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Seismic Stratigraphy and Cenozoic Evolution of West Sumatra Forearc Basin[1]

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ABSTRACT

Late Tertiary (Neogene) sediments deposited in the Sunda forearc reveal the stratigraphic and structural evolution of this active plate margin. A dense grid of multichannel seismic reflection data and information from 17 exploratory wells were used to establish a detailed seismic-stratigraphic framework of the forearc region from 0° to 6°N. Several important tectonic cycles are recognized: Paleogene orogeny, Neogene subsidence, and late Tertiary tectonism. Superimposed on these regional tectonic events are three major transgressive-regressive cycles of sedimentation related to changes in sea level and provenance.

Paleogene and older metasedimentary and metamorphic rocks comprise basement beneath the landward (inner) margin of the forearc basin. Both basement rocks and lower Tertiary sedimentary rocks were deformed and eroded approximately 25 to 30 Ma. The continental shelf was exposed to subaerial erosion, and basin deposits were restricted offshore, coincident with a worldwide lowstand of sea level in the Oligocene. The Paleogene orogeny probably occurred prior to the erosional event that cut the prominent angular unconformity on the shelf.

The Neogene history of forearc basin development is characterized by subsidence and nearly continuous sedimentation. A basal transgression began in latest Oligocene time and culminated in the middle Miocene. Alternating sequences of limestone and shale comprise two second-order cycles of sedimentation that are superimposed on an overall transgressive event. A major regressive sequence followed in the Pliocene, owing to an influx of siliciclastic clay, silt, and sand derived from Sumatra. Sedimentation rates were high, and large volumes of terrigenous material were deposited in deltaic systems on the shelf. The shelf-slope break prograded basinward nearly 10 km (6 mi) through lateral accretion and aggradation during a relative highstand or stillstand of sea level.

INTRODUCTION

Forearc basins containing thick sediments are important features of continental margin arc-trench systems with high sedimentation rates (Dickinson and Seely, 1979). Where an outer-arc ridge is present, arc-derived sediments are dammed behind the ridge and can accumulate in great thicknesses in the forearc basin. Many such forearc basin systems are 50-100 km (30-60 mi) wide and several hundred kilometers long, with the forearc basin commonly segmented into many subbasins by transverse highs. Most forearc basins received sediment derived from their volcanic arcs. These arc massifs provide a provenance that varies both spatially and temporally. In addition, carbonate sediments are important in forearc basins formed in tropical regions. Thus, sedimentary sequences deposited in different forearc basins differ considerably.

Depositional processes within forearc basins are greatly affected by the basin's tectonic environment. Changes in relative sea level and in sediment supply also affect forearc-basin deposition. This complex interplay ~~between~~ among tectonics, sea level change, and sedimentation rate has been documented in the Mesozoic forearc basin of California (e.g., Ingersoll, 1983, and references therein) and the forearc basin of Luzon (Bachman et al, 1983). In this paper we present the results of a study of the seismic stratigraphy and sedimentary history of the Sunda forearc basin of west-central Sumatra, Indonesia. It is another example of a forearc basin that has been affected by the interplay of tectonics and sea level fluctuations.

The western Sunda forearc has been the focus of recent ongoing land and marine investigations by the International Decade of Ocean Exploration/Studies of East Asian Tectonics and Resources program (IDOE/SEATAR). Previous studies have established the regional tectonic and stratigraphic setting and have outlined the geologic history of west Sumatra (e.g., Hamilton 1979; Karig et al, 1979, 1980; Cameron et al, 1980; Moore et al, 1980, 1982; Beaudry and Moore, 1981). Against this background, we collected multichannel seismic-reflection data across the shelf and deep-water areas of the central Sumatra forearc basin during the Scripps Institution of Oceanography's RAMA Expedition in October 1980. In this paper we present and interpret these new seismic reflection data, establish a regional stratigraphic framework, and infer the depositional history of the western Sunda forearc region.

REGIONAL TECTONIC SETTING

The zone of convergence between the Indian-Australian and the China (Southeast Asian) plates extends from the

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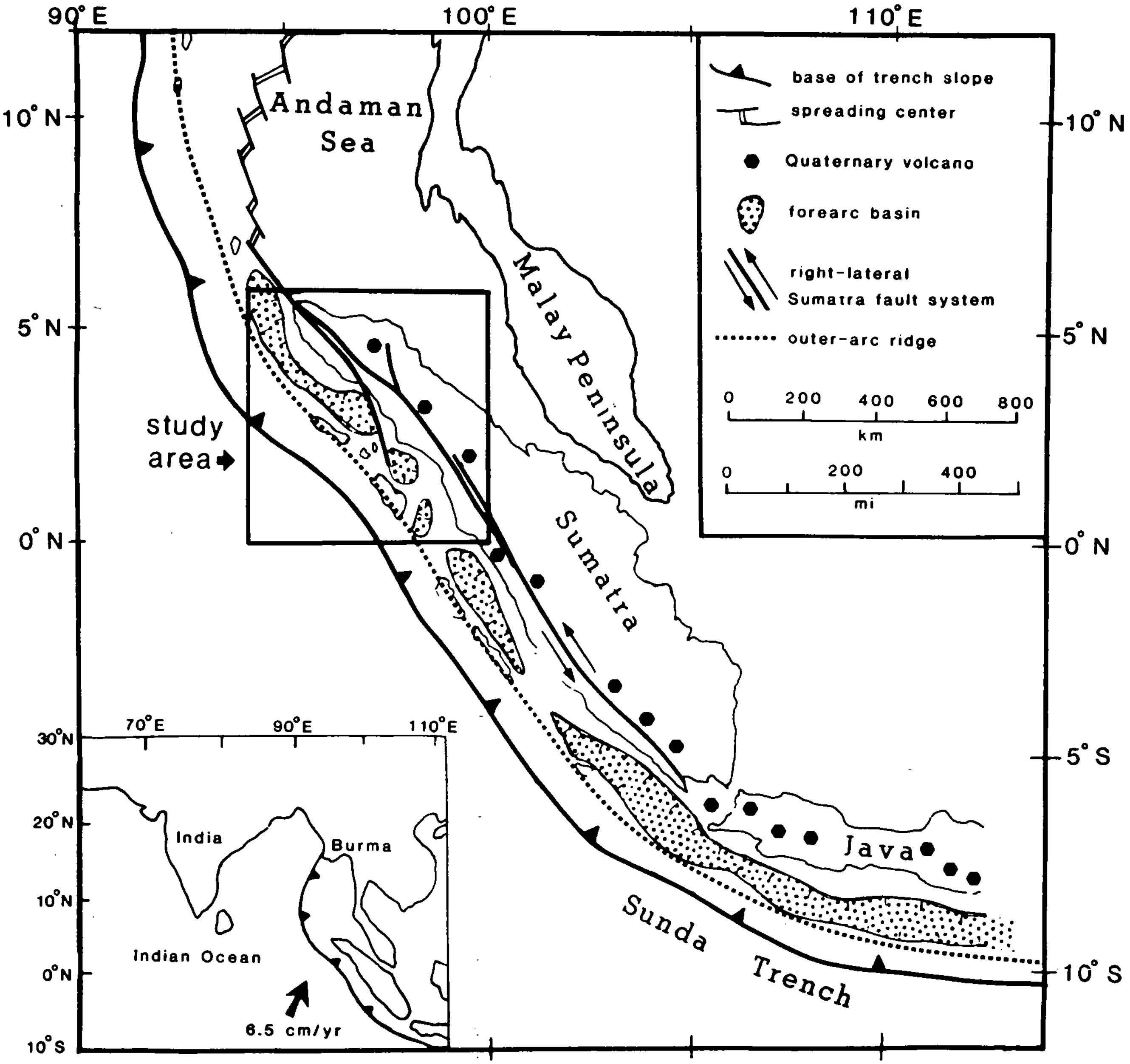

Figure 1—Tectonic map of western Sunda arc showing location of study area. Structure and magnetic anomaly patterns based on Sclater and Fisher (1974), Johnson et al (1976), Hamilton (1978), Curray et al (1979), and Karig et al (1980).

