

Stratigraphic evolution of Oligocene–Miocene carbonates and siliciclastics, East Java basin, Indonesia

Essam Sharaf, J. A. (Toni) Simo, Alan R. Carroll, and Martin Shields

ABSTRACT

The Oligocene–Miocene of East Java is characterized by multiple stages of isolated carbonate mound growth surrounded by deeper marine off-mound sediments or by shallow-marine siliciclastics. Three stratigraphic intervals are recognized: Kujung (carbonate mound and off-mound), Tuban (mixed carbonate-siliciclastic), and Ngrayong (siliciclastic). Exposures of the Kujung unit (~28–22 Ma) are limited to a few isolated outcrops. At the base, the Kujung is represented by a high-energy, extensive, shallow-marine carbonate facies that grades laterally into deep-marine off-mound sediments of calcareous mudstone and chalk (lower Kujung). In other locations, shallow-water carbonate deposition was restricted to faulted topographic highs in the middle–upper Kujung. The shallow-marine sediments of the lower Kujung were covered by thick chalk and marl sediments of the middle–upper Kujung. The Tuban unit (~22–15 Ma) consists of widely exposed shallow-marine mixed carbonate and siliciclastic and poorly exposed open-marine shale and chalk facies. The Tuban consists of at least six stacked cycles that reflect deltaic deposition with episodes of shallow-marine carbonate mound growth. The Ngrayong unit (~15–12 Ma) represents a period of regional siliciclastic influx and progradation of tidally influenced deltas and grades into turbidites, basinal shale, mudstone, and chalk. Ngrayong beds are truncated by Bulu carbonates (Serravallian–Tortonian). This is consistent with the tectonic evolution of the region.

INTRODUCTION

Through the Cenozoic to the Holocene, southeast Asia accumulated extensive shallow-marine carbonates and siliciclastics reflecting active tectonism and favorable conditions for carbonate-secreting

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organisms (Wilson, 2002). In addition, the sedimentary successions in southeast Asia reflect a complex depositional setting, including the closing of the tropical Indonesian seaway (Kennett et al., 1985), the development of the Indonesian throughflow (Nathan et al., 2001, 2003; Olson et al., 2001), and an increase in plate restructuring and influx of clastic material (Hall, 2002). The East Java basin (Figure 1) sedimentary fill reflects the relative influence of regional and local tectonics, sea level variations, weathering of land masses, and influx of clastics. The East Java basin contains significant accumulations of Tertiary carbonates and clastics (Najoan, 1972) that form large petroleum reservoirs, mostly in carbonate buildups (Soetantri et al., 1973), and currently contains the sixth largest oil reserves in Indonesia (Alexander's Gas and Oil Connections, 2004). East Java has oil reserves located in several localities, including the Cepu block in the Bojonogoro area, the Tuban block, and the Gresik area in northeastern Java. The East Java basin constitutes a part of the southeast Asia Tertiary petroleum system, which owes its origin to extensional tectonics and deposition of thick syn- and postrift lacustrine organic-rich shale, the most prolific source for hydrocarbons in this area (Brandsen and Matthews, 1992; Cole and Crittenden, 1997). The traps are both stratigraphic and structural (Todd et al., 1997) (Figure 2). Oligocene to Miocene carbonate mounds are occasionally dolomitized; dolostones form reservoirs in the region because they contain both primary and secondary porosity. One of the main contributions of this work is the definition of several units as Burdigalian and Langhian in age. Previously, the majority of the sandstones had been designated as Serravallian. Early Tertiary lacustrine sandstones and Miocene deltaic and deep-water sandstones are also reservoirs. These reservoirs are similar to the Miocene–Pliocene Segitiga platform, East Natuna Sea, Indonesia (Bachtel et al., 2004), and the middle Miocene carbonate reservoirs, Nam Con Son basin, Vietnam (Matthews et al., 1997; Mayall et al., 1997). Estimated crude oil production in 2002 was 2540 and 10,676 bbl/day from Cepu and Tuban blocks, respectively (Petroleum Report of Indonesia, 2002–2003, American Embassy–Jakarta, 2004).

This study incorporates outcrop and subsurface data of Oligocene–Miocene sequences of the East Java basin. The outcrop area (Figures 1, 2) is located in the Rembang zone and the northern part of the Randublatung zone (van Bemmelen, 1949). The Rembang zone consists of a series of east-west–oriented hills with maximum elevation of about 500 m (1600 ft). These hills generally represent anticlines that may or may not be fault bounded. The Randublatung zone (also called Ngimbang zone by Duyfjes, 1938) is to the south (Figures 1, 2) and represents a physiographic depression that contains a few major folds such as the Pegat and Ngimbang anticlines (Duyfjes, 1938). To the south of the study area is the Kendeng zone (van Bemmelen, 1949) (Figures 1, 2) that shows tight, east-west anticlines, and it is close to the active volcanic arc (Darman and Sidi, 2000). The subsurface data studies are distributed throughout the three zones, but we only report our

work from the northern area where seismic and outcrop data can be integrated.

The goals of this study are to establish a stratigraphic framework to document the basin-scale depositional history for the Oligocene–Miocene of the East Java basin that integrates outcrop mapping, petrography, age dating, and seismic correlation of the Oligocene–Miocene sequences. Fieldwork includes measuring and correlating stratigraphic sections throughout the Rembang zone. Laboratory work includes sample (~500 slabs), thin sections (~375), and strontium isotope analyses. Subsurface analyses include interpretation and integration of 28 seismic lines and 16 well logs.

GEOLOGIC SETTING

During the Cenozoic, the East Java basin was affected by the relative movement of the Indian, Eurasian, and Australian plates and experienced a complex history of initial extension followed by differential basin subsidence and later tectonic inversion (Hamilton, 1979). Paleogene differential subsidence defined northeast-southwest-trending highs and lacustrine sediment-filled lows (Hamilton, 1979; Cole and Crittenden, 1997). Later, in the Eocene to early Oligocene, a marine transgression associated with increased subsidence flooded the area, and marine carbonates were deposited across the entire region. Isolated carbonate mounds generally formed above the highs. Rifting ceased in the early Miocene, whereas mound growth continued through the middle Miocene; but through time, mounds occupied a more restricted area, and most of mounds drowned as a result of the sea level rise during the early Miocene (Darman and Sidi, 2000). Off-mound facies are marls and chalks with occasional shallow-water carbonate debris derived from the mounds. The Burdigalian–Langhian represents the initiation of clastic influx; clastic deltas prograded from north to south (Koesoemadinata and Pulunggono, 1975), initially intertonguing with carbonate mounds and later (in Serravalian time) overwhelming the entire region. During the late Miocene–middle Pliocene (~7–3.6 Ma), the region (especially the Rembang area) was affected by contraction, forming south-verging thrusts and en echelon east-west folds (Figures 1, 2). A final reorganization of the basin occurred during the late Pliocene to Holocene (~3.6–0 Ma), when the southern area of the East Java basin (Kendeng zone) was affected by north-verging thrusts and uplift. The uplift was accompanied by volcanoclastic influx from the volcanic arc

to the north (Soeparjadi et al., 1975). The major regional angular unconformity in the Rembang zone separates the slightly folded Pliocene–Pleistocene Karren limestone from the underlying folded and thrustured Oligocene–Miocene strata (Figure 2). Another regional unconformity occurs at the base of the Quaternary, and volcanoclastic sandstones onlap against Pliocene and older structures.

STRATIGRAPHY AND CHRONOSTRATIGRAPHY

Little work has been published on the Tertiary sequence in the East Java basin. The main stratigraphic and structural references are those of Verbeek and Fennema (1896), Duyfjes (1936), van Bemmelen (1949), Baumann et al. (1972), Najoan (1972), Hamilton (1979), Hutchison (1989), Joliviet et al. (1989), Bransden and Matthews (1992), Ardhanan et al. (1993), Matthews and Bransden (1995), Hall (1997, 2002), Lunt et al. (2000), and Kusumastuti et al. (2002). These provide a reference framework for the definition of intervals of deposition in the East Java basin used in this study (Figure 3). The exposed Oligocene–Miocene stratigraphic units of interest are the Kujung, Tuban, and Ngrayong formations and the Bulu Member of Wonocolo Formation (Figure 3). The older Ngimbang Formation is not exposed in the East Java basin. However, the chronostratigraphy is based on a synthesis of all the paleontological data available, and the identification of large benthic and planktonic foraminifera, as well as strontium isotopes from field samples (Sharaf, 2004). The biostratigraphy from the index foraminifera is in agreement with the ages constrained by strontium isotope analyses (Figure 3). For the studied area, the top of the Kujung Formation has been placed at around 22 Ma; the top of the Tuban Formation has been placed at about 15 Ma; and the top of the Ngrayong Formation has been placed at about 12.5 Ma (Sharaf, 2004).

