

Ancient shelf ridges—A potentially significant component of the transgressive systems tract: Case study from offshore northwest Java

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ABSTRACT

Detailed stratigraphic evaluation of three-dimensional (3-D) seismic volumes calibrated with well-log and core data from the Miocene section of the offshore northwest Java shelf reveals the extensive presence of preserved shelf ridge deposits. These features are long linear bodies ranging from 0.3 to 2.0 km wide, more than 20 km long, and up to 17 m high. On close inspection, these features appear to be asymmetric, characteristically sharp-edged and thicker on one side and gradually thinning with an irregular edge on the other side. Possible sand waves, smaller in scale, are observed superimposed on these ridges and oriented oblique to the long axes of the ridges. The observed shelf ridge deposits tend to be sand prone and overlie ravinement surfaces. The ridges appear to be oriented parallel with the axes of broad paleoembayments associated with the structural fabric of the basin. 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 significantly less commonly recognized in the subsurface or in outcrop. The features observed here represent examples of preserved ancient shelf ridges. These ridges are thought to have formed as a result of erosion and subsequent reworking of sand-prone deltaic and/or coastal-plain deposits by shelf tidal currents, which became active immediately after shoreline transgression. These deposits appear to have migrated across the ancient sea floor and represent an important component of the transgressive systems tract.

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

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INTRODUCTION

Shelf sediments have been the focus of much analysis recently, especially within the context of recently developed 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 (Caston and Stride, 1970; Swift and Field, 1981; Stride et al., 1982; Amos and King, 1984; 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. Sandstones isolated in mid- to outer-shelf settings have been observed and documented. Whereas significant debate as to their origin persists (Snedden and Bergman, 1999; Suter and Clifton, 1999), they nonetheless have been most commonly interpreted to have formed not as shelf ridges but instead as incised valley or lowstand shoreface deposits (e.g., Plint et al., 1987; Van Wagoner et al., 1991; Posamentier and Chamberlain, 1993; Bergman and Walker, 1995; Bergman and Walker, 1999; Burton and Walker, 1999; MacEachern et al., 1999). These interpretations reflect the impact of the sequence stratigraphic approach during the past decade. Consistent with this approach, such shelf sands were suggested to have been transported onto and across the shelf during lowstands of sea level, when much of the shelf would have been subaerially exposed. This mechanism afforded a more elegant mechanism for transportation of relatively coarse-grained sediment across a shelf by nonmarine processes than having sediment transported across a submerged shelf either by traction or suspension (sourced from the shoreline area) (Scheiing 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 significant preservation potential to be recorded in the rock record.

This article identifies widespread ancient shelf sand bodies of the late Miocene offshore northwest Java. These features were first recognized on seismic

data and later calibrated using borehole data. Two areas offshore northwest Java where three-dimensional (3-D) seismic coverage was available were the focus of this article (Figure 1): (1) the area around the FXE-1 well, covered by 167 km² of 3-D seismic data, and (2) the area of the E field, covered by 110 km² of 3-D 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 article focuses on the upper part of the Main Member of the Upper Cibulakan Formation, which comprises a middle–upper Miocene shallow-marine siliciclastic succession (Arpandi and Patmosukismo, 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, and sandstones are less common (Noble et al., 1997). Sandstone reservoirs within the Upper Cibulakan Formation have been estimated to contain approximately 75% of all the hydrocarbon reserves discovered to date in ARCO Indonesia's offshore northwest Java Production Sharing Contract (PSC) (Atkinson et al., 1993) within a section up to 700 m thick. More than 700 million bbl of oil and 0.7 tcf of gas have been produced from this unit to date.

The study area lies within the southwest-northeast-trending Tertiary Northwest Java Basin. The underlying structural fabric is that of a series of extensional half grabens initiated during the late Eocene–Oligocene. Associated faults remained active during the late Cibulakan, 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 3-D seismic horizon slices and interval attributes. Horizon slices were generated at 2 msec intervals using Paradigm's STRATIMAGIC (patented from Elf Sismage technology) seismic interpretation soft-

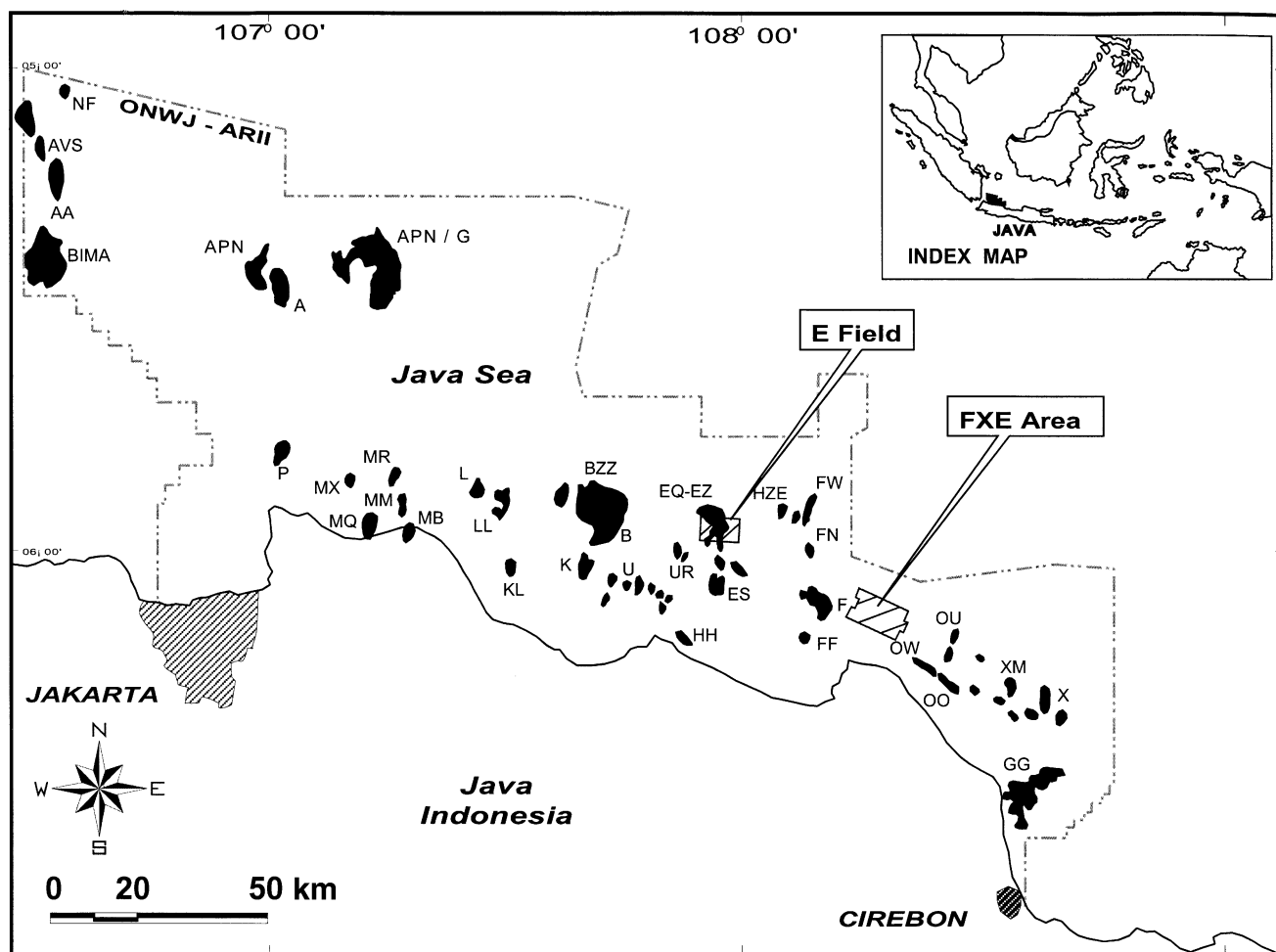


Figure 1. Map illustrating the location of E field and FXE area offshore northwest Java. (ONWJ-ARII = Offshore Northwest Java-Atlantic Richfield Indonesia Inc.)

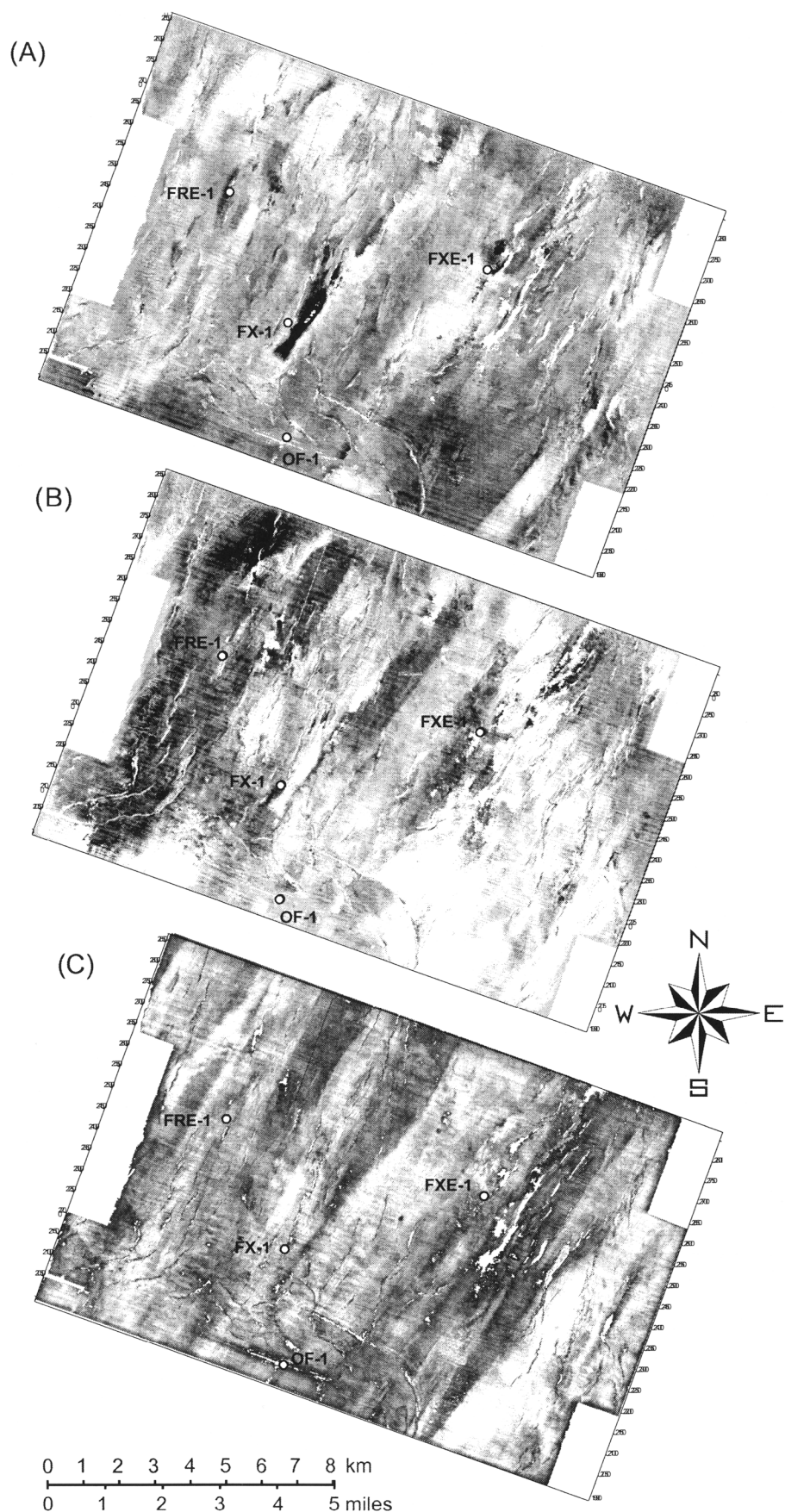
ware. Reconnaissance horizon slicing was accomplished using multiple reference horizons, each having been chosen for its reflection continuity. Successive reference horizons generally were spaced at 100 msec intervals. Each horizon slice represented an amplitude extraction from a level at a fixed interval below or above the reference horizon. Where features were observed that warranted closer inspection, a variety of additional attributes were generated and analyzed.

Calibration of seismic images was achieved by tying borehole data to the seismic slices. Well-log tendencies (e.g., fining-upward and coarsening-upward trends) relating to features such as coherent amplitude distributions 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.

OBSERVATIONS

At several stratigraphic levels in each of the two focus areas, long linear features were observed on reconnaissance seismic horizon slices (Figure 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 20 to 30° east of north. In some instances, the bands narrow and even appear to pinch out. In other instances, the features appear less as bands than as sharp-edged elongate patches (see discussion of the 2732-West anomaly in following sections). The linear bands commonly range in width from less than 0.5 km up to 4 km, although in some instances they can be significantly narrower than 0.5 km (Figure 3). Commonly, the bands appear well defined on one side and poorly defined on the other.

Figure 2. Reflection amplitude extractions based on horizon slices from three levels (A = 2300, B = 2320, C = 2480; numbers refer to depth in feet referenced to well FXE-1) within the Upper Cibulakan Formation, Main Member stratigraphic unit, at FXE field.



The following section describes several of these Miocene-age asymmetric linear- to patchlike features from the FXE and E field areas (Figure 1). All the examples come from the Main Member of the Upper Cibulakan Formation (Reksalegora et al., 1996). Note that there are no borehole data available for calibration of the feature in the FXE area, shown in Figure 2. This example is presented here because the seismic data quality is excellent and because it is similar to features observed in the E field, where there is extensive available borehole data. The observations in the FXE area strictly involve seismic attributes. In contrast, in the E field area, there exist many such features with numerous borehole penetrations. The following sections describe the relevant observations.

FXE Area Seismic Data

Figure 4A illustrates a close-up of the band imaged in Figure 2A. 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. The dimensions of this feature are 0.8–1.0 km wide, more than 6 km long (this feature extends beyond the seismic coverage), and up to 17 m thick (see Table 1 for a summary of all shelf ridge dimensions). Figure 4B–D illustrates three seismic sections across the seismic band imaged in Figures 2 and 4A. Figure 4B shows the interval across which various attributes were derived. These seismic sections illustrate cross sectional views across the

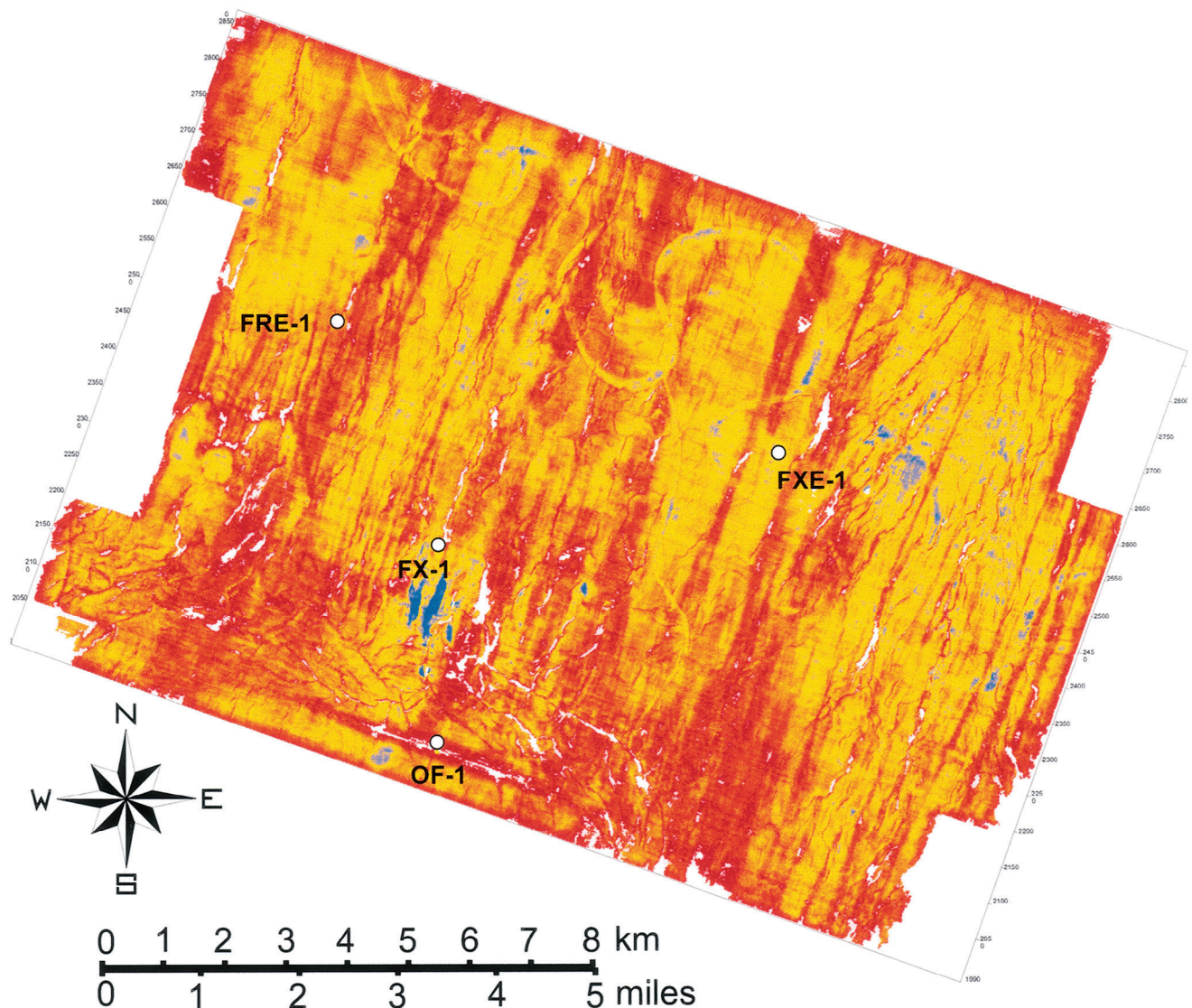


Figure 3. Horizon slice from FXE field (at approximately the 2600 ft level, referenced to well FXE-1) showing well-defined shelf ribbons oriented northeast-southwest. Note that the shelf ridges (shown as dark bands) range in width from 0.3 to 0.7 km, and some extend the width of the data set.