Himalayan foothills in northern Burma to the zone of collision between the Australian continent and eastern Indonesia (Figure 1). Along this plate boundary, oceanic crust of Late Cretaceous to early Paleogene age is being subducted beneath Sumatra and Java at high convergence rates of 7 cm/year (2.8 in./year) (Moore et al, 1980).

The western Sunda arc presently is a continental margin arc-trench system characterized by oblique subduction and transcurrent faulting (Fitch, 1972; Hamilton, 1979). The normal component of convergence across the Sunda Trench decreases, and the lateral component increases northward as the strike of the trench becomes subparallel to the direction of convergence (Figure 1). This tectonic regime is expressed by transcurrent faulting along the right-lateral Sumatra fault system (Katili, 1973; Posevac et al, 1976) and by sea-floor spreading in the Andaman Sea (Curray et al, 1979).

A major strand of the right-lateral Sumatra fault system, the Batee fault, trends offshore at approximately 3°N and disrupts the shelf and basin morphology (Figure 2). The trace of this structure crosses the Banyak Shelf and intersects the late Pliocene flexure on Nias Island, which is thought to represent the rear edge of subduction-related deformation (Karig et al, 1980).

GEOLOGIC HISTORY OF NORTH SUMATRA

Western Sumatra has been at, or near, an active convergent plate boundary at least intermittently since the Late Permian (Karig et al, 1979; Cameron et al, 1980). Much of east and central Sumatra is believed to be underlain by

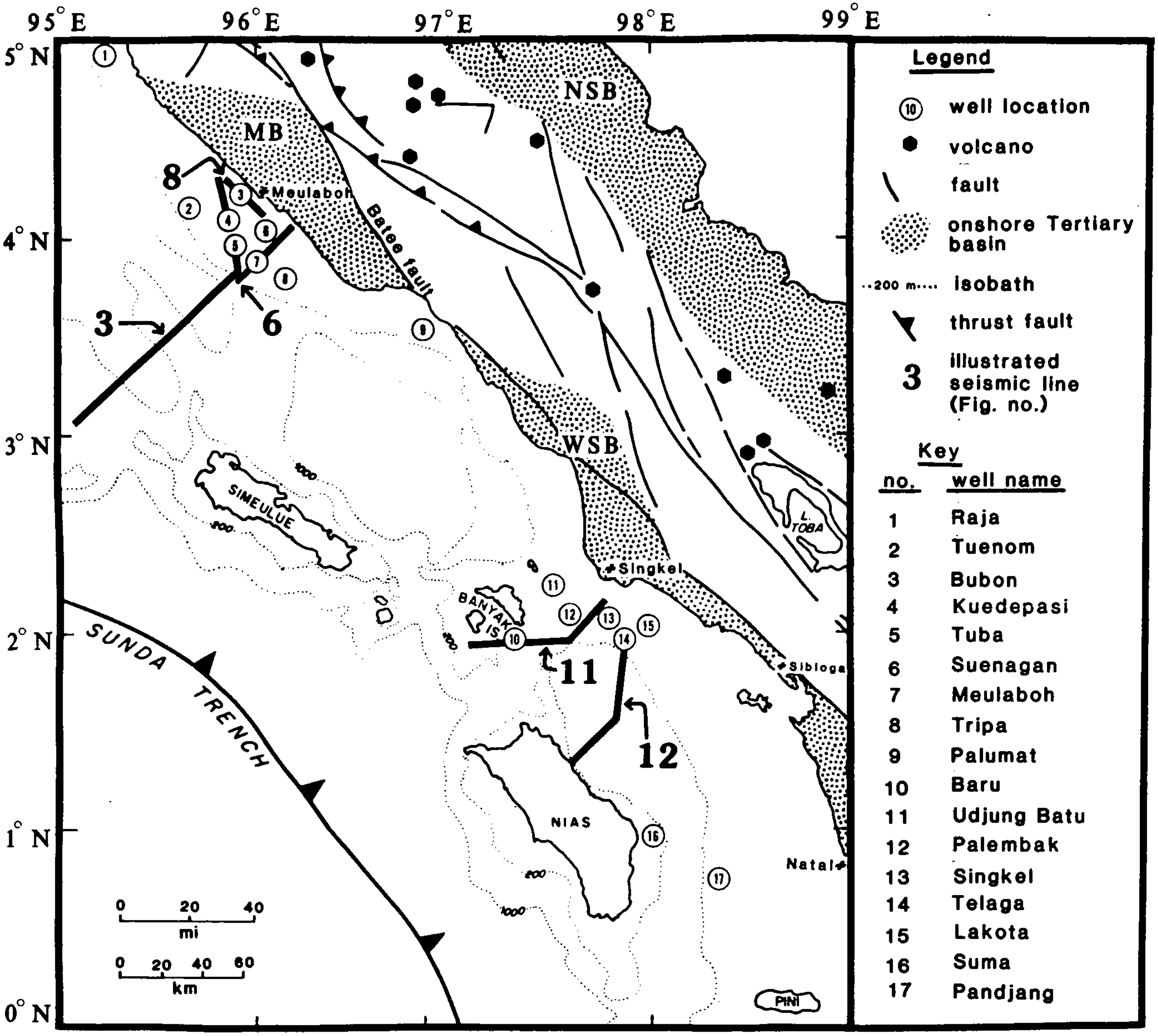

Figure 2—Structure map of north Sumatra. Modified from Cameron et al (1980). Shaded area outlines surface exposure of Tertiary sedimentary basins: MB = Meulaboh basin, WSB = West Sumatra basin, NSB = North Sumatra basin. Exploration wells are numbered and listed in the key.

continental crust older than the late Paleozoic, and the oldest mappable sedimentary rocks date from the late Paleozoic (Cameron et al, 1980). Permo-Carboniferous rocks occur as scattered outcrops throughout north Sumatra and consist of a thick succession of mainly quartzarenite and thinly bedded mudstone and siltstone (Kluet Formation, Cameron et al, 1980). Permian granites also are exposed in west Sumatra. Granitic magmatism of latest Mesozoic and earliest Tertiary age was widespread in Sumatra. Considerable volumes of Paleozoic, Mesozoic, and Cenozoic volcanic rocks have been mapped in north Sumatra (Page et al, 1979). Sumatra was probably emergent from the Late Cretaceous to the Eocene because no sedimentary record of this period can be found on mainland northern Sumatra.

Changes in relative plate motions between the Indian and Eurasian plates have been responsible for Cenozoic changes in the tectonic regime along the Sunda arc. Studies of marine magnetic anomalies in the Indian Ocean suggest that the initial collision of the Indian and Asian continents occurred during the Eocene, causing a slowdown in convergence and beginning deformation of the Eurasian plate, which led to uplift of the Himalayan Range (Molnar and Tapponnier, 1975; Curray et al, 1979). At approximately 40-45 Ma, the direction of spreading of the Indian-Australian plate changed from north-south to northeast-southwest (Sclater and Fisher, 1974). This change in spreading direction increased the convergence component along the western margin of Sumatra. The rate of subduction remained steady at 5 cm/year (2 in./year) until 10 Ma, when the rate increased to nearly 7 cm/year (2.8 in./year) (Karig et al, 1979).

