SEISMIC STRATIGRAPHY AND GEOMORPHOLOGY OF OLIGOCENE TO MIOCENE CARBONATE BUILDUPS OFFSHORE MADURA, INDONESIA

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ABSTRACT: A variety of carbonate landscapes have been imaged on 3D seismic data from the offshore area north of Madura Island, Indonesia. This paper is a case study based exclusively on seismic geomorphologic and seismic stratigraphic analyses. Carbonate buildups ranging from small patch reefs to platforms with outliers, and tide influenced elongate large patch reefs are observed within the Kujung 2, Kujung 1, and Wonocolo Formations. Clastic input characterized by low-angle clinoforms from the north-northwest and ubiquitous polygonal fracturing occurred between deposition of the Kujung 1 and the Wonocolo formations. Subsequent to Wonocolo deposition, the basin gradually became subaerially exposed and was ultimately the site of densely spaced fluvial systems.

The small patch-reef buildups of the Kujung 2 range in size from less than 120 m up to 500 m in diameter. Across the platform these buildups are closely spaced, with less than 100 m separating isolated buildups. Each buildup is circular in plan view, with vertical relief of approximately 25–40 m. Hundreds of these features are observed within the 3D seismic volume.

Larger scale patch reefs of the Kujung 1 coalesced to form a northwest–southeast-trending platform. Individual buildups within the platform range from 600 m to 2 km in diameter and from 200 to 300 m in thickness. Smaller patch reefs ranging from 60 to 120 m in diameter are observed at the tops of these buildups. Large-scale buildups form off the platform and can be up to 400 m thick with diameters from 1 to 6.5 km. The Kujung 1 reefs are circular to elliptical in planform. Anastamosing channels up to 200 m deep and 650 m wide trend normal to the platform buildup and terminate at the buildup margin.

The Woncolo carbonate buildups generally are larger than the Kujung buildups and are characterized by internal clinoform architecture. These buildups are circular to elliptical in planform and range in size from 4 to 10 km wide and up to 20 km in length. They are separated from each other by tidal channels 1.2–2.5 km wide. The buildup tops are characterized by a complex network of channels, some up to 200 m wide.

KEY WORDS: carbonates, Madura, Indonesia, seismic stratigraphy, seismic geomorphology

INTRODUCTION

3D seismic data can play a vital role in hydrocarbon exploration and development, especially with regard to mitigating risk associated with the presence of reservoir, source, and seal facies. Such data can afford direct imaging of depositional elements, which can then be analyzed using integrated seismic stratigraphy and seismic geomorphology to yield predictions of lithologic distribution, insights to compartmentalization, and identification of stratigraphic trapping possibilities. Benefits can be direct, whereby depositional elements at exploration depths can be identified and interpreted, and indirect, where well-imaged depositional systems can provide analogues and depositional models for more poorly imaged exploration targets.

With the development of 3D seismic acquisition techniques, opportunities to image geologic features in map view have opened up new approaches to geologic prediction (e.g., Weimer and Davis, 1996). Various reflection attributes such as amplitude, dip magnitude, time-depth structure, and curvature, to name just a few, can be observed to yield direct images of depositionally and structurally significant features. In addition, analysis of seismic intervals and volumes, involving mapping of peak amplitudes, seismic facies, curvature, dip, etc., can lend further insights into such features.

The study of depositional systems in map view using 3D seismic-derived images has been referred to as seismic geomorphology (Posamentier, 2000). This represents a significant step change in how seismic interpreters evaluate seismic data from the perspective of reservoir prediction. In general, depositional environments had commonly been inferred on the basis of cross-section-derived stratigraphic architecture and subsequent mapping of seismic facies leading to lithologic predictions (Vail et al., 1977). With the advent of seismic geomorphology, discrete, detailed depositional environments could be interpreted directly from map-view images leading to a significantly more accurate understanding of lithologic distribution patterns and enhanced prediction of the distribution of reservoir, source, and seal facies (Posamentier, 2005). It is important to note, however, that although lithofacies prediction can be facilitated with this approach, understanding of reservoir quality (i.e., porosity and permeability) nonetheless requires additional analyses of core, geophysical, and petrophysical data.

STRATIGRAPHY

The area offshore northeast Madura Island, Indonesia (Fig. 1) has been the object of numerous studies (Mudjiono and Pireno, 2001; Adhyaksawan 2003; Johansen, 2003; Maynard and Morgan, 2005; Carter et al., 2005; Posamentier and Laurin, 2005). This area, and specifically the carbonate deposits there, have been the site of prolific hydrocarbon discoveries (e.g., Mudjiono and Pireno, 2001; Carter et al., 2005; Maynard and Morgan, 2005; Cahyono and Burgess, 2007; Wiyono et al., 2007). This basin constitutes one of several back-arc systems and lies to the southeast of the stable Sunda Shield and approximately 500 km north of the Java trench. Within these basins, shallow-water reefal carbonates are observed to alternate with siliciclastic deposits sourced largely from the Sunda Shield area to the northwest (Kenyon, 1977; Fulthorpe and Schlanger, 1989; Ardhana, 1993). Four discrete episodes of carbonate buildup are present in the Oligo-Miocene section. Three of the carbonate systems are addressed in this paper, including the Kujung 2, Kujung 1, and

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FIGURE 1.—Map of Southeast Asia showing location of study area offshore Madura Island, Indonesia.

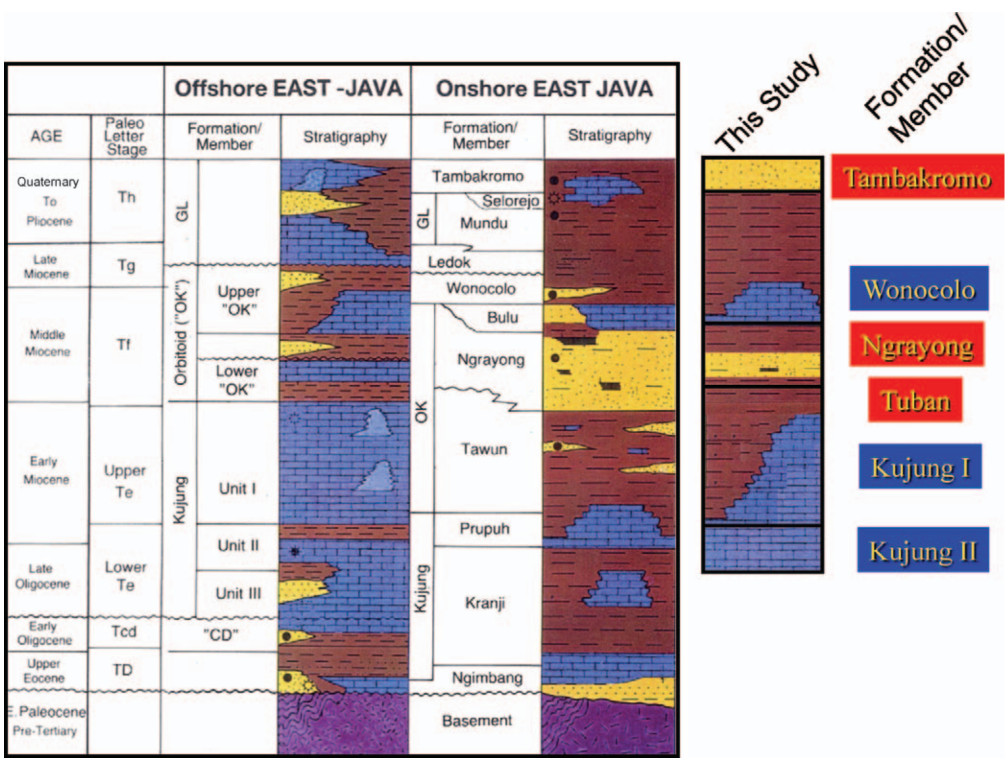

FIGURE 2.—Stratigraphic column for the Miocene section offshore Madura, Indonesia. The study focuses on the Miocene Kujung 2, Kujung 1, and Wonocolo carbonate buildups. The blue and red formation and member names represent carbonate and siliciclastic lithologies, respectively (modified from Mudjiono and Pireno, 2001).

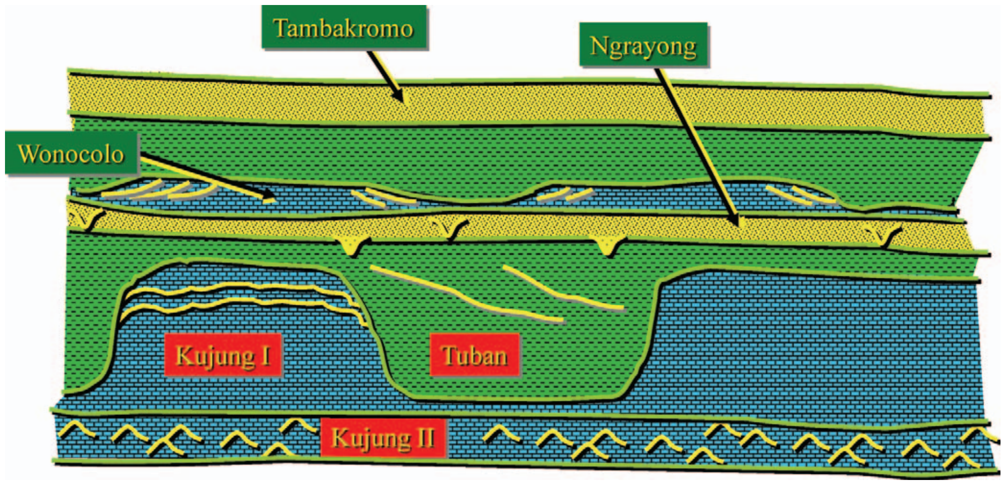

FIGURE 3.—Schematic depiction of stratigraphic architecture in the study area. The basal Kujung 2 is characterized by numerous small patch reefs. It is overlain by the Kujung 1, comprising a large carbonate platform and reef outliers. Relief from buildup top to basin floor was up to 200 m. The Tuban shale subsequently filled in the bathymetric lows, paving the way for later Ngrayong fluvial deposition. Carbonate deposition resumed with the Wonocolo buildups. The stratigraphic section is ultimately capped by Tambakromo nonmarine deposition.

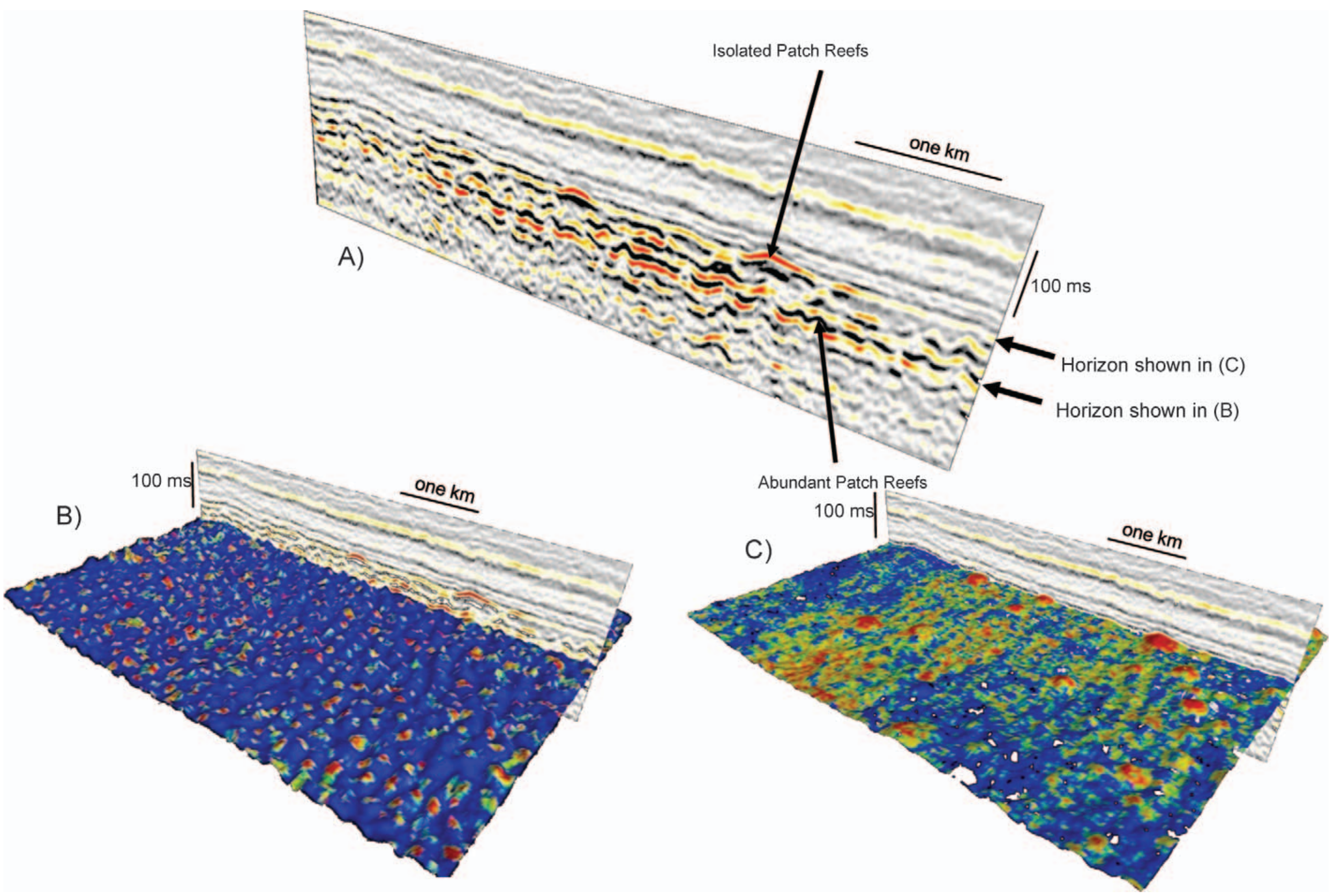

FIGURE 4.—Perspective view of Kujung 2 carbonate build-ups. A) In the lower Kujung 2, densely spaced buildups are observed. B) Reflection amplitude draped on a horizon from within the lower Kujung 2 section illustrating the geomorphology and densely-spaced nature of these small build-ups. C) In the upper part of the Kujung 2 section, patch reefs are larger and more widely spaced.

