the purpose of more accurately describing the internal and external architecture of this type of depositional element. Figure 6 illustrates three seismic sections across the seismic band imaged in Figures 2 and 5. Figure 6A illustrates the interval...
across which various attributes were derived. These seismic sections illustrate cross-sectional views across the band shown in Figure 5. In each instance, the cross-sectional view illustrates an apparent reflection phase reversal at the base of the feature at the northwestern edge of the seismic band. Likewise there is a consistency of expression marking the cross-sectional view of the southeastern edge of the seismic band. On that side, the edge of the seismic band is characterized on some sections by an onlapping reflection (Figs. 6B and 6C).

Several attributes for the interval bracketing the seismic feature illustrated in Figures 5 and 6 were generated for the purpose of further evaluating the stratigraphic body. Based on the interpreted top and base of this feature the resulting thickness map (in time) illustrates the asymmetric aspect of this deposit with the maximum thickness preferentially located on the northwestern side (Fig. 7). Note also the linear northwestern edge of this feature. The dip map of the upper bounding horizon (Fig. 8) illustrates the sharp linear edge as well as the high gradient of the northwestern edge of this feature. Other attributes (Figs. 9 and 10) also illustrate the linear aspect of this feature as well as the sharp delineation on the northwestern side contrasted with the more poorly defined edge on the southeastern side.

Two seismic attributes provide potential insight as to the internal stratigraphic architecture of this deposit (Figs. 11 and 12). Figure 11 illustrates a seismic facies map across the linear seismic anomaly. This map illustrates the result of grouping of seismic trace segments into “families” for the interval shown on Figure 6A, using CGG Petrosystems Stratimagic’s neural network approach. The analysis results in a map illustrating areas with similar seismic response and therefore similar rock properties. A arcuate-shaped area of uniform seismic response is observed oriented oblique to the long axis of the linear anomaly. A similar arcuate-shaped amplitude anomaly is observed in Figure 12. On this attribute map, two and possibly three parallel features are observed similar to that observed in Figure 11.

The seismic anomaly shown in Figure 3B is from same formation (i.e., Upper Cibulakan) but at E Field, located approximately 40 km to the northwest. This feature, described in Posamentier et al. (1998), is similarly sharp-edged on one side, and gradational on the other. In contrast to the feature shown in Figure 5, this feature does not thicken sufficiently to allow resolution of top and bottom. Rather, this feature is expressed in cross-section view as an increased amplitude (Fig. 13). Several parallel amplitude anomalies are observed at this level, separated by a 3-5 km gap (Fig. 14).

BOREHOLE OBSERVATIONS

The feature shown in Figure 5 has not been penetrated by drilling. Consequently there is no ground truth calibration available there. However, the feature shown in Figures 3 and 14 has been penetrated by several wells. Both wells (Fig. 15) and cores (Fig. 16) illustrate a sand-rich section sharply overlying a mud-rich section. Note that the log signatures associated with this feature range from coarsening upward to blocky to fining upward. The coarsening upward trend seems to be associated with the sharp-edged side of the patch shown on the western side of Figure 3 (Fig. 15A). Thinning characterizes the west to east trend across this seismic anomaly (Fig. 15A).

Conventional cores through this feature are available from the EZC-2 well at E-Field (Fig. 16). The deposits are intensely burrowed so that no primary sedimentary structures are preserved. The grain size ranges from upper fine to medium. These sands are abruptly separated from the underlying muddy section by a well-defined surface characterized by a Glossifungites ichnofacies, with Thalassanoides traces common.

GEOLOGIC INTERPRETATION

Both the seismic and borehole observations point to an interpretation of shelf ridges for the band and patch anomalies observed on Figures 2 and 3 respectively. These features appear to have migrated across the shelf, likely during a time of shoreline transgression. Figure 17 illustrates the stages that characterize the formation of these deposits. The presence of upper fine to medium sand within these interpreted features suggests that it would be unlikely that these sediments were brought out as plumes through the water column (Scheiing and Gaynor, 1991). Rather, these relatively coarse sediments likely were transported onto and across the shelf within fluvial or distributary channels across alluvial and/or coastal plains, en route to deltas and shorelines beyond. These deposits then were eroded during the subsequent transgression and re-deposited on the shelf as palimpsest deposits. Both
ridges and ribbons seem to have formed at that time (Figs. 2, 3, and 4). Based on the near total absence of sedimentary structures indicative of wave action in this area (Posamentier et al., 1998), coupled with the presence of tidal indicators (Posamentier et al., 1998), a tidal current origin for these features is suggested.