From the Eocene onward, Sumatra was the site of an intermittently active volcanic arc and widespread associated volcaniclastic sedimentation. Eocene to lower Oligocene volcanic and limestone rocks are found in north Sumatra. The Eocene-Oligocene sediments that were drilled in offshore wells may be forearc sediments of this arc (Karig et al, 1979; Cameron et al, 1980). Paleogeography in the late Oligocene–early Miocene was dominated by an elongate landmass in the south and a chain of intermittently active volcanic islands in the north. Localized seaways, open through the islands to the Indian Ocean, are indicated by outcrops of sediments of this age in eastern Sumatra (Cameron et al, 1980). Uplift in Sumatra began in the late middle Miocene (zone N12-13 of Blow, 1969), probably climaxed at the Miocene-Pliocene boundary, and has continued irregularly until the present. The main axis of uplift was in the Barisan Mountains, although parts of the west Sumatra Shelf were emergent.

SUMATRA FOREARC BASIN

The forearc basin of west Sumatra is a "constructed" basin in which sedimentary fill onlaps the arc massif on the landward side of the basin and accreted material on the seaward side (Dickinson and Seely, 1979). The nature of the crust underlying the central part of the basin is poorly defined. It may be either subsided accretionary complex or attenuated continental crust (Karig et al, 1979; Kieckhefer et al, 1980). The forearc region contains a nearly continuous sequence of Miocene and Pliocene strata that lap onto the arc massif (Figure 3). An elevated trench-slope break forms the seaward structural boundary of the forearc basin.

Two distinct environments of deposition are found within the modern forearc: a relatively shallow shelf flanking the arc and a deeper basin offshore (Figure 3). The shelf occupies the area from the present coastline to the 200-m (650-ft) isobath. This depth marks the modern shelf-slope break, which separates the shelf environment from the basinal environment. Neogene and Quaternary shelf deposits form a transgressive-regressive wedge of strata up to 2,500 m (8,200 ft) thick at the shelf edge. The sediments drilled in exploration wells consist of sand, silt, clay mud, carbonate mud, and carbonate sand deposited in a neritic environment (Figure 4).

The deep, partially filled basin between the shelf and the outer-arc ridge represents a separate depositional environment (Figure 3). Offshore basin deposits comprise flat-lying, onlap-fill seismic facies units that interfinger laterally and vertically with prograded slope deposits of equivalent age. Deposition presently occurs in 600-1,000 m (2,000-3,000 ft) of water. Wells drilled across the Banyak Shelf give evidence that shallow marine and nearshore sedimentary rocks pass laterally offshore into a thick sequence of interbedded sandstone, siltstone, and claystone of Miocene and Pliocene age (Figure 5). These rocks are interpreted as turbidites by Karig et al (1979) on the basis of sedimentary structures observed in cores.

Regional Shelf Unconformity

Multichannel seismic reflection profiles across the shelf reveal a prominent angular unconformity at the base of the Neogene sedimentary section (Figure 6). The unconformity separates acoustic basement and erosionally truncated reflections from an orderly sequence of prograded shelf and slope deposits. The smooth, uniform morphology of the erosional surface and the truncated reflections below indicate that the unconformity was primarily formed by erosion. Reflections above the unconformity terminate by basal onlap in a landward direction, and the overlying Neogene sedimentary section thins toward the present shoreline.

Only a few of the exploratory wells drilled on the shelf penetrated the unconformity, which was considered to be economic basement. Pre-unconformity rocks are comprised of upper Eocene and lower Oligocene dolomitic limestones and well-indurated, pyrite-rich shales with steep dips. These strata may represent the lateral (offshore) facies equivalent of the Paleogene sandstones mapped below the unconformity along the west coast of Sumatra near Sibolga and Natal (Figure 2). In the Sibolga area, these sediments are massive quartzose sandstones and minor noncalcareous shales and conglomerates (Karig et al, 1979).

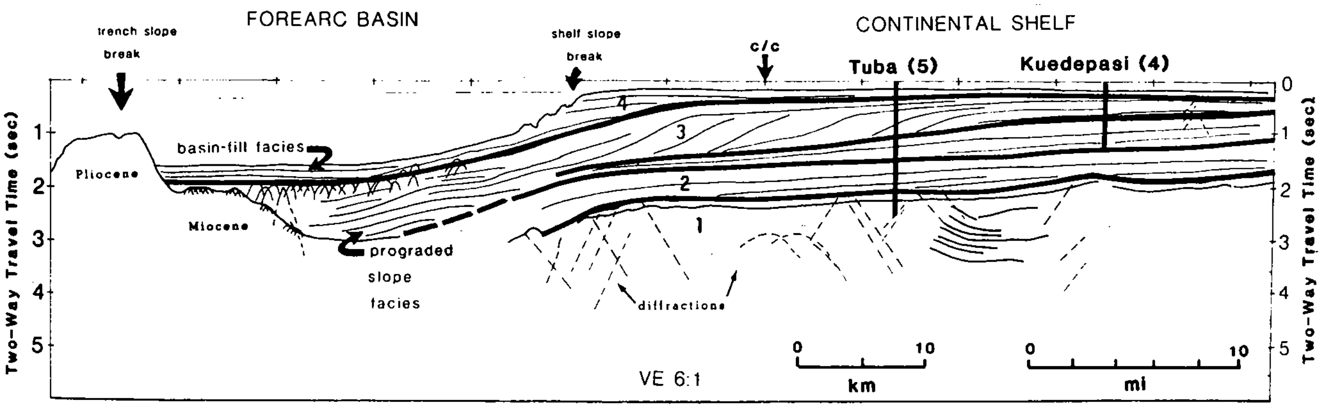

Figure 3—Line drawing of multichannel seismic-reflection profile across forearc basin between shelf and outer-arc ridge. Heavy black lines delineate seismic sequence boundaries. Four depositional sequences were identified on basis of age, lithology, and internal reflection geometry (see Table 1). See Figure 2 for location of profile.