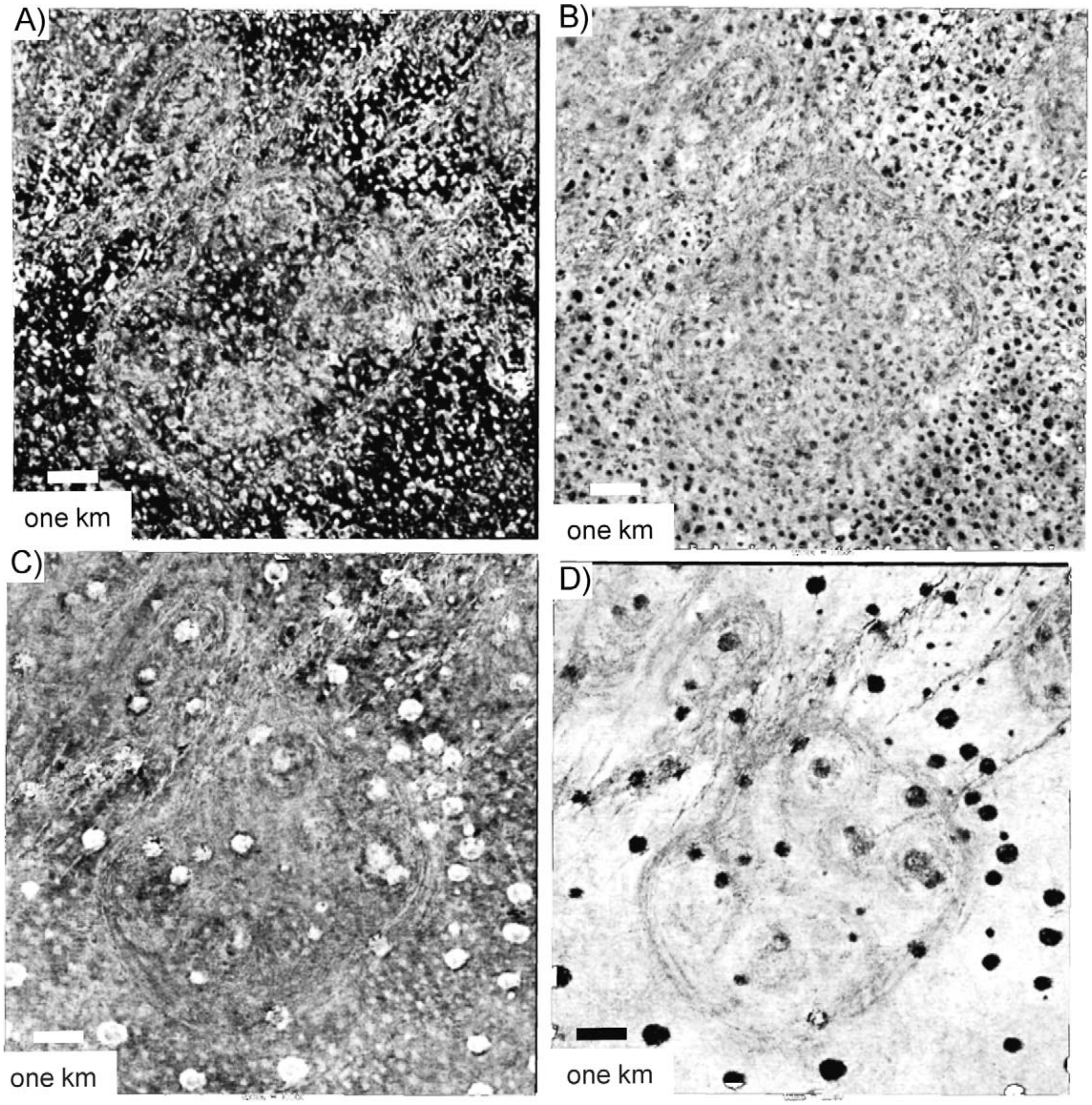

FIGURE 5.—Reflection amplitude extractions from a succession of horizon slices through the Kujung 2 section. These slices are spaced at 56 ms between A and B, 12 ms between B and C, and 12 ms between C and D. The deepest (i.e., the oldest) slice is shown in A and the shallowest (i.e., the youngest) slice in D. One ms equals approximately 2 m. Note the seismic shadow of the larger Kujung 1 reef, which lies stratigraphically above. C, D) Larger but more isolated patch reefs are present. Locations of slices are shown in Figure 6.

Wonocolo, as shown in a stratigraphic column (Fig. 2) as well as schematically (Fig. 3). The stratigraphy and geomorphology of these carbonate systems, deposited at or near the equator in the shallow-water, paleo-Java Sea, will be described and discussed in subsequent sections.

The data comprise a large, 3,963 km^2, high-quality multi-client 3D seismic survey acquired by PGS in 2003. Inline spacing was 15.625 m and crossline spacing was 12.5 m, and sampling was at 2 ms intervals. Examples shown in this paper are extractions from the full stack time-migrated volume.

KUJUNG 2

The Kujung 2 carbonate system (Fig. 3) is characterized by a swarm of scores of small patch reefs that appear to have populated a broad shallow platform area (Fig. 4). These buildups are closely spaced and cover much of the study area. Maynard and Morgan (2005) showed similar Kujung 2 buildups from their study area, some 50 km to the west. Figure 5 illustrates the sequential development of these deposits through a series of horizon slices produced by flattening on the top of the Kujung 2 and then slicing parallel to that surface. In the early stage of development, these buildups are ~ 100 m diameter with relief of ~ 15–20 m (Fig. 5A–C). At that time the build-ups were spaced approximately 150–200m apart. In the latter stages of Kujung 2 time the density of these build-ups decreased dramatically and the size and relief of individual buildups increased significantly (Fig. 5D). At that time patch reefs were larger, up to 300 m diameter and up to ~ 25–40 m in relief, and kilometers apart from one another. What does not change through Kujung 2 time, however, is the markedly circular pattern that characterizes these buildups. Although circular features observed on strata slices could represent karst development, in this

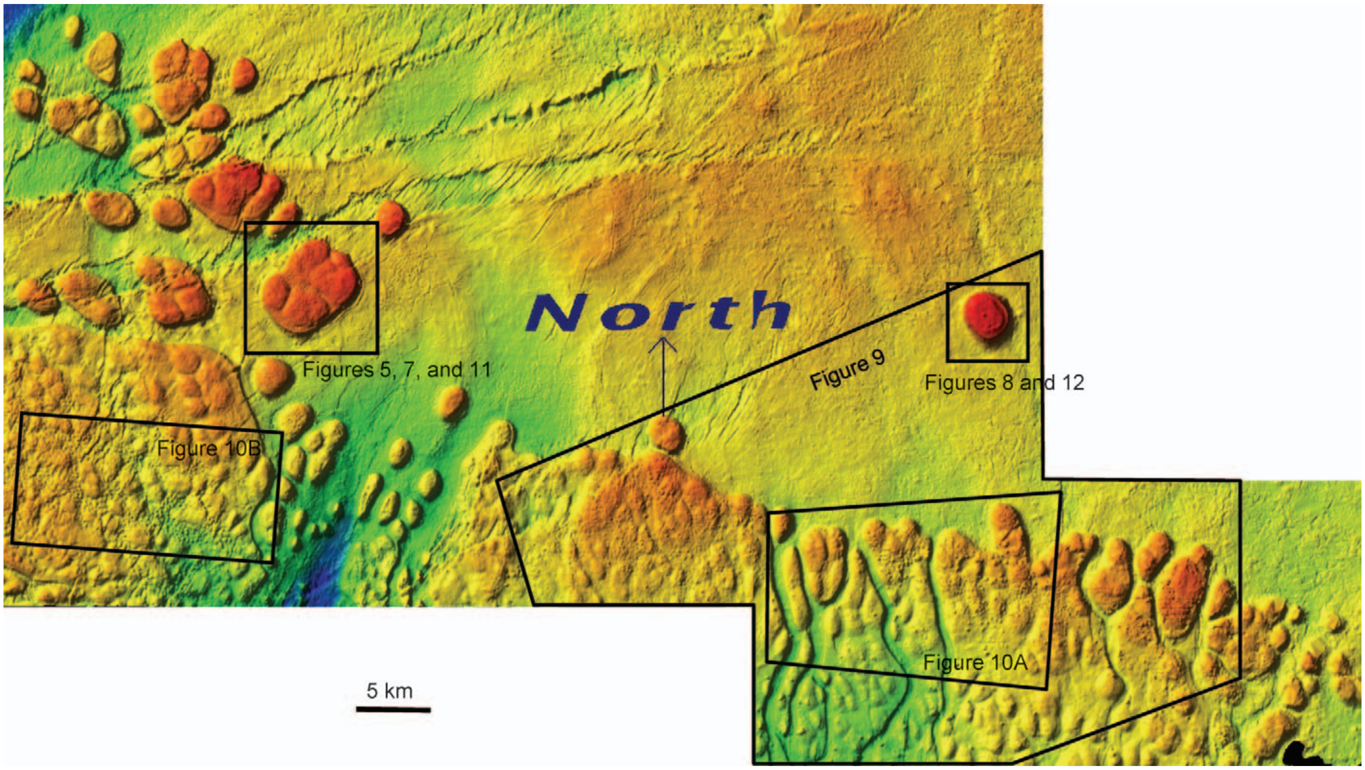

FIGURE 6.—Time structure map of the surface bounding the top of the Kujung 1 carbonate deposits. The southern part of the study area is characterized by a broad carbonate platform topped by reefs ranging from 3 to 5 km diameter. Outlier buildups up to 8 km in diameter are observed to the north and northwest.

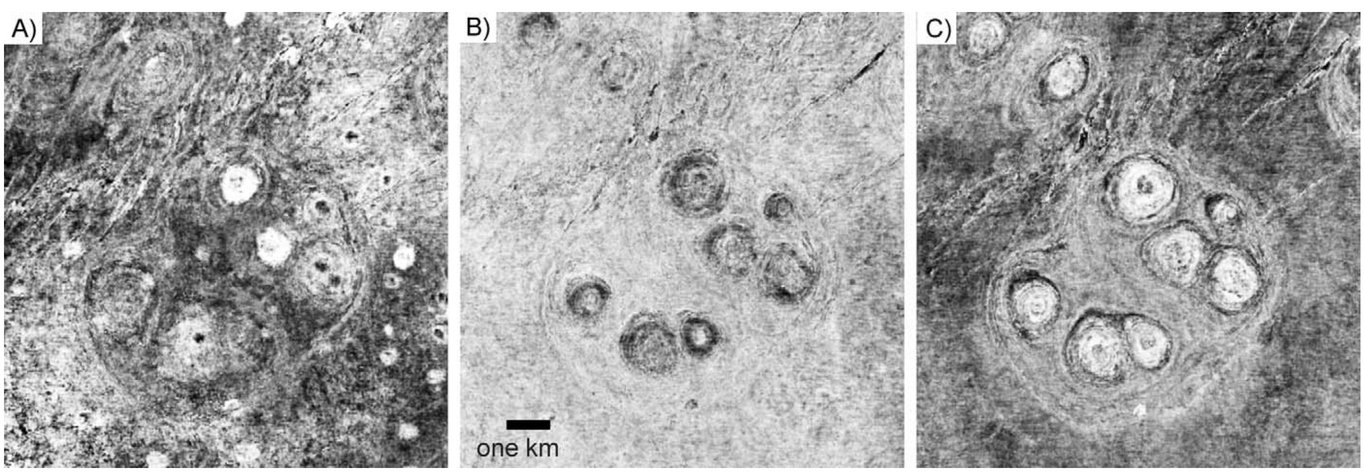

FIGURE 7.—Succession of reflection amplitude extractions from seismic stratal slices through early stage Kujung 1 carbonate buildups shown in A), B), and C), from oldest to youngest. Separation is 28 ms between A and B, and 12 ms between B and C. Note the circular map pattern and the symmetrical "growth rings" that characterize these buildups. Note also the progressive coalescing of individual patch reefs through time. Locations of slices are shown in Figure 6.

instance these circular features seem to represent positive rather than negative topography, as shown in Figure 4. Throughout this section there is no compelling evidence for dissolution features or karst development. Consequently, any subaerial exposure of this area seems to have been minimal.