The Kujung is exposed in the eastern part of the Rembang zone (Figure 1). In this area, the Kujung can be mapped as three distinct units: the lower is reefal; the middle is alternating shale and chalk; and the upper is alternating shale, chalk, and carbonate turbidites. In the subsurface, at certain localities (e.g., Kembang-Baru and Mudi wells), the middle and upper Kujung grade laterally into reefal carbonates (Figure 3). Strontium isotope data from the lower Kujung Formation that is exposed provide an age of 28.20 ± 0.74 Ma, corresponding to the base of late Oligocene, Chattian

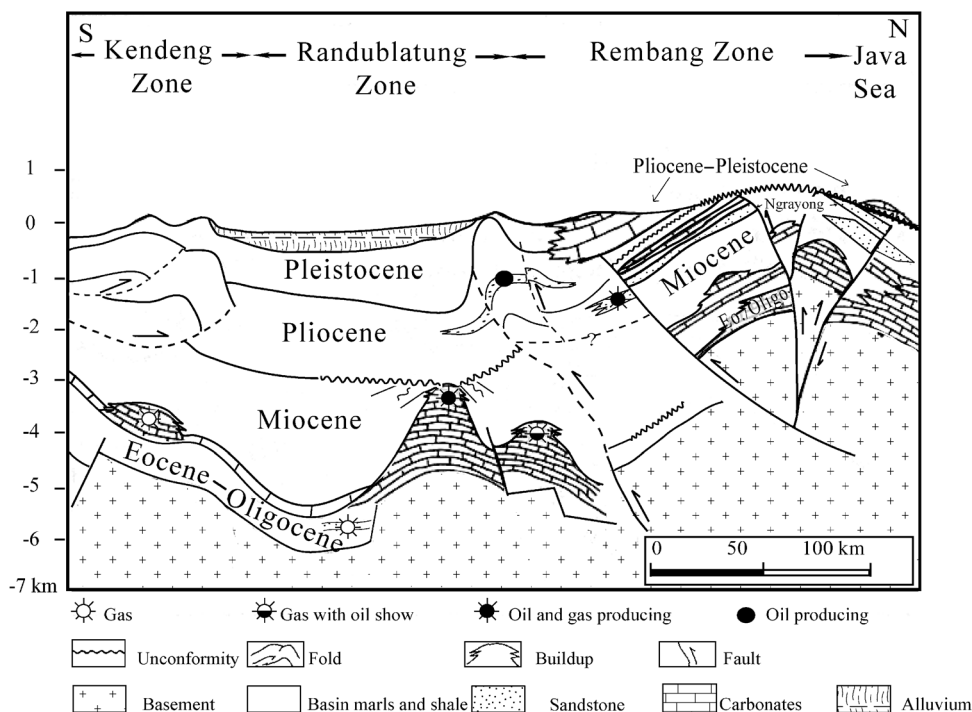


Figure 2. Regional schematic north-south cross section summarizing the structure of East Java and Madura Island. Modified from Latief et al. (1990, cited in Darman and Sidi, 2000). Notice the position of some of the most common petroleum reservoirs of the East Java basin.

(P21). Index planktonic foraminifera from the middle and upper Kujung indicate a Chattian (P22) and Aquitanian (N4–N5) ages for these intervals. Strontium isotope data from the upper Kujung Formation (23.44 ± 0.74 and 24.31 ± 0.74 Ma) indicate a late Chattian to early Aquitanian age for this interval.

The Tuban Formation is a complex stratigraphic unit with reefal carbonates, deep-water shales, and subtidal to intertidal sandstones. The Tuban Formation outcrops have a stratigraphic range from uppermost Aquitanian to upper Langhian (upper Te5–Tf2 of van der Vlerk, 1955, or N5–N9 of Blow, 1969). Strontium isotope data for the oldest sandy carbonate unit exposed in the Tuban Formation indicate an age of 20.80 ± 0.74 Ma. The strontium dating of the well-exposed Tuban carbonates yields an age of 20.17 ± 0.74 Ma (Burdigalian, N5) to 15.25 ± 1.36 Ma (Langhian, N9). Strontium data from two samples separating the Tuban carbonates from the Ngrayong Formation yield ages of 15.34 ± 1.36 and 15.25 ± 1.36 Ma (Figure 3).

The age obtained from strontium isotopes of a sample near the base of the Bulu Member of the Wo-

nocolo Formation at Prantakan River is 12.98 ± 1.36 Ma (upper Serravallian) and is characterized by the index fossil *Katacycloclypeus annulatus*. This age constrains the Ngrayong Formation between 15 and 13 Ma (Figure 3).

Sedimentology

We divide the depositional history of the area into three intervals: an initial phase dominated by carbonate mounds and off-mound facies and typified by the Kujung Formation; an intermediate interval characterized by mixed carbonate and siliciclastic lithologies and illustrated by the Tuban Formation; and a final interval dominated by siliciclastic sedimentation and exemplified by the Ngrayong Formation. These intervals reflect a large-scale cycle of sedimentation representing regional tectonic activity with an initial phase of subsidence, followed by contraction and uplift (Soeparjadi et al., 1975). The stratigraphic and sedimentologic work is an integration of outcrop and sample descriptions and well logs and seismic interpretations. Figures 4 and 5 represent a good example of this

Figure 1. Geologic map of East Java basin showing different stratigraphic units, main oil wells, structural elements, location of the measured sections, and location of the cross section illustrated in Figure 4. Stratigraphic units are illustrated in Figure 3. Modified from Pringgoprawiro and Sukido (1992), Situmorang and van Vessum (1992), and Hartono and Suharsono (1997). Note: the Randublatung zone is also referred to as the Ngimbang zone by Duyfjes (1938).

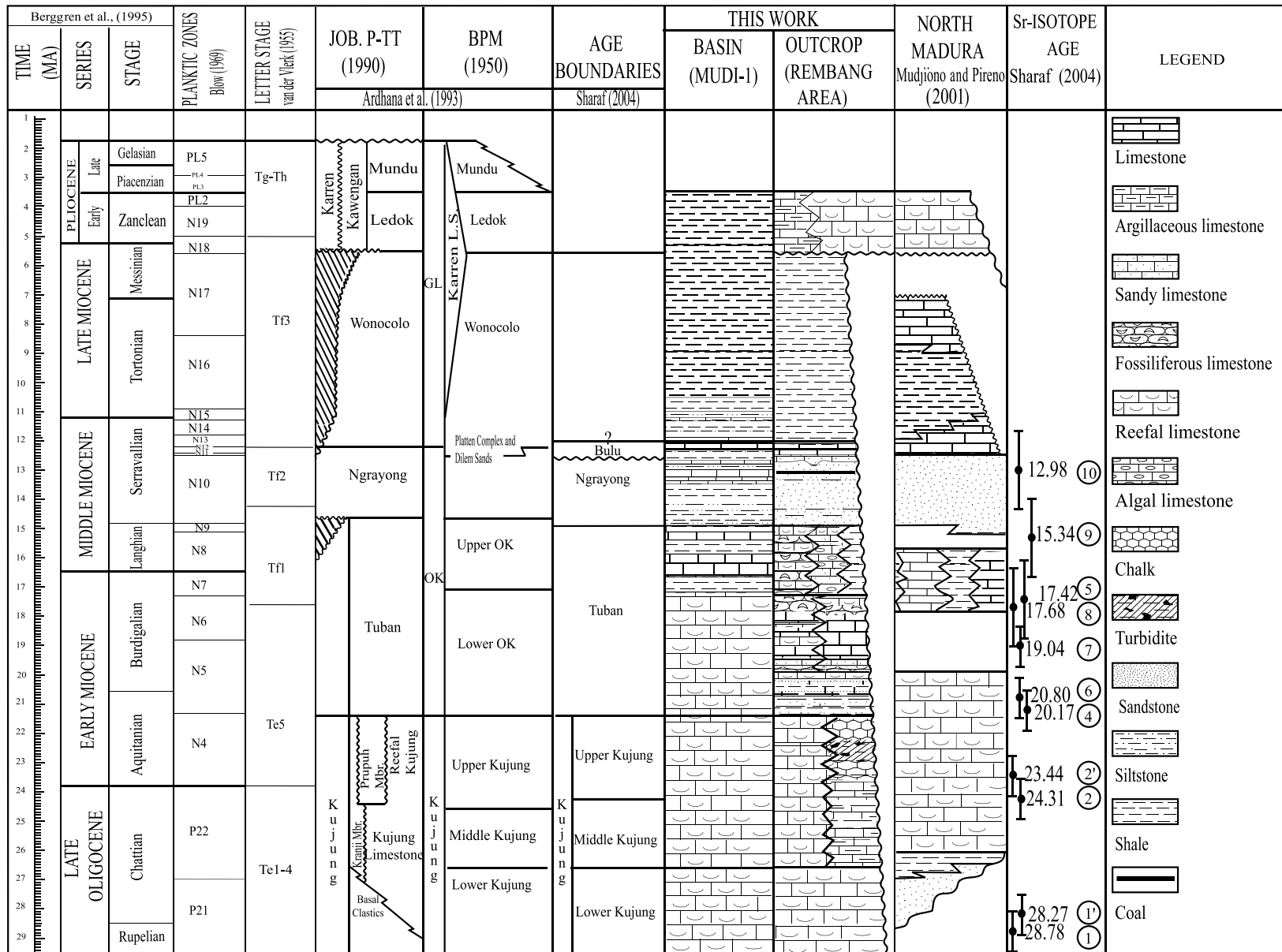


Figure 3. Stratigraphic nomenclatures, age boundaries, and strontium isotope ages of East Java basin and north Madura. Description of the circled numbers is shown in Table 1.