Figure 4. (A) Close-up of shelf ridge located in southeast corner of horizon slice 2300, shown in Figure 2A. Note the sharply delineated northwestern edge. Parts B–D show seismic profiles across the shelf ridge shown in A. (B) In-line seismic profile 2139 (see Figures 2A, 4A for location) shows the seismic interval that was the basis for the attributes illustrated in Figure 5C–F. Arrows indicate the lateral limits of the shelf ridge. (B, 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 (B). The color bars on the seismic sections correspond to the seismic facies shown on Figure 5E.

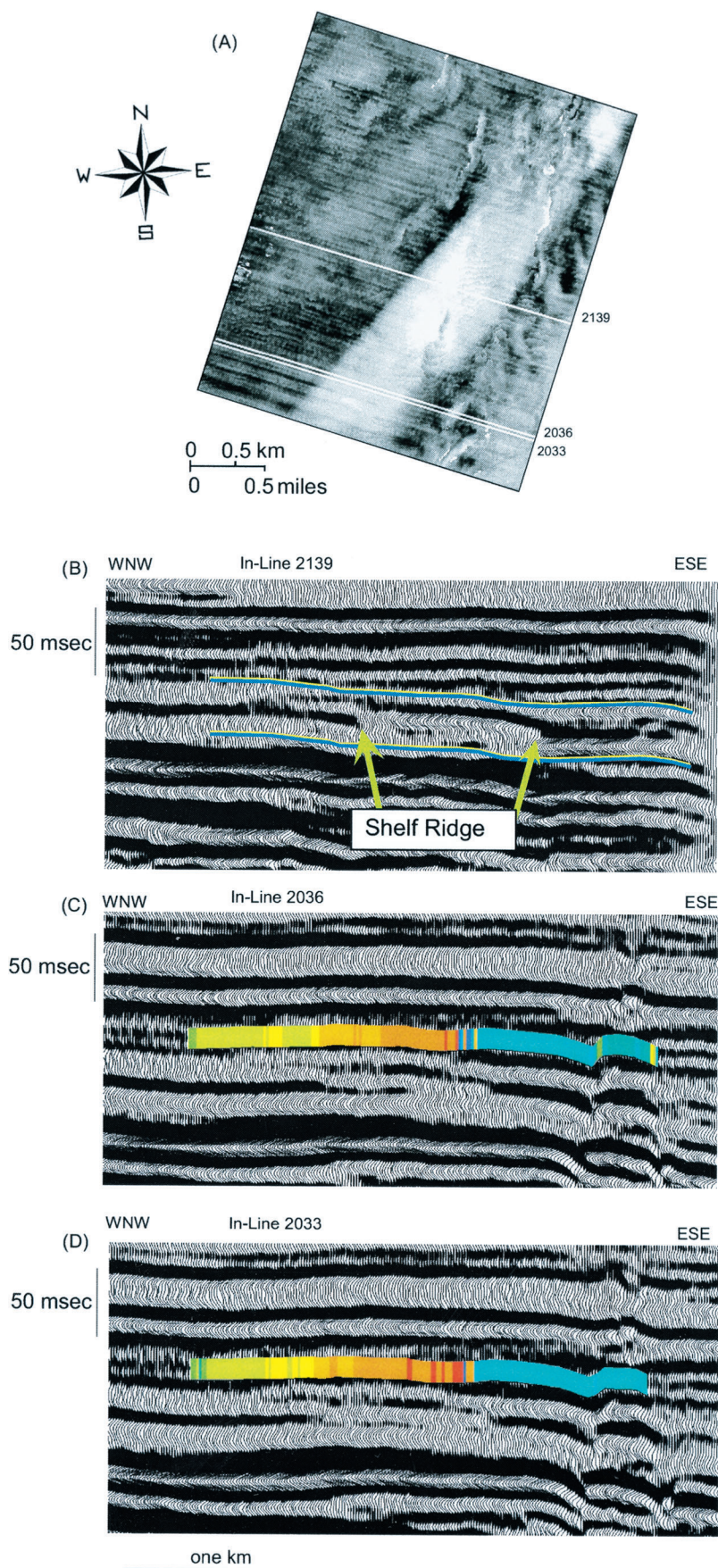


Table 1. Summary of Shelf Ridge Attributes in FXE and E Field Areas

Ridge Name*	Reference:		Reference:	Width (km)	Length (km)**	Thickness	Fluids	Log Response†	Spacing (km)	Zero Pinch-Out Confidence Level (1–10)††	Area	Best Expressed	Apparent Migration Direction
	Horizon Slice	Relative to Datum (msec)	Horizon										
2480 ¹		30		0.5	2.2	2	gas	bell	isolated	10	E-Field, east	E-10 (2480 MD)	NW
2528 ³			X	2	6+	12	oil	cu	0.8	9	E-Field, west	EE-1 (2528 MD)	NW
2635 ¹		–52		0.5	3+	3		bell-fu	isolated	8	E-Field, east	ETB-25T (3292 MD)	
2732 ²		–42		0.7	4+	4	oil	cu-bell-fu	0.8	2	E-Field, east	ETB-4 (3377 MD)	NW
2767 ⁴			X	0.5	4+	5		bell-fu	0.3–0.8	3	E-Field, west	E-6 (2767 MD)	
2836 ¹		12		0.3	3+	7		fu	0.5 (?)	3	E-Field, east	ETA-4 (3355 MD)	
2877 ¹		16		0.3	3.5+	6		cu-bell	0.3	2	E-Field, east	ETB-1 (2831 MD)	
2894 ⁴		38		0.4	3.5+	6		fu-bell	isolated	9	E-Field, west	E-6 (2894 MD)	
2910 ¹		26		0.4	4+	7	gas	fu	0.3	5	E-Field, east	E-10 (2910 MD)	
2300e ⁵		–44		0.8	6+	17			isolated	7	FXE, east		NW
2300w ⁵		–44		1.3	6+	2+	gas/water	bell	isolated	7	FXE, west	FX-1 (2273 MD)	SE
2320 ⁵		–36		1.2	10+				isolated	7	FXE, east		NW
2480e ⁵			X	1.7	12+				0.5	7	FXE, east		SE
2480w ⁵			X	1.3	6+				0.5–2.0	7	FXE, west	FX-1 (2437MD)	SE
2690 ⁵			X	0.2–0.4	8+				0.3	2	FXE		

*1 = referenced to well E-10; 2 = referenced to well ETB-4; 3 = referenced to well EE-1; 4 = referenced to well E-6; 5 = referenced to well FXE-1.

**+ indicates a ridge length that extends beyond the 3-D grid.

†cu = coarsening upward; fu = fining upward; bell = bell-shaped (i.e., coarsening, then fining upward).

††1–10 indicates a low to high confidence level that a zero pinch-out of the shelf ridge can be determined.

band shown in Figure 4A. In each instance, the cross sectional view illustrates an abrupt 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 commonly characterized by an onlapping reflection against a more ramplike seismic configuration (Figure 4B).

Several attributes for the interval bracketing the seismic feature illustrated in Figure 4 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 (Figure 5A). Note also the linear northwestern edge of this feature. The dip map of the upper bounding horizon (Figure 5B) illustrates the sharp linear edge, as well as the high gradient of the northwestern edge of this feature. Other attributes (Figure 5C, D) 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 (Figure 5E, F). Figure 5E illustrates a seismic facies map across the linear seismic anomaly. This map illustrates the result of grouping seismic trace segments into classes for the interval shown on Figure 4B, using Paradigm's Stratimagic neural network approach. The analysis results in a map illustrating areas with similar seismic response and, therefore, possibly similar rock properties. An arcuate-shaped area of uniform seismic response is observed oriented oblique to the long axis of the linear anomaly. A similar arcuate-shaped ampli-

tude anomaly is observed in Figure 5F. On this attribute map, two, and possibly three, parallel arcuate features are observed similar to that observed in Figure 5E.

E Field Area

Several seismic anomalies similar to that described at FXE field were observed in the E field area (Figure 1). Seismic and associated borehole observations are presented for three of these features, two of which (designated the 2480 and 2732 ridges) are shown in profile on Figure 6B. Also on this same seismic profile (Figure 6B), two other ridges are observed (designated the 2836 and 2910 ridges). The numerical designation of these features is based on borehole depths of key wells (Table 1).

2480 Anomaly

The 2480 seismic anomaly is shown on the horizon slice in Figure 7. This seismic anomaly is separated into two segments. Each segment is approximately 2.5 km long and 0.75 km wide. Their long axes are both oriented north-northeast by south-southwest. The two anomalies appear to slightly overlap each other, with the north segment lying slightly farther (approximately 100 m) to the west of a north-northeast by south-southwest axial line. A sharp linear edge on the west-northwest side and a more poorly defined edge on the east-southeast side define each anomaly segment. Each segment seems to widen southward, giving each segment the appearance of bulging to the south.

Figure 8 illustrates a seismic facies map and associated seismic facies correlation map. Figure 8 also illustrates the seismic facies distribution according to trace class, and, more important, it illustrates how well each trace correlates with its designated class. This approach to seismic facies mapping involves neural

Figure 5. (A) Isochron map of the shelf ridge shown in Figure 4. Note that the thickest part of the ridge is located closest to its northwestern edge. The northwestern pinch-out edge is markedly linear. Maximum thickness is 15 msec (approximately 20 m). (B) Dip map of the upper bounding surface of the shelf ridge shown in Figure 4. Note the sharp, steep boundary characterizing the northwestern edge of the ridge. (C) Map of the strongest negative polarity events within the interval shown on Figure 4B. Note the well-defined northwestern edge of the shelf ridge. (D) Map of summed amplitudes corresponding to 20% of the total amplitude of the highest amplitude trace segment within the seismic interval shown on Figure 4B (the interval thickness is 36 msec). (E) Seismic facies map using neural network algorithms of Paradigm's Stratimagic software. In this analysis of the seismic interval shown on Figure 4B, all traces are grouped by affinity to 24 trace classes and then shown in map view. Note the arcuate-shaped class, suggesting the possible presence of a smaller sand wave superimposed on the larger shelf ridge and aligned slightly oblique to it. (F) Map of the third derivative of amplitude distribution within the seismic interval shown in Figure 4B. Note the arcuate fields within the shelf ridge boundaries (compare with part E), again suggesting the possible presence of smaller sand waves superimposed on the larger shelf ridge.

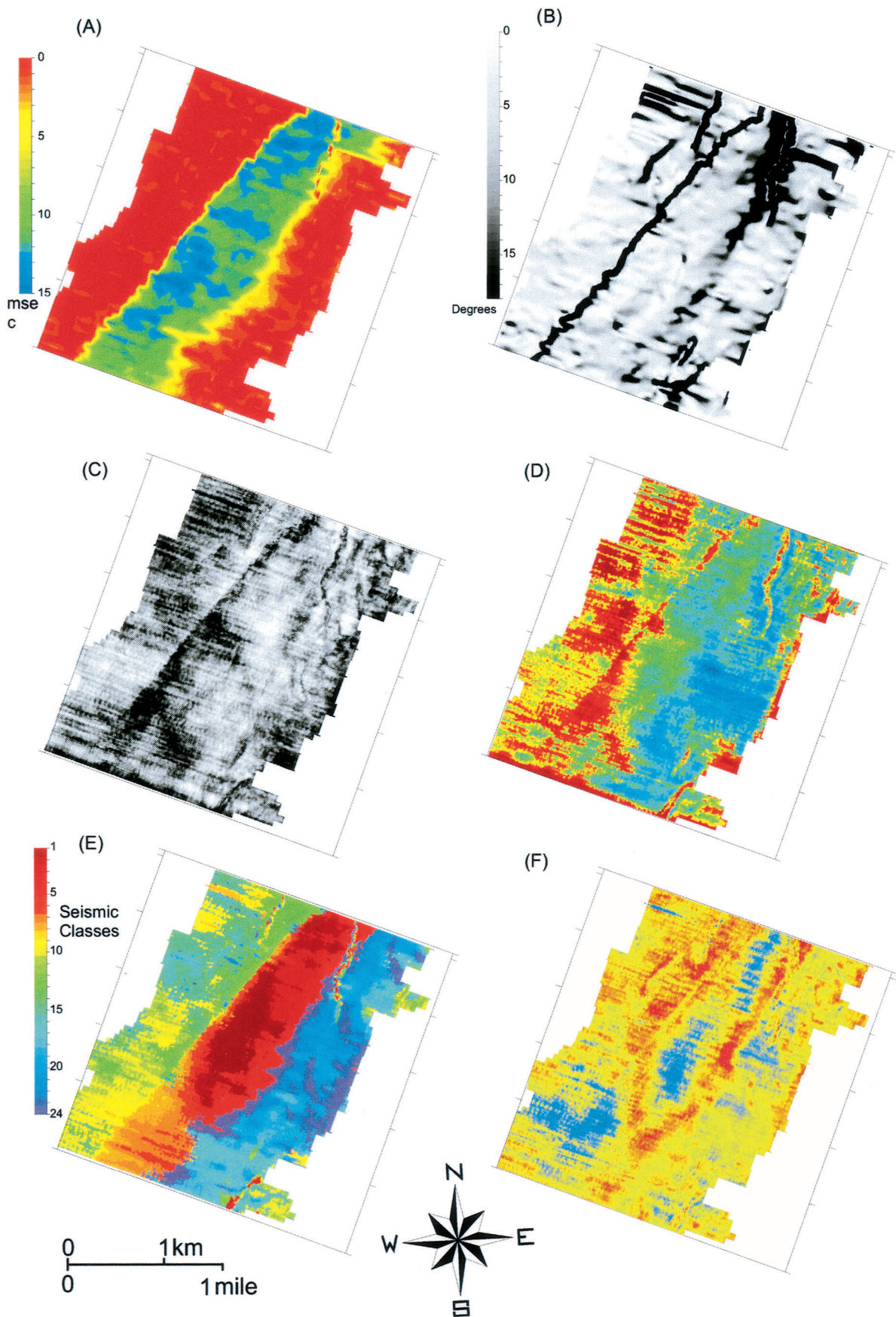
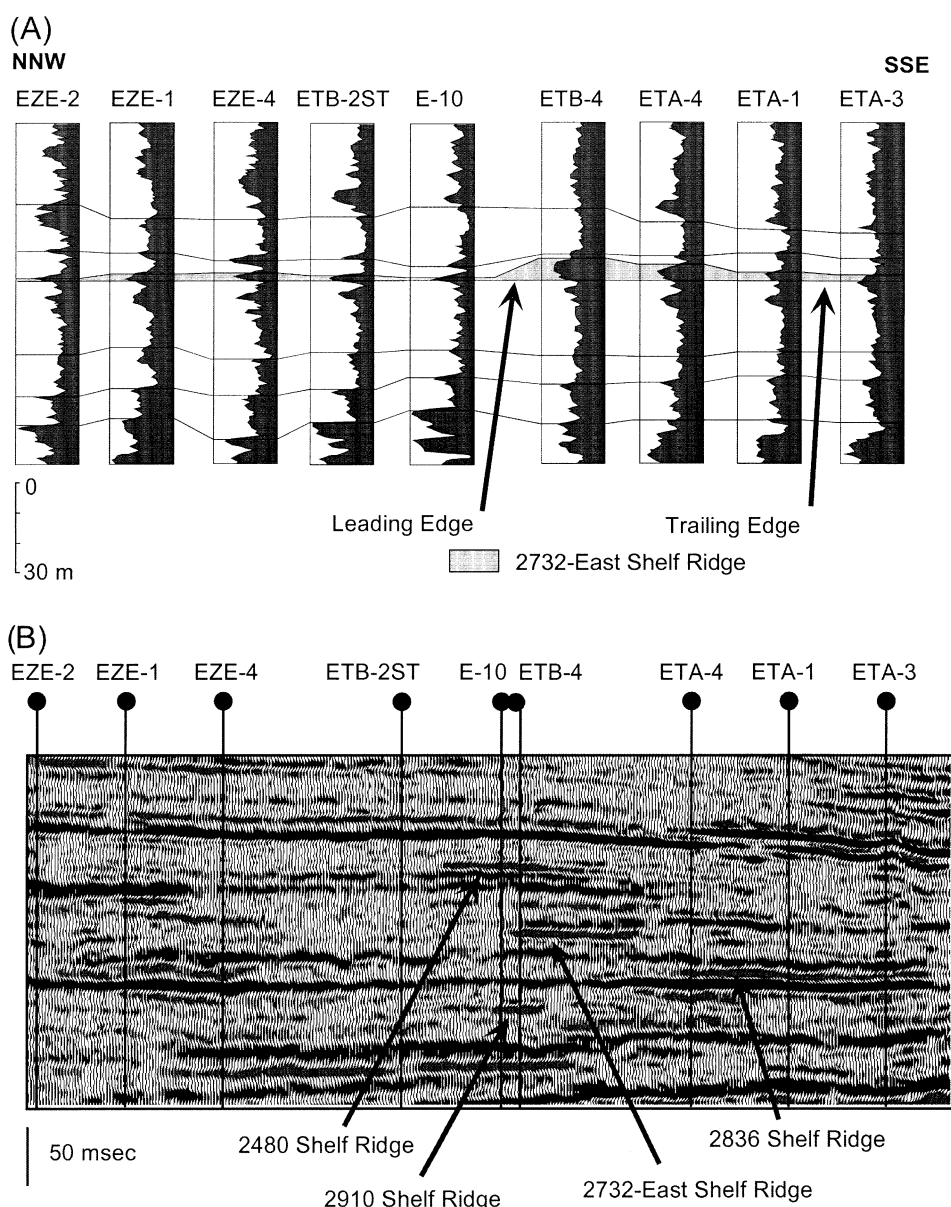