KUJUNG 1

Kujung 1 time was characterized by a continuation of nearly circular buildups within the study area. This predominantly circular shape, also recognized by Maynard and Morgan (2005) approxi-

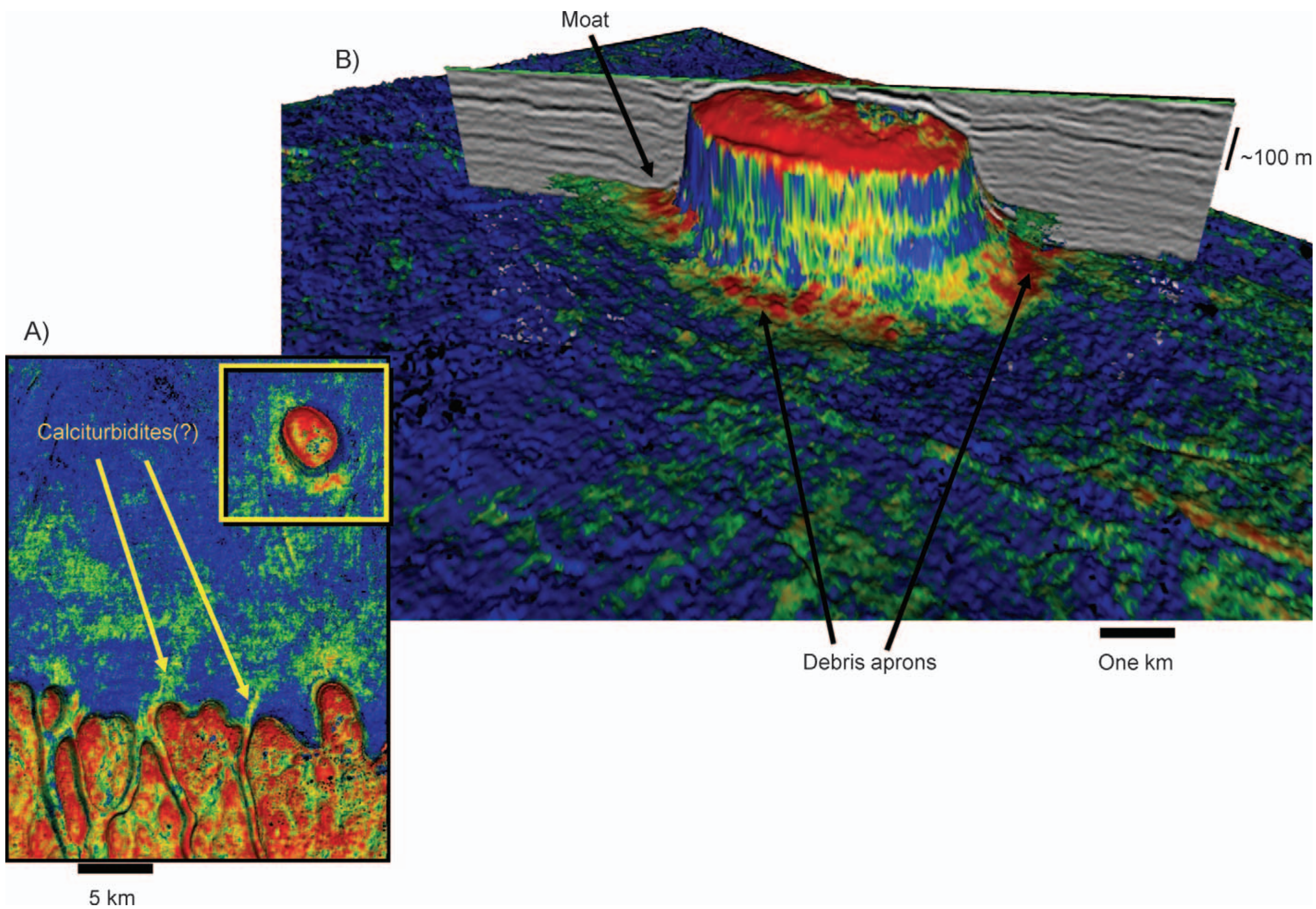

FIGURE 8.—A) Plan and B) perspective views of seismic amplitude map of an outlier buildup in the northern part of the study area. Debris aprons expressed as amplitude brights (reds and yellows) extending 1–2 km away from this buildup characterize the adjacent basin-floor areas. Plumes of amplitude brights are observed to emanate from the mouths of platform channels (A). Location of outlier is shown in Figure 6.

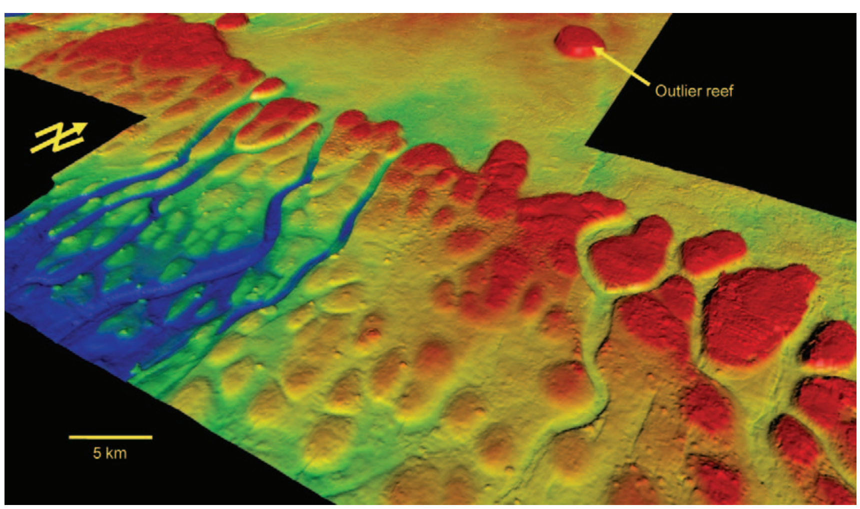

FIGURE 9.—Perspective view of carbonate platform crosscut by anastamosing tidal channels. The platform margin is roughly linear in map view, though in detail characterized by numerous protuberances. The platform top is marked by patch reefs 2–4 km wide which, in turn, are topped by smaller patch reefs (< 100 m wide). Location of platform is shown in Figure 6.

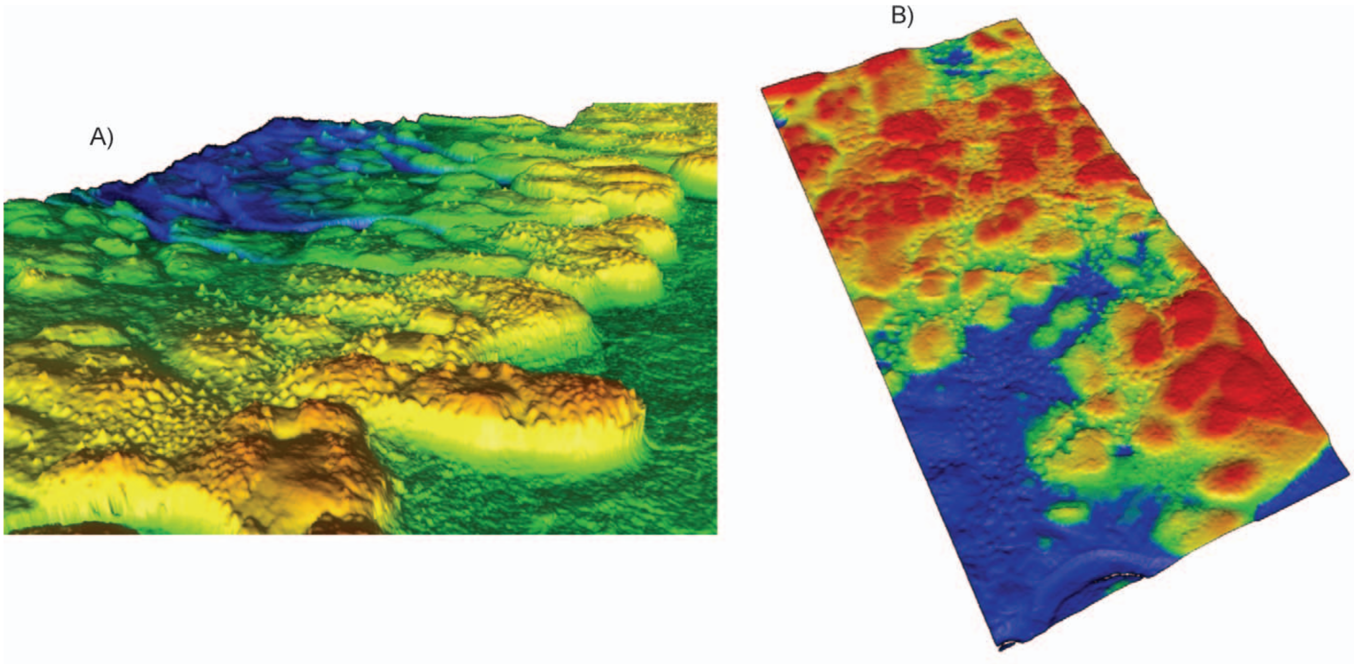

FIGURE 10.—Two perspective views (A and B) of time structure maps on top of Kujung 1 carbonates showing numerous small (< 100 m wide) patch reefs. Location of area is shown in Figure 6.

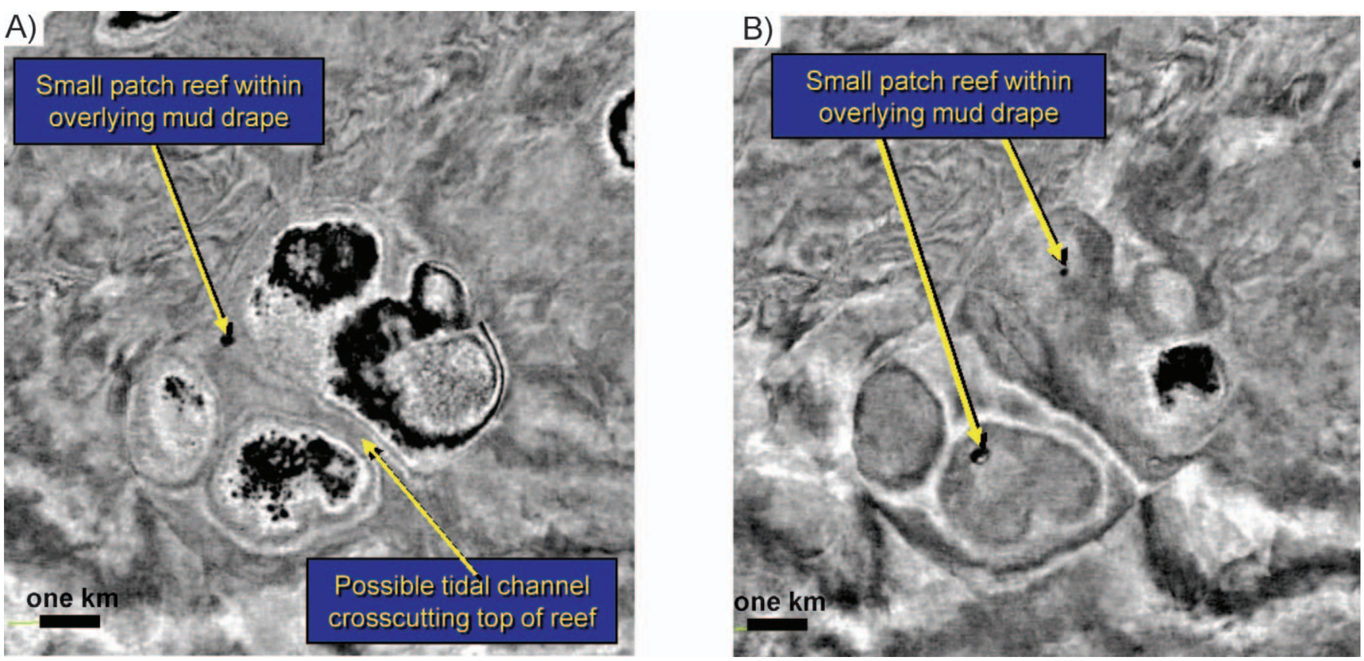

FIGURE 11.—Succession of reflection amplitude extractions from seismic stratal slices through late stage Kujung 1 carbonate buildups. Slices shown in A and B are 36 ms apart, from oldest to youngest. Small patch reefs at the top of the reef can be observed in A. Isolated patch reefs are observed embedded within the mudstones that overlie the reef. Locations of slices are shown in Figure 6.