The surface at the base of the sand deposits observed in EZC-2 (Fig. 16) separates muddy shelf deposits below from shelf ridge deposits above. The presence of a Glossifungites ichnofacies suggests erosion of a partially indurated substrate (MacEachern et al., 1992). The currents that eroded the substrate also acted as winnowing agents resulting in deposition of lag deposits across this erosion surface. The lag nature of such deposits is illustrated in Figure 18. The sand characterized by the bell-shaped gamma-ray log signature at 3574-3590 ft (1089-1094 m) can be separated into two genetic units near the peak of the gamma-ray curve. As shown by the UV-light illuminated core, the permeability is markedly better above this surface than below. Once again, this bounding surface is characterized by a Glossifungites ichnofacies. This surface is interpreted to constitute a transgressive surface separating underlying regressive deposits from overlying shelf-redeposited transgressive lag deposits. The higher permeability of the overlying sediment is indicative of its cleaner (i.e., less muddy) character.

A shelf ridge origin for these deposits is indicated by 1) the striking linearity of these deposits as observed on the seismic data (Figs. 2 and 3), 2) the presence of a sharp erosional contact marked by a Glossifungites ichnofacies at the base of these deposits, 3) the presence of muddy shelf sediments immediately underlying as well as overlying these deposits, 4) the presence commonly of a sharp edge on one side of these features, and 5) the asymmetry of these features, generally being thicker along the more sharply defined edge.

The direction of shelf ridge migration can be inferred to be in the direction of the sharp edge of these deposits (Figs. 7, 8, 9, and 10). The sharp edge is believed to represent the leading edge, whereas the gradational side is believed to represent the trailing edge. The presence of the best developed coarsening-upward log pattern (well EE-1 in Fig. 15A) near the leading edge of the shelf ridge shown in Figure 3, supports the sense of migration and progradation in that direction.

The detailed architecture of the ridge is shown by two interval attributes (Figs. 11 and 12). The anomalies superimposed on the shelf ridge could represent sand waves superimposed upon and migrating down the long axis of the ridge (Fig. 19). Note the apparent en echelon aspect of these features (Fig. 12). The orientation of these superimposed features suggests a subordinate vector toward the sharp edge of the ridge, with a dominant vector down the long axis of the ridge.

**Modern Analog**

The shelf ridges described by Liu et al. (1998) serve as a modern analog for the deposits described here. Liu et al. (1998) described a field of shelf ridges that formed during the late Pleistocene to early Holocene transgression within the greater Pleistocene Yang-Tze embayment in the East China Sea shelf area (Fig. 20). These ridges were formed in a tide-dominated setting that characterized the Yang-Tze embayment mouth during transgression. With each successive landward step of the embayment mouth, a new cluster of ridges formed (Fig. 20). Eventually, the result of this landward stepping of depositional environments was a field of shelf ridges (the oldest located at the outer shelf and the youngest located on the inner shelf) c. 200 km wide from one side of the paleo embayment to the other, and from the outer to the inner shelf (Fig. 20).

Individual ridges described by Liu range from 2-5 km wide, up to 30-40 km long, and up to 25 m high. A transverse seismic profile across one such ridge is shown in Figure 21. Note the asymmetry as well as the sharp leading edge. Note also the progradational architecture within this ridge. Although the same level of internal detail shown in Figure 21 is not available for the Miocene Java sea example, the sense of progradation within the East China Sea example, indicated by the oblique tangential clinoform seismic reflections, is consistent with the sense of progradation indicated by the log signature of the Miocene Java Sea example (well EE-1 in Fig. 15A). The similar origin of the two features is further underscored by the similarity of the dimensions, shape, and form.

The striking similarities between the East China Sea shelf ridges and the Miocene deposits of offshore northwest Java described here suggest a shelf ridge origin for the latter features. Taking this comparison
further, we would suggest that the Miocene linear shelf-ridges are oriented parallel to paleo-embayment long axes (i.e., north-northwest to south-southeast). This interpretation is consistent with the regional orientation of land and sea, as well as the orientation of the long axes of structurally influenced embayments (Reksalegora, 1993; Reksalegora et al., 1996).

**EXPLORATION SIGNIFICANCE**

The findings of this study suggest that shelf ridges can constitute a significant transgressive systems tract play type. These deposits are long (>20 km) and narrow (from a few tens of meters up to 2 km wide), and can be up to 15 m thick. They are also strikingly linear in plan view. Based on borehole penetrations they appear to be sand prone, containing up 80% net sand. This play type is known to produce at several fields within the offshore northwest Java PSC.