Figure 6. (A) Well-log cross section through 2732-East shelf ridge. Note that the number designation of shelf ridges refers to corresponding depths in key wells (see Table 1 for reference). Maximum borehole-penetrated thickness of this shelf ridge is 4 m, as observed at well ETB-2. Note progressive thinning of the shelf ridge from the leading toward the trailing edge. (B) Seismic profile parallel with well-log cross section shown in A. Note the stacked shelf ridges: 2480, 2732, 2836, and 2910. Each is characterized by an increased amplitude or a brightening of a seismic trough.



network algorithms using Paradigm's STRATIMAGIC software, wherein traces are grouped by affinity into computer-defined seismic trace models based on analysis of a subset of all seismic traces from a user-defined seismic interval. Similar colors on the seismic facies map (Figure 8A) imply similar acoustic properties. Note that the correlation map (using an 87% threshold) shown in Figure 8B illustrates that, for much of the area of coverage, there exists only poor correlation between seismic traces and their assigned class. The notable exception is from the vicinity of the seismic anomaly shown in Figure 7, where correlation coefficients systematically are greater than 87%. This suggests that the seismic traces in the areas of poor cor-

relation correspond to sections with acoustically indistinct properties that are barely distinguishable from background noise. In contrast, those traces in the vicinity of the amplitude anomaly, which correlate well with their respective classes, suggest a lithology with distinctive and regionally distributed acoustic properties.

Figure 9B illustrates a series of seismic transects across the southern segment of the 2480 anomaly. Successive east-west lines spaced at 250 m show the seismic profile expression of this anomaly. Note that it is expressed clearly as an amplitude brightening from seismic lines 630 to 710, with the best expression on line 710. As shown on line 710, the anomaly brightens

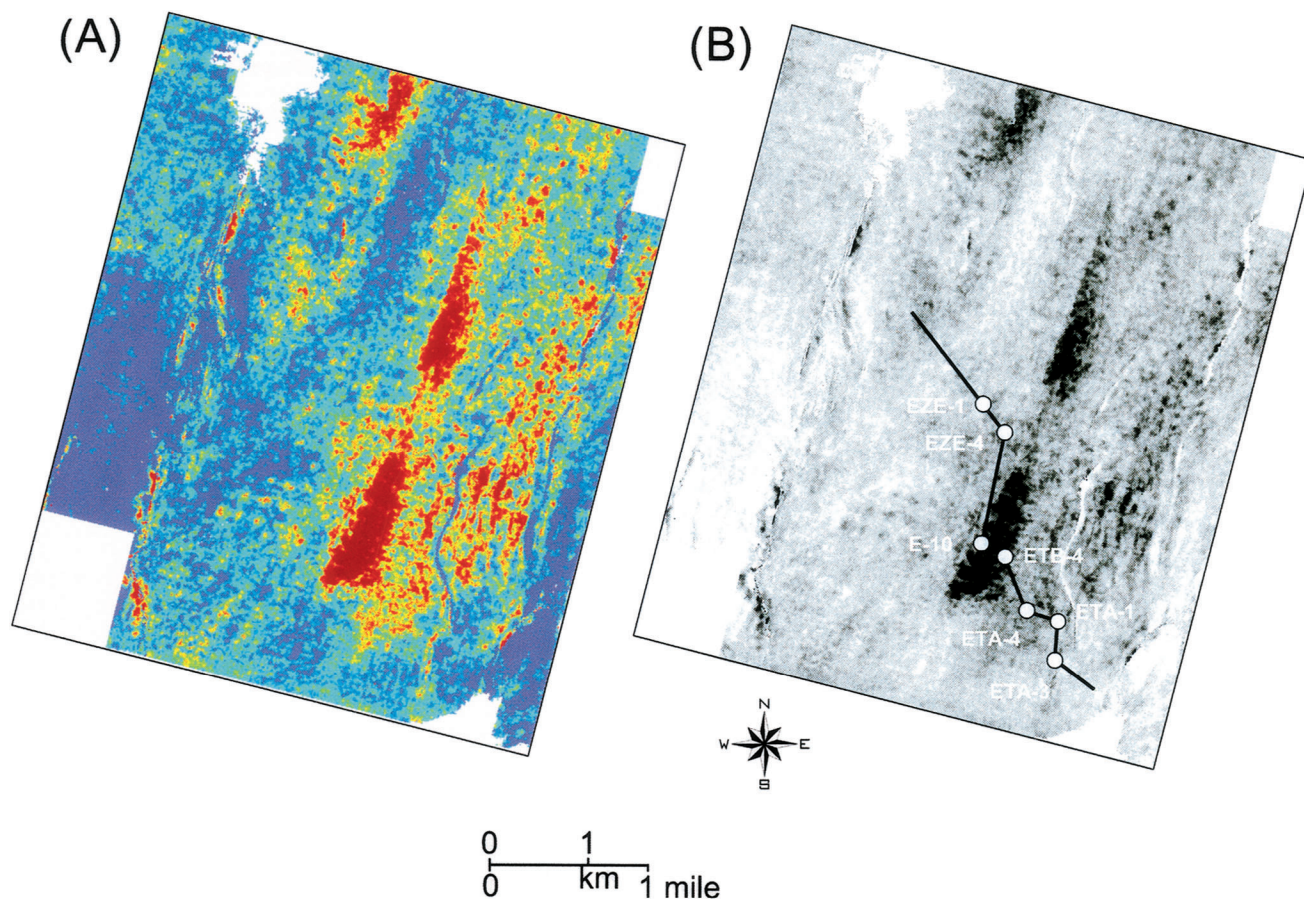


Figure 7. Color (A) and gray tone (B) horizon slice 30 msec below reference datum, illustrating shelf ridge 2480 at E field area. Two small shelf ridges are shown here; note that they overlap slightly. Both are characterized by a well-defined northwest boundary (i.e., the leading edge) and a more vaguely defined southeast boundary (i.e., the trailing edge). Both ridges are characterized by widening to the south.

abruptly (at the point marked as the leading edge), remains bright for 0.5 km, and then progressively dims to the east. This brightening likely is associated with a seismic tuning effect between the top and base of the feature. In map view, the abrupt westward boundary of the anomaly segment is noted as the leading edge, and the more poorly defined eastern boundary is marked as the trailing edge (Figure 9A).

A transverse well-log cross section across the southern segment of the 2480 anomaly is shown in Figure 10A. This section mirrors the orientation of the seismic section shown in Figure 10B. The leading edge of the anomaly is located between wells EZE-4 and E-10, with the latter well located just inboard of the leading edge. Wells EZE-1 and EZE-4 penetrate no sandstone at this level. At E-10, approximately 3 m of sandstone was penetrated, decreasing in an eastward direction and pinching out by wells ETA-1 and ETA-3. No grain-size trend could be established because of the

small thickness of the sandstone relative to the resolution of the logging tools used. Resistivity logs indicate that the sandstone is hydrocarbon charged.

2732-East Anomaly

The 2732-East seismic anomaly is one of several similar anomalies from the same seismic level as shown in Figure 11. The 2732-East anomaly lies 60 msec below the 2480 anomaly discussed previously, as shown in Figure 6B and illustrated in plan view in Figure 12. The 2732-East anomaly has characteristics similar to the 2480 anomaly; it is characterized by a similar trending north-northeast to south-southwest longitudinal axis and sharply defined western edge. This anomaly also seems to widen toward the south. This anomaly maps out somewhat more extensively when additional seismic attributes are analyzed. Figure 12C, D illustrates seismic interval attributes, which suggest that the anomaly extends significantly farther northward than indicated

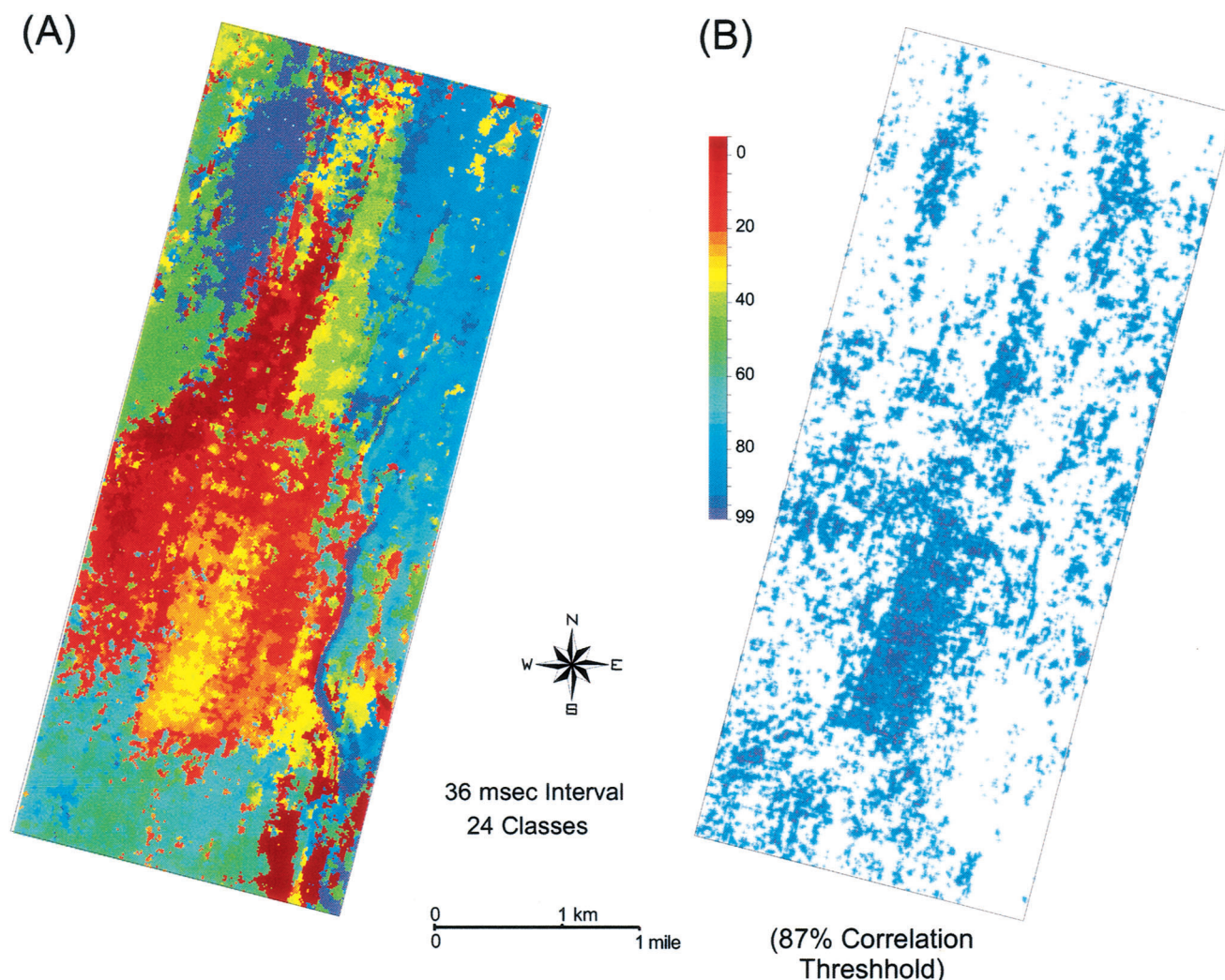


Figure 8. Seismic facies classification map (A) and seismic facies correlation map (B) of shelf ridge 2480 at E field area. This seismic facies map was produced using Paradigm's Stratimagic neural network algorithm. This process groups individual traces into the class with which each trace has the best correlation (A). Traces of a given class are presumed to correspond to lithologies of similar acoustic characteristics. The correlation map (B) shows the degree of correlation each trace has with its respective class (see text for discussion). This seismic facies analysis was done for a 36 msec interval that bracketed the 2480 shelf ridge; 24 classes were created. Note that the area of highest correlation corresponds to the area of the shelf ridge.

by the horizon slice shown in Figure 12A. Based on its seismic attributes, the anomaly is approximately 0.8–1.0 km wide and up to 10 km long. Note that a well-defined west-northwest by east-southeast-trending anomaly, which crosses the 2732-East anomaly and is shown on the interval attribute maps of Figure 12B–D, lies stratigraphically just below but is separated by a section of mudstone from the 2732 level. This anomaly has been interpreted as a delta-plain distributary channel (Posamentier et al., 1998).

A succession of equally spaced seismic transects illustrates the profile expression of this anomaly (Fig-

ure 13B). As with the 2480 anomaly, the 2732-East anomaly also is expressed as an amplitude brightening. Here again, the western or leading edge is abrupt, and the eastern or trailing edge is gradational.

A well-log transect across the 2732-East anomaly is shown in Figure 6A. At this level the E-10 well lies just outboard of the anomaly (Figures 6B, 13A). At well E-10, less than 1 m of sandstone is penetrated, whereas at well ETB-2, 4–5 m of sandstone are penetrated at this level. As with the lithologic expression of the 2480 anomaly, the sandstone progressively thins in an eastward direction away from the leading edge.