mately 50 km west of the study area, is dissimilar from the largely elongate shape of similar-aged deposits described by Carter et al. (2005) and speaks to differences in paleo-oceanographic controls between the two areas, approximately 100 km apart. However, in contrast with the buildups of Kujung 2 time, coalescence of Kujung 1 reefs, particularly in the southern part of the study area, resulted in formation of a broad carbonate platform; to the north associated outliers are observed (Fig. 6). During the early stages of Kujung 1

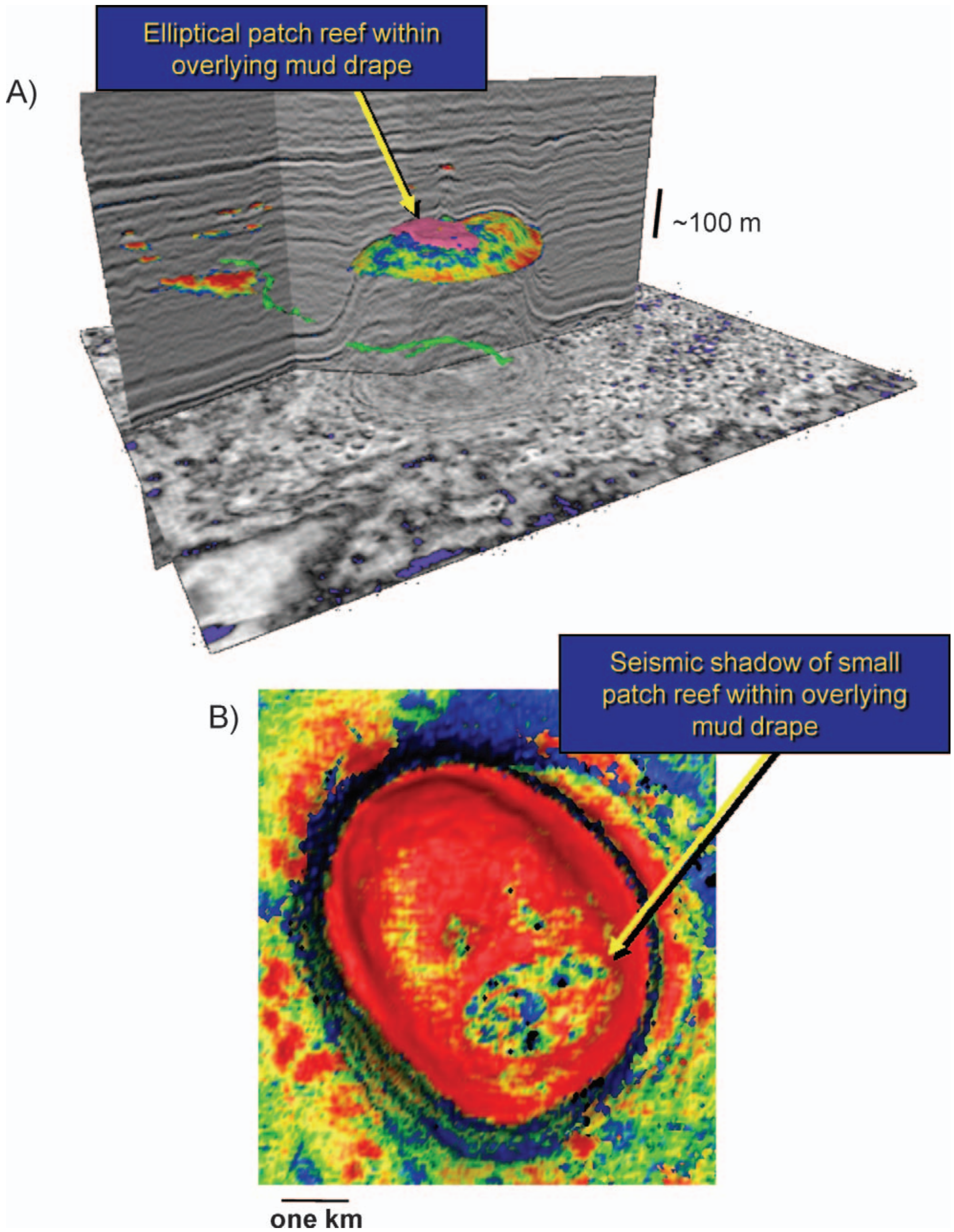

FIGURE 12.—Small post-Kujung 1 carbonate buildups are observed on amplitude maps draped over structure. A) Interpreted carbonate buildups as seen in a perspective view of a time slice cut by an arbitrary seismic line. B) Plan view of amplitude extraction of the large Kujung 1 buildup overlain by late-stage small post-Kujung buildups. The most significant such buildups are observed immediately overlying the large Kujung 1 reef; however, smaller mud-encased patch reefs can be observed away from this reef as well (A). Location of area is shown in Figure 6.

time some of the late stage Kujung 2 patch reefs served as nucleation sites for larger and higher-relief Kujung 1 buildups. The seismic images suggest concentric evolution similar to that observed for Kujung 2 (Fig. 7). Carter et al. (2005) reported that Kujung 1 buildups in their study area comprise well-sorted skeletal packstones, local framestones, and interbedded wackestones. By the end of Kujung 1 time, the platform areas were elevated relative to adjacent basinal areas by as much as 150– 200 m.

Isolated outlier buildups are observed in the deeper basin to the north and northwest. These outliers range in size from ~2 to 8 km. Circular morphology characterizes these outliers as well. Adjacent to some of these outliers, debris aprons of limited extent can be observed (Fig. 8). These debris aprons seem to be uniformly distributed around these buildups, which tower as much as 150 m above the adjacent basin floor. The debris aprons extend to no more than 1–2 km away from the base of the buildups. Carter et al. (2005) have suggested that these debris aprons are associated with periodic exposure of the platform; however, no direct evidence for exposure in the form karst development was observed in the seismic data. Also along the flanks of some of the platform areas, moat-like features have been observed. This was especially seen in proximity to the large platform outliers (Fig. 8). These moats are approximately 1 km wide and 30–50 m

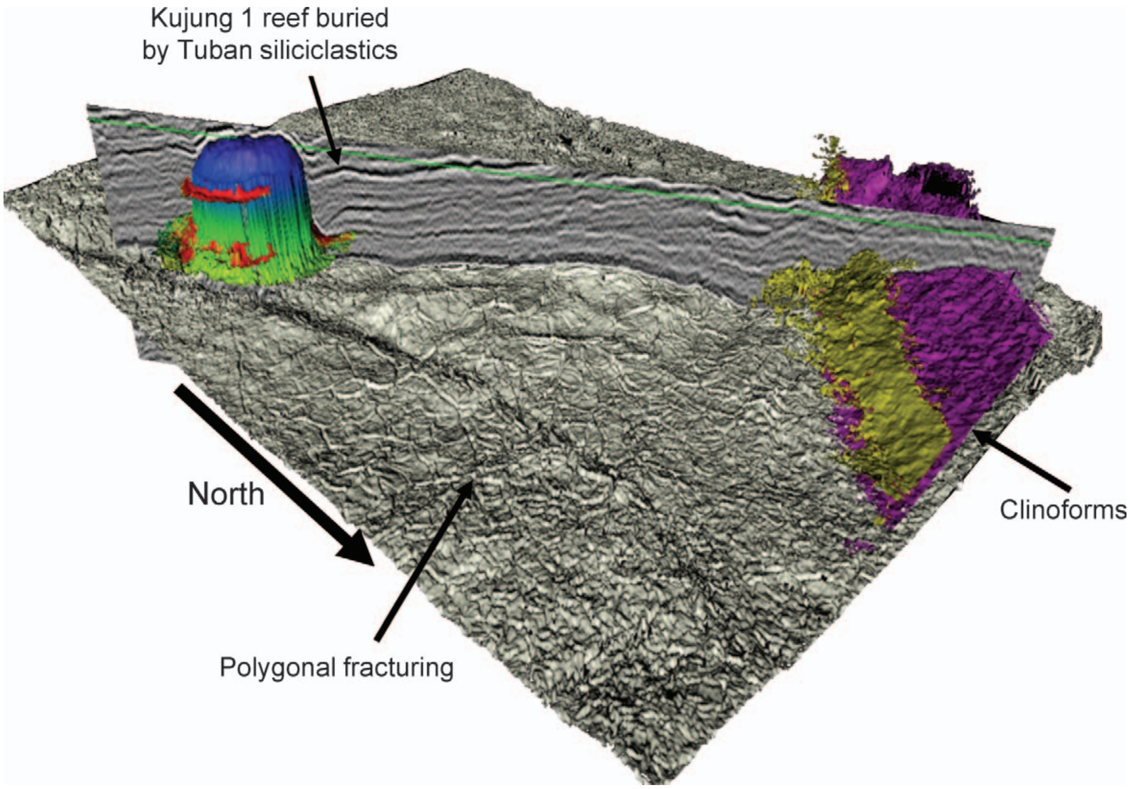

FIGURE 13.—Kujung 1 outlier (approximately 4 km wide) with later Tuban mudstones prograding from the northwest. These mudstones eventually bury the Kujung 1 carbonates and form the platform across which Ngrayong siliciclastics are deposited. The basin floor is characterized by polygonal fracturing, suggesting the presence of marl across the basin floor. The outlier reef shown is the same as that shown in Figures 6, 8, and 9.

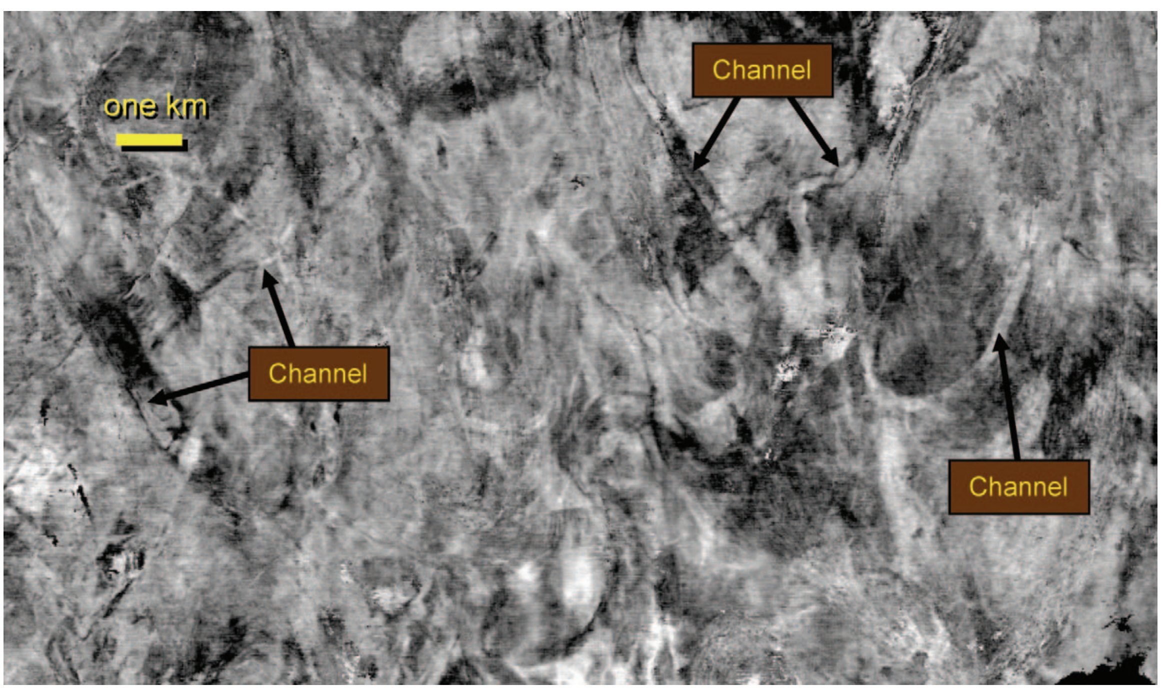

FIGURE 14.—Seismic reflection amplitude extraction from a stratal slice through the Ngrayong siliciclastic section. Numerous small channels can be observed.