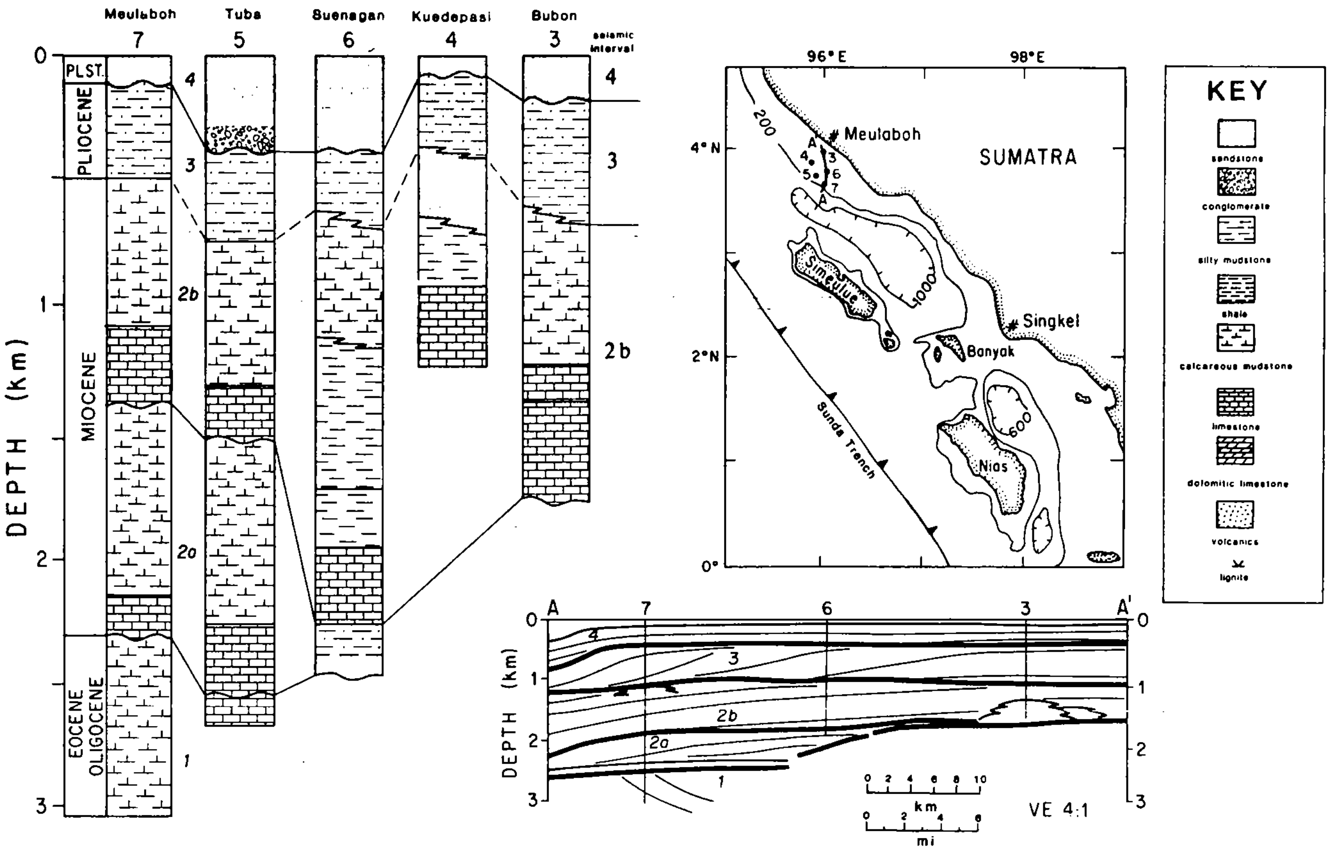

Figure 4—Stratigraphic correlation diagram, Meulaboh basin. Ages and lithologies of depositional sequences identified on seismic-reflection profiles were interpreted from well completion reports. Interval velocities from downhole surveys were used to construct depth section in lower corner of figure (explanation same as Figure 3).

SEISMIC STRATIGRAPHY

The seismic-stratigraphic framework was established on the Meulaboh Shelf, where the well control is excellent and the sedimentary section is the most complete (Figure 6). Figure 7 illustrates the correlation between well stratigraphy and depositional patterns observed on seismic-reflection records. The stratigraphic framework can be subdivided into four seismic intervals (depositional sequences) on the basis of sequence boundaries and seismic facies. The seismic characteristics of each of the depositional sequences are summarized in Table 1. The following discussion will trace the development of the shelf from the base of the sedimentary section through Pleistocene time.

Tertiary Unit 1: Pre-Neogene

The regional unconformity at the base of the Neogene sedimentary section marks the top of Tertiary unit 1. It is correlated with an erosional hiatus identified in some of the wells drilled on the outer continental shelf (Figure 7). The Raja, Meulaboh, Tuba, and Pandjang wells penetrated upper Eocene and lower Oligocene dolomitic limestones and calcareous mudstones unconformably overlain by lower Miocene siltstone that contains shallow-water foraminifera and detrital limestone (Figure 4). A thin nonmarine sequence of reworked sands lies immediately above the unconformity, suggesting that shoreline erosion accompanied a widespread basal transgression.

Tertiary Unit 2: Lower Miocene-Middle Miocene

Tertiary unit 2 is subdivided into two transgressive-regressive pairs (units 2a and 2b) that comprise an overall landward-onlapping sequence (Figure 7). Each pair contains a thin, high-amplitude seismic facies unit overlain by a low-amplitude, prograded sequence.

Unit 2a: lower to middle Miocene.—Two to four continuous, high-amplitude reflections onlap the eroded basement complex in a landward direction (Figure 6). This strong reflecting sequence forms a prominent marker bed throughout much of the basin. A thick sequence of low-amplitude, parallel reflections downlaps the high-amplitude interval and buries contemporaneous topography. The internal reflection geometry of the latter seismic facies unit signifies very low-angle basinward progradation.

The thin, high-amplitude seismic facies unit onlapping pre-Neogene basement is correlated with a thin, carbonaceous siltstone that passes upward into 200 m (650 ft) of detrital limestone of early Miocene age (Figure 7). We attribute the high reflection amplitudes to the large impedance contrast between the limestone and the overlying siltstone.