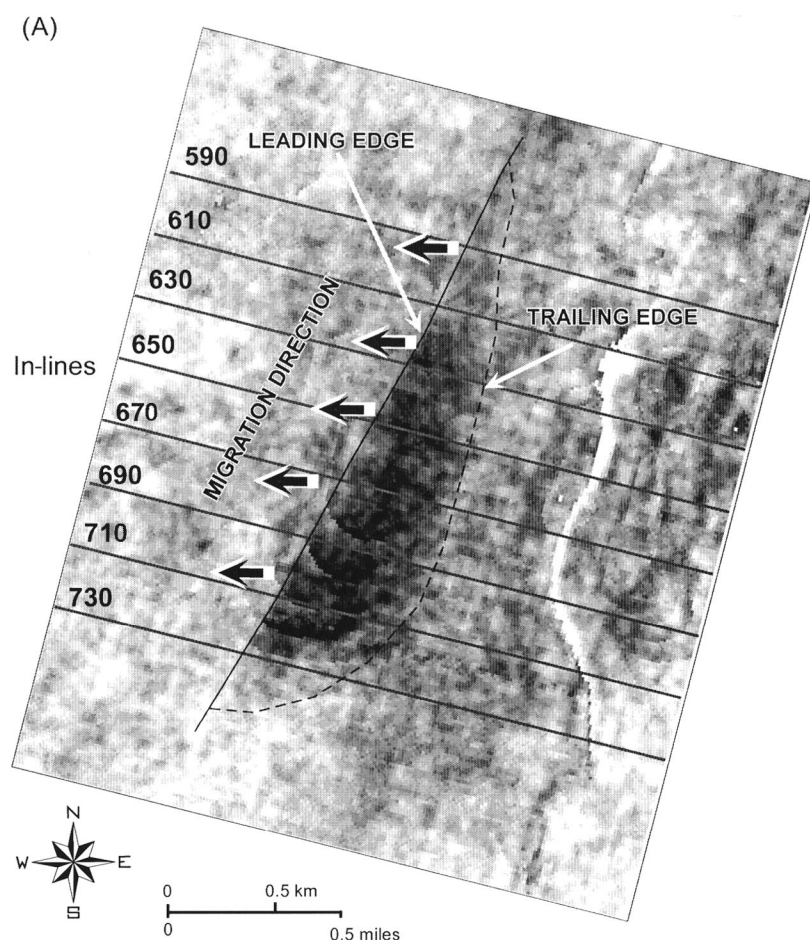
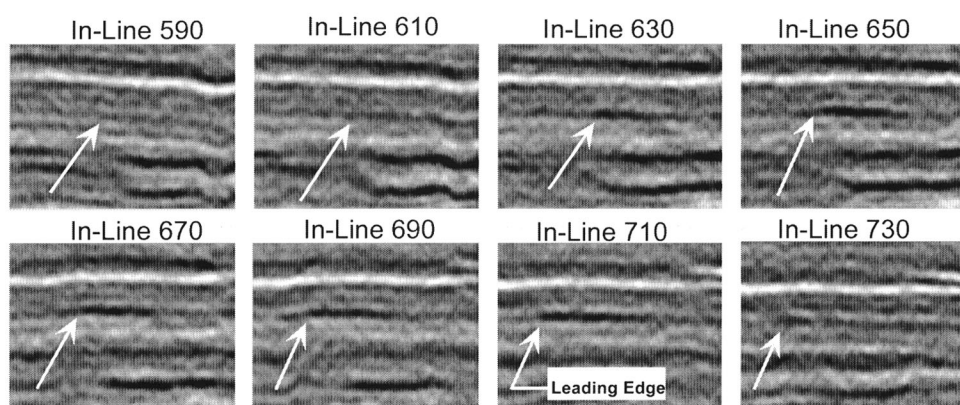


Figure 9. (A) Horizon slice close-up (see Figure 7) of southernmost of the two 2480 shelf ridges at E field area. The leading edge, trailing edge, and migration direction of the shelf ridge are indicated. (B) A succession of in-line seismic profiles spaced at 250 m shows the cross sectional seismic expression of the shelf ridge. Note that the shelf ridge is best expressed near the southern end of the ridge (i.e., in-line 710), with an abrupt change in reflection amplitude at the leading edge and gradational change of amplitude at the trailing edge.

(B)

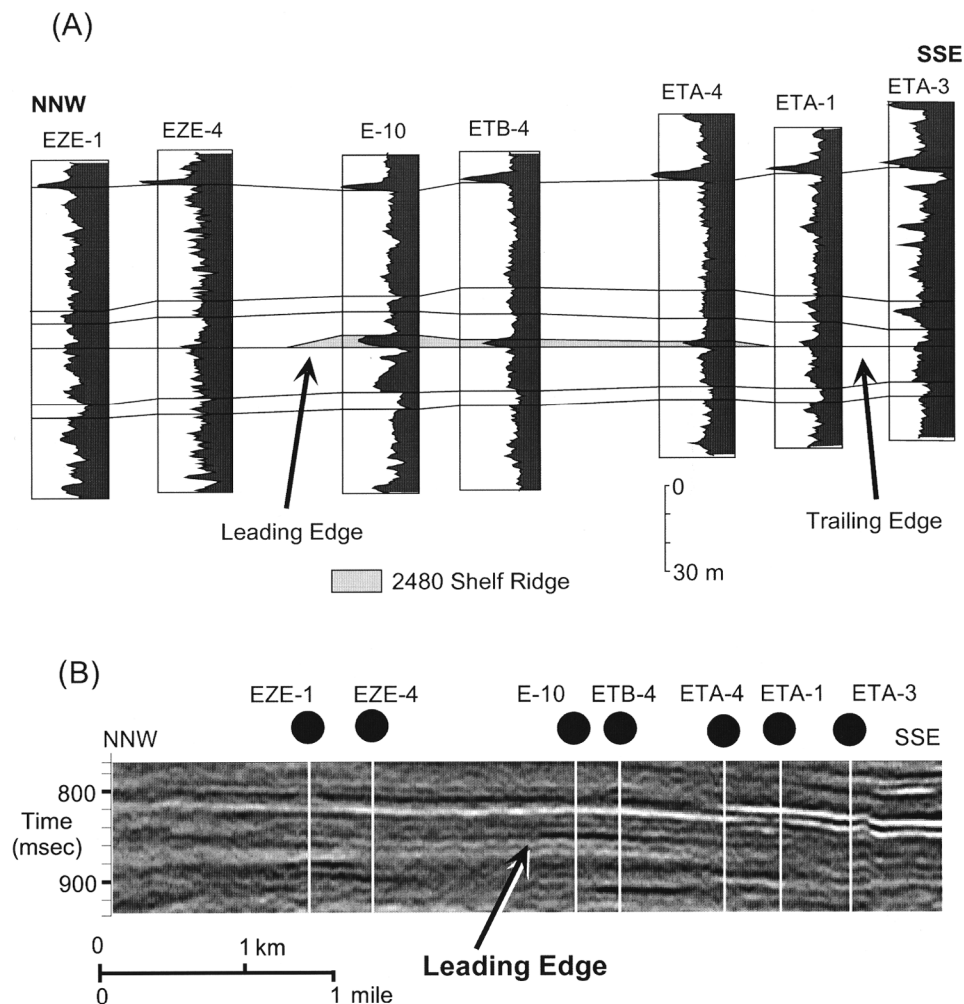


2732-West Anomaly

The 2732-West anomaly again has attributes similar to those of the previously discussed anomalies. It, too, has a sharply defined western edge, its long axis trends north-northeast to south-southwest, and it widens to the south (Figure 14A). The maximum width of this anomaly is approximately 2 km, and the length is at

least 7 km (it extends off the data set). Just to the east of this anomaly lies another distinct anomaly (Figures 11, 14A). This secondary anomaly is somewhat more amorphous than the 2732-West anomaly, but it, too, is elongate north-northeast to south-southwest, though oriented slightly more northward (Figure 14B, C). In addition, this secondary anomaly also is characterized

Figure 10. Well-log cross section (A) and parallel seismic profile (B) through the 2480 shelf ridge at the E field area. The thickest section of the ridge penetrated was encountered at the E-10 well, just inboard of the leading edge of the ridge. Note the absence of sand outside the ridge (i.e., at EZE-1 and EZE-4, to the west of the ridge, and at ETA-1 and ETA-3, to the east of the ridge).



by a better-defined western rather than eastern boundary.

Detailed inspection of the 2732-West anomaly reveals a secondary superimposed pattern similar to that observed on the anomaly at FXE. Figure 14D, E illustrates what appears to be an arcuate-shaped feature, oriented subparallel with the leading (i.e., sharply defined) edge, tangential to this boundary at the north end of the arcuate shape and curving away from the anomaly edge to the south (compare with Figure 5E, F).

Figure 15B illustrates a succession of seismic profiles across the 2732-West anomaly, spaced 312.5 m apart (Figure 15A). These sections show that again the anomaly is characterized by amplitude brightening, dimming abruptly at its western edge and gradationally at its eastern edge.

The well-log transect illustrated in Figure 16 shows that this anomaly corresponds to a significantly thicker sandstone than the others documented here.

At wells EC-3 and EC-1, the sandstone thickness is approximately 17–18 m. This sandstone is characterized by a marked coarsening-upward trend at these well locations. The sandstone thickness associated with the secondary anomaly just to the east (Figure 14A) is 8–9 m, and the log response there is coarsening upward to blocky. Note the abrupt sandstone thinning outboard of both the principal 2732-West anomaly (at wells E-3 and E-12; Figure 16) and the secondary anomaly just to the east (at wells EH-1 and EH-3; Figure 16).

Miscellaneous Anomalies

In addition to those anomalies discussed in previous sections, several others were observed in the E field 3-D seismic data set and are shown in Figure 17. Two of those illustrated in Figure 17 can be observed on the seismic profile shown in Figure 6B. Note that in each instance the anomaly is expressed as amplitude brightening.

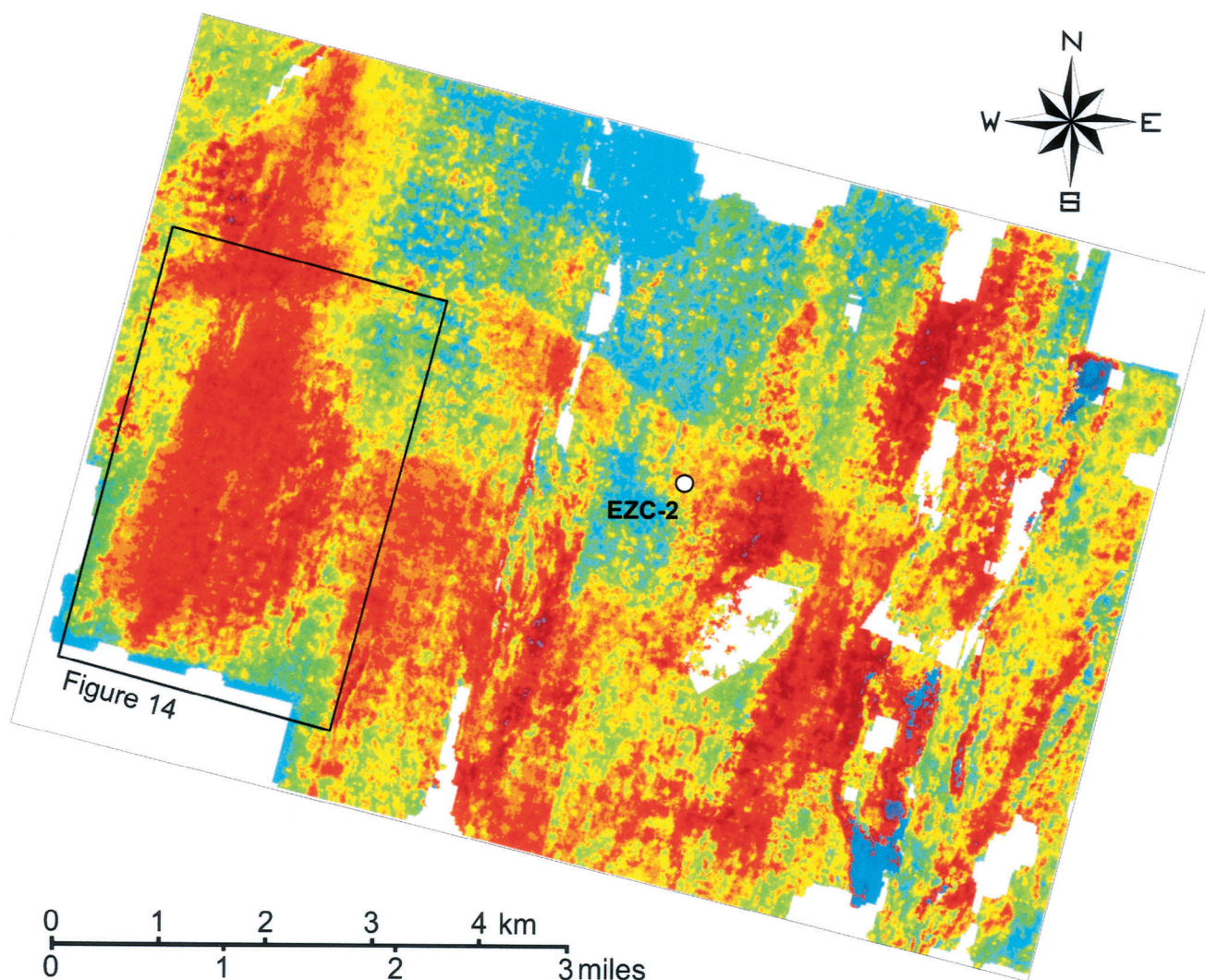


Figure 11. Map of summed amplitudes corresponding to 20% of the total amplitude of the highest amplitude trace segment within a seismic interval 120 msec thick containing the shelf ridge 2732-East (Figures 12, 13) and 2732-West (Figures 14, 15). Note the additional linear shelf ridges in the central part of the area shown.

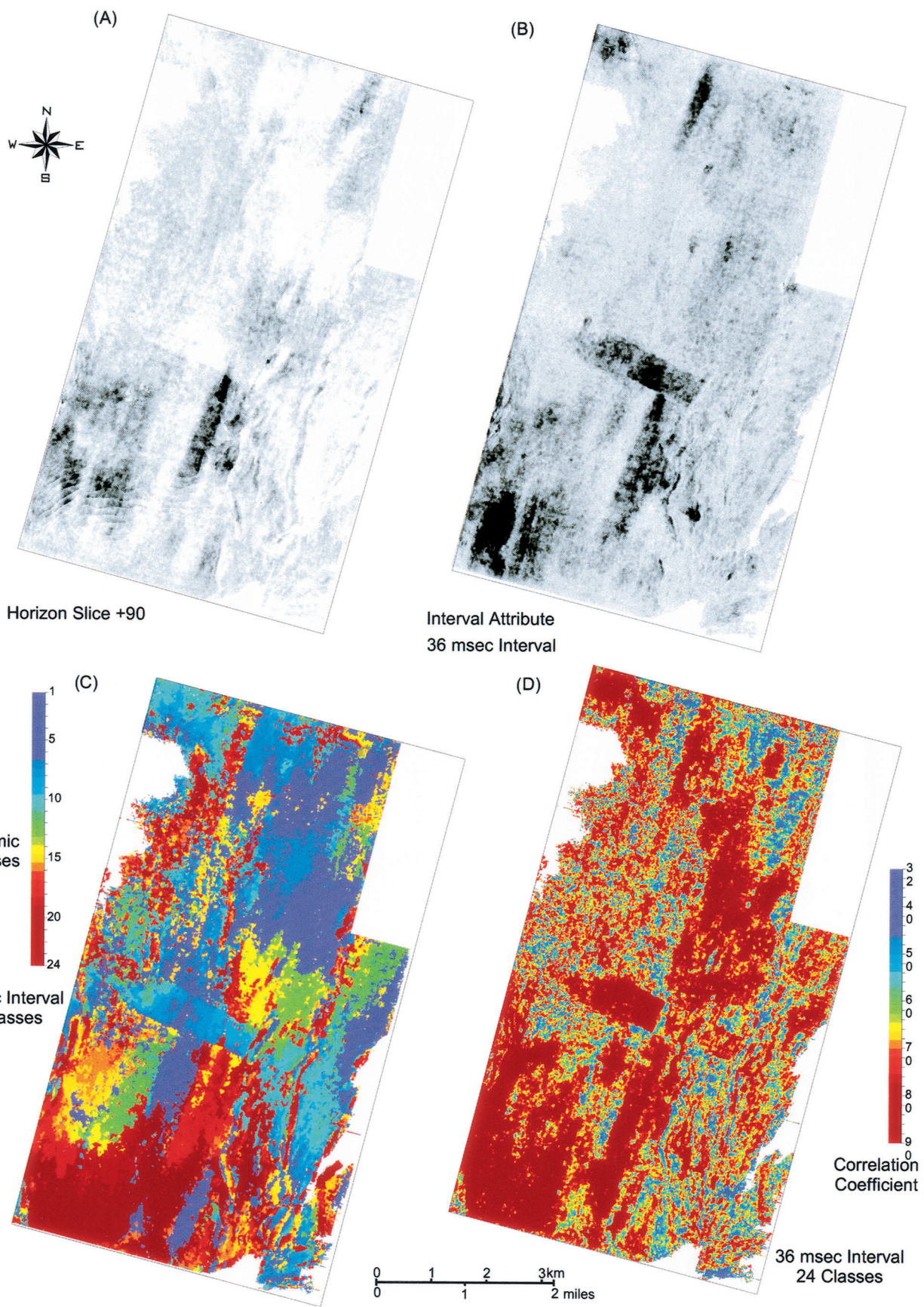
The key attributes for all seismic anomalies observed in the FXE and E field areas are summarized in Table 1. Figure 18 illustrates the map view of most of these. Note that the dimensions of the anomalies observed at FXE are more than twice those observed at E field. Note, also, that these anomalies can be distributed in clusters on one extreme and isolated on the other. The orientation of all anomalies is strikingly similar, at north-northeast to south-southwest.

Conventional Core Observations

Only one conventional core penetrates the observed seismic anomalies in the FXE and E field areas. This core, from the EZC-2 well, is from the 2732 level, just

to the west of the 2732-East anomaly (Figure 11). The deposits corresponding to the anomaly are intensely burrowed so that no primary sedimentary structures are preserved (Figure 19). 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 filled with sand from the overlying stratigraphic unit common just below the basal contact.

Another core taken from a borehole at BM-2, approximately 25 km to the west of E field, illustrates the contrast between sedimentary rocks associated with similar amplitude anomalies and underlying deposits (Figure 20). In this example, the sedimentary rocks



overlying the contact are characterized by significantly more permeable sandstone than the underlying sediments, as suggested by the higher fluorescence under ultraviolet light.