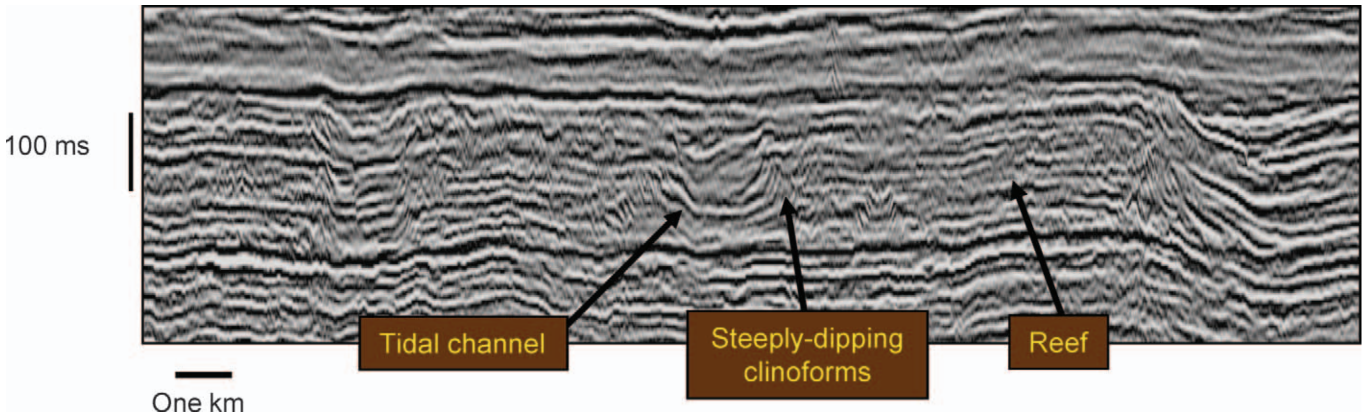

FIGURE 15.—Seismic section through Wonocolo carbonate reefs. The reef interior is characterized by moderate- to high-amplitude discontinuous reflections, whereas the channels between the reefs are characterized by high-amplitude continuous reflections.

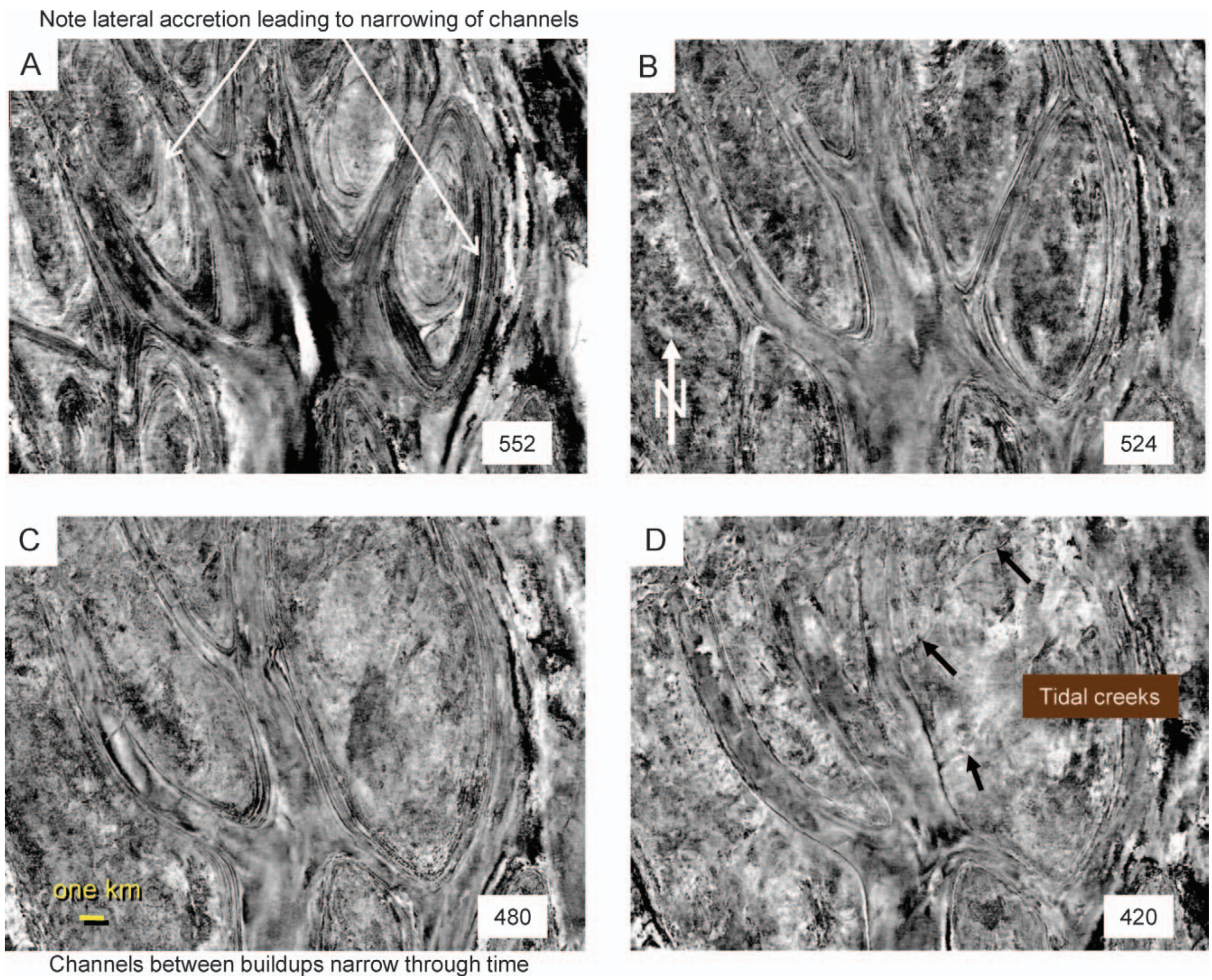

FIGURE 16.—Succession of reflection amplitude extractions from seismic stratal slices through the Wonocolo carbonate buildups are shown in A, B, C, and D, from oldest to youngest. The interval between A and B is 28 ms, B and C 44 ms, C and D 60 ms. These buildups are markedly asymmetrical. Note the progressive narrowing of low-sinuosity anastamosing tidal channels through time. Within the reefs, small, moderate-sinuosity channels can be observed.

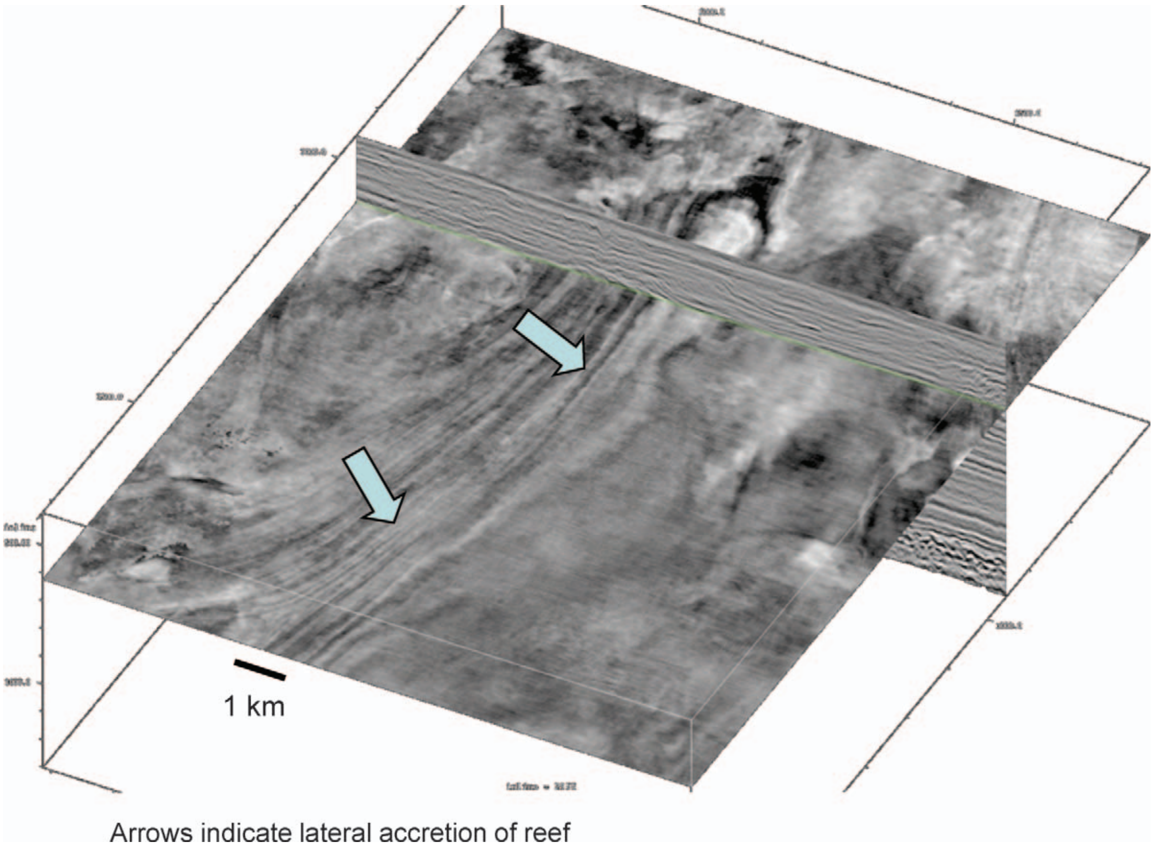

FIGURE 17.—Seismic reflection amplitude extraction from a stratal slice through a Wonocolo reef and associated transverse seismic cross section. The stratal slice clearly shows the lateral accretion through time.

deeper than the adjacent basin floor, and are likely associated with accentuated tidal currents along outlier platform margins.

The Kujung 1 carbonate platform extends across the southern part of the study area and is cross-cut by several 1–1.5 km wide, low-sinuosity anastamosing tidal channels (Fig. 9). These channels are steep-sided and characterized by depths of ~150 m. Where these channels debouch onto the deeper-water basin floor to the north, plumes of sediments seem to be present suggesting the possible presence of channel-sourced detrital sediments in the form of calciturbidites (Fig. 8) (Scholle et al., 1983).

At the tops of the Kujung 1 buildups, smaller scale patch reefs, similar in scale and in proximity to one another to those observed in the early Kujung 2 section, can be observed (Fig. 10). These small-scale buildups represent the last phase of carbonate production during Kujung 1 time.

Subsequent to Kujung 1 time, in the overlying drape deposits just above (i.e., within 25–50 m), isolated small circular (i.e., < 150 m in diameter) (Fig. 11) to elliptical (~ 3 km long) (Fig. 12) buildups can be observed. These small buildups are embedded within mudstones of the overlying siliciclastic deposits of the Tuban Formation. Most commonly these small reefs form immediately above the highest points of the underlying Kujung 1 buildups, though in at least one instance a small buildup is observed within the drape deposits directly above a late Kujung 1 channel (Fig. 11B). The presence of these small buildups as the last vestige of carbonate production is indicative of an inability of the carbonate factory to keep up with creation of accommodation space.

The coeval basinal deposits adjacent to Kujung 1 buildups are inferred to be calcareous mudstones deposited in water depths up to 200 m. Seismically, these deposits are characterized by continuous moderate- to high-amplitude reflections. In places, these deposits are characterized by polygonal fracturing (Fig. 13). Such patterns have been reported to be a common feature associated with dewatering mudstones (Cartwright et al., 2003).

WONOCOLO

Following Kujung carbonate deposition, a period of siliciclastic influx sourced from the northwest occurred, likely associated with the slowly rising Sunda shield area. This siliciclastic influx is expressed as low-angle, mud-rich clinoforms (R. Noble, personal communication) dipping towards the southeast (Fig. 13). These mud-rich deposits may have been at least partially responsible for shutting down Kujung carbonate production in the area. However, in the absence of supporting evidence in the form of precise age control, the alternative mechanism for shutting down carbonate production, rapid rise of relative sea level, cannot be discounted. The major Kujung carbonate platform in the south as well as all the outliers to the north were buried during this period (Fig. 13). During the early stages of this burial process, small patch reefs continued to remain active for a short time before being forced to shut down as discussed above (Figs. 11, 12). Once the basin filled in with these mud-rich clinoform deposits, fluvial systems of the Ngrayong Formation built across the area. These fluvial systems were characterized by channels of varying scales, ranging