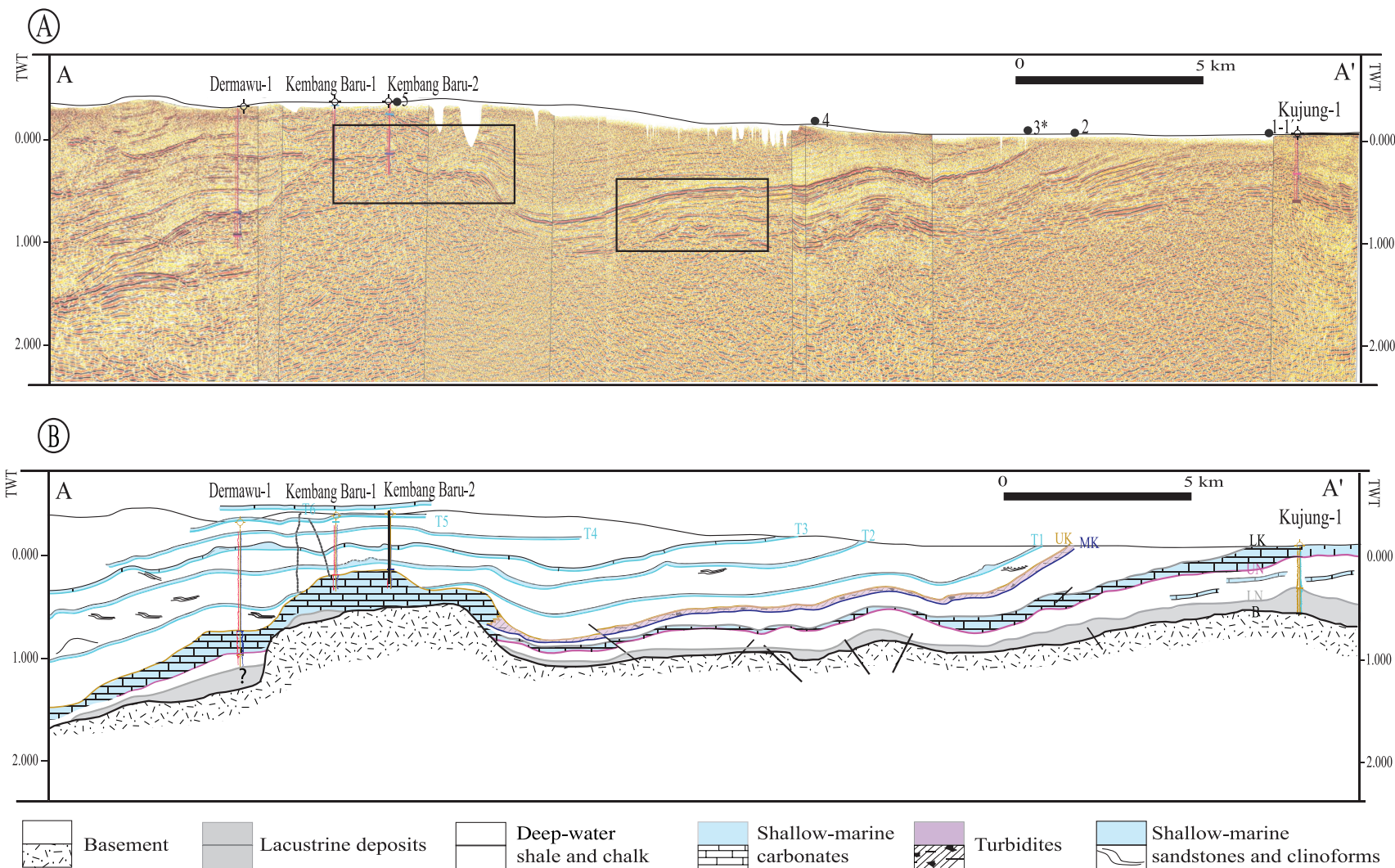
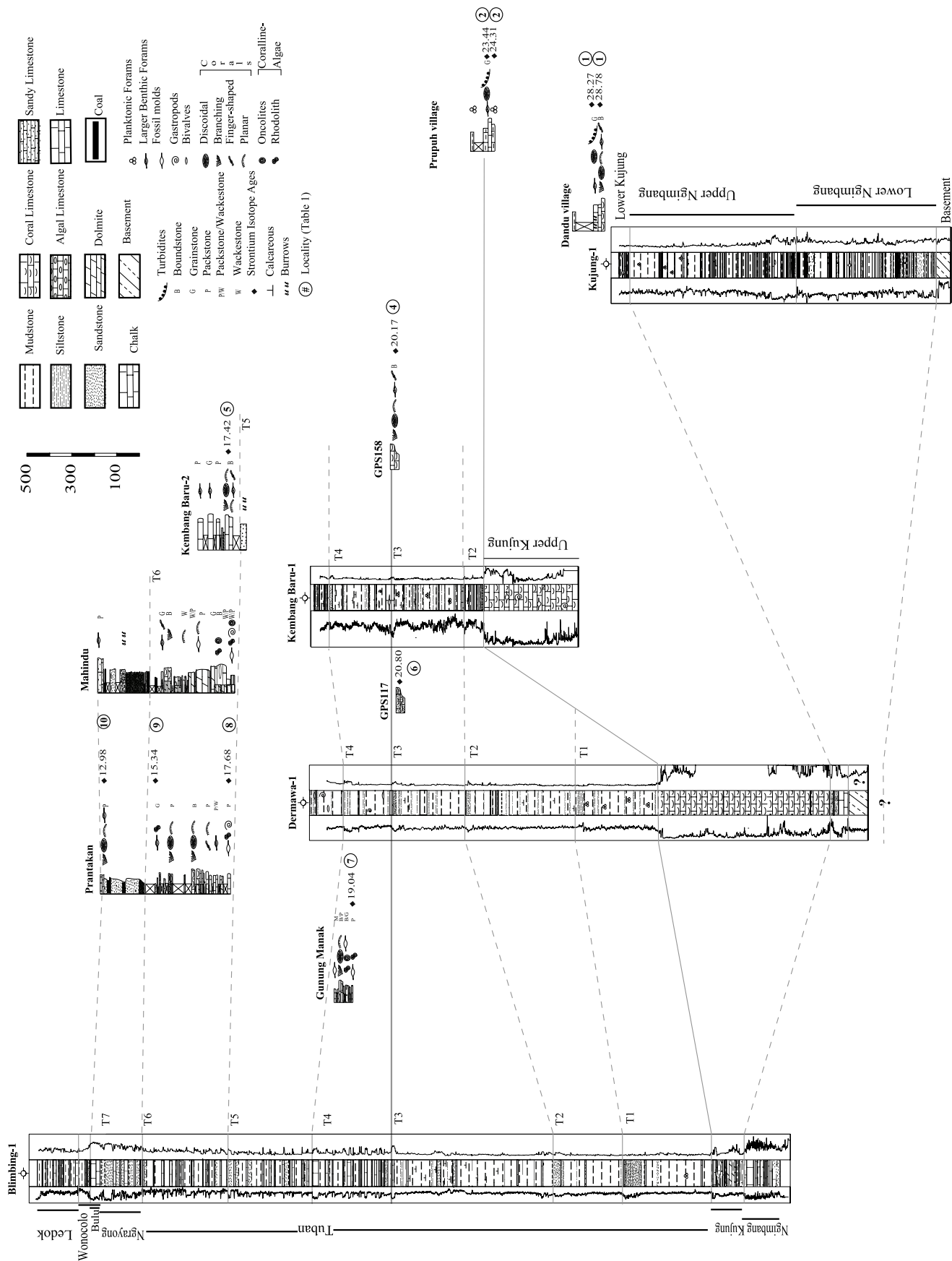


Figure 4. East-west composite seismic line showing the general stratigraphic framework for the outcrops of the Rembang area, including well data (Dermawu-1, Kembang Baru-1, and Kembang Baru-2) and surface geology observations (see Table 1). Line segment is shown in Figure 1. (A) Uninterpreted seismic line; (B) interpreted lithologies and horizons; TWT = two-way travelttime; B = basement; LN = lower Ngimbang; UN = upper Ngimbang; LK = lower Kujung; MK = middle Kujung; UK = upper Kujung; and T1–T6 = Tuban.



integration and show an east-west composite seismic line (Figure 4) on which the age-dated outcrops have been placed and correlated with the main reflectors and tied with the well logs (Figure 5). Santa Fe-Pertamina Blimbing-1 well (Figures 1, 5) is used as a reference for correlation because it represents the most complete Oligocene–Miocene section in the northern East Java basin. Table 1 is a reference of localities along Figure 4 that are shown in Figure 1, as well as other correlative seismic lines. These localities are related to reflectors that have been correlated throughout the study area.

Kujung Formation: Carbonate Mound and Off-Mound Interval

The carbonate-mound and off-mound interval (Chattian–Aquitania) is represented by the Kujung Formation and is the most important hydrocarbon reservoir in the East Java basin (Petroleum Report of Indonesia, 2002). It overlies the Ngimbang Formation and, in some localities, rests unconformably over the basement (Ardhana et al., 1993). Its upper boundary appears to be transitional to abrupt with the shallow-marine Tuban Formation. Kujung carbonates are widespread throughout the East Java basin; they have been drilled in many wells such as the Santa Fe-Pertamina Kujung-1, Dermawu-1, Kembang Baru-1, Kembang Baru-2, Ngimbang-1, Karang Anyar-1, Porong-1, and Mudi-1 wells, but they are only exposed at the eastern part of the Rembang zone (Kujung anticline, Figure 1). Exposures of the lower Kujung are restricted to near the Dandu village. The upper Kujung is exposed along the Prupuh ridge near the Prupuh and Sukowati villages (Figure 1).

The Kujung interval consists of two main lithofacies that are time equivalent: the mound facies (up to 430 m [1410 ft] thick) or shallow-water carbonates and the off-mound facies or deep-water carbonates (up to 540 m [1771 ft] thick), chalks, and shale (Figure 4). Initially, the lower Kujung shallow-water carbonate platform (up to 62 m [203 ft] thick) is widely distributed, but through time, the off-mound facies became dominant (middle–upper Kujung). Figures 4 and 5 show the regional relation between the mound and

the off-mound facies in cross sections. Figure 6 represents typical seismic characteristics of the main facies described, and Figure 7 shows the extension of Kujung shallow water (shelf and mound facies) and deep water (chalk facies) in map view at different times.