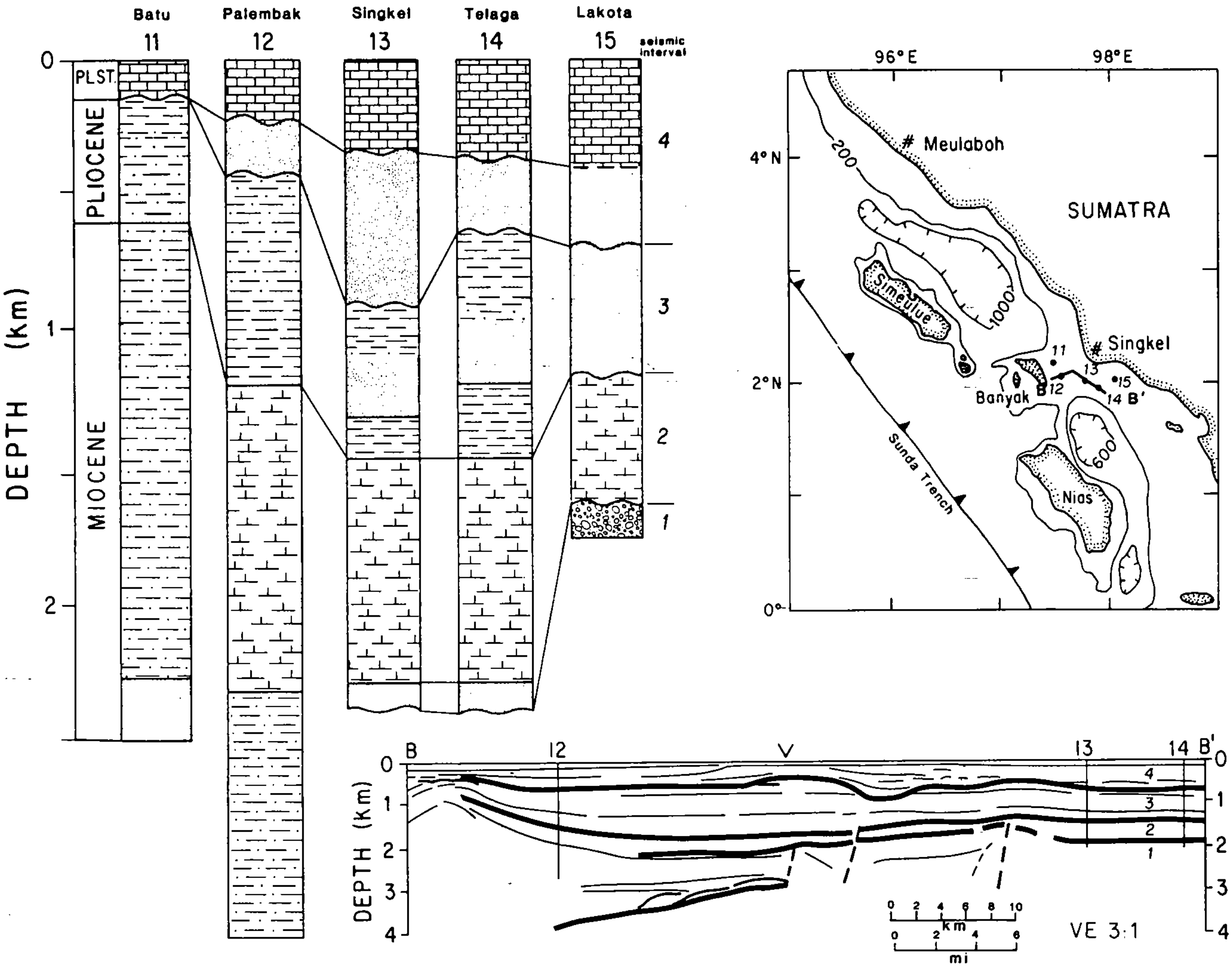

Figure 5—Stratigraphic correlation diagram, West Sumatra basin. Explanation and key same as Figure 4.

The overlying prograded seismic facies unit correlates with a lower to middle Miocene calcareous mudstone (Figure 7). Low reflection amplitudes are attributed to thin bedding and uniform, shale-prone lithology (Sangree and Widmier, 1979). The progradational pattern indicates that the fine-grained clastic sediments were eroded from the volcanic-arc terrane. Truncation of reflections along the upper sequence boundary may mark a minor regression in the early middle Miocene.

Unit 2b: middle to upper Miocene.—One or two continuous, high-amplitude reflections are generated along the lower sequence boundary of interval 2b (Figure 6). This thin, high-amplitude seismic facies unit onlaps the lower Miocene mudstone in a landward direction and directly overlies pre-Neogene basement at the eastern end of the line (Figure 7).

On the inner shelf, the Bubon well bottomed in a limestone reef of middle Miocene age (Figure 8). This mounded carbonate facies is overlain by approximately 300 m (1,000 ft) of middle Miocene marls that pass upward into a thin-bedded limestone facies of late Miocene–early Pliocene age (Figure 4). We correlate this depositional unit with seismic interval 2b. Low-amplitude, continuous, parallel reflections are diagnostic of uniform, shale-prone lithologies (Sangree and Widmier, 1979). Thus, this seismic facies unit probably represents mudstones that bury preexisting topography and downlap the middle Miocene reef horizon offshore.

The upper sequence boundary of unit 2b is delineated by a continuous reflection that exhibits lateral amplitude variations (Figure 7). Diffractions generated at the edges of the amplitude anomalies indicate the presence of patch reefs (Bubb and Hatlelid, 1977). This packet of high-amplitude reflections thickens locally, forming small, isolated mounds that create local relief (Figure 6). Some sigmoid progradational patterns, possibly fore-reef facies, can be resolved immediately basinward of the mounded structures. Well data verify that these mounded features are carbonate buildups of late Miocene age (Figures 4, 7).

Tertiary Unit 3: Upper Miocene–Pliocene

This seismic interval contains an assemblage of three seismic facies units (Figure 6). The lower part of the interval contains bottomset strata characterized by low-amplitude, continuous reflections that downlap the upper

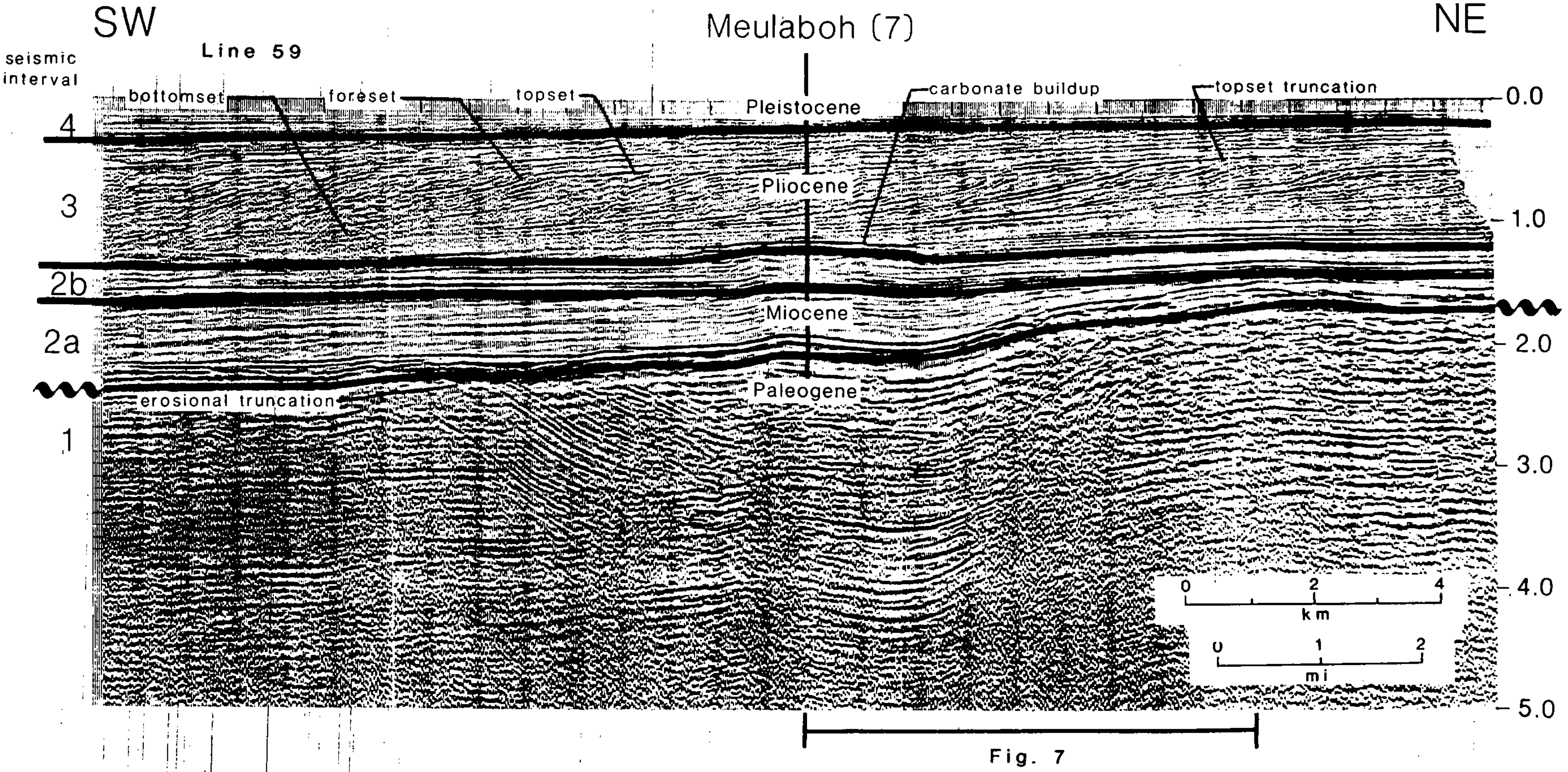

Figure 6—Multichannel seismic-reflection profile (line 59) across the Meulaboh Shelf. Basal unconformity separates landward-dipping, erosionally truncated reflectors below, from flat-lying, onlapping reflectors above. An upper Miocene unconformity separates onlapping, transgressive seismic sequence (Tertiary unit 2), from prograding, regressive seismic sequence (Tertiary unit 3). Numbered seismic intervals are identified and described in Table 1. See Figure 2 for location of profile.