GEOLOGIC INTERPRETATION

The following discussion summarizes, based on seismic and borehole observations, the case that can be made for an interpretation of shelf ridge deposits for the anomalies observed in the Miocene section in the FXE and E field areas offshore northwest Java. These deposits and others like them in other nearby areas offshore Java are a common feature of the middle Miocene Upper Cibulakan Formation in this area. They are strikingly similar to one another in orientation, as well as scale, tending to be elongated north-northeastward to south-southwestward and ranging in dimensions from 0.3 to 2 km wide, 3–12+ km long, and 2–17 m thick (Figure 18; Table 1).

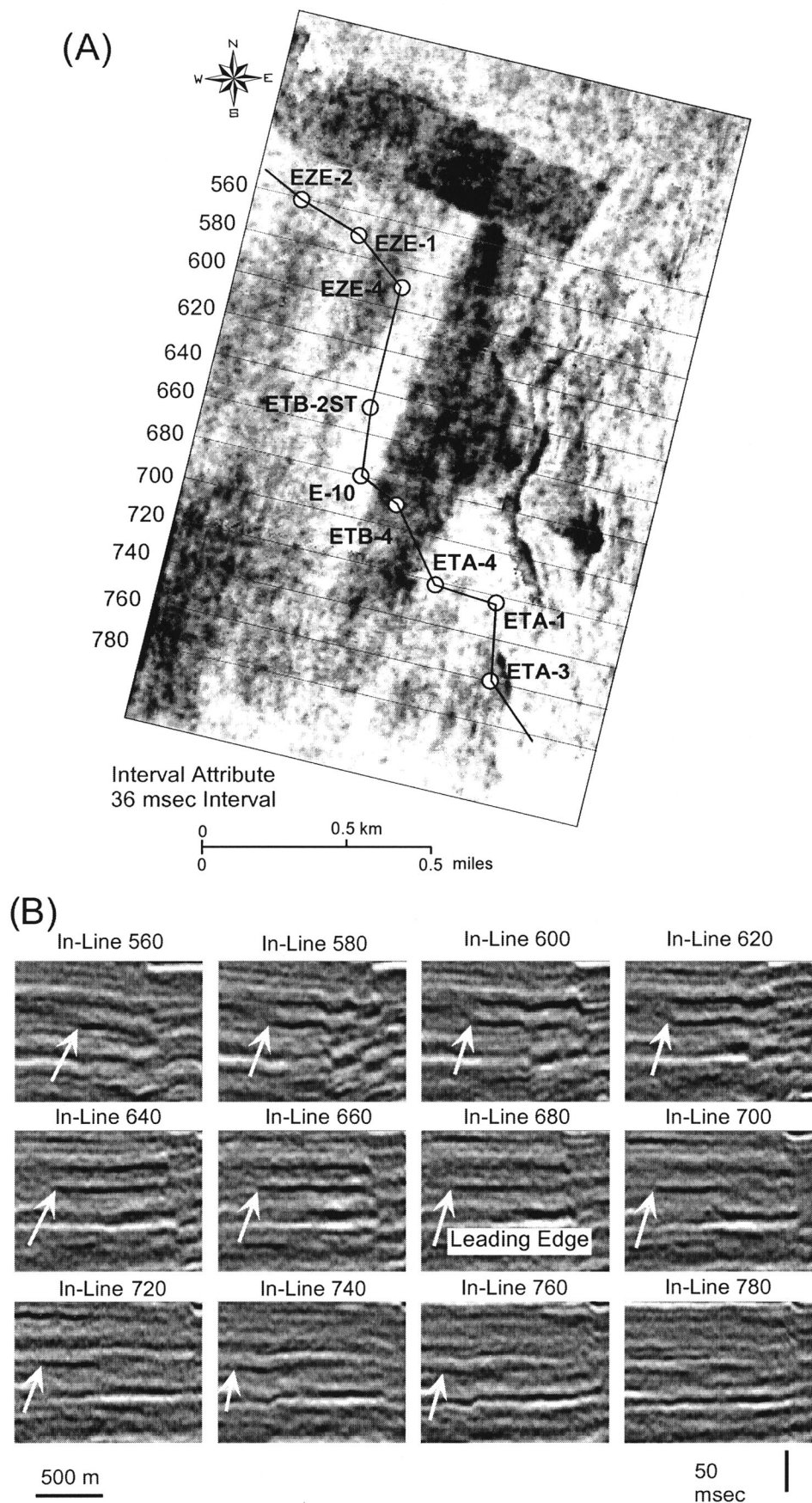
A shelf ridge origin that is erosive in nature is suggested for these deposits, based on (1) the striking linearity and parallel distribution of these deposits as observed on the seismic data (Figures 2, 11, 18), (2) the orientation of these linear features orthogonal to oblique to the regional paleoshoreline, (3) the presence of a sharp erosional contact marked by a *Glossifungites* ichnofacies at the base of these deposits (Figures 19, 20), (4) the presence of muddy shelf sediments immediately underlying, as well as overlying, these deposits, (5) the common presence of a sharp edge (i.e., the leading edge) bounding one side of these features, (6) the asymmetry of these features, generally being thicker along the more sharply defined edge, (7) the presence of relatively coarse sediments, as well as isolated shell fragments, within these deposits, and (8) the absence of any wave-formed sedimentary structures either within the proposed shelf ridge sections or in the sections that bracket these deposits.

Shelf ridges in modern settings seem to be associated primarily with two end-member processes: wave and tidal energy (Off, 1963; Kenyon et al., 1981; Huthnance, 1982a; Yang and Sun, 1988; Berné et al., 1989; Yang, 1989; Snedden et al., 1994; Berné, 1996; Liu et al., 1998; Snedden and Dalrymple, 1999). The shelf ridges interpreted here are inferred to be associated with tidal rather than wave energy. Evidence for tidal energy but not wave energy previously has been observed in this part of the Upper Cibulakan Formation offshore northwest Java (Posamentier et al., 1998). The apparent absence of wave-influenced deposits appears to be associated with the fact that (1) the area was at or near the equator at the time of deposition; winds in this latitudinal setting tend to be inconsistent and generally low velocity, and (2) the available fetch was low at this time, limited by an island arc to the south and the Eurasian landmass to the north.

Shelf ridges formed predominantly by tidal processes associated with transgression of a broad river valley have been described for the East China Sea by Yang and Sun (1988), Yang (1989), and Liu et al. (1998) and are shown in Figure 21A. The orientation of the shelf ridges described there is parallel with the trunk valley that underlies these deposits and is therefore orthogonal to oblique to the paleoshoreline. Liu et al. (1998) argued that this field of shelf ridges formed during the late Pleistocene–early Holocene transgression within the greater Pleistocene Yangtze River embayment in a tide-dominated setting. With each successive landward step of the embayment mouth, a new cluster of ridges formed (Figure 21B–E). Eventually, the result of this transgressive 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) approximately 200 km wide from one side of the paleoembayment to the other and 200 km long from the outer to the inner shelf (Figure 21A). Presumably, available wave energy was insufficient to significantly alter the original sea floor morphology.

Figure 12. Seismic expression of the 2732-East shelf ridge. (A) Horizon slice 90 msec below reference horizon. (B) Maximum negative polarity amplitude within 36 msec interval bracketing the shelf ridge. Note the presence of another linear feature, presumed to be another small shelf ridge, near the northern edge of this map. Note also the presence of a linear feature oriented west-northwest to east-southeast. This feature is interpreted as a distributary channel and lies approximately 8 m below the level of the shelf ridges (Figure 16A) (Posamentier et al., 1988). (C) Seismic facies classification map for a 36 msec interval and using 24 classes. (D) Seismic facies classification map for the classification scheme shown in C. Note that the relatively high correlation area corresponds to the area of the shelf ridge and that this area of high correlation continues across the transversely oriented distributary channel. Similar to Figure 11, the 2732-East shelf ridge has greater linear extent on the seismic facies correlation map (D) than on the horizon slice and interval attribute maps shown in parts A and B, respectively.

Figure 13. (A) Close-up of the 2732-East shelf ridge (see Figure 12B), south of the distributary channel. (B) A succession of in-line seismic profiles spaced at 250 m shows the cross sectional seismic expression of the shelf ridge.



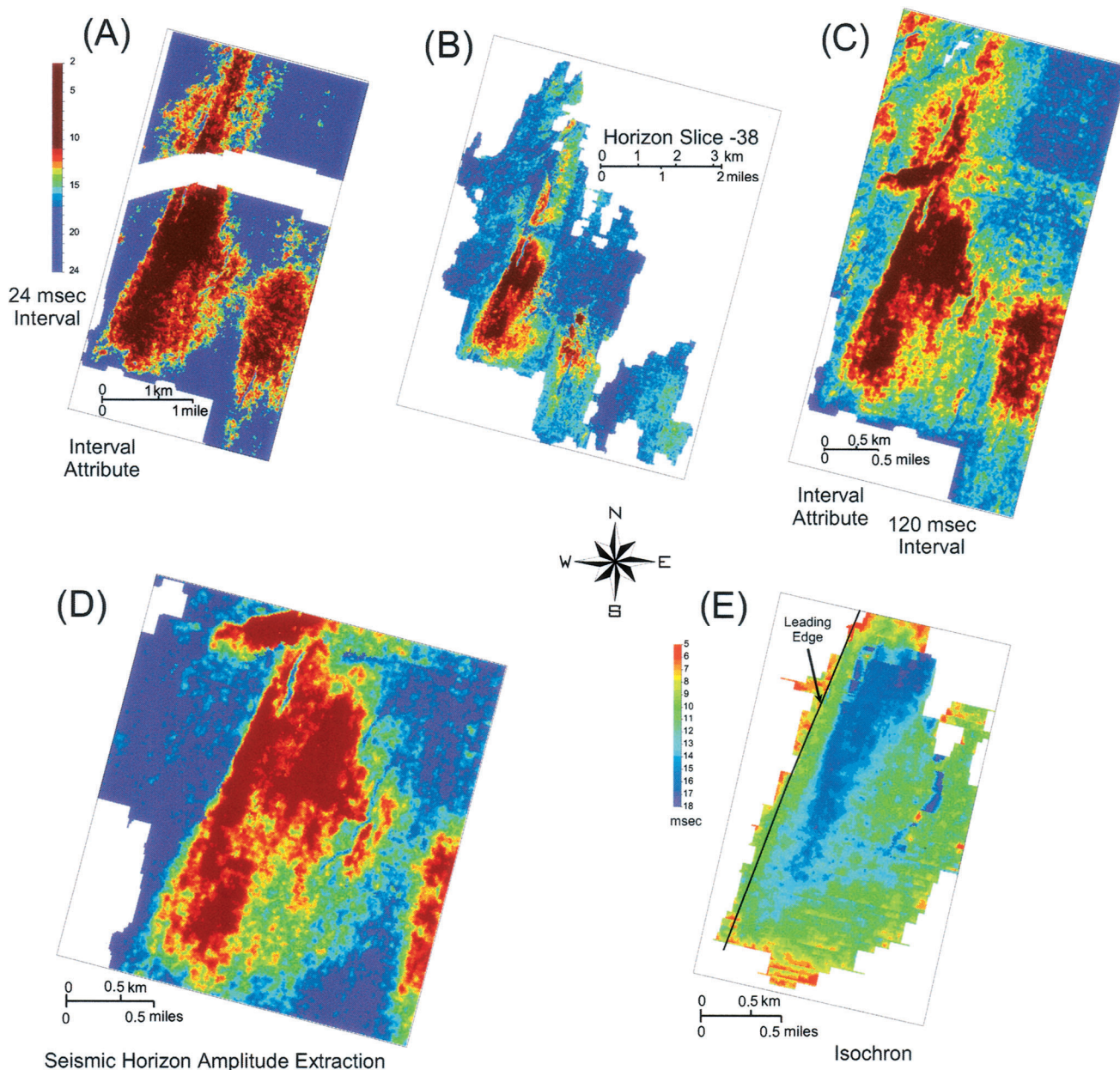
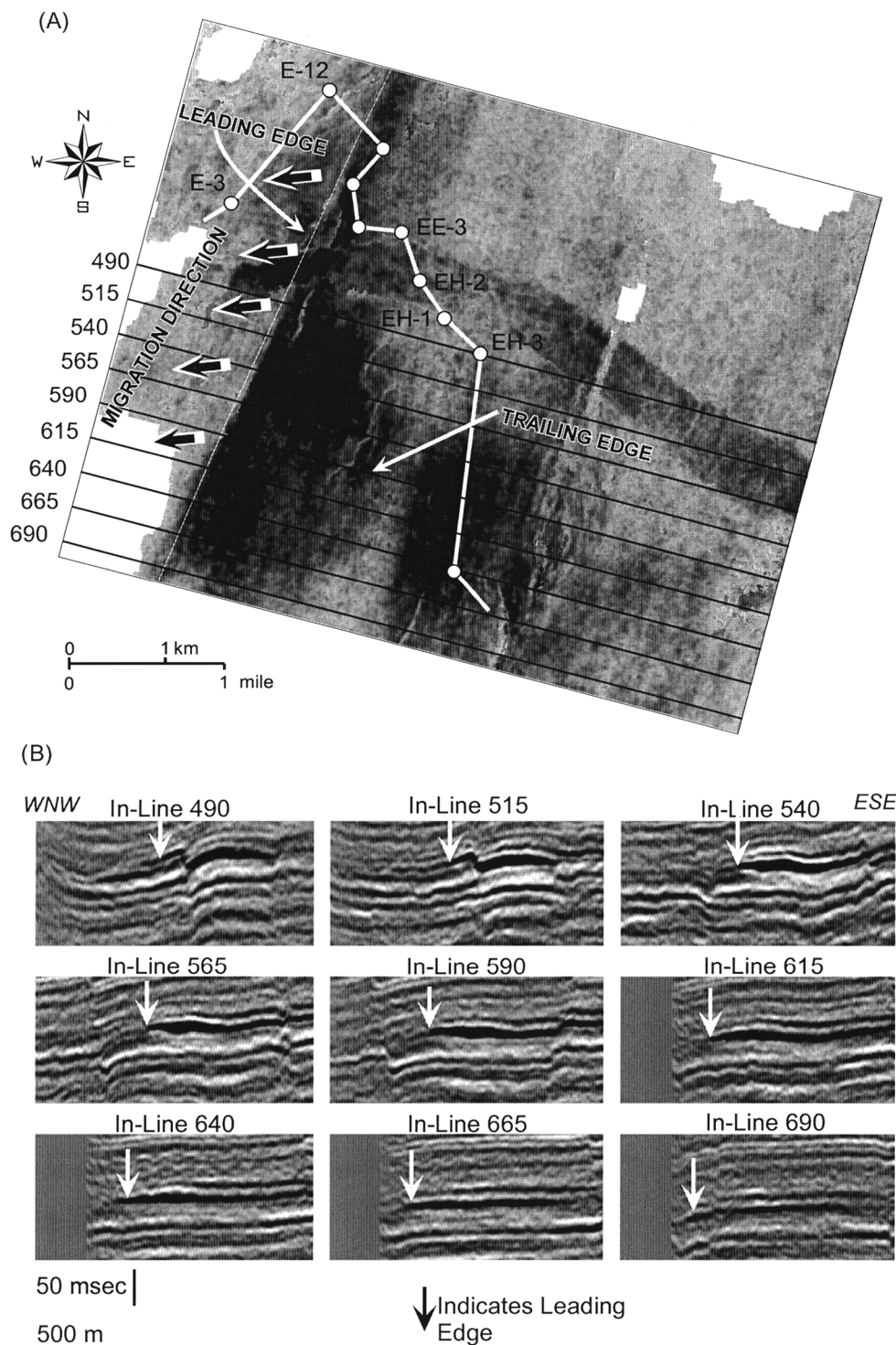


Figure 14. Seismic expression of the 2732-West shelf ridge. (A) Map of summed amplitudes corresponding to 20% of the total amplitude of the highest amplitude trace segment within a 24 msec interval bracketing the shelf ridge. Note the sharp western boundary of this ridge, as well as the widening of the ridge toward the southeast. Note also the secondary ridge located on the southeastern part of the map. (B) Horizon slice 38 msec above reference datum. (C) Maximum negative polarity amplitude map over a 120 msec interval bracketing the ridge. (D) Seismic amplitude extraction from the reflection corresponding to the shelf ridge. (E) Isochron map between the zero crossings at the top and base of the shelf ridge seismic reflection. Note the arcuate-shaped amplitude anomaly and isochron thick associated with the shelf ridge on parts D and E, respectively (compare with Figure 5E, F).