The extensive lower Kujung platform (Figures 4, 7; Table 1) was studied and sampled in eastern Rembang and is represented by red-algal, coral-rich (Figure 8A) carbonates alternating with bioturbated and cross-bedded fossiliferous wackestone to grainstones (Figure 8B). These lithologies are yellowish white to yellowish brown, and they are very thick bedded. In outcrop, they are partially to completely dolomitized. Strontium age dates of these dolomites provide an age (28.27 ± 0.74 Ma, late Chattian) very close to the age of undolomitized skeletal fragments, suggesting syndepositionary dolomitization prior to burial. The grainy lithologies are very coarse grained and are composed of large benthic foraminifera (lepidocyclinids, miogypsinids, operculinids, alveolinids, and nummulitids), echinoids, coralline algae, broken coral fragments, and some mollusk shell fragments.

The lower Kujung was drowned (Figures 4, 6), and carbonate deposition retreated to several smaller areas, such as one centered on an uplifted block drilled by the Santa Fe-Pertamina Kembang Baru-1, Kembang Baru-2, and Dermawu-1 wells (Figure 4). The carbonate mound has an abrupt and steep margin and grades laterally into off-mound facies. Apparently, normal faults affected the mound's postdeposition (Figure 4). Throughout the study area, several other mounds are present (Figure 7). The mound penetrated by Dermawu-1, Kembang Baru-1, and Kembang Baru-2 wells (Figure 4) is the thickest middle–upper Kujung mound penetrated in the area. Seismic and well data indicate that the mound thickness ranges from 686 m (2250 ft) at Dermawu-1 to about 495 m (1624 ft) at Kembang Baru-2, and its lateral extension is about 9 km (5.5 mi). The well descriptions indicate that the lower portion penetrated (particularly at Kembang Baru-1 and Kembang Baru-2 wells; Figures 4, 5) is dominated by corals and larger benthic foraminifera, and the upper portion

Figure 5. East-west cross section showing lithologic description, facies variation, and different intervals identified by biostratigraphic and strontium ages. The well logs are leveled on the boundary between Aquitania and Burdigalian (T3). Strontium ages of the stratigraphic units identified in the field are reported in Table 1. The lateral distance from west to east is Blimbing-1–Gunung Manak = 20.04 km (12.45 mi); Blimbing-1–Dermawu-1 = 32.01 km (19.89 mi); Prantakan–Dermawu-1 = 5.08 km (3.15 mi); Dermawu-1–GPS117 = 1.63 km (1.01 mi); GPS117–Mahindu = 0.62 km (0.38 mi); Mahindu–Kembang Baru-1 = 1.60 km (0.99 mi); Kembang Baru-1–Kembang Baru-2 = 1.00 km (0.62 mi); Kembang Baru-2–GPG158 = 11.09 km (6.89 mi); GPS158–Kujung-1 = 15.40 km (9.56 mi); Kujung-1–Dandu village = 2.90 km (1.80 mi); and Dandu village–Prupuh village = 26.16 km (16.25 mi).

Table 1. Description of the Different Outcrops Used to Date the Stratigraphic Intervals Shown in Seismic (Figure 4) and Stratigraphic (Figure 5) Correlations

Sample	Formation	Locality*		Lithology	Age
		Lat. Dec.	Long. Dec.		
1	lower Kujung	Dandu Village – 6.970030	112.239490	carbonate: yellowish brown, coarse grained, larger foraminifer grainstone with interbedded fine laminated wackestone, locally bioturbated with moderate amount of clastic fragments	late Oligocene (Chattian – Rupelian) 28.78 ± 0.74 Ma
1'	lower Kujung	Dandu village – 6.963690	112.240320	carbonate: yellowish brown, burrowed, with abundant larger benthic foraminifera and coral fragments; most of the fossils are well preserved and not encrusted; absent or very sparse clastic grains, moderately dolomitized	late Oligocene (Chattian) 28.27 ± 0.74 Ma
2	upper Kujung	northwest–southeast Tuban road intersection, west of Gunung Ngimbang – 6.974760	112.124630	alternation of carbonate turbidites and chalk beds; carbonate turbidites: yellow to off-white, massive, with abundant larger foraminifera and large clasts of corals, echinoids, and red algae chalk: rich in planktonic foraminifera, some chert nodules and generally dolomitized	Oligocene–Miocene 24.31 ± 0.74 Ma
2'	upper Kujung	Sukowati village – 7.019280	111.930920	carbonate: pale white, coarse-grained, poorly sorted coral fragments, larger benthic foraminifera and echinoids, few chalk clasts with planktonic foraminifera; absent sand clasts	Oligocene–Miocene 23.44 ± 0.74 Ma
3**	Tuban	near Sukowati village (not along the line of section) – 6.901611	112.393083	shale: greenish gray, massive, poorly laminated, rich in planktonic foraminifera and sparse glauconite grains; exposures of this shale are sparse along the line of section but can be mapped around the Kujung anticline and are observed in other localities	early Miocene (Aquitanian)
4	Tuban	east of Dermawu village – 6.982270	112.042750	carbonate: yellowish orange, massive, hard, common larger benthic foraminifera, massive corals, sparse clastic fragments	early Miocene (Aquitanian) 20.17 ± 0.74 Ma
5	Tuban	Kembang Baru-2 well site (see Figure 9) – 7.014720	111.964400	sandstone: yellowish white, moderately sorted, fine to medium grained, quartz sandstone interbedded with silt and mudstone, burrowed, with some centimeter-scale mud clasts and mud cracks; the sandstones are overlain by gray to yellowish white massive limestone, with abundant corals, echinoids, and larger benthic foraminifera, grading vertically to planar coral-bedded limestone with fewer larger benthic foraminifera; the section is capped by siltstone, quartz sandstone, and shale (T5)	early Miocene (Burdigalian) 17.42 ± 1.36 Ma
6	Tuban	east of Dermawu-1 well site – 6.920520	112.448970	carbonate: yellow, medium hard, massive, with abundant fine to medium quartz sand, fragments of foraminifera, planar corals and red algae, and glauconitic clasts (T4)	early Miocene (Aquitanian) 20.80 ± 0.74 Ma

7	Tuban	north Gunung Manak anticline — 6.932290 111.868090	carbonate: yellowish brown, with abundant larger benthic foraminifera; few coral fragments; the fossils are well preserved; absent or very sparse clastic grains	early Miocene (Burdigalian) 19.04 ± 0.74 Ma
8	Tuban	base of Prantakan measured section — 7.034910 111.925160	carbonate: yellow, coarse grained, hard, massive, with abundant larger foraminifera, common mollusk fragments, sparse coralline-algae, sparse well-sorted, fine-grained sand	early Miocene (Burdigalian) 17.68 ± 1.36 Ma
9	Tuban	top of Prantakan measured section — 7.068520 111.858910	shale: gray, laminated, with abundant fossil fragments, mainly larger benthic foraminifera, few echinoids and smaller foraminifera, common glauconite and pyrite grains	middle Miocene (Langhian) 15.34 ± 1.36 Ma
10	Wonocolo Formation (Bulu Member)	Bulu carbonates at Prantakan River — 7.022270 111.854000	carbonate: pale white, hard, massive, coarse grained, contains small cracks, with abundant moderately well-sorted larger foraminifera, red algae and massive corals; absent or sparse clastic grains	middle Miocene (Serravallian) 12.98 ± 1.36 Ma

*Dec. = decimal.

**Description was based on samples collected for the same unit east of the seismic line.

is sparsely fossiliferous and argillaceous. Other upper Kujung mounds are restricted to the north and south and are illustrated in Figure 7. The upper Kujung mound and off-mound facies show different seismic characters (Figure 6). The mound seismic facies can be divided into mounded and parallel offlapping. Note that the parallel-offlapping facies grade laterally to the well-bedded, high-amplitude off-mound seismic facies described below (Figure 6).

The estimated thickness of the middle and upper Kujung off-mound facies is 340 m (1115 ft). For the middle and upper Kujung, the off-mound facies show two seismic facies: a lower chaotic one (Figure 6) that corresponds to the exposed middle Kujung chalk and shale succession and an upper one that is represented by a high-amplitude basinwide continuous reflector that, in outcrop, corresponds to the upper Kujung carbonate turbidite succession (Figures 4, 8C). The off-mound facies to the west, south, and north appear to be of the chaotic type (Figure 4). The shale, sparsely exposed, is yellowish brown, gray to green in color, and may contain glauconite and pyrite grains. The shale is rich in planktonic foraminifera (*Globigerinoides primordius* and *Globorotalia kugleri*). The chalk is whitish in color and highly bioturbated, and the bed thickness ranges from a few centimeters to decimeters. Chalk facies has abundant planktonic foraminifera (Figure 8C). Chalk associated with the carbonate beds also contains disseminated, silicified, large benthic foraminifera; coralline algae; and coral debris; as well as chert nodules and veins. Throughout the area, the chalk is dolomitized.

The alternating thin-bedded chalk and thick-bedded carbonate turbidite beds occur at the top of the off-mound Kujung interval (approximate thickness exposed is 105–175 m [344–574 ft]; Duyfjes, 1949, cited in Lunt et al., 2000) and form the resistant Prupuh ridge. The thick-bedded carbonate beds form fining-upward packages and have scour bases and transitional tops. The main components are rip-up clasts (generally of chalk lithology, diameter up to 2 cm [0.8 in.]), large benthic foraminifera (particularly *Spiroclypeus*), coralline-algae (rhodolith), echinoids, and coral debris (Figure 8C). These fauna suggest a source from a high-energy mound margin.