The extent to which shelf ridge deposits can stratigraphically trap hydrocarbons is unclear at the present time. It is not clear whether these deposits can be characterized as fractal equivalents of much smaller starved ripple sedimentary bedforms. If they can be so characterized, then the absence of sand between ridges will be associated with discrete pinchout of sands away from the ridges. Such a pinchout, or potential stratigraphic trap, will be best defined at the leading rather than the trailing edge of these features.

From a field development perspective, the recognition of these features may provide valuable insight to reservoir compartmentalization and the identification of possible sweet spots (Figs. 11 and 12). This would allow optimization of primary and secondary recovery strategies.

Where shelf ridges are observed to be deposited directly on shelf muds and separated from those muds by a sharp surface representing a significant time gap, the surface upon which those deposits are lying could constitute a sequence boundary. A mode of origin as shown in Figure 17 suggests that in some instances the surface upon which the sand ridges lie could constitute a zone of sedimentary bypass between inner-shelf highstand deposits and outer-shelf lowstand deposits. Thus, in those instances the presence of thin transgressive lag, or thicker shelf ridges, would point to the outer shelf as a possible location of lowstand shoreface or deltaic deposits.

**SUMMARY AND CONCLUSIONS**

Shelf ridges can potentially constitute a significant transgressive play type. They have a distinctively linear form and are common throughout the Miocene Upper Cibulakan Formation of offshore northwest Java. Such deposits are known to produce from several sections in numerous fields within the Offshore Northwest Java (ONWJ) PSC. Shelf ridges observed here commonly range from 0.5-2.0 km wide, >20 km long, and up to 17 m thick. They are observed to contain up to 80% net sand. Because of the winnowing process associated with their deposition, reservoir quality is excellent in comparison with deltaic and shoreface sands in the area.

The shelf ridges observed and described in this study represent one of the first unequivocal examples of a stratigraphic feature common on modern sea floors but conspicuous in their absence from the geologic literature with regard to ancient deposits. This suggests that shelf ridges do have the potential for preservation into the rock record and opens the door for the possible reinterpretation of similar deposits elsewhere.