Individual ridges described by Liu et al. (1998) range from 2 to 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 22. Note the asymmetry, as well as the sharp leading edge. Note also the progradational architecture within this ridge. Al-

though the same level of internal detail shown in Figure 22 is not available for the Miocene Java Sea ridges, the sense of progradation within the East China Sea example, as indicated by the oblique tangential clinoform seismic reflections, is consistent with the sense of progradation indicated by the log signature of the

Figure 15. (A) Map of amplitude extraction from the 2732-West shelf ridge seismic reflection at E field area (compare with Figure 14D). The leading edge, trailing edge, and migration direction of the shelf ridge are indicated. Note the second ridge just to the east and south (i.e., penetrated by the E-6 well) of the larger 2732-West ridge. (B) A succession of in-line seismic profiles spaced at 312.5 m shows the cross sectional seismic expression of the shelf ridge. Note the sharp termination of the high-amplitude reflections on the western leading edge side contrasted with the more gradual decrease of amplitude on the eastern trailing edge side of the principal 2732-West ridge.



Miocene Java Sea example (well EE-1 in Figure 16). The similar origin of the two features is further underscored by the similarity of the dimensions, shape, and form.

Another area that can serve as a modern analog for the Miocene Java Sea ridges is the Gulf of Korea, east-

ern Yellow Sea. A cluster of shelf ridges 8–30 m high, 8–65 km long, and spaced 2–10 km apart has been described there by Off (1963). Most are composed of sand and are oriented parallel with tidal currents, which range between 1 and 5 knots (Off, 1963). Kenyon et al. (1981) describe their profiles as either

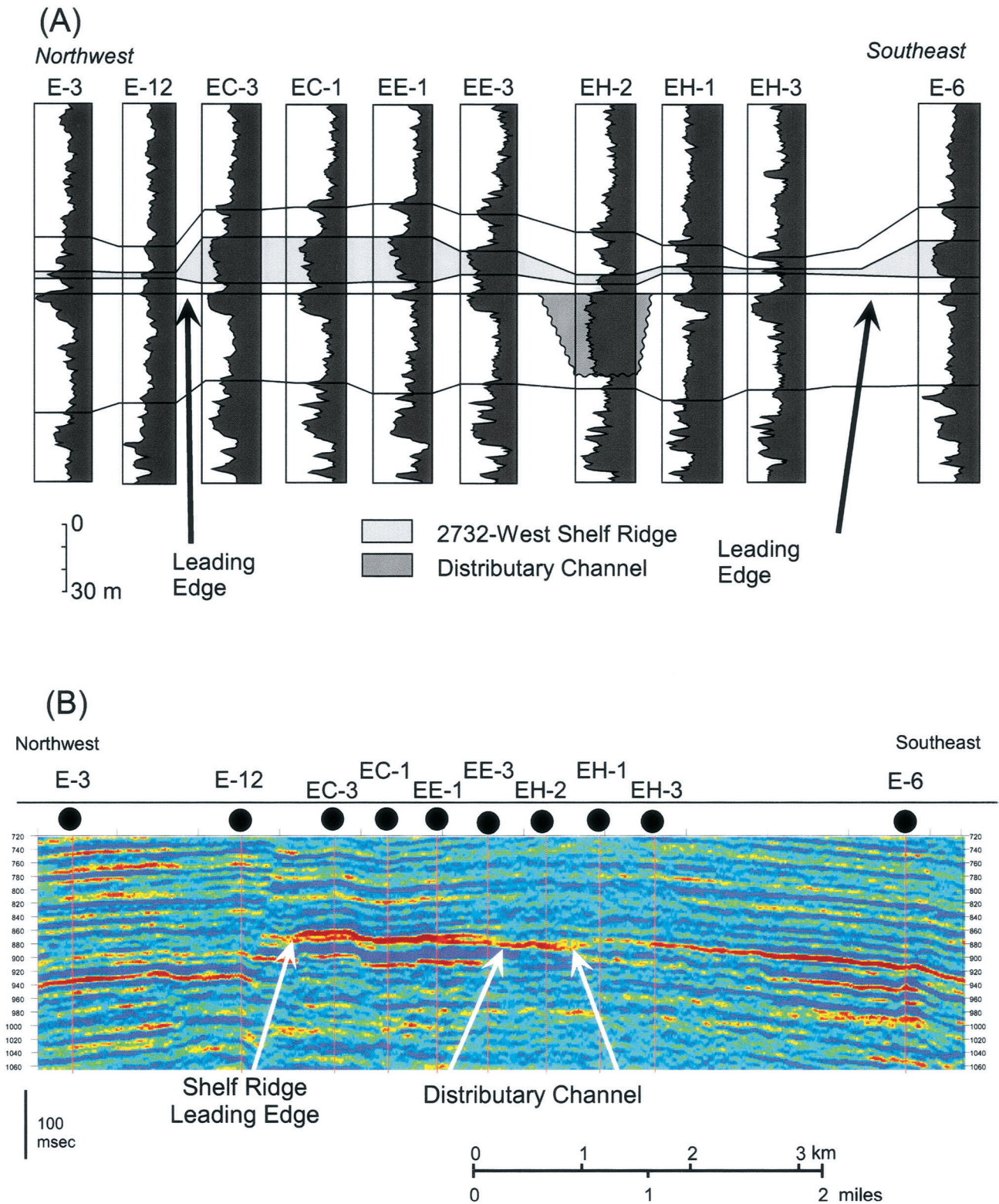


Figure 16. Well-log cross section (A) and parallel seismic profile (B) through the 2732-West shelf ridge at the E field area. The thickest section of the ridge penetrated was encountered at the EC-3, EC-1, and EE-1 wells, just inboard of the leading edge of the ridge. Note the absence of sand outside the ridge (i.e., at E-3 and E-1, to the west of the ridge). At E-6, the second ridge just to the south and east of the principal 2732-West ridge, 15 m of sandstone is penetrated.

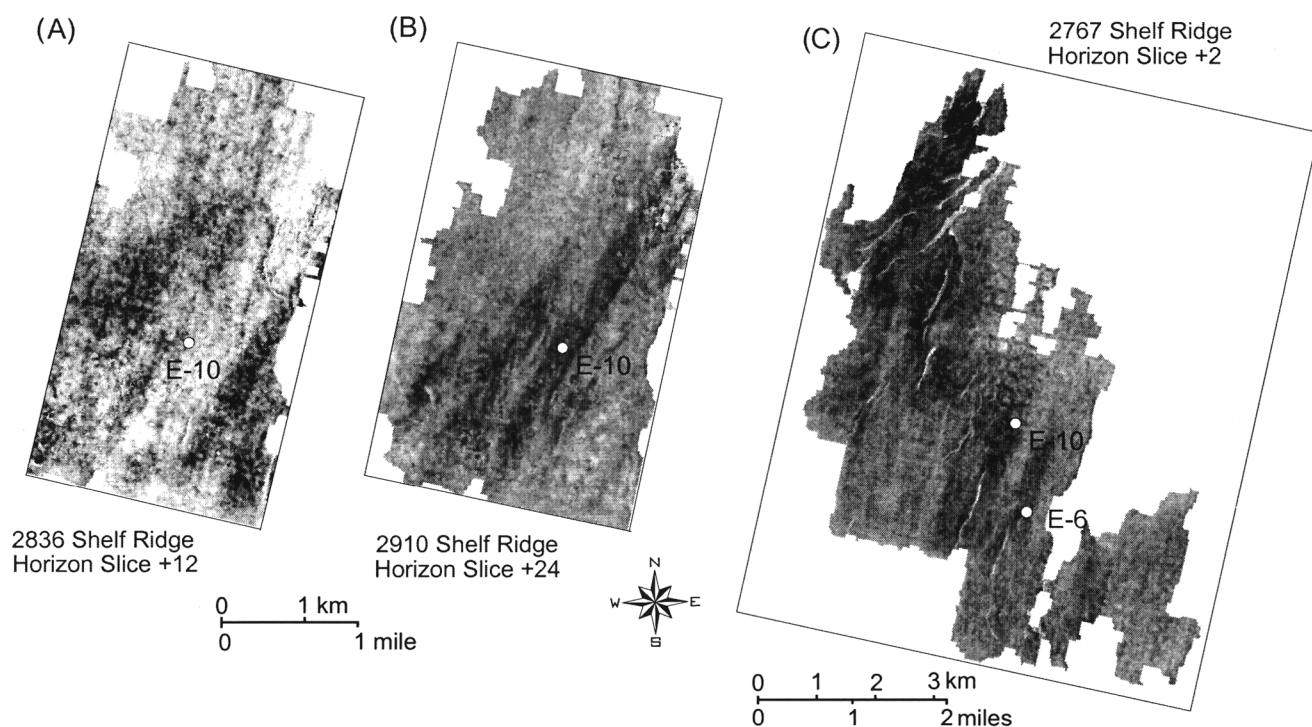


Figure 17. Shelf ridges observed at additional levels at the E field area. (A) The 2836 shelf ridge (see Figure 6), imaged on a horizon slice 12 msec below a reference seismic reflection. (B) The 2910 shelf ridge (see Figure 6), imaged on a horizon slice 24 msec below a reference seismic reflection. (C) The 2767 shelf ridge imaged on a horizon slice 2 msec below a reference seismic reflection.

symmetrical or steeper on their western sides. Off (1963) also identifies similar shelf ridge clusters at the northern end of the Persian Gulf and the Gulf of Cambay on the west coast of India that are potential analogs for the Miocene Java Sea ridges.

The striking similarities between the East China Sea shelf ridges and the Miocene deposits of offshore northwest Java described here support a shelf ridge origin for the latter features. Taking this comparison further, we would suggest that the Miocene linear shelf ridges are oriented parallel with paleoembayment long axes (i.e., north-northwest to south-southeast) and orthogonal to oblique to the regional paleoshoreline. 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 inferred to have existed here (Reksalegora, 1993; Reksalegora et al., 1996).

The features observed in the Upper Cibulakan Formation appear to have migrated across the shelf, as suggested by their sharp-based lithologic expression and the fact that they are commonly embedded within a silty mudstone section. The time of migration likely was during periods of shoreline transgression. Figure 23

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). Instead, 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 redeposited on the shelf as palimpsest deposits (Figure 24). Both ridges and ribbons seem to have formed during this time of transgression (Figures 2, 3, 11).

The surface at the base of the sand deposits observed in EZC-2 (Figure 19) 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 20. The sand characterized by the bell-shaped gamma-ray log sig-

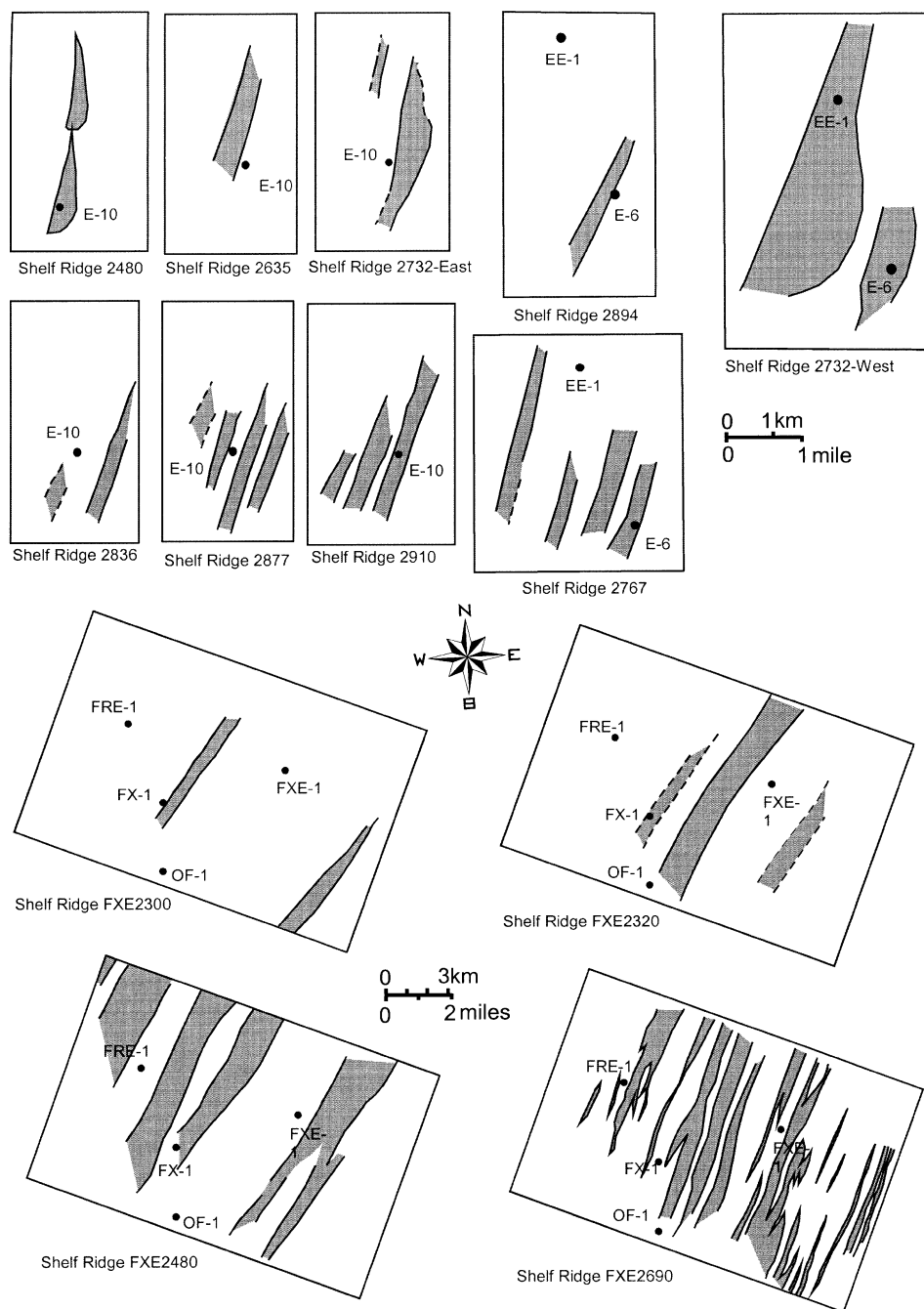


Figure 18. Map view of all the shelf ridges observed at FXE and E field areas.

nature at 3574–3590 ft (1089–1094 m) can be separated into two genetic units near the minimum point of the gamma-ray curve (i.e., at 3582 ft). The ultra-violet light-illuminated core shows greater fluorescence above the ravinement surface, which implies higher original oil saturation and better rock quality. Here, too, this bounding surface is characterized by a *Glossifungites* ichnofacies (Figure 19). 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.

The direction of shelf ridge migration can be inferred to be in the direction of the sharp edge of these deposits (e.g., Figures 5, 7, 9A, 13A, 15A). The sharp edge is suggested to represent the leading edge, whereas the gradational side is suggested to represent the trailing edge. The presence of the best developed coarsening-upward log pattern (well EE-1 in Figure

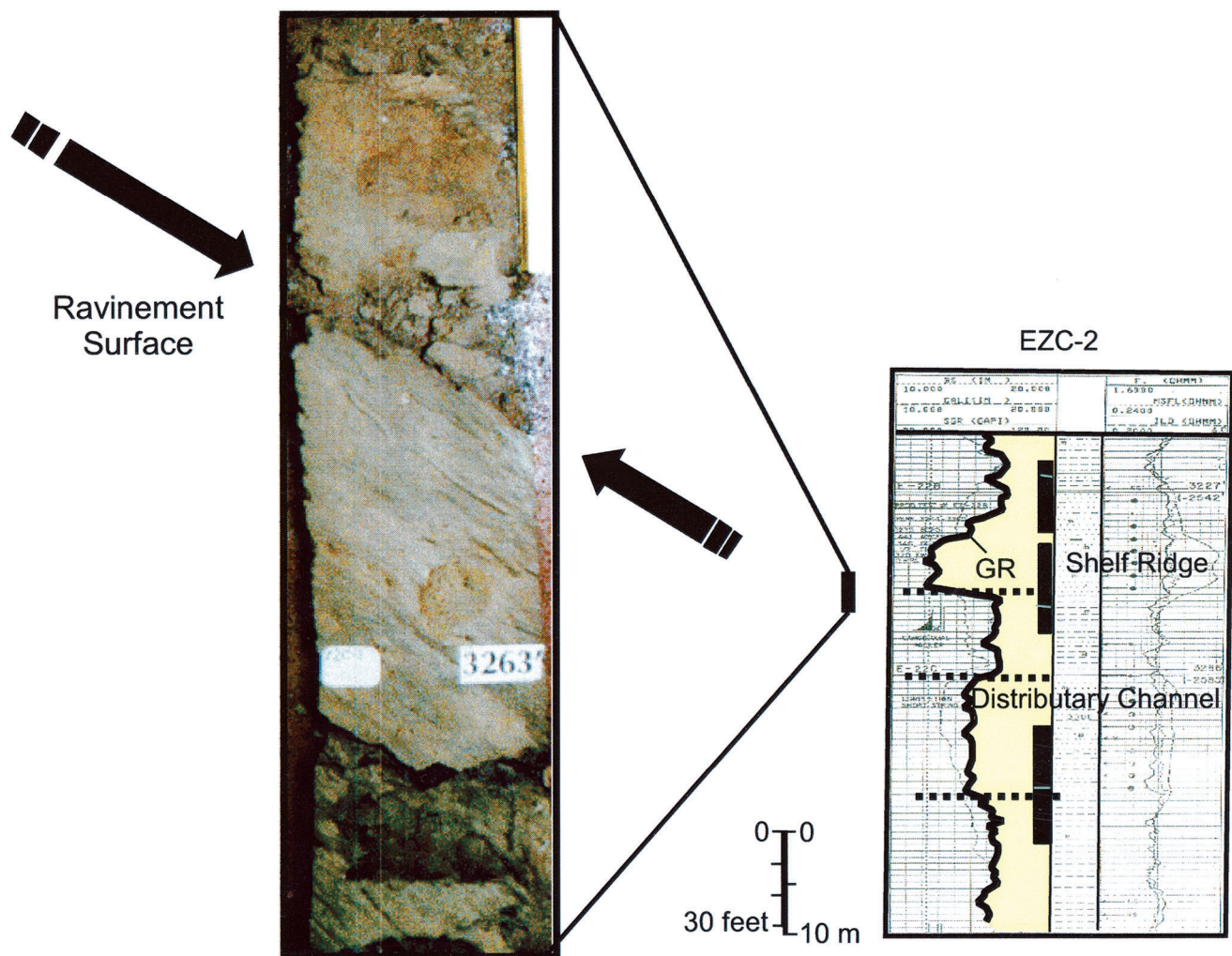


Figure 19. Core with well log from 2732 shelf ridge deposits at EZC-2 well (see Figure 11 for location). The log signature is characterized by a sharp base and fining-upward trend. The core indicates the presence of *Glossifungites* ichnofacies at the contact between upper fine-grained to medium-grained sandstone above and mudstone below. The sand is interpreted to be shelf ridge sand separated from offshore mud by a transgressive ravinement surface (Posamentier et al., 1998). Note that the shelf ridge deposits are separated from the underlying distributary channel fill by 8 m of mudstone.