The exposed shallow-water carbonates of the lower Kujung indicate a high-energy environment in which coral and coralline-algae mounds competed with skeletal shoals. The corals form large domes, generally well preserved (not incrustated or bored) but commonly show evidence of constant wave reworking. The outcrops studied are close to the top of the lower Kujung carbonates

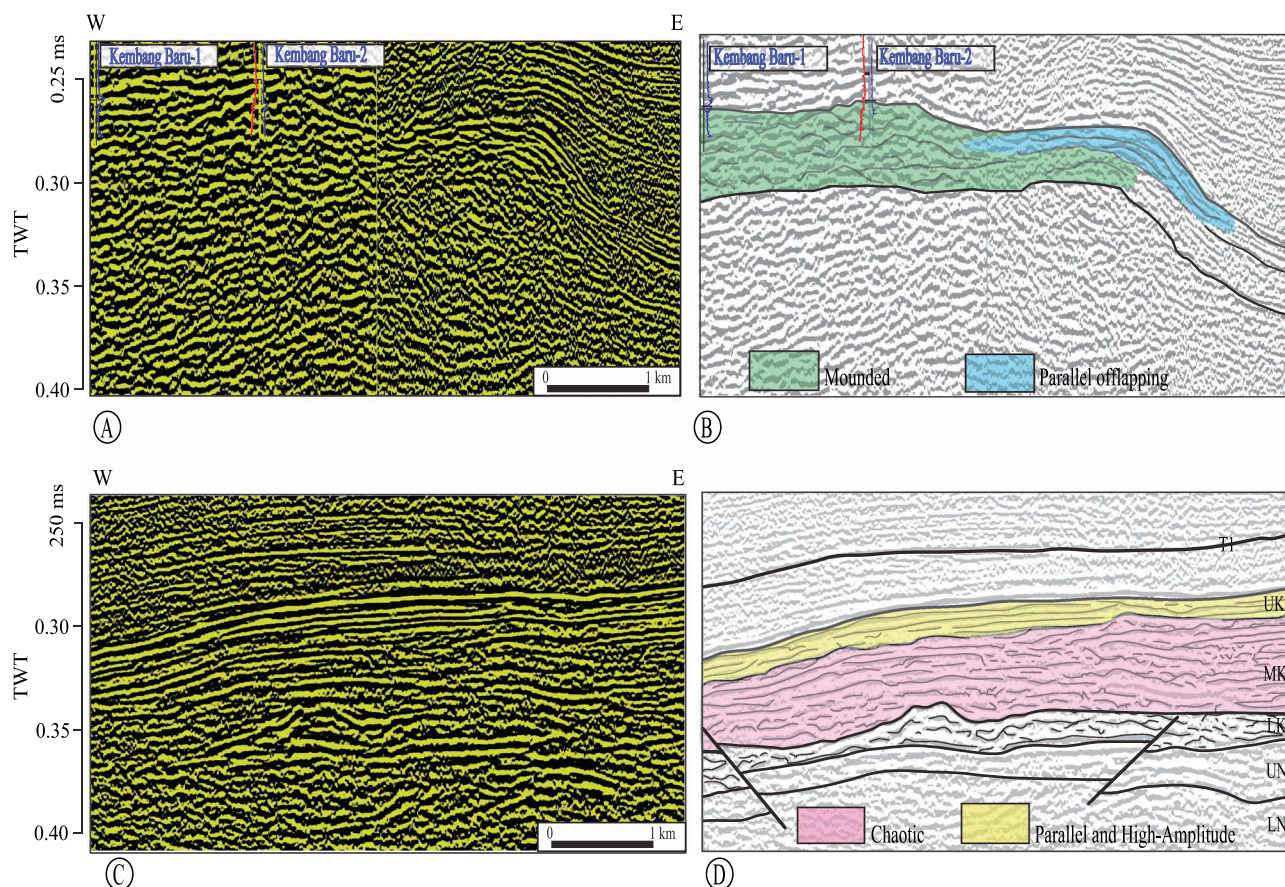


Figure 6. Close-ups of parts of the seismic line illustrated in Figure 4 showing Kujung seismic facies characteristics. The figures in (A) and (C) are uninterpreted, and the figures in (B) and (D) are the interpretation of (A) and (C). The abbreviations for the seismic horizons are the same in Figure 4.

and may represent shallowing prior to middle Kujung drowning.

The lower Kujung extensive and high-energy shallow-water platform was drowned at around 28 Ma, but carbonate sedimentation continued on basement-controlled topographic highs (Figure 4), where mounds formed towering structures with steep margins and limited geographic extent between approximately 28 and 22 Ma. Postmound normal faulting may have affected parts of the mound. During the time of mound aggradation, chalk and minor shales (\sim P22) were deposited over the former carbonate platform, covering and blanketing attempted mound growth outside basement highs. Mound growth on topographic highs kept pace with increasing accommodation space. The mound margin apparently started to shed and form extensive resedimented carbonates (23.44 ± 0.74 to 24.31 ± 0.74 Ma). The source of this material may be a different mound than the one shown in Figure 4 and may reflect resedimentation from several mounds in the region.

Tuban: Mixed Carbonate-Siliciclastic Interval

A mixture of lithologies of late Aquitanian to early Langhian age represents the Tuban Formation of Ardhana et al. (1993). This interval is well exposed along the Rembang zone and is present in many of the outcrops and throughout the subsurface. The Tuban interval contains three main lithologies (sandstone, carbonate, and shale and chalk) that alternate in time and space. The Tuban shale is exposed throughout the Rembang area, but the Tuban carbonates and sandstones are only recognized in the west of the studied area (Figures 1, 4). The estimated thickness of the Tuban interval is 1500 m (4900 ft) off the Kujung mound (e.g., Santa Fe-Pertamina Dermawu-1 well), 1200 m (3900 ft) over the mound (Kembang Baru-1 and Kembang Baru-2), and thins to the south to nearly 300 m (1000 ft) (Karang Aayar-1, Figure 1). In the studied area, we have recognized a minimum of six depositional cycles that can be traced across the region (Figures 4, 5). Parts of these cycles are partially exposed

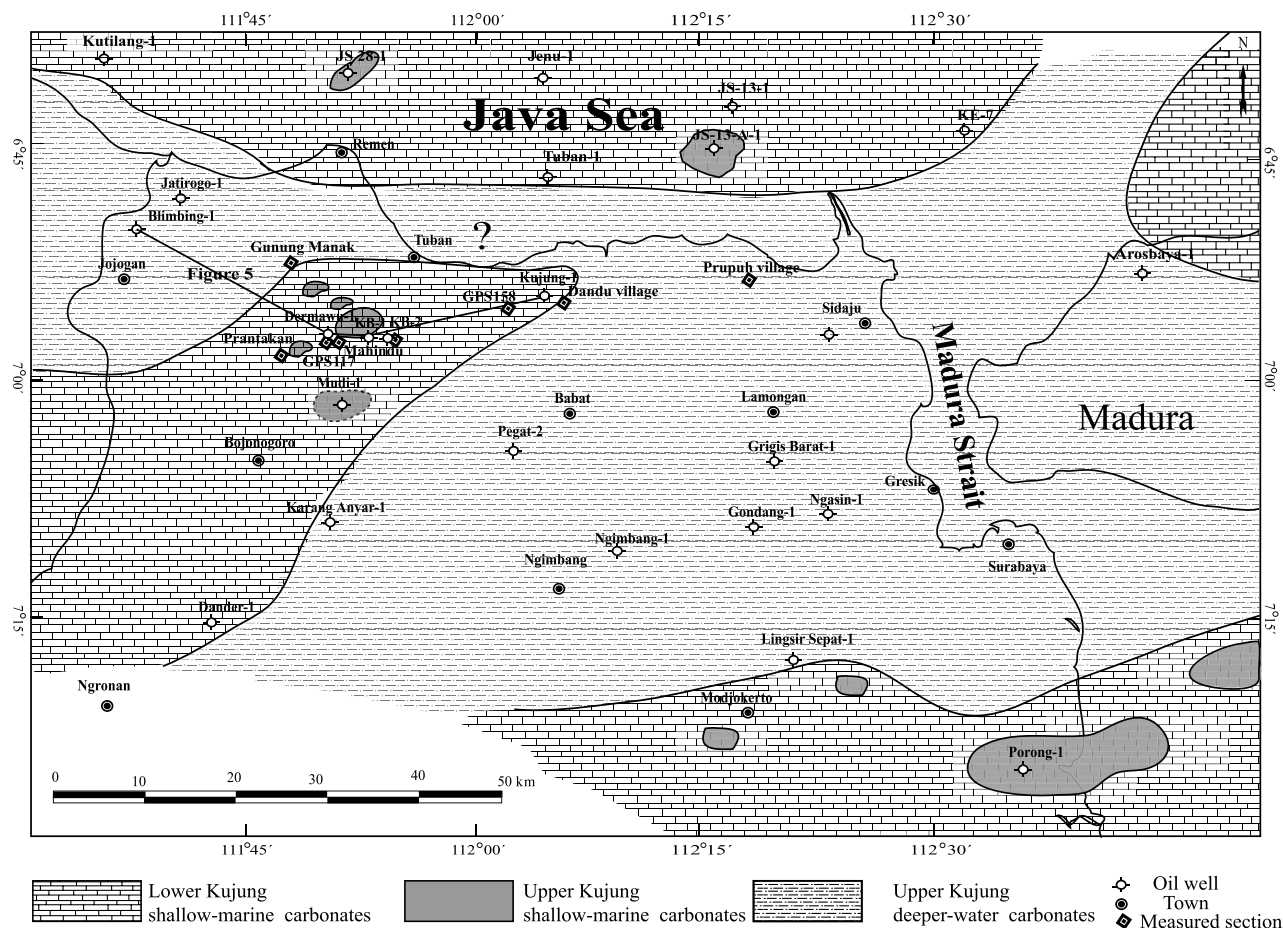


Figure 7. Facies distribution map of the time of Kujung deposition showing the distribution of shallow-marine and deep-water facies. The lower Kujung shows extensive areas of shallow-water deposition, whereas the middle and upper Kujung shallow water is restricted to small mounds, and the remaining area is deep-water chalk and carbonate turbidites. The dashed line shows the direction of the lithologic cross section illustrated in Figure 5.