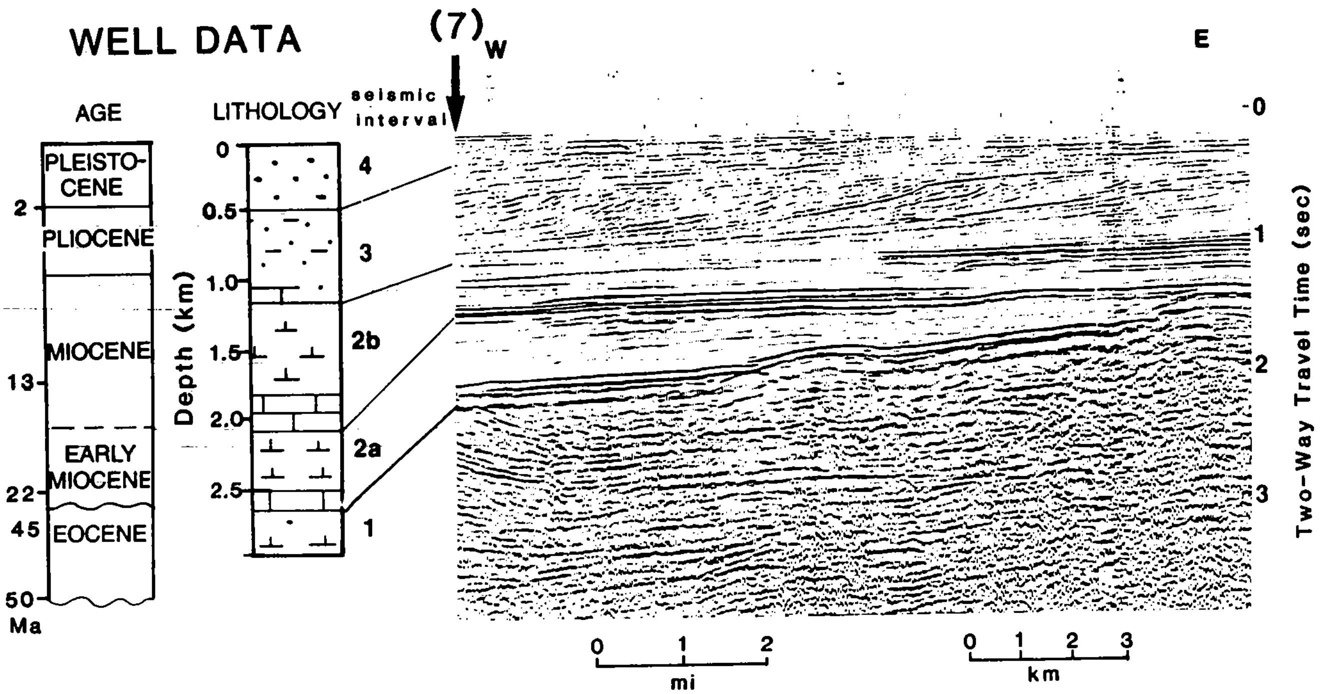

Figure 7—Correlation of well stratigraphy with seismic data. Correlations were based on interval velocity information, erosional unconformities, and facies interpretations. Numbered seismic intervals are identified and described in Table 1.

Miocene sequence. The middle zone consists of relatively steeply dipping reflections interpreted as prograding clinoforms or foresets. Variable amplitude and low continuity of seismic reflections and high bedding angles suggest deposition in a high-energy, sand-prone environment (Sangree and Widmier, 1979). The upper part of this seismic interval is characterized by subhorizontal topset reflections and toplap truncation. This lateral and vertical facies assemblage is characteristic of depositional environments commonly found within a deltaic complex (Rich, 1951; Coleman, 1976). As the delta (or bank) advanced basinward, the foreset strata prograded over deeper water marine strata and buried upper Miocene and lower Pliocene patch reefs that had developed on the outer continental shelf (Figure 6).

This interpretation is supported by the vertical succession of lithofacies observed in the well data (Figure 7). Bottomset strata are correlated with lower Pliocene marls. Lithologic units include carbonaceous shales with thin coal seams and shales containing arenaceous foraminifera and quartz grains. The lithology of the upper Pliocene consists of interbedded sands, silts, and clays that shoal upsection. We correlate these lithofacies units with the foreset/topset facies assemblage inferred from the seismic data. The sand fraction contains abundant volcanic lithic fragments and quartz, reflecting an increasing supply of terrigenous material derived from the eroding arc terrane.

Tertiary Unit 4: Pleistocene to Recent

Tertiary unit 4 is represented by a thin sheet or wedge of onlapping reflections that diverge across the shelf edge (Figure 3). This seismic interval is correlated with nonmarine Pleistocene deposits that consist of coarse-grained sand, gravel, and lithic fragments (Figure 7). The lithic fragments are both plutonic and volcanic, indicating unroofing and exposure of batholithic rocks by this time. Erosion and winnowing of sediment during Quaternary time were undoubtedly enhanced by abrupt sea level changes in response to Pleistocene glaciations. The nonmarine Pleistocene sediments in wells on the outer continental shelf may be relict sands stranded during the recent sea level rise (Figure 4).

The Pliocene-Pleistocene boundary is partly erosional. A large channel on the shelf near Singkel was eroded into Pliocene shelf strata and filled with Pleistocene sand, gravel, and conglomerate (Figure 9). No fan deposits could be identified in the basin seaward of this channel. The buried channel disappears landward, although it is in fairly good alignment with the Singkel River system on the mainland. It is the only subsurface channel observed on the shelf and probably formed as a Pleistocene erosional feature cut by the Singkel River during a low stand of sea level.

SUMMARY OF SHELF STRATIGRAPHY

The depositional history of the shelf is summarized in Figure 10. A regional angular unconformity at the base of the Neogene sedimentary section marks the top of the eroded basement complex and represents the beginning of the present cycle of subsidence and sedimentation. The regional extent of this unconformity suggests that the paleoshoreline extended as far seaward as the modern shelf break.