16) near the leading edge of the shelf ridge shown in Figure 14A supports the sense of migration and progradation in that direction. The predominant direction of migration of these middle Miocene shelf ridges was to the west-southwest, suggesting a shelf tidal current flowing predominantly from the northeast to the southwest.

The detailed internal architecture of the middle Miocene ridges is suggested by interval attributes of the ridges shown in Figures 5E, F and 14D, E. The arcuate forms observed within the confines of the interpreted ridges could represent sand waves superimposed on and migrating down the long axis of the ridge (Figure 25). Note the apparent en echelon aspect of these fea-

tures (Figure 5E, F). 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.

DISCUSSION

The shelf ridge deposits described here constitute the expression of the transgressive systems tract in the shelf environment. These deposits form at the time that the shoreline is migrating landward and the shelf environment has been recently flooded. At this time, sediments coming from the hinterland are trapped inboard

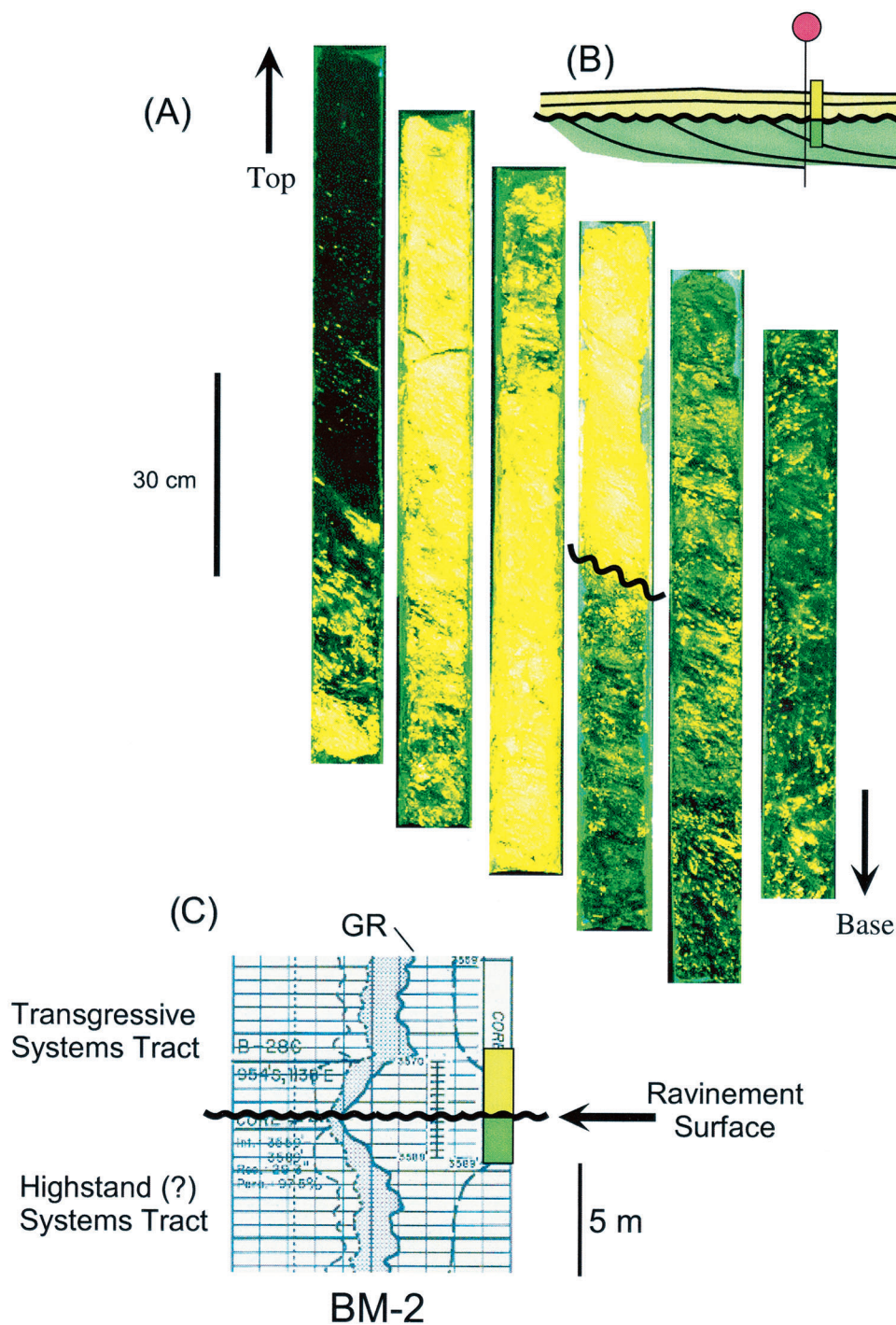


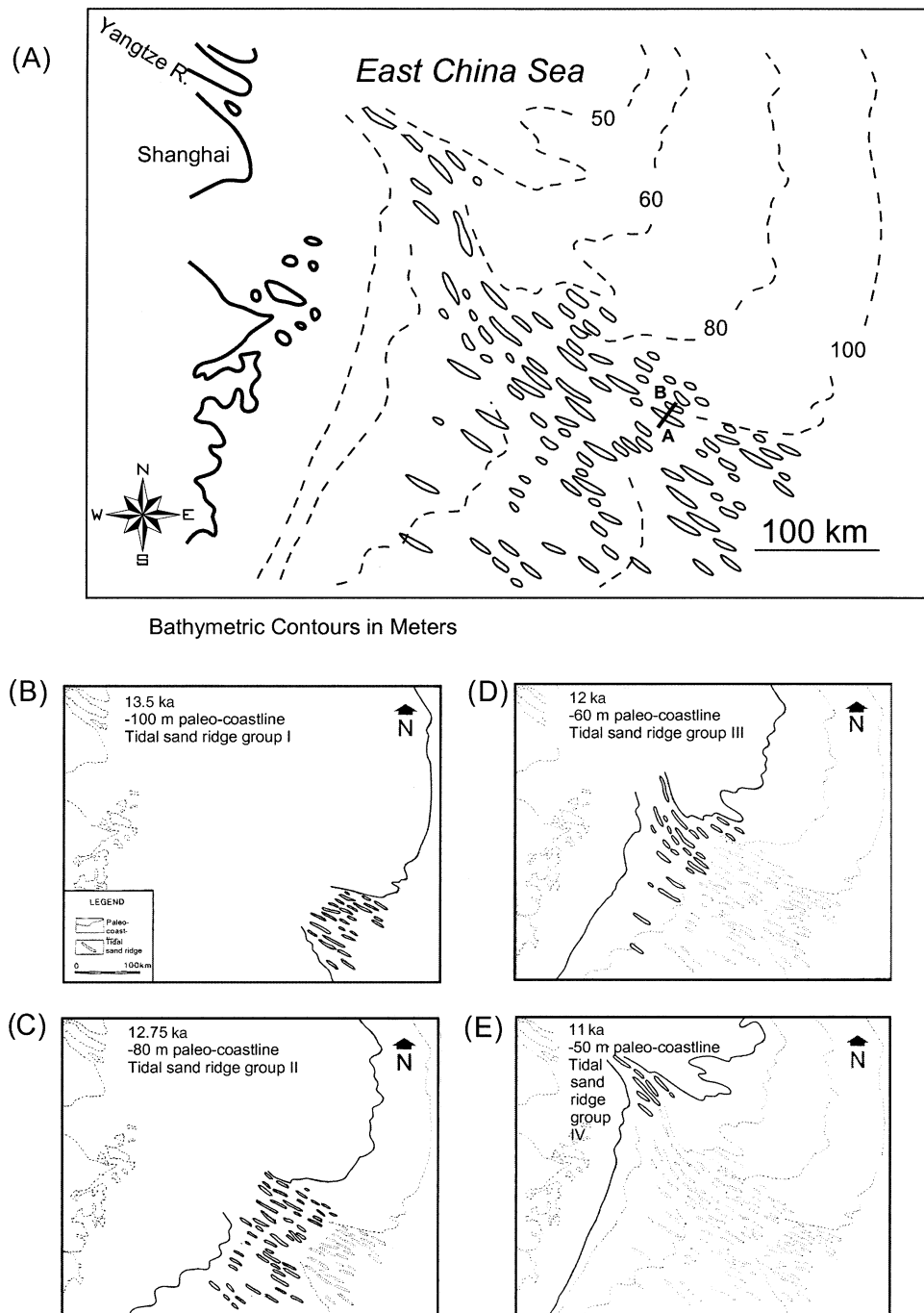
Figure 20. Core (A) and well log (C) from BM-2 in offshore northwest Java illustrate the lithologic and log expression of transgressive shelf deposits overlying regressive shelf deposits. The gamma-ray trough is associated with a *Glossifungites* ichnofacies, which characterizes a ravinement surface, and is interpreted to separate transgressive deposits above from regressive deposits below (B). The ultraviolet light-illuminated core (A) shows greater fluorescence above the ravinement surface, which implies higher original oil saturation and better rock quality. The section of core overlying the gamma-ray trough is characterized by greater fluorescence under ultraviolet light, implying that these sediments are markedly more saturated with residual oil than those below and, therefore, corresponding to deposits with markedly better reservoir properties. This is consistent with the notion that transgressive processes tend to induce sediment winnowing of fines and therefore relative enhancement of reservoir quality.

of the shoreline, in estuarine and back barrier settings, leaving the shelf relatively impoverished of sediment sourced directly from the hinterlands. During that time, however, newly flooded areas are subjected to a variety of processes, such as wave action, tidal currents, and other shelf currents, that can significantly erode previously deposited sediments. This cannibalization

of the substrate results in temporary addition to the overall sediment supply budget in the shelf environment.

The sediments that are being eroded from the substrate can locally be relatively coarse grained. These sediments can include a variety of high-energy facies, such as alluvial and delta-plain distributary channel

Figure 21. (A) Pleistocene–Holocene shelf ridges on the East China Sea shelf outboard of the Yangtze River (modified 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 group by group during the late Pleistocene–early Holocene transgression as the shelf was progressively drowned (B–E). These shelf ridges are up to 20 km long, 4 km wide, and up to 20 m thick and occupy an area nearly 400 km wide. Note that the orientation of the long axes of these ridges is parallel with the embayment axis rather than any regional shoreline trend.



(Figure 24), distributary mouth bar, shoreface, and delta-plain crevasse splay deposits. Posamentier (2001) has shown that in the offshore northwest Java basin margin, lowstand alluvial bypass channel deposits, embedded within offshore marine mudstones, are common. These alluvial deposits can be thin (i.e., < 5 m) and, therefore, can be completely eroded by current-related processes and ultimately be reworked into shelf ridges. This would result in the deposition of shelf

ridges over a ravinement surface, with the shelf ridges embedded within marine mudstones. Note that although the orientation of the middle Miocene ridges remains relatively uniform across offshore northwest Java, the orientation of underlying or overlying channels can be highly variable, ranging from orthogonal to parallel, because channels, especially those on delta plains in fluvial-dominated environments, are more free to have locally highly variable orientation (e.g.,

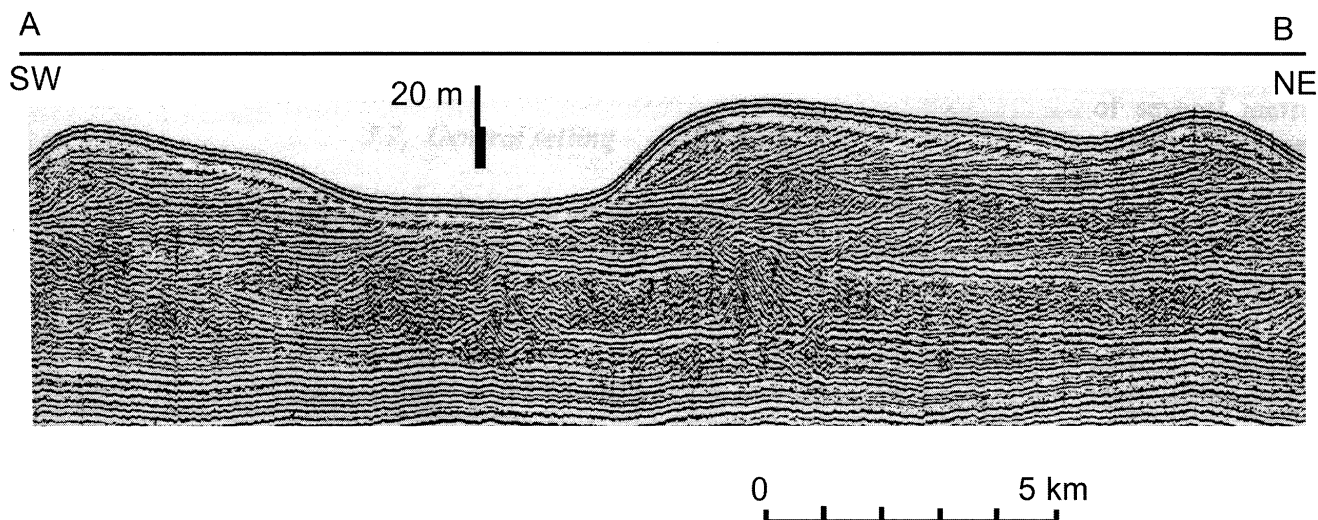


Figure 22. The seismic section shown here represents a transverse section through one of the ridges shown in Figure 21A. Note the asymmetry of the stratigraphic unit. Note also the internal clinoforms within the ridge, suggesting a progradational origin for this feature (modified from Liu et al., 1998).

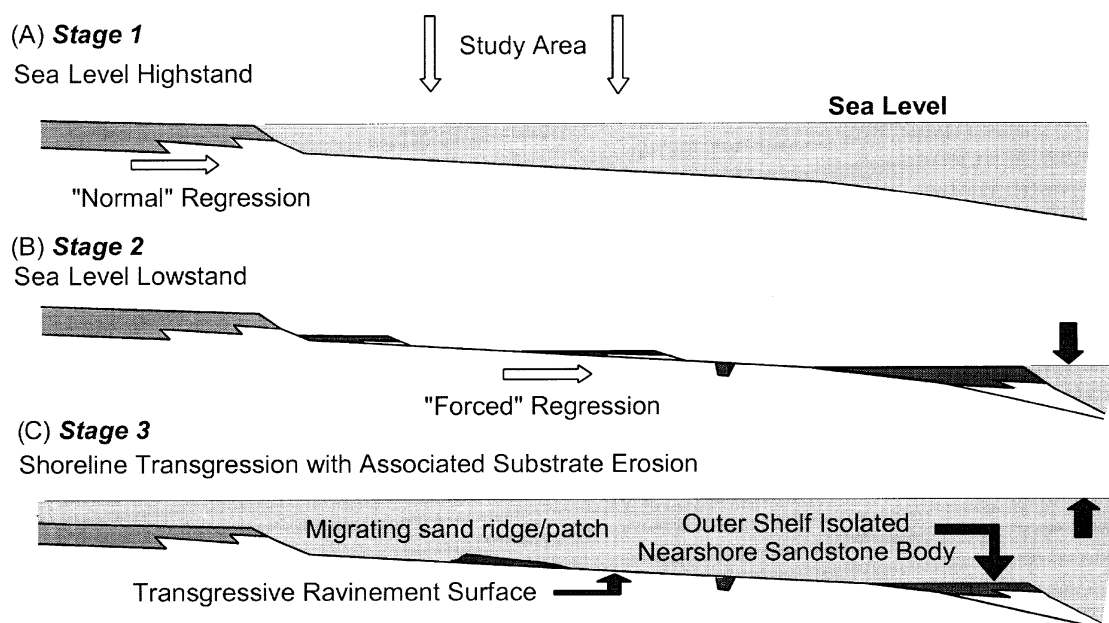


Figure 23. Illustration depicting the stages that characterize the formation of shelf ridge deposits. (A) Time 1 represents a time of sea level highstand. At this time, only muds are deposited on the shelf, and the shoreline lies landward of the study area. (B) At time 2, sea level fall exposes the sea floor, and the shoreline moves seaward across the study area. Ephemeral downstepping shoreface and deltaic sediments, as well as channelized (uncut by bypass alluvial) sediments, can be deposited on the shelf at this time. (C) At time 3, sea level has again risen, and the shelf has been flooded. Erosive processes associated with transgression erode the substrate, and shelf (tidal?) currents winnow the deposits, producing localized shelf ridges (modified from Posamentier et al., 1998).