(Figures 4, 5; Table 1). The cycles show a shallowing-upward trend. Each cycle consists of deeper marine shale at the base that is overlain by calcareous mudstone and siltstone, shallow-marine carbonate and/or sandy carbonates, and sandstone rich in fossil fragments. These cycles consist of zones of chaotic reflectors separated by parallel to subparallel, continuous reflectors with high amplitude (Figure 4). The cycles onlap and overlap the Kujung mound and, in general, show thickening away from the mound. In wells, the chaotic seismic facies correspond to calcareous mudstones, shale, and siltstones (Figures 4, 5). Within these seismic facies, the pattern of seismic reflectors refers to clinoforms that appear to be lobate in shape and generally prograde to the southeast and southwest. In addition, carbonate mounds with sizes and shapes similar to the ones exposed are recognized within the chaotic seismic facies.

Based on descriptions of the wells, the parallel to subparallel continuous high-amplitude reflectors appear to correspond to sandy carbonates, and they may show mounding. In outcrop, the sandy carbonates also contain beds with planar-coral boundstone. The description of the exposed lithologies corresponding to the seismic facies follows.

The Tuban shale and chalk facies are poorly exposed, with the exception of river cuts near the Sukowati village (Kujung anticline, Figure 1). In this locality, the shale is greenish gray, massive, rich in planktonic foraminifera, and may contain some glauconite grains. Mapping suggests that these outcrops belong to the lowermost Tuban cycle (Figures 1, 4; Table 1).

The Tuban sandstones are well exposed throughout the Mahindu anticline and especially well at the Kembang Baru-2 well site (Figures 1, 9). Correlation

Figure 8. Kujung facies types: (A) shallow-marine carbonate bed of lower Kujung reefal facies showing thin planar corals exposed near Dandu village, Kujung anticline; (B) shallow-marine carbonate bed of lower Kujung showing coarse bioclastic grainstone changing upward into fine-grained low-angle cross-bedded grainstone, lower Kujung, Dandu village, Kujung anticline; (C) thin section showing the contact between the bioclastic graded-bedded carbonate facies and the chalk facies. Upper Kujung, Prupuh section.



(A)



(B)



(C)

with the seismic lines and well logs (Figures 4, 5) suggests that they belong to Tuban cycle 5. The sandstones are light yellow to orange in color, thin to medium bedded, bioturbated, and well sorted. The upper part of the section has thin mudstone and claystone with mud cracks. Planar cross-bedding and asymmetrical ripples are common.

The Tuban carbonates consist of aurally restricted mounds and laterally extensive sandy (quartz and skeletal-rich) carbonates (Figures 4, 5). Tuban carbonates are reported in many well logs from the

Rembang zone, Randublatung zone, and Kendeng zone (Soetantri et al., 1973) and Madura (Kusumasuti et al., 2002). The exposed mound facies are up to 300 m (1000 ft) thick and 1–2 km (0.6–1.2 mi) wide (Figure 10). Two lithologies are common in the mound: coral-algal (Figure 11A) and bedded algal (Figure 11B) boundstones that are capped by skeletal grainstone-wackestone (Figure 11C). The coral-algal and bedded algal boundstone consists of coralline algae (branches and rhodolith morphologies), corals (domal to planar to branching morphologies, Figure 11B), large

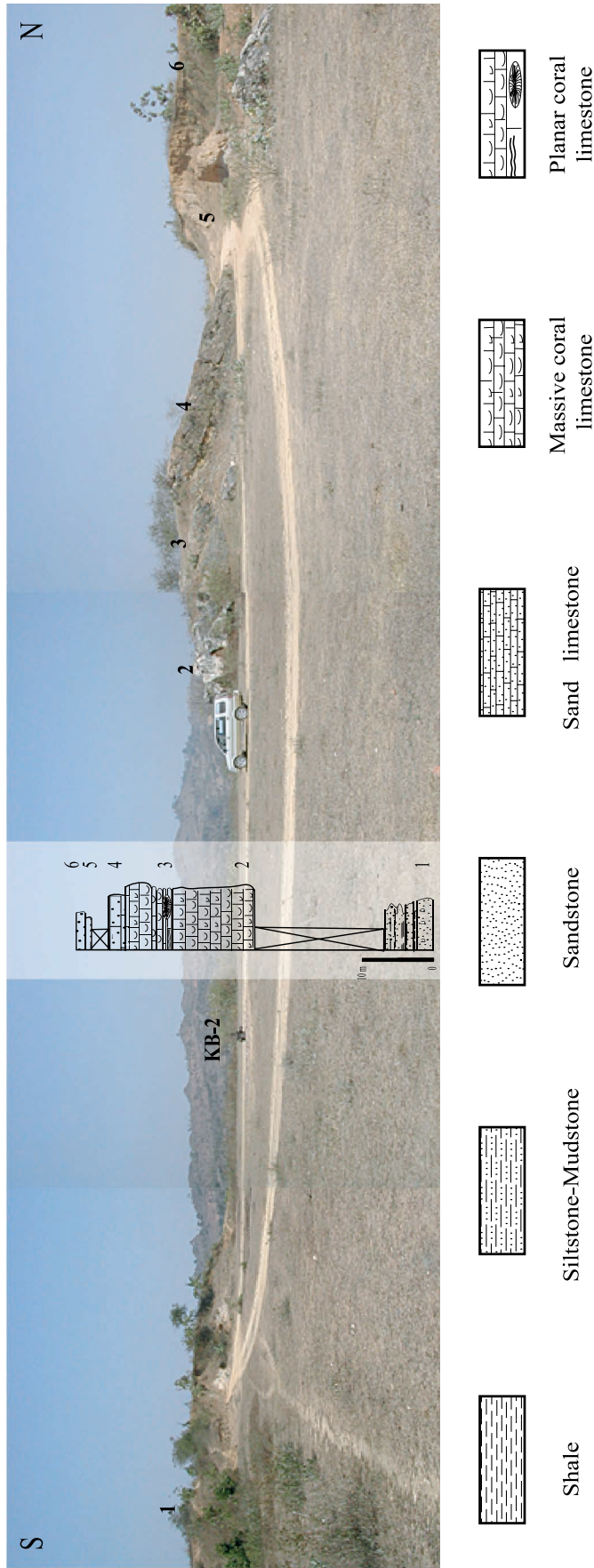
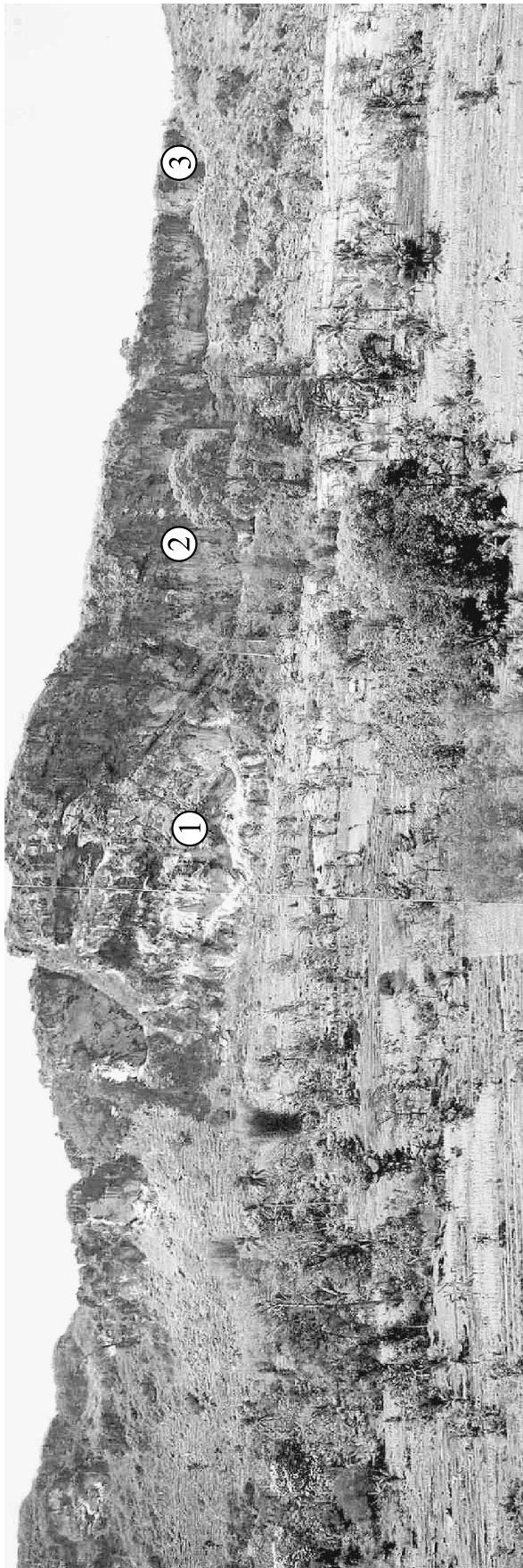


Figure 9. Panorama photo showing the Tuban mixed carbonate-siliciclastic package exposed at the Kembang Baru-2 well site with a simplified stratigraphic column of the measured stratigraphic units. Note that the well head was drilled near the core of an anticline. 1 = Bioturbated sandstone, siltstone, and mudstone; 2 = thick massive coral boundstone-packstone; 3 = bedded skeletal grainstone with in-place nodular thin planar corals; 4 = sandy skeletal grainstone; 5 = nonfossiliferous silty mudstone; and 6 = massive-bedded sandstone.



benthic foraminifera (alveolinids and operculinids, lepidocyclinids, miogypsinids, and numulitids), echinoderms, and sparse planktonic foraminifera. Fine-grained to silt-sized quartz grains may be up to 25% in some thin sections. Parts of the sections are dolomitized (Figure 5), and porosity is high (up to 30%). The capping bedded skeletal grainstone-wackestone is found in the majority of the measured sections. This lithology is thin to very thick bedded, poorly sorted, and its maximum grain size is granule. The dominant biogenic constituents are large benthic foraminifera (lepidocyclinids, miogypsinids, operculinids, alveolinids, and numulitids), gastropods, oysters, and bivalves. Other elements are smaller benthic foraminifera, echinoids, coralline algae, coral fragments, *Halimeda* plates, bryozoans, and mollusk shell fragments (Figure 11C).