The eroded basement complex is unconformably overlain by a transgressive sequence of shallow-water marine strata. Calcareous, prograded mudstones and shallow-

Table 1. Seismic Facies Characteristics

Seismic Interval	Reflection Geometry at Sequence Boundaries	External Form	Internal Reflection Configuration	Facies	Lithology	Depositional Environment
4 Pleistocene to Recent	Toplap at top; onlap at base	Thin sheet or wedge	Slightly divergent	Topset	Sand and gravel; some reefal	Inner neritic
3 Pliocene to Upper Miocene	Toplap at top; onlap and downlap at base	Thin sheet or wedge	Slightly divergent	Topset	Sand, silt and clay	Shelf
	Truncation at top; downlap at base	Wedge or bank	Oblique progradation	Foreset		Shelf margin
	Truncation at top; downlap at base	Sheet	Even, parallel	Bottomset	Silt and clay	Prodelta
2b Middle to Upper Miocene	Truncation at top; downlap at base	Sheet	Sigmoid progradation	Prograded	Calcareous mudstone	Shallow-water marine
	Concordant at top; onlap at base	Mounded	Parallel, continuous high amplitude	Reefal	Detrital limestone	Shelf margin
2a Lower Miocene	Truncation at top; downlap at base	Wedge	Sigmoid progradation	Prograded	Calcareous mudstone	Shallow-water marine
	Concordant at top; onlap at base	Mounded	Parallel, continuous, high amplitude	Reefal	Detrital limestone	Shelf margin
1 Paleogene	Truncation at top	Eroded syncline	Parallel, landward-dipping	—	Dolomitic limestone; Indurated shale; pyritic sandstone	Marginal marine

water detrital limestones, deposited as alternating sequences (Tertiary units 2a and 2b), represent cyclic phases of deposition superimposed on a net transgression that began in latest Oligocene time and culminated in the middle Miocene (Cameron et al, 1980). Wells drilled across the shelf suggest that shoreline erosion accompanied the marine transgression. Thin, lignitic, shallow-water sands and silts pass upward into detrital limestone and limy mudstone of early Miocene age. The vertical succession of lithofacies indicates an overall deepening toward offshore marine conditions due to shelf subsidence and rapidly rising sea level.

The Miocene transgression was followed by a depositional regression in the late Tertiary. A thick wedge of shallow-water deltaic deposits prograded basinward and buried upper Miocene and lower Pliocene patch reefs that had started to develop on the outer continental shelf. Sedimentation rates exceeded subsidence rates, and the shelf-slope break was built basinward through lateral accretion and aggradation during a relative highstand or stillstand of sea level. Tertiary unit 4 is predominantly nonmarine and represents deposition near base level, where the sediments were reworked extensively owing to rapid sea level fluctuations in the Quaternary.

LATERAL FACIES RELATIONSHIPS

The same depositional sequences identified in the Meulaboh basin can be recognized in the West Sumatra basin east of the Batee fault zone (Figure 2). On line 25, across the Banyak Shelf, the basal unconformity occurs at the base of the Miocene reefal facies (Tertiary unit 2a), which in turn is buried beneath upper Miocene and Pliocene prograded shelf and slope deposits (Figure 11). The unconformity dips westward, and a faint basal reflection is visible to a depth of 4.6 to 4.7 sec (two-way travel time) beneath the flexure-fault zone forming the seaward margin of the basin. In a landward direction, the unconformity shoals, and the Neogene sedimentary section wedges out against it.

Offshore, the sedimentary section thickens dramatically, and the shelf remains shallow (Figure 11). Wells drilled along the margins of the Banyak Islands (Baru, Palembak, and Udjung Batu wells) penetrated thick sequences of middle to upper Miocene and Pliocene turbidites capped by Pleistocene to Recent limestone reefs (Figure 5). Although stratigraphic units are known to be different on the east and west sides of the basin, this important change in facies and lithology is masked on reflection profiles by a

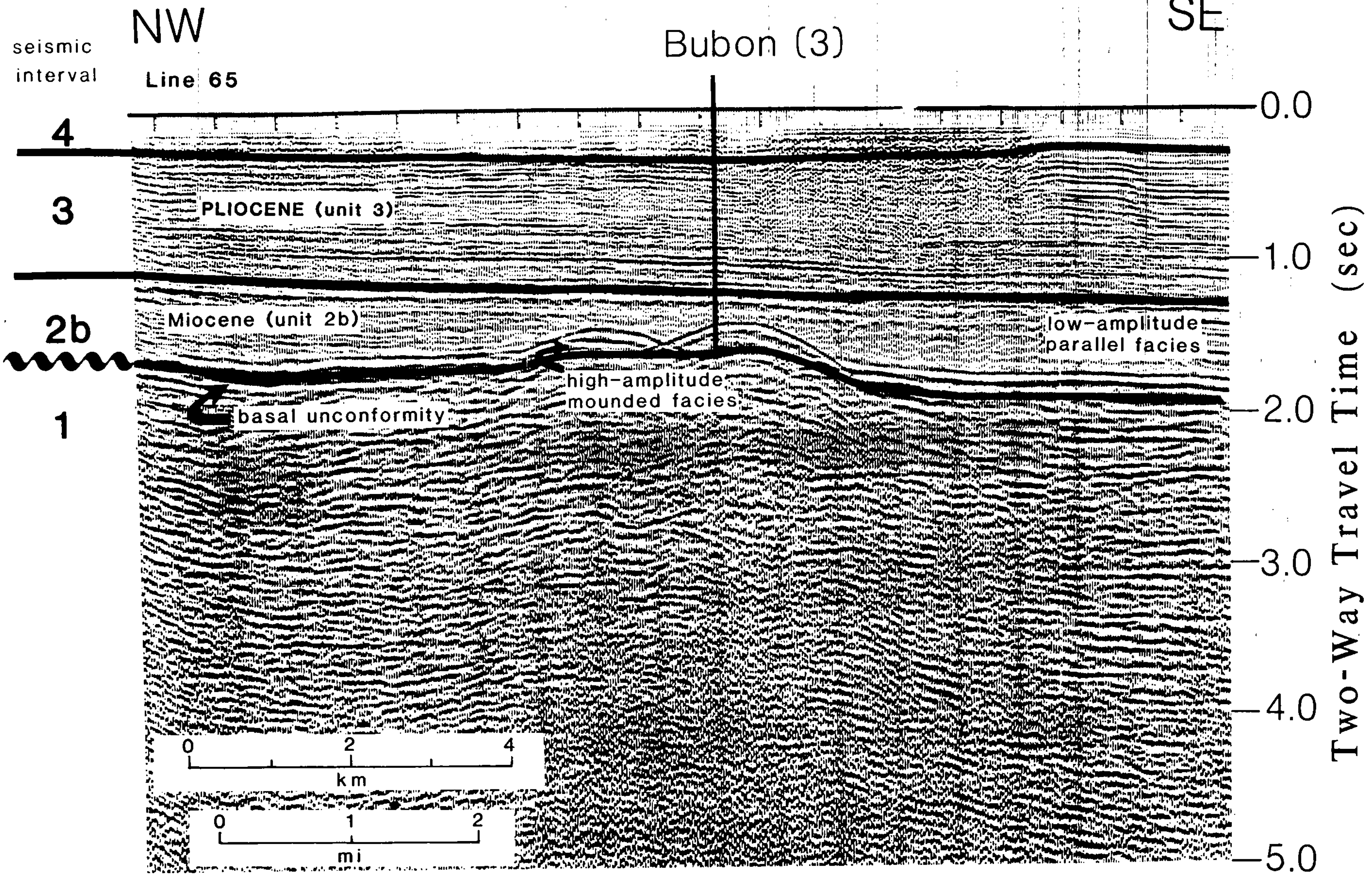

Figure 8—Multichannel seismic-reflection profile (line 65) across inner shelf. Seismic stratigraphy and well data summarized in Figure 4. See Figure 2 for location of profile.