Figure 15A). The dominant northeast-southwest orientation of the ridges suggests that shelf currents in this same general direction characterized the paleo-Java Sea offshore northwest Java. This inferred tidal current direction, subparallel with the ridges' long axes, is con-

sistent with modeling by Caston (1972) and Huthnance (1973, 1982a, b) and analyses of similar ridges by Kenyon et al. (1981).

The erosive processes acting on the newly submerged shelf selectively sort out the relatively

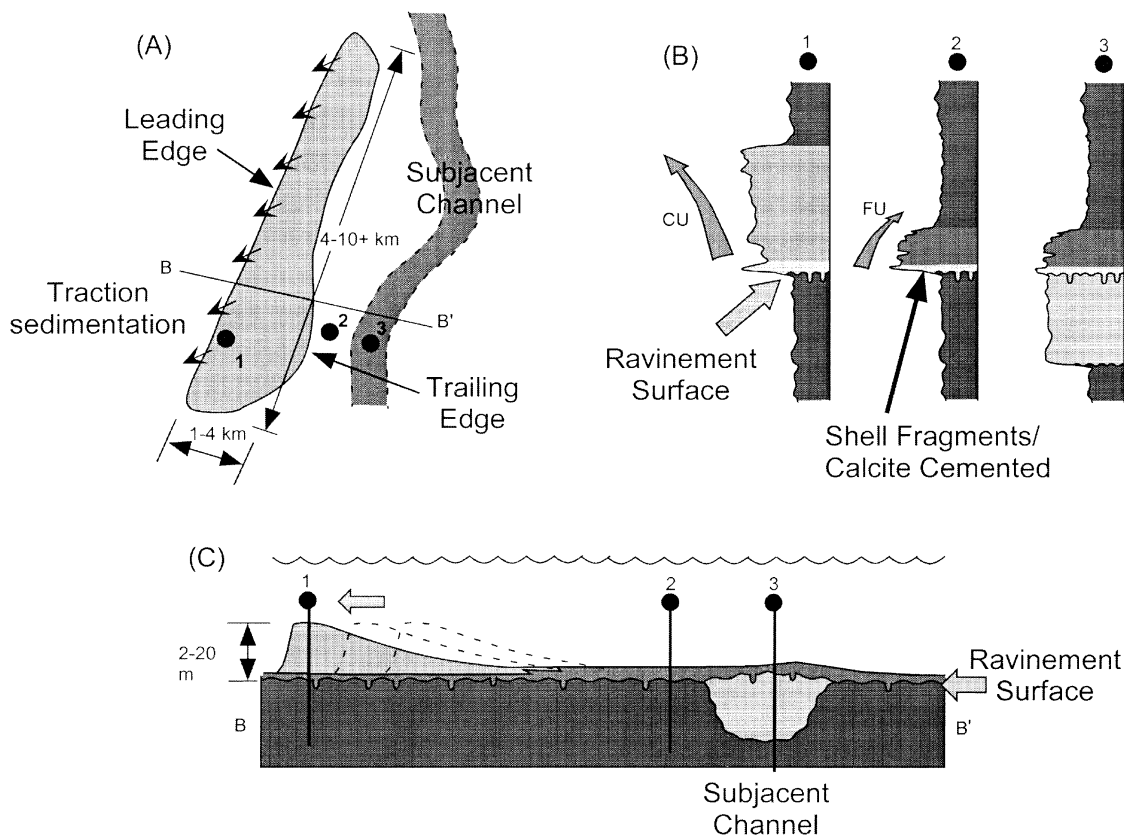


Figure 24. (A) Schematic depiction of a generic shelf ridge, showing map view of the ridge, with leading edge, trailing edge, and subjacent sand mother lode. (B) Schematic gamma-ray log expression through a typical shelf ridge. (B, C) Basal erosional contact is characterized by a *Glossifungites* ichnofacies, defining a ravinement surface. Immediately overlying this basal contact is a calcite-cemented zone associated with the presence of shell fragments within a lag deposit. Outboard of the trailing edge of the ridge, the shell-fragment section is overlain by the winnow product of the passing shelf ridge and commonly has a fining-upward log response. Within the shelf ridge, especially in proximity to the leading edge, the sand-prone deposits commonly are characterized by a fining-upward grain-size trend.

coarse-grained from the relatively finer grained sediments. This winnowing process results in the concentration of the coarsest grained sediments within the transgressive systems tract deposits immediately overlying a transgressive surface, commonly expressed as a ravinement surface (Figures 19, 20). Subsequent to substrate erosion, the sediments are influenced by whatever available environmental energy is present and are molded and shaped accordingly. In this area, offshore northwest Java, where tidal and/or other current-producing processes appear dominant, these deposits take the shape of asymmetric ridges oriented parallel with paleoembayment axes. In general, the sandier the substrate being eroded, the sandier the overlying transgressive deposits. Where the substrates are mud prone, only small isolated ridges form (e.g., Figure 7), but where substrates are sand prone, ridges can form in clusters and can also be larger (e.g., Figure

11). The sandier the transgressive deposits, the greater the likelihood that the sand from one ridge is linked to the sand in adjacent ridges. This, of course, negatively impacts the potential for such deposits to stratigraphically trap hydrocarbons.

The amount of substrate erosion during the period immediately following shoreline transgression is difficult to estimate. Although it is true that the "absence of evidence is not evidence of absence," it should be noted, nonetheless, that certain features are conspicuous by their absence at the base of the transgressive deposits. This observation holds true for most of the Upper Cibulakan Formation throughout offshore northwest Java, where very little evidence for subaerial exposure has been documented. The missing features include soil horizons, rooted zones, and delta or coastal plain sediments, all indicators of the presence of subaerial conditions prior to transgression. This, plus the

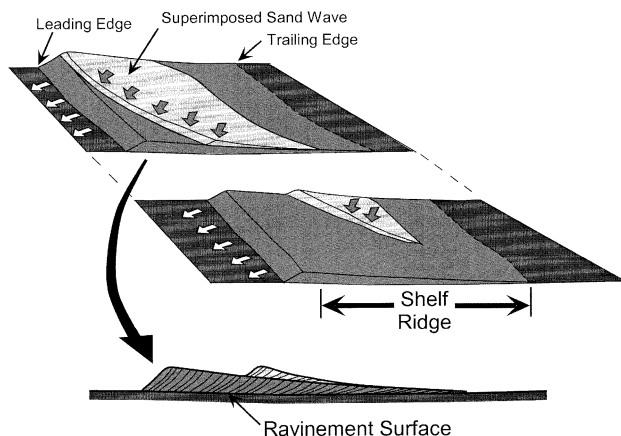


Figure 25. Schematic illustration of shelf ridge morphology. The leading edge is sharply defined and linear, whereas the trailing edge is more poorly defined. Superimposed on the crest of the ridge is a smaller sand wave oriented oblique to the long axis of the shelf ridge (compare with Figures 5E, F; 14D, E).

presence of a *Glossifungites* ichnofacies at the base of the transgressive deposits, suggests that enough erosion had occurred during transgression to have removed all indications of prior subaerial exposure and that such erosion exposed at the sea floor an exhumed, partially indurated substrate that would be amenable to the formation of a firmground depositional setting. Consequently, substrate erosion of approximately 3–6 m, probably by tidal or other shelf currents, is suggested, at a minimum.

The difference in shelf ridge size between the FXE and E field areas can possibly be explained by the fact that the E field area is located on a syndepositional high, as illustrated by the depositional thinning of the middle Miocene section that can be observed there (Posamentier et al., 1998). This would place the E field area on a relative paleotopographic high within the overall embayment described previously. This is in contrast with the FXE area, which is not associated with a paleotopographic high. High areas might be less prone to extensive deposition of sand-rich channels, which would tend to preferentially seek out topographically low areas. Fewer and smaller such channels would result in less sand available to be eroded from the substrate during transgression and, therefore, less coarse-grained material available for the construction of shelf ridges. This could account for the fact that the shelf ridges observed at E field are smaller than those observed in the FXE area (Table 1).

Seismic anomalies that can be mistaken for shelf ridges can range from data artifacts, to structure-

related features, to a depositional element other than a shelf ridge. Interpreters must initially establish that an observed anomaly is not an acquisition or processing artifact. Direct alignment of such an anomaly with either in-lines or cross-lines should raise concerns in this regard. Iterative inspection of horizon slices and seismic profiles should reveal whether an observed anomaly is structurally or stratigraphically caused. If it can be determined that an anomaly is neither a data artifact nor a structurally related feature, then a stratigraphic origin should be considered.

The types of depositional features that potentially can have a narrow linear expression in plan view include shelf ridges, straight alluvial or distributary channels, beach ridges, and strand plains. Each has certain unique attributes, however, that should enable the interpreter to distinguish between them. Analysis of associated seismic profiles, plus integration of other types of data, ultimately should establish which interpretation is most reasonable.

When analyzing seismic data, the interpreter should recognize that seismic data are responsive to rock properties. Such properties include not only lithology but also pore-fluid type. Consequently, care must also be taken to integrate an analysis of fluid effect and distribution with lithology in an evaluation of the geological significance of an anomaly.

EXPLORATION SIGNIFICANCE

The findings of this article 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 17 m thick. They can be preserved in clusters or as isolated deposits and are strikingly linear and parallel in plan view (Figure 18). Based on borehole penetrations, they appear to be sand prone, containing up to 80% net sand. This play type is known to produce oil and gas at several fields within the offshore northwest Java PSC. An isolated shelf ridge such as the one described in the FXE area (Figures 2A, 4) could contain reserves of more than 10 million bbl of oil or more than 30 bcf of gas if it were completely filled.

The extent to which shelf ridge deposits can stratigraphically trap hydrocarbons is unclear at the present time. Whether these deposits can be characterized as fractal equivalents of much smaller starved ripple sedimentary bedforms is not clear. If they can be so characterized, then the absence of sand between ridges is

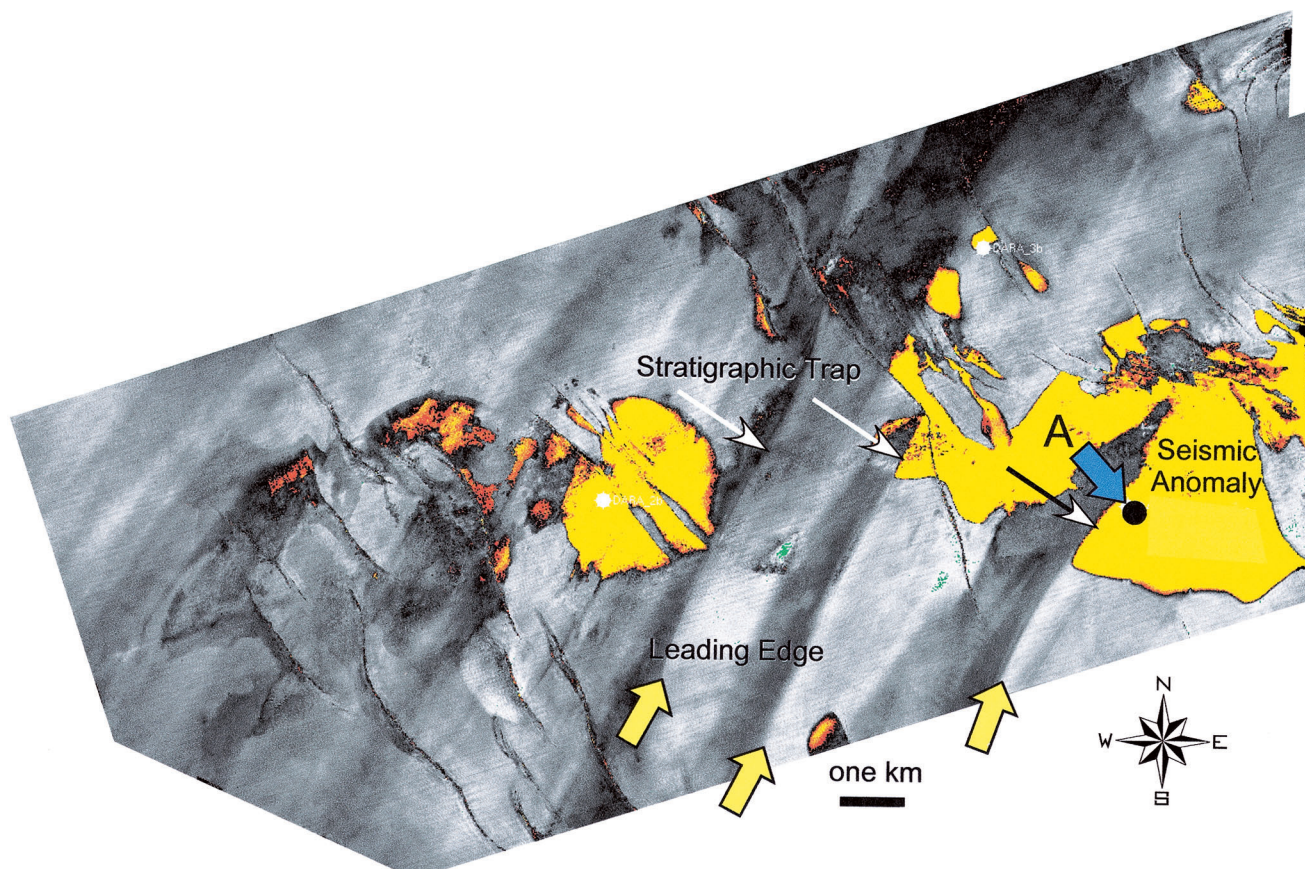


Figure 26. Seismic horizon slice of a shelf ridge cluster in the Natuna Sea area offshore Indonesia. Amplitude anomalies can be observed that conform in part to structure and in part to inferred stratigraphic pinch-out at the leading edge of the shelf ridges. Pinch-out at the leading edge confirms the stratigraphic trapping potential of these shelf ridges. The well drilled at location A encountered 9 m of excellent quality reservoir, as well as hydrocarbons (data courtesy of TotalFinaElf).

associated with discrete pinch-out of sands away from the ridges. Such a pinch-out, or potential stratigraphic trap, is best defined at the leading rather than the trailing edge of these features. An example of an apparent shelf ridge stratigraphic trap is illustrated in Figure 26. The limit of the amplitude anomaly clearly coincides with the leading edge of the shelf ridge. In general, the greater the tendency toward shelf ridge isolation rather than clustering, the greater the potential for stratigraphic trapping.

From a field development perspective, the recognition of these features may provide valuable insight to hydrocarbon distribution, reservoir compartmentalization, and the identification of possible high-productivity and high-recovery factor sweet spots (Figure 5E, F). This would allow optimization of well placements for both 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 on which those deposits are lying could constitute a sequence boundary. A mode of origin as shown in Figure 23 suggests that, in some instances, the surface on 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 hydrocarbon exploration play type. They have a distinctively linear form and are observed to occur either as isolated features or in clusters. These

deposits are common throughout the middle Miocene Upper Cibulakan Formation of offshore northwest Java. Such deposits are known to produce oil and gas from several sections in numerous fields within the offshore northwest Java (ONWJ) PSC. Shelf ridges observed here commonly range from 0.3 to 2.0 km wide, greater than 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, with the exception of those deposits that contain shell fragments and are carbonate cemented.

The shelf ridges observed and described in this article represent reasonable examples of a stratigraphic feature common on modern sea floors but notably absent from the geologic literature with regard to ancient deposits. This suggests that under certain paleoenvironmental conditions, shelf ridges do have the potential for preservation within the rock record, thus opening the door for the possible reinterpretation of similar deposits elsewhere.

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