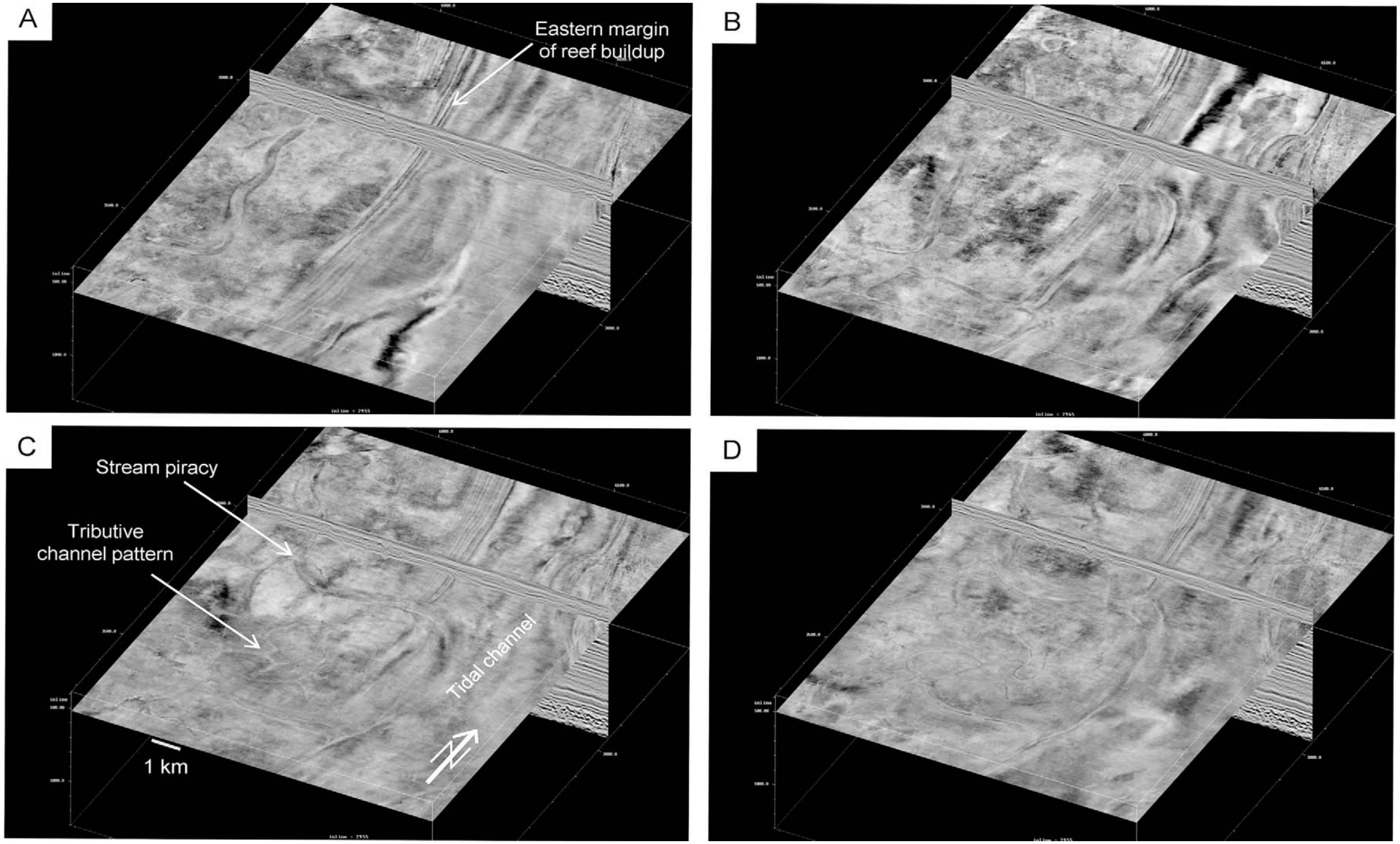

FIGURE 18.—Succession of reflection amplitude extractions from seismic stratal slices through the Wonocolo carbonate buildups are shown in A, B, C, and D. Slices are separated from each other by 20 ms (A and B), 12 ms (B and C), and 8 ms (D and E), from oldest to youngest. The eastern margin of this reef is readily apparent. To the west of this margin, in the reef interior, numerous small channels can be observed, ranging in scale from over 1 km to less that 100 m wide. Stream piracy can be observed between slices B and C where the channel draining eastward has captured the drainage from the channel that formerly drained the reef interior towards the west.

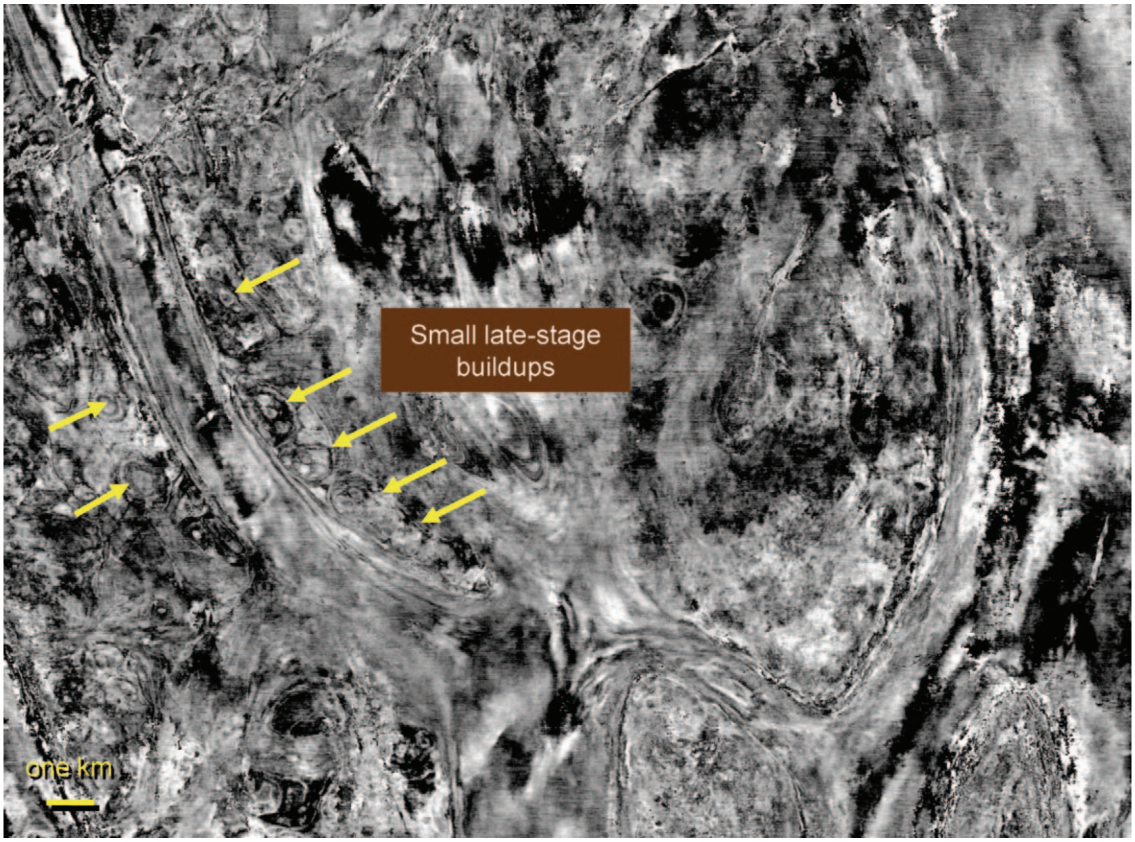

FIGURE 19.—Seismic reflection amplitude extraction from a stratal slice through late stage Wonocolo reef deposition. Numerous small buildups overlie the margins of the underlying pod-shaped Wonocolo reefs, suggesting that the reef flanks were bathymetrical high and served as nucleation points for these late-stage deposits.

from approximately 100 m wide up to channel belts in excess of 3 km wide (Fig. 14).

Subsequent to fluvial deposition, flooding of the shelf once again reestablished a marine fairway in this area and carbonate production resumed (Fig. 15). The pattern of this renewed carbonate production, however, was significantly different from that which characterized the earlier Kujung 1 and 2 carbonate buildups. In contrast with the circular pattern of buildup that characterized the Kujung 1 and 2 build-ups, the Wonocolo buildups were characterized by a pod-shaped, elongate map pattern as much as 15 km long and 7 km wide (Fig. 16). Strong lateral progradation associated with these elongate buildups characterizes the Wonocolo. Long-lived, wide, low-sinuosity tidal channels separate discrete Wonocolo buildups (Fig. 16). These channels show a pattern of progressive infill and consequent narrowing as the Wonocolo reefs expanded laterally (Fig. 16A, 17). Some of the channels filled in completely during the latter stages of growth (note that the NE–SW trending channel crosscutting the reef on the eastern side of Fig. 16B has been almost completely abandoned in Fig. 16C), but most persisted until the end of Wonocolo time. The relief of the Wonocolo buildups was in the order of $\sim$ 50–75 m from reef top to channel floor (Fig. 15).

The internal seismic architecture of the Wonocolo buildups is characterized by low-amplitude discontinuous reflections. The margins of these buildups are characterized by clinoform reflections dipping at 12–18 degrees (Fig. 15). The clinoforms exhibit complex geometries characterized by angular discordances suggesting reef growth in stages. Unfortunately, the lack of seismic reflection continuity from reef margins to interior makes it impossible to accurately characterize internal reef stratigraphy whereby angular discordances on the flanks could be related to distinct reef-interior architecture.

Channels separating the reefs as well as channels within the reefs can be observed. Within the oblong Wonocolo buildups complex, small, shallow channels commonly less than 75 m wide can be observed (Fig. 18). These channels are characterized by low to moderate sinuosity and in some instances by a tributive pattern. The channels originate within the central regions of the reefs, possibly within lagoonal settings. They typically are short and are characterized in some instances by stream piracy, such as is observed between times associated with Figure 18B and 18C. The drainage network observed for the buildup shown in Figure 18 suggests the presence of an elevated reef margin along the eastern side, with interior drainage consistently directed towards the west. The pattern of westward drainage is interrupted by stream piracy associated with a major channel from the east that captures the interior drainage of the lagoon during the latter stage of its development. The channel that flows towards the east breaches the marginal reef and debouches into the bordering large tidal channel that is oriented parallel to the long axis of the carbonate platform. Within the bordering channel, there is a suggestion of predominant flow towards the south as indicated by the south-directed seismic reflection pattern where the platform channel enters the large tidal channel. Elsewhere, very late stage carbonate production, just prior to abandonment, was characterized by small circular buildups along tidal channel margins (Fig. 19). Ultimately these reefs were buried by siliciclastic deposits that eventually culminate in the reestablishment of a fluvial terrain (Fig. 20).

Lithologically, the Wonocolo Formation has been characterized as

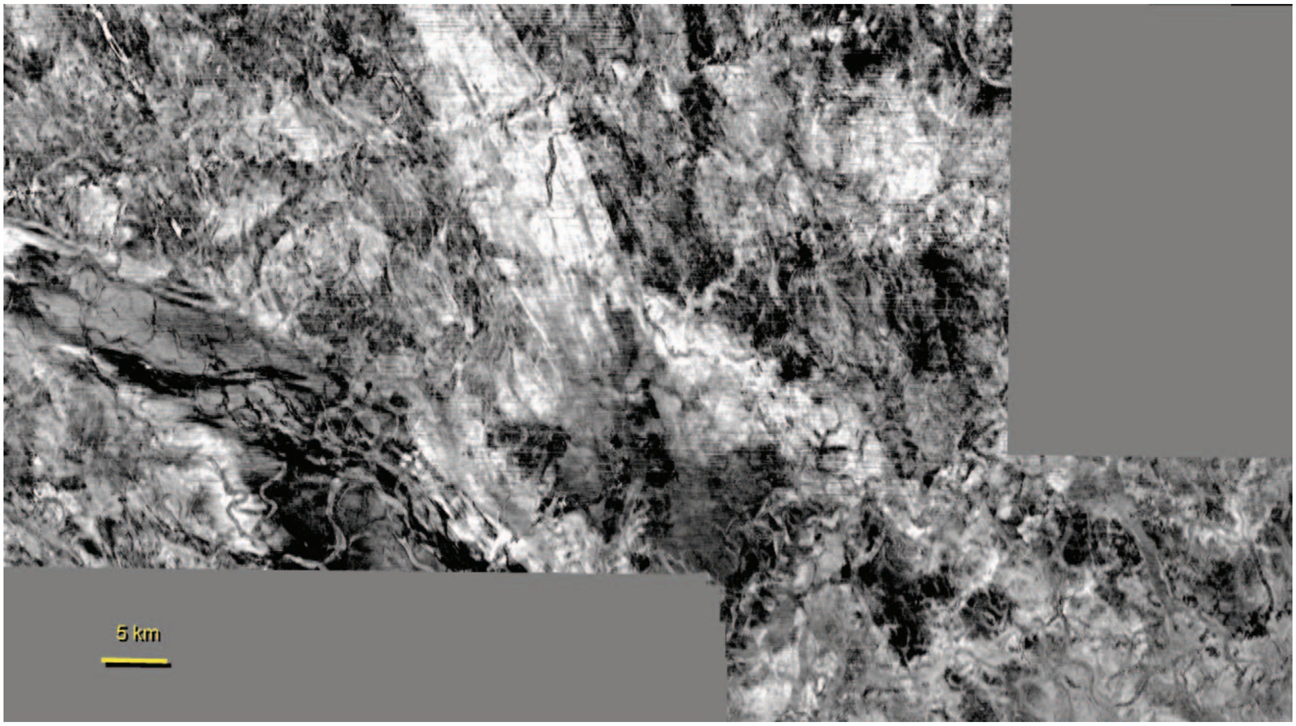

FIGURE 20.—Seismic reflection amplitude extraction from a stratal slice through Tombokromo continental deposits. Numerous, small fluvial and tidal channels are imaged.

comprising well-bedded carbonates rich in large benthic foraminifera and platy corals, and sandy fossiliferous carbonates (Adhyaksawan, 2003).