The sandy carbonates, 10–30 m (33–100 ft) thick, consist of moderately sorted, fine to medium glauconite and quartz (up to 30%) grains mixed with abraded larger benthic foraminifera (particularly miogypsinids), echinoids, bryozoans, mollusk fragments, and in-place thin planar corals (Figure 9).

The cyclic Tuban succession is interpreted as a low-relief, mixed siliciclastic-carbonate delta system that buried the mound topography of the previous depositional interval. The modern Kepulauan Seribu patch reef complex (Jordan, 1998) can be an analog for a relatively shallow, generally fine-grained, siliciclastic shelf with carbonate reefs forming at subtle topographic highs. The outcrop area appears to represent a prodelta to delta-front setting. The stratigraphic pattern may show a reciprocal model of deposition (Wilson, 1967) in which siliciclastic sediment prograded at times of high siliciclastic sediment supply and low accommodation space, and carbonates developed during low clastic influx and creation of accommodation space. A similar model has been interpreted for the Mahakam delta (Roberts and Syndow, 1996; Saller et al., 2004). However, our observations from seismic lines suggest that some carbonate mounds formed at different times of the depositional cycle, complicating the depositional model. Sometimes, the mounds appear to grow immediately above the high-amplitude reflectors, but other times, the mound grew over topographic

Figure 10. Panorama photo, looking south, of Tuban carbonate interval, dipping west, at Mahindu outcrop showing 1 = coralline algae-dominated grainstone-packstone; 2 = planar coral-dominated wackestone; and 3 = skeletal-dominated packstone.

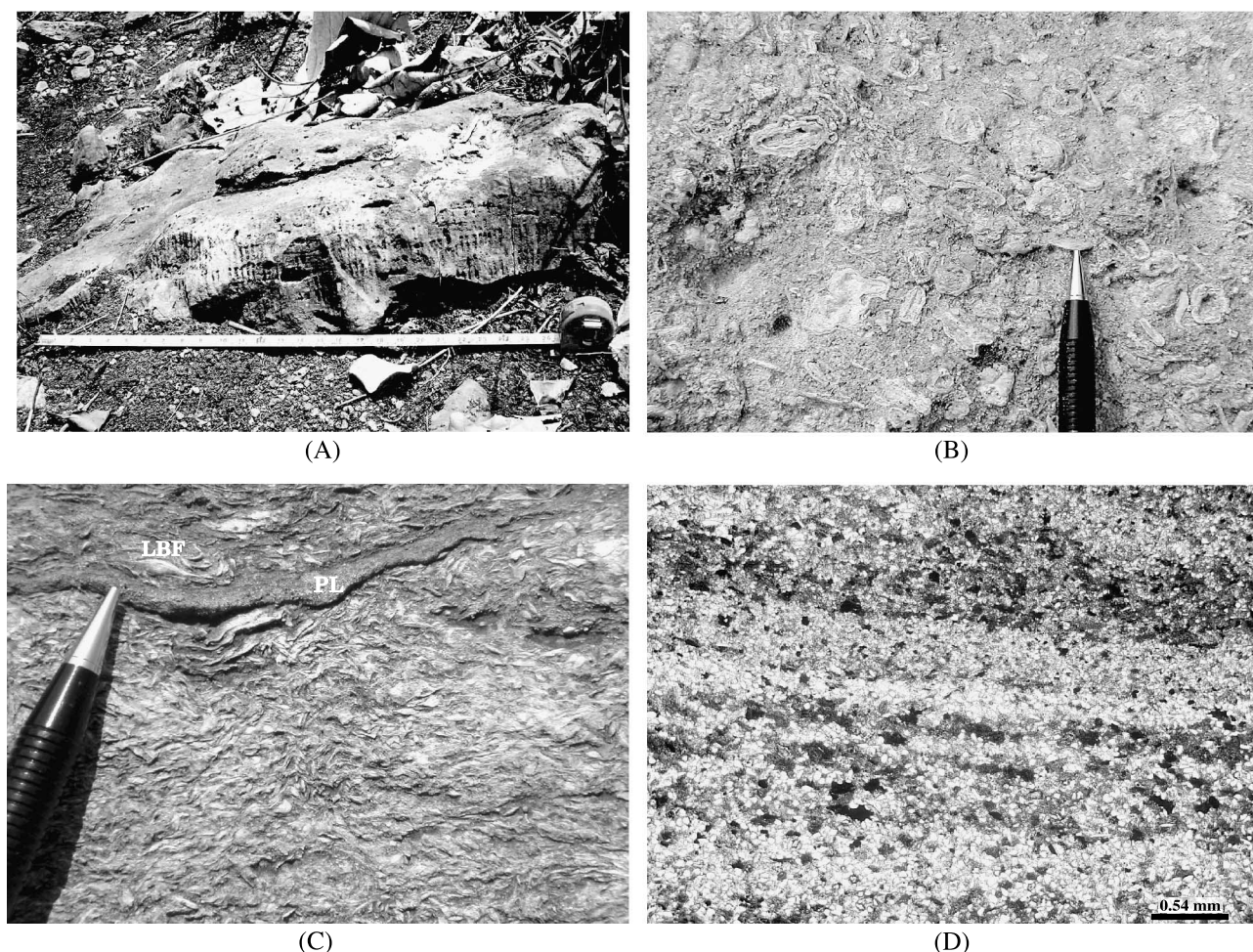


Figure 11. (A–C) Tuban carbonate facies: (A) close-up photo of massive columnar corals exposed near the Prantakan River, Prantakan outcrop; (B) close-up photo of highly porous coralline algae-dominated carbonate package exposed at the Mahindu outcrop (Figure 10); and (C) close-up photo of skeletal-dominated grainstone with abundant larger benthic foraminifera (LBF) and a planar coral (PL), Kembang Baru-2. (D) Photomicrograph showing fine-laminated, well-sorted, very angular quartzarenite sandstone, Ngrayong Formation, Prantakan River. The laminae are mostly fine siltstone and mudstone. The gray grains are glauconite and lithic fragments, and the black grains are iron oxides and opaque minerals.

highs (e.g., previous mounds) as well as abandoned prograding delta-front deposits.

The proposed model argues for a minimum of six cycles of deposition during the Aquitanian–Languian (~7 m.y. duration). Integration of seismic and well data indicates that these cycles consist of a shallowing-upward succession starting with marine shale overlain by shallow-marine carbonates rich in fossil and coral fragments and commonly capped by sandstone (Sharaf, 2004). The depositional model represents the formation of a low-energy shallow sea between Borneo and Java very similar to the modern Java Sea (Jordan, 1998) and suggests an increase in sediment supply and relative decrease in subsidence of the north-

ern parts of the basin, starting at the end of the upper Kujung deposition, which accommodated the Tuban delta system. The upper Kujung mound at this time was faulted and probably subaerially exposed and was not covered by marine sediments until the Tuban-2 delta system. The Tuban-1 system does not show mound facies. Prograding clastics appear to dominate the thick Tuban-2, but mounds are common in the Tuban-3 to Tuban-6, suggesting a relative increase in accommodation through the Tuban interval. The Tuban is thinnest where it overlies Oligocene–early Miocene mounds and thickest where it overlies the off-mound areas. The Tuban thickness suggests a balance between creation of accommodation space and sediment supply.

Ngrayong: Clastic Shelf Interval

The Ngrayong interval (late Langhian–middle Serravalian) represents a regional influx of siliciclastics (Ngrayong Formation) that blankets the region with quartzarenite sandstones north of Madura Island (Soeparyono and Lennox, 1990), shales and sandstones in the Rembang and Randublatung zones, and mostly shales in the Kendeng zone. The sandstones are productive in the onshore East Java basin (Soetantri et al., 1973; Bransden and Matthews, 1992). It represents the main reservoir of the Cepu oil fields in the southwest (Soeparyono and Lennox, 1990). From well logs, the contact between the Ngrayong interval and the Tuban lithologies appears to be gradational but, in the field, is represented by a few centimeters of glauconitic and broken and stained skeletal grains, suggesting sediment starvation and possible drowning. The upper contact of the Ngrayong is an erosional surface, with meter-scale conglomerate-filled channels at the Prantakan River area. These channels are overlain by the Bulu Member (Figure 12A) of the Wonocolo Formation, a marker bed consisting of massive carbonates rich in larger benthic foraminifera (especially *Cycloclypeus annulatus*) and small patches of corals, red algae, and sandy carbonates that can be mapped throughout the study area.