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**REFERENCES**


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FIGURE 1 - Location map illustrating the location of E and FXE fields in offshore northwest Java.
FIGURE 2 - Horizon slices and reflection amplitude extractions from three levels (A - 2300, B - 2320, C - 2480; numbers refer to depth in feet referenced to well FXE-1) within the Upper Cibilakan Formation, "Main" stratigraphic unit, at FXE field.
FIGURE 3 - Horizon slices from two different levels at E field illustrating shelf ridges oriented northeast-southwest. Note that each of the ridges is well defined on its northwestern side. A) illustrates two small isolated shelf ridges, and B) illustrates a relatively large shelf ridge lower in the section. Note the channel oriented nearly orthogonal to the shelf ridge. This channel lies stratigraphically below the level of the shelf ridge.
FIGURE 4 - Horizon slice from FXE field showing well-defined shelf ribbons oriented northeast-southwest. Note that the shelf ridges (shown as dark bands) range in widths from 0.3 to 0.7 km wide and some extend the width of the data set.
FIGURE 5 - Close-up of shelf ridge located in southeast corner of horizon slice shown in Figure 2A. Note the sharply delineated northwestern edge. The inlines highlighted are shown in Figure 6.
FIGURE 6 - Three seismic sections oriented transverse to the long axis of the shelf ridge shown in Figure 5. 
A) This section illustrates the shelf ridge and the seismic interval that formed the basis for the attribute extractions illustrated in Figures 7-12. (B) and (C) Note the seismic phase reversal at the left edge of the shelf ridge (shown in A) and note the onlapping seismic reflection against the eastern side of the ridge. The color bars on the seismic sections correspond to the seismic facies shown on Figure 11 (for an explanation of the significance of this attribute, refer to caption for Fig. 11). See Figure 5 for line location.
FIGURE 7 - Isochron map of the shelf ridge shown in Figures 5 and 6. Note that the thickest part of the ridge is located closest to its northwestern edge. The northwestern pinchout edge is markedly linear. Maximum thickness is 15 msec (approximately 20 m).
FIGURE 8 - Dip map of the upper bounding surface of the shelf ridge shown in Figures 5 and 6. Note the sharp, steep boundary characterizing the northwestern edge of the ridge.
FIGURE 9 - Map of the strongest negative polarity events within the interval shown on Figure 6A. Note the well-defined northwestern edge of the shelf ridge.
FIGURE 10 - Map of summed amplitudes corresponding to 20% of the total amplitude of the highest amplitude trace segment within the seismic interval shown on Figure 6A (the interval thickness is 36 msec).
FIGURE 11 - Seismic facies map using neural network algorithms of CGG Petrosystems Stratimagic software. In this analysis of the seismic interval shown on Figure 6A, all traces are grouped by affinity to 24 trace families and then shown in map view. Note the arcuate-shaped family suggesting the possible presence of a smaller sand wave superimposed on the larger shelf ridge and aligned slightly oblique to it.
FIGURE 12 - Map of the third derivative of amplitude distribution within the seismic interval shown in Figure 6A. Note the arcuate fields within the shelf ridge boundaries (compare with Fig. 11), suggesting the possible presence of smaller sand waves superimposed on the larger shelf ridge.
FIGURE 13 - Succession of seismic sections spaced at 312.5 m intervals across the E-Field shelf ridge illustrated in Figure 3B. Line 490 is the farthest north and line 690 is the farthest south. Note the sharp termination of the high-amplitude reflections on the western side (inferred to be the leading edge of the shelf ridge) contrasted with the more gradual decrease of amplitude on the eastern side (inferred to be the trailing edge of the shelf ridge). For location, see Fig. 15B.
FIGURE 14 - Map of summed amplitudes corresponding to 20% of the total amplitude of the highest amplitude trace segment within a seismic interval 120 msec thick containing the shelf ridge shown in Figures 3B and 13. Note the additional linear shelf ridges in the central and southern part of the area shown.
FIGURE 15 - Well-log cross-section (A) across the sand ridge shown in Figures 3B and 13. Note that the thickest section is located close to the northwestern pinchout and that a coarsening up log profile marks the well-log signature. The maximum sand thickness is 17 m. B) illustrates the orientation of the well log cross section as well as the locations of inlines illustrated in Figure 13.
FIGURE 16 - Core with well-log from basal shelf ridge deposits at EZC-2 well. The log signature is characterized by a sharp base and fining-upward trend. The core indicates the presence of a Glossifungites ichnofacies at the contact between upper fine to medium-grained sandstone above and mudstone below. The sand is interpreted to be shelf ridge sand separated from offshore mud by a transgressive ravinement surface (after Posamentier et al., 1998).
FIGURE 17 - This illustration depicts the stages that characterize the formation of shelf ridge deposits. Time 1 represents a time of sea-level highstand. At this time only shelf muds are deposited and the shoreline lies landward of the study area. At time 2, sea-level fall exposes the sea floor and the shoreline moves seaward across the study area. Ephemeral downstepping shoreface and deltaic sediments as well as channelized (incised valley?) sediments can be deposited across the shelf at this time. At time 3, sea level has again risen and has flooded across the shelf. Erosive processes associated with transgression erode the substrate and shelf (tidal?) currents winnow the deposits producing localized shelf ridges (after Posamentier et al., 1998).
FIGURE 18 - Core and well log from BM-2 in offshore northwest Java illustrates the lithologic and log expression of transgressive shelf deposits overlying regressive shelf deposits. The core, illuminated with UV light, illustrates that the sediments overlying the gamma ray peak are markedly more saturated with residual oil than those below. This is consistent with the observation that transgressive processes tend to induce sediment winnowing of fines and therefore relative enhancement of reservoir quality.
FIGURE 19 - Schematic illustration of shelf ridge morphology. The leading edge is sharply defined and linear whereas the trailing edge is more poorly defined. Superimposed on the crest of the ridge is a smaller sand wave oriented oblique to the long axis of the shelf ridge (compare with Figs. 11 and 12).
FIGURE 20 - Pleistocene to Holocene shelf ridges on the East China Sea shelf outboard of the Yangtze River (from Liu et al., 1998). These ridges formed under the influence of tidal energy within the broad embayment associated with the paleo-Yangtze River. They formed during the late Pleistocene to early Holocene transgression as the shelf was progressively drowned. These shelf ridges are up to 20-km long, 4 km wide, and up to 20 m thick, occupying an area nearly 400 km wide. Note that the orientation of the long axes of these ridges is parallel to the inferred embayment axis rather than any regional shoreline trend.
FIGURE 21 - The seismic section shown here represents a transverse section through one of the ridges shown in Figure 20. Note the asymmetry of the stratigraphic unit. Note also the internal clinoforms within the ridge suggesting a progradational origin for this feature (from Liu et al., 1998).