DISCUSSION

Multiple episodes of carbonate buildup characterize the Miocene section of offshore Madura, Indonesia. The style of carbonate production is variable, ranging from small patch reefs less than 75 m diameter, which are common in the Kujung 2 section to large carbonate platforms greater than 30 km wide, which are common in the Kujung 1 section. The symmetry of these buildups is also variable, ranging from circular to oblong map patterns. The thickness of these buildups from Kujung 2 to Wonocolo time is also variable, ranging from a few meters during Kujung 2 time to approximately 200 m during Kujung 1 time.

The abundance of small buildups during Kujung 2 time is remarkable, covering an area greater than 2500 km. These buildups are uniformly small commonly at less than 100 m in diameter. However, during the latter stages of Kujung 2 time they increased in area as well as relief, and became significantly more isolated. A possible analog for these features can be observed on Glover's Island offshore Belize (Andrefouet et al., 2003), where numerous carbonate buildups of similar size have been preserved. Another analog is in the Maldives, where abundant small patch reefs can be observed (Fig. 21). However, the patch reefs in the Maldives cover a much smaller area and are somewhat larger than the bulk of the Kujung 2 reefs. During the late stage of Kujung 2 time, the patch reefs, though still circular, are somewhat larger and of higher relief than during the early stage of Kujung 2 time. This suggests that relative sea-level rise likely accelerated, causing many of the smaller reefs to "give up". Some of the reefs, however, were able to "keep up" with sea-level rise. With fewer reefs present and deeper water, these late-stage reefs likely benefitted from the more favorable living conditions (from the perspective of increased nutrients because of less restricted oceanic circulation and less competition, e.g., Scholle et al., 2003) and were able to achieve larger size.

The transition from Kujung 2 to Kujung 1 time is marked by apparent accelerated sea-level rise as implied by the significantly greater relief of Kujung 1 reefs. Carbonate production during Kujung 1 time was characterized by extensive platform development in the southern part of the study area and large (up to 8 km wide) isolated outliers in the north and northwest (Figs. 6, 8, 9). The relief from reef top to base was as great as 200 m. The basin floor at this time is characterized seismically by continuous reflections, locally broken up by polygonal fracturing. This type of fracture pattern has been shown to be typical of fine-grained sediments, in this instance marl, undergoing a process of dewatering (Cartwright et al., 2003).

Examination of early Kujung 1 deposits, in particular the outlier reefs, reveals that at least some of these deposits originated by nucleating on late Kujung 2 patch reefs. Stratal slices through these early Kujung 1 reefs are commonly characterized by an onion-like pattern of concentric rings (Fig. 7). This pattern suggests concentric growth, implying the absence of active currents or predominant wind direction. As the Kujung 1 reefs grew they coalesced into larger reefs and platforms (Fig. 22). The outlier reef shown in Figure 22 illustrates coalescing reefs crossed by channels that persisted through the life of the buildup. It is likely that these channels were tidal in origin, where active tidal processes prevented infilling by sediments.

The large Kujung 1 platform in the southern part of the study area likely formed as a result of the coalescence of numerous small buildups, much as the outlier reefs developed. However, because of the attenuation of the seismic signal through the platform area, the early stages of platform development are obscured. Thus, any structural control on reef distribution can only be inferred. The northern margin

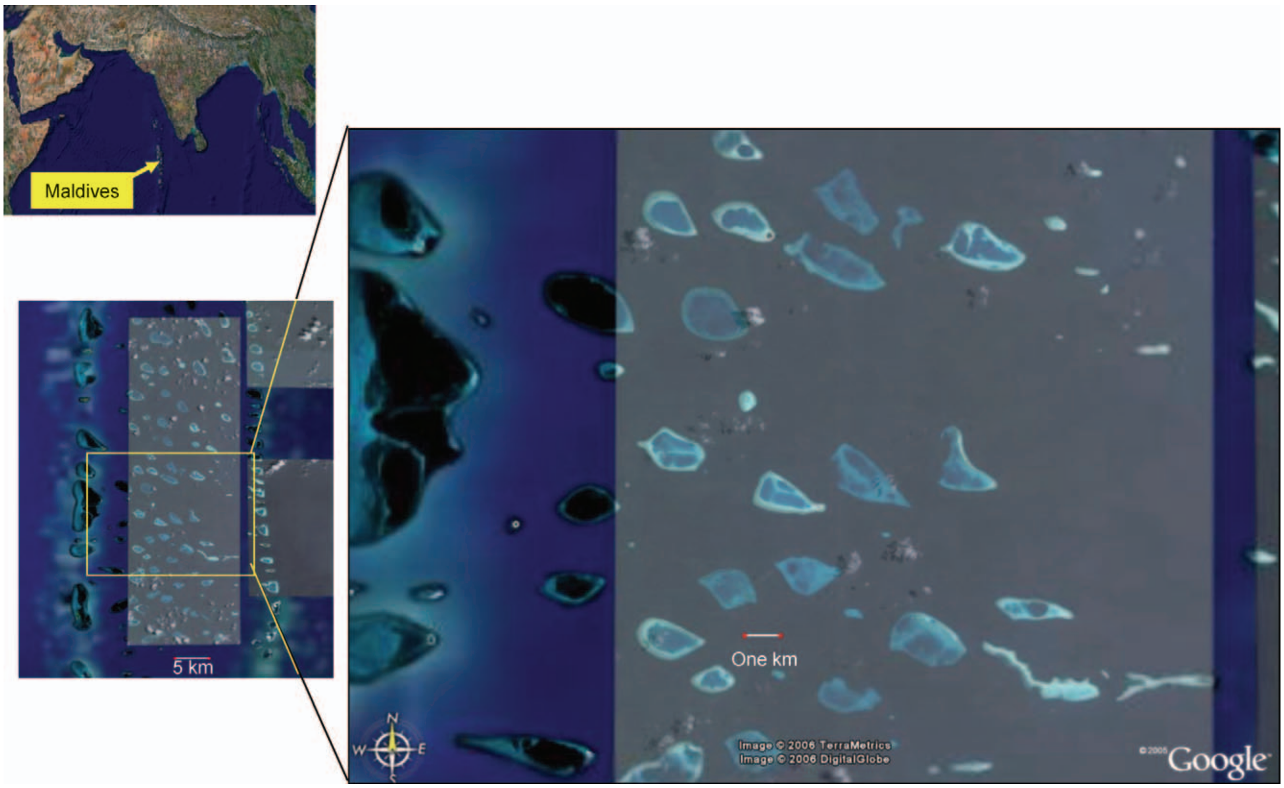

FIGURE 21.—Satellite image of modern patch reefs from The Maldives, analogous to patch reefs of the Kujung 1 and 2 (image courtesy of Google Earth, NASA, TerraMetrics, and DigitalGlobe, 2006).

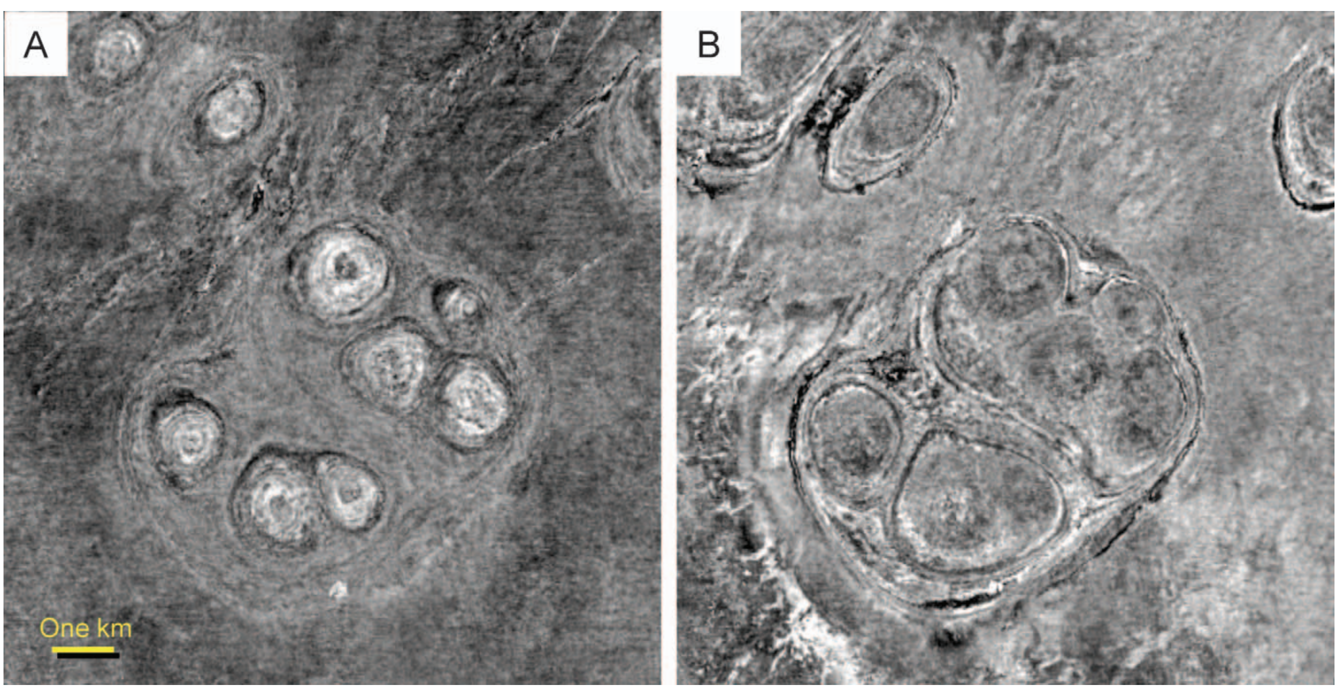

FIGURE 22.—Seismic reflection amplitude extraction from a stratal slice through A) early and B) late-stage Kujung 1 reef deposition showing long-lived channels crosscutting the reef. These channels formed early in the evolution of this reef and persisted until the end of reef deposition.

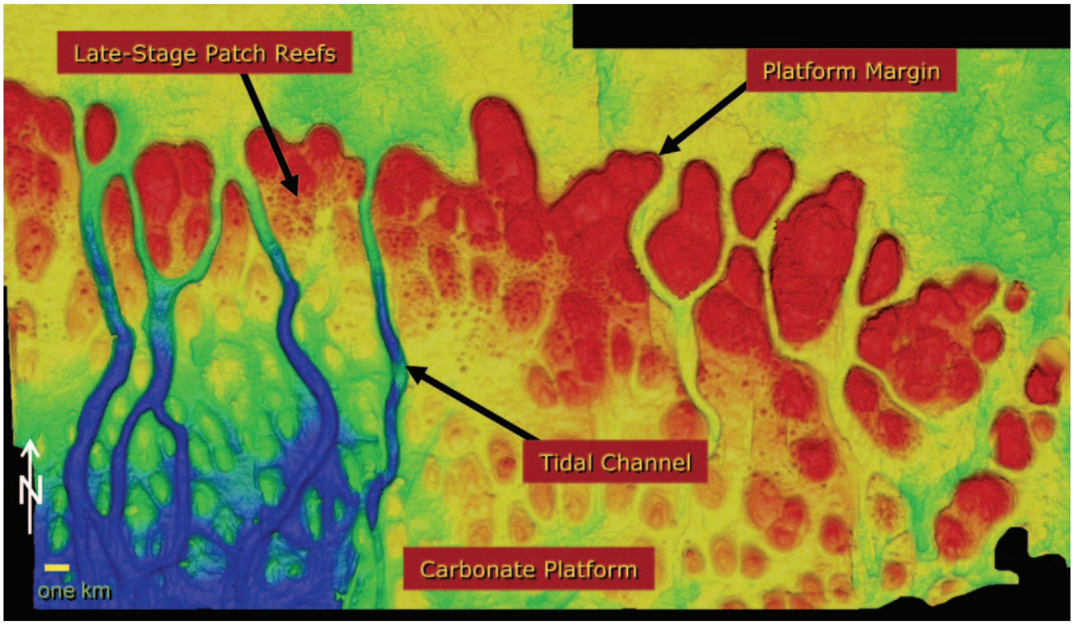

FIGURE 23.—Map view of time structure map on the top of the Kujung 1 carbonate platform. Note the anastamosing tidal channels as well as the late-stage small buildups at the top of the platform.