The exposed Ngrayong interval is nearly 200 m (660 ft) thick and shows multiple coarsening-upward successions (Figure 5). The base is characterized by alternating shale and argillaceous fine sand. The shale contains shell fragments, echinoids, and broken larger benthic foraminifera. The argillaceous fine sandstone has planar cross-stratification, is bioturbated, and contains subspherical to ellipsoidal calcareous concretions. Upward, the lithologies become fine- to medium-grained sandstones (Figure 12A) with thin mudstone layers and coal seams (Figure 5). Occasionally, the grains are very coarse sand grains. The sandstones are well bioturbated and sorted. The dominant components are angular quartz grains, and the secondary are mica, glauconite, and trace minerals of iron oxide (Figure 11D). Sedimentary structures, such as tabular cross-bedding (Figure 12B) and asymmetric ripples, are very common. In the subsurface Randublatung zone, the Ngrayong Formation is represented by deep-water deposits up to 900 m (2900 ft) in thickness (Ardhana et al., 1993), containing cross-bedded sandstones, mudstones, thin limestone beds, sandy turbidites, and mudstones (Ardhana et al., 1993). The clastic sequence is represented at the Kendeng zone by bathyal deposits of sandstone, siltstone, calcareous mudstone, and marl, attaining a thickness of up to 520 m (1700 ft) (Ngimbang-1, Dander-1, and

Karang Anyar-1 wells). The thickness pattern suggests seaward progradation and fill of the Tuban slope system.

The clastic shelf interval is interpreted to represent an increasing supply of siliciclastic sediments represented by a large-scale tidal-influenced delta. Ngrayong outcrops show mud drapes and reactivation surfaces, suggesting tidal influence, but mostly contain burrows, unidirectional cross-bedding, and interbedded fine sand, silt, and mudstone that reflect episodic sedimentation. The outcrop shows evidence of a general shallowing- and coarsening-upward succession that can be subdivided into three minor cycles of deposition (Figure 5). Toward the northwest, coal beds are preserved, suggesting swampier conditions. The prodelta was localized in the Randublatung zone, although the geometry of the delta front could have had many reentrants as it prograded over a low-gradient shelf. The basin deepens to the south in the Kendeng zone, and the last clinoforms have been observed east of the Ngimbang anticline and penetrated by the Santa Fe-Pertamina Gondang-1, Ngasin-1 and Grigis Barat-1 wells (Figure 1).

DISCUSSION AND CONCLUSIONS

The stratigraphic correlation of seismic facies and geometries with exposed rocks allow for the interpretation of the Oligocene and Miocene sequences in the East Java basin within a biostratigraphic and strontium isotope chronostratigraphic framework (Figures 3, 4). Eustatic sea level change and structural movements associated with local tectonics had a significant influence on the stratigraphic evolution of the basin. Outcrops throughout the Rembang area provide lithologic and fossil information that reinforce subsurface data. The integration of surface and subsurface data provides compelling evidence of three stages of Oligocene–Miocene deposition: an Oligocene–Aquitania carbonate mound stage, an Aquitania–Langhian mixed carbonate-siliciclastic low-angle shelf stage, and an uppermost Langhian–Serravalian siliciclastic-dominated tidal-delta stage. This progression reflects the regional tectonic evolution. It initiated with extension and associated differential subsidence that drowned the platforms and the mounds (Kujung interval, Oligocene–early Aquitania). This stage was followed by the increasing influx of clastics in the East Java basin, filling the mound seafloor topography and decreasing the accommodation space in the East Java basin during the late Aquitania–early Serravalian (Tuban and Ngrayong

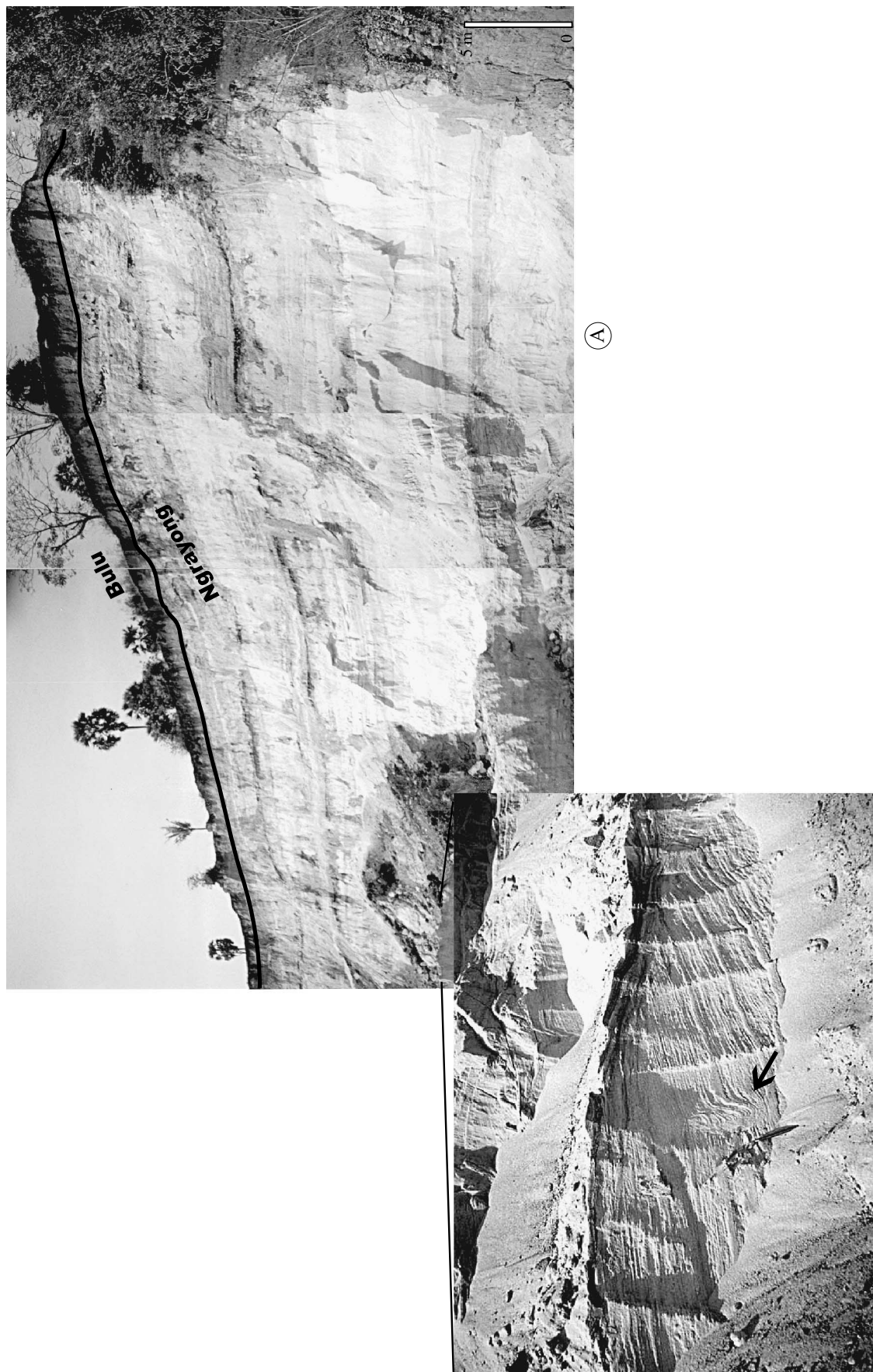


Figure 12. (A) Thick clastic section of the Ngrayong Formation capped by a thin carbonate bed of the Bulu Member. Ngepon Quarry, Lodan anticline. (B) Close-up photo of the bioturbated cross-bedded (arrow) fine sandstone unit at the base of the measured section.

intervals). Accommodation space increased in the late Serravalian–Tortonian (Wonocolo) and ended with tectonic exposure of the Rembang zone in the late Miocene (late Tortonian–Messinian). The tectonic template is punctuated by multiple scales of sea level changes and the effects of siliciclastic supply in carbonate production.

The proposed model correlates well with the plate-tectonic reconstruction for the region (Hall, 2002). During the late Oligocene–early Miocene, the East Java basin was still readjusting to the Eocene–early Oligocene subsidence, and fault-controlled shelf margins and carbonate mounds developed. Borneo became the main source for siliciclastics starting in the latest Oligocene with uplift followed by rotation through the early Miocene. Although no large delta systems are present in southern Borneo today, early Miocene reconstructions show that present-day southeastern Borneo was south-facing the East Java basin (Hall, 1997, 2002). Potentially, rivers like the Mahakam, with a large delta, would have provided clastics to the East Java basin at that time. The maximum influx of clastics in the East Java basin is in the early Serravalian. Clastic grains are almost exclusively composed of quartz. A similar observation has been made in the modern Kayahan and Rungan rivers of central Kalimantan, where point bars are made entirely of quartz sand (Cecil et al., 2003). As Borneo rotated counterclockwise in the early Miocene, coarse clastics shifted to the east (Madura region) and northeast, and the East Java basin became dominated by fine-grained clastics (Wonocolo Formation) later in the Serravalian.

During the early to middle Miocene, the shelf and deep-water troughs, which had carbonate mounds on faulted blocks between Borneo and the East Java basin, gradually filled up, initially with fine-grained clastics and later with coarse-grained deltaic sandstones. Carbonate mounds and tabular mixed carbonate-siliciclastic deposits punctuate the section. The siliciclastic system, during this time, shows at least six prograding depositional packages separated by tabular mixed carbonate-siliciclastic deposits with or without associated mounds. Carbonate mounds grew at different stratigraphic intervals in these packages.

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