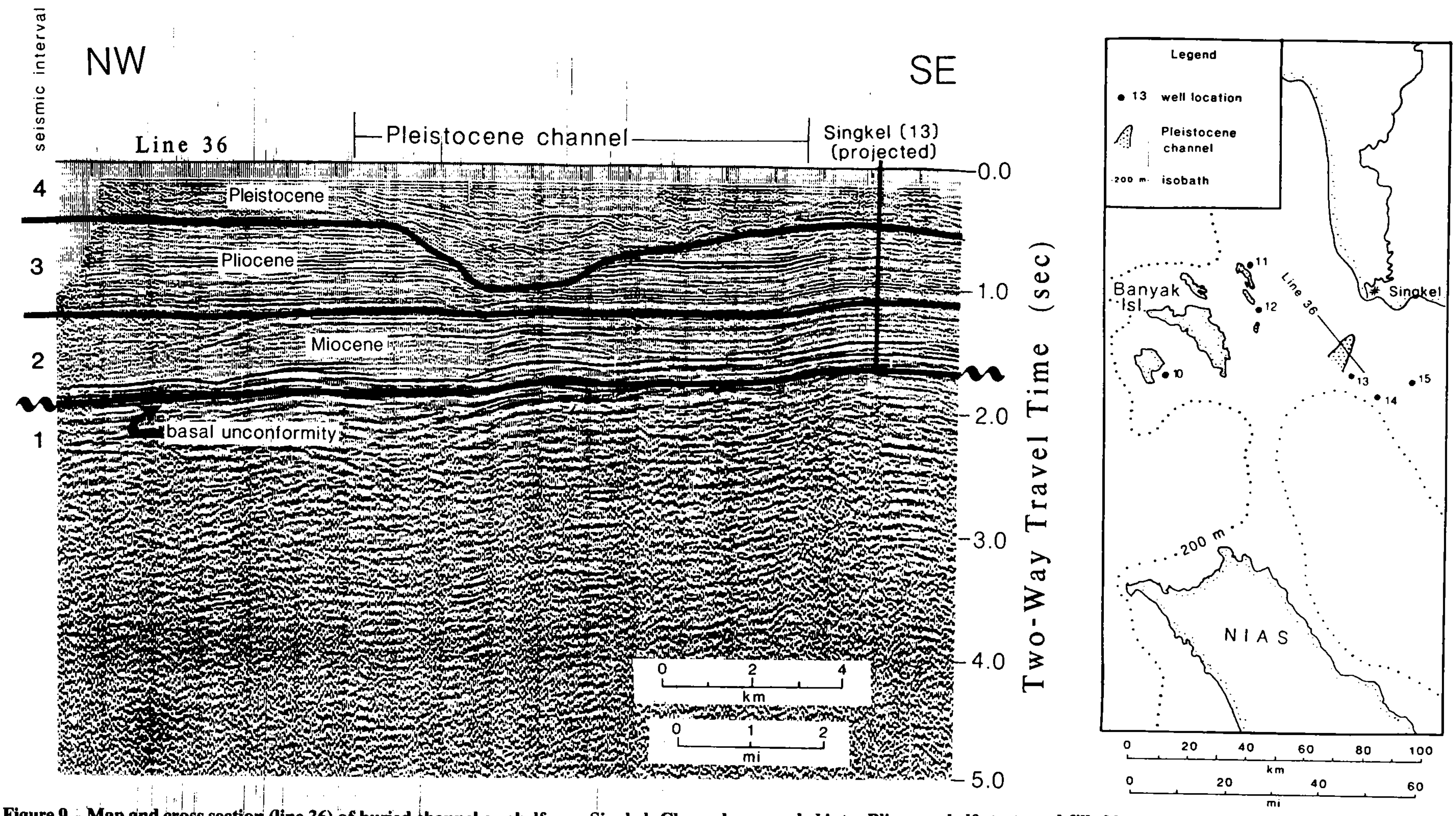

Figure 9—Map and cross section (line 36) of buried channel on shelf near Singkel. Channel was eroded into Pliocene shelf strata and filled by Pleistocene sands and gravels. Seismic stratigraphy and well data summarized in Figure 5.

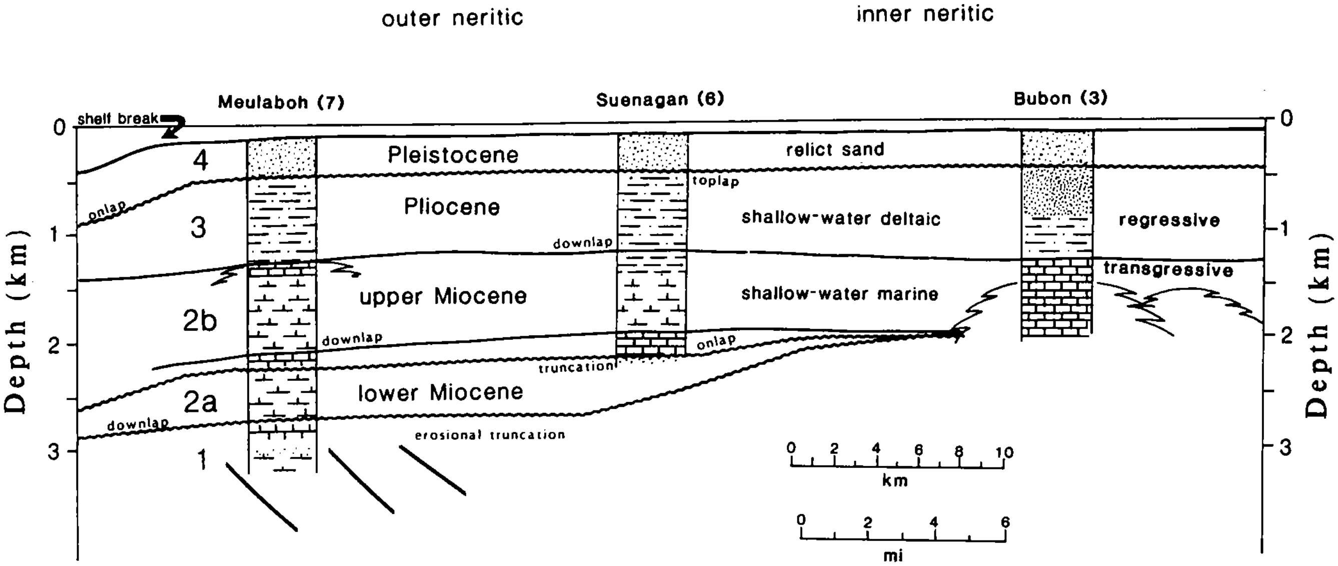

Figure 10—Summary of shelf stratigraphy and depositional history. Schematic columnar sections based on well completion reports summarized in Figure 4.

highly reflective carbonate bank on the shallow shelf (Figure 11).

S.I.O. RAMA Expedition multichannel reflection data collected across the deeper portion of the forearc basin allow us to resolve seismic facies units, identify depositional sequences, and extend age control beyond the shelf edge. The prominent shelf unconformity has been correlated offshore along the base of the distinctive lower Miocene seismic interval (Figure 12). It dips westward from a depth of 1.6 sec (two-way traveltime) at the shelf edge to 3.3 sec along the outer-arc ridge.

A high-amplitude, mounded seismic facies unit overlies the prominent reflecting sequence at the base of the sedimentary section (Figure 12). These seismic intervals correlate with the lower and middle Miocene reefal facies (Tertiary units 2a and 2b) on the basis of stratigraphic position and seismic facies characteristics. This depositional sequence is interpreted to be a transgressive carbonate sheet with pinnacle buildups (Klement, 1967; Bubb and Hatlelid, 1977). The carbonate buildups exhibit up to 200 m (650 ft) of relief, indicating significant reef growth during the Miocene. The occurrence of this facies unit beneath 1,700 m (5,600 ft) of basin fill indicates rapid subsidence since the Miocene.

The Miocene reef horizon passes laterally offshore into prograded slope deposits that downlap an older depositional sequence in the