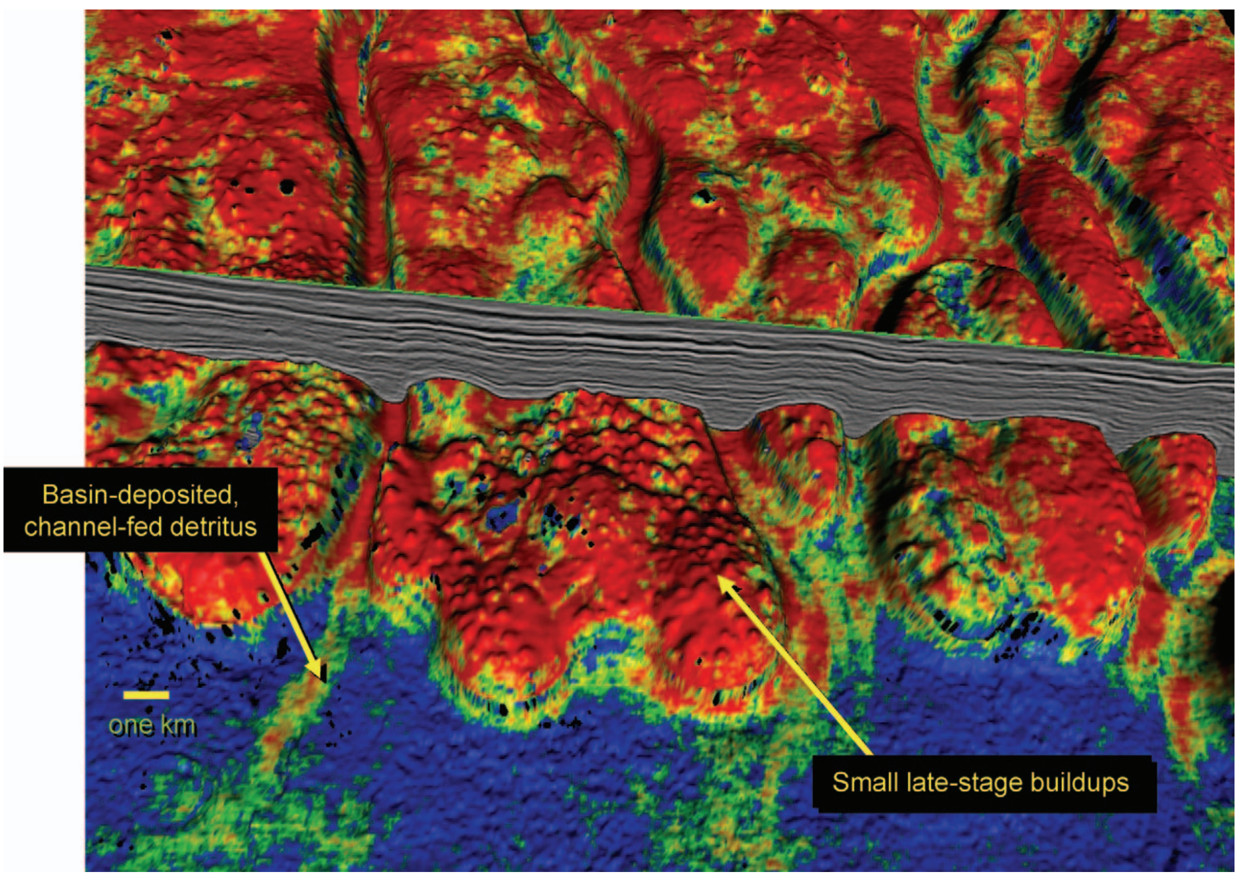

FIGURE 24.—Seismic profile and amplitude map draped on time structure on top of the Kujung 1 carbonate platform. Channel relief, late-stage small buildups, and detrital deposits across the adjacent basin floor (i.e., calciturbidites) are shown.

FIGURE 25.—Satellite image of modern reef-interior, channelized tidal flats on Andros Island, Bahamas, analogous to tidal channels in the Wonocolo reefs (image courtesy of Google Earth, NASA, TerraMetrics, and DigitalGlobe, 2009).

of the platform area is irregular and is characterized by numerous bulges associated with precursor circular reef buildups (Fig. 23). The nearly linear character of the margin suggests that the limiting factor on margin expansion was increasing water depth to the north. The platform interior is characterized by an anastamosing pattern of channels approximately 1 km wide (Figs. 9, 23). These channels are marked by low sinuosity, are symmetric in cross section view, and are largely oriented orthogonal to the platform margin. Outboard of some of these channel mouths, deposits associated with higher-amplitude reflections can be observed on the basin floors (Figs. 8A, 23). These inferred calciturbidites were sourced from the platform interior and extend outboard 10–15 km. The paleo–water depth that characterized these channels was approximately 50–75 m (Fig. 24).

The culmination of Kujung 1 time was characterized by late-stage small patch reefs similar in scale and distribution to those that formed during Kujung 2 time (Figs. 10, 24). These patch reefs also likely represent late-stage, keep-up carbonates that represented the last vestige of carbonate production under the influence of renewed rapid relative sea-level rise, which ultimately cut off carbonate production. The Kujung platforms and reefs ultimately were buried in Tuban shale (Fig. 13), sourced from the rising Sunda Shield to the northwest. This effectively marked the end of Kujung 2 carbonate production. Small patch reefs can be observed embedded in the immediately overlying mudstones. These commonly are observed to nucleate immediately above Kujung 1 highs (Figs. 11, 12).

The last phase of carbonate production in this area is referred to as the Wonocolo. The style of carbonate buildup is dramatically different from the preceding Kujung 1 and 2 buildups. In contrast to the predominantly symmetrical Kujung 1 and 2 reefs, the Wonocolo buildups are markedly asymmetrical, characterized by elongate pod-shaped reefs (Fig. 16). An anastomosing network of channels separate these buildups. Most of these channels persist throughout the Wonocolo though they become progressively narrower through time as a result of reef progradation orthogonal to the long axes of these buildups (Figs. 16, 17). These buildups seem to have had a barrier reef on at least one side that sheltered the interior of the buildup and resulted in a lagoonal or intertidal environment in the reef interior. A similar environment can be observed inboard of the southwest margin of Andros Island in the Bahamas (Fig. 25). The Wonocolo reef interior is characterized by a network of moderate- to high-sinuosity tidal channels (Fig. 18). Within the intertidal, interior reef environment, local stream piracy can be observed. Note that the drainage of the lagoon was initially directed westward (Figs. 18A, B) until a channel draining eastward captured the drainage, beheaded the drainage system, and redirected the interior drainage towards the east (Figs. 18C, D). Similar depositional environments were observed in most of the Wonocolo reefs.

Ultimately, Wonocolo buildups were flooded by relatively rapid sea-level rise. The late-stage buildups once again were characterized by small localized patch reefs (Fig. 19). These small reefs (< 1 km diameter) tended to be localized along underlying Wonocolo reef margins, supporting the suggestion that the reef margins were the site of framework carbonates that remained topographically higher than the reef interiors, thereby serving as nucleation points for late-stage patch reefs.

CONCLUSIONS

3D seismic data from offshore Madura, Indonesia, afford recognition of three phases of carbonate buildup of Miocene age. In the absence of well-based ground truth, reconstruction of carbonate factory evolution is nonetheless possible through the application of seismic geomorphologic and seismic stratigraphic analyses. Features such as small patch reefs, large carbonate platforms, tidal channels (small and large) and detailed stratigraphic architecture can be observed, mapped, and interpreted by employing an integrated analysis of section and plan views coupled with visualization of stratigraphic horizons in three dimensions.

Three buildup systems are observed: Kujung 2, Kujung 1, and Woncolo. Each is characterized by unique stratigraphic architecture and geomorphology. The oldest imaged carbonates, at Kujung 2 time, are characterized by small, symmetrical patch reefs that are nearly ubiquitous across the study area. During late stages of Kujung 2 time, reef density decreased but reef size increased. The symmetrical reef growth suggests that little wave or current activity was active at that time.

Carbonate production resumed during Kujung 1 time and at a larger scale. These buildups nucleated on isolated late-stage Kujung 2 patch reefs. A large platform, crosscut by kilometer-scale anastamosing straight-walled, low-sinuosity tidal channels, was established in the southern part of the study area, and isolated outliers as much as 8 km wide formed to the north and northwest. These buildups also were characterized by symmetric growth, again suggesting an absence of prevailing winds or currents. In the final stages of Kujung 1 development, clusters of small patch reefs formed at the tops of the larger platforms and outliers.

Subsequent to the drowning of the Kujung 1 reefs, and deposition of siliciclastics across the area, a final phase of carbonate development comprising the Wonocolo buildups occurred. These deposits were markedly different from the earlier buildups in that their development was characterized by asymmetric pod-shaped growth. Reef planforms ranged from 10–12 km long and 5–7 km wide. These asymmetric buildups were characterized by rapid lateral growth and the establishment of long-lived anastamosing channels 1–2 km wide. Reef interiors were characterized by a denser drainage of smaller tidal creeks, commonly less than 200 m wide and with moderate to high sinuosity. Ultimately, Wonocolo reef development was halted by renewed sea-level rise, with late stage reef growth once again characterized by development of small patch reefs that nucleated over underlying Wonocolo reef margins.

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REFERENCES

Adhyaksawan, R., 2003, Seismic facies and growth history of Miocene carbonate platforms, Wonocolo Formation, North Madura area, East Java basin, Indonesia: Indonesian Petroleum Association, 30th Annual Convention and Exhibition, October, 2005, Proceedings, p. 317–330.

Ardhana, W., 2003, A depositional model for the early middle Miocene Ngrayong Formation and implications for exploration in the east Java basin: Indonesian Petroleum Association, 22nd Annual Convention and Exhibition, October 2003, Proceedings, p. 395–443.

Carter, D.C, Mandhiri, D., Park, R.K., Asjhari, I., Basyuni, S., Birdus, S., Bradfield, J.P., Iriawan, A., Nasfiah, M., and Nugroho, M.A.A., 2005, Interpretation methods in the exploration of Oligocene–Miocene carbonate reservoirs, offshore Northwest Madura, Indonesia: Indonesian Petroleum Association, 30th Annual Convention and Exhibition, August, 2005, Proceedings, p. 179–215.

Cahyono, A.B., and Burgess, C.F., 2007, Cepu 3D seismic – variations in Oligo-Miocene carbonate buildup morphology: Indonesian Petroleum Association, 31st Annual Convention and Exhibition, October, 2007, Proceedings, p. 561–567.

Cartwright, J.A., James, D.M.D., and Bolton, A.J., 2003, The genesis of polygonal fault systems: a review, *in* Van Rensbergen, P., Hillis, R.R., Maltman, A.J., and Morley, C.K., eds., Subsurface Sediment Mobilization: Geological Society of London, Special Publication 216, p. 223–242.

Fulthorpe, C.S., and Schlanger, S.O., 1989, Paleo-oceanographic and tectonic settings of early Miocene reefs and associated carbonates of offshore Southeast Asia: American Association of Petroleum Geologists, Bulletin, v. 73, p. 726–756.

Johansen, K.B., 2003, Depositional geometries and hydrocarbon potential within Kujung carbonates along the North Madura platform, as revealed by 3D and 2D seismic data: Indonesian Petroleum Association, 29th Annual Convention and Exhibition, October, 2003, Proceedings, p. 137–162.

Kenyon, C.S., 1977, Distribution and morphology of early Miocene reefs, East Java Sea: Indonesian Petroleum Association, 6th Annual Convention and Exhibition, May, 1977, Proceedings, p. 215–238.

Maynard, K., and Morgan, W.A., 2005, Appraisal of a complex platform carbonate, Bukit Tua discovery, Ketapang PSC, East Java basin, Indonesia: Indonesian Petroleum Association, 30th Annual Convention and Exhibition, August, 2005, Proceedings, p. 317–330.

Mudjiono, R., and Pireno, G.E., 2001, Exploration of the North Madura platform, offshore East Java, Indonesia: Indonesian Petroleum Association, 28th Annual Convention and Exhibition, October, 2001, Proceedings, p. 707–726.

Posamentier, H.W., 2000, Seismic stratigraphy into the next millenium: a focus on 3D seismic data: American Association of Petroleum Geologists Annual Conference, New Orleans, April 16–19, 2000, p. A118.

Posamentier, H.W., 2005, Application of 3D seismic visualization techniques for seismic stratigraphy, seismic geomorphology and depositional systems analysis: examples from fluvial to deep-marine depositional environments, *in* Dore, A.G., and Vining, B.A., eds., Petroleum Geology: Northwest Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference: Geological Society of London, p. 1565–1576.

Posamentier, H.W., and Laurin, P., 2005, Seismic geomorphology of Oligocene to Miocene carbonate buildups offshore Madura, Indonesia: Society of Exploration Geophysicists, Annual Meeting Proceedings, v. 24 p. 429–431.

Scholle, P. A., Arthur, M. A. and Ekdale, A. A., 1983, Pelagic environment, *in:* P. A. Scholle, D. G. Bebout and C. H. Moore (eds)., Carbonate Depositional Environments: Tulsa, OK, American Association of Petroleum Geologists, Memoir 33, p. 619–691.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap, *in* Payton, C.E., ed., Seismic Stratigraphy – Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoir 26, p. 63–81.

Weimer, P., and Davis, T.L., 1996, Applications of 3-D seismic data to exploration and production: American Association of Petroleum Geologists, Studies in Geology, no. 42, Society of Exploration Geophysicists Geophysical Development Series, no. 5, 270 p.

Wiyono, J., Rakhmanto, F., Andriyani, F., Susilo, A., and Masdar, A.M., 2007, Characterization of carbonate reservoir at "X" field using attribute and seismic inversion: Indonesian Petroleum Association, 31st Annual Convention and Exhibition, October, 2007, Proceedings, p. 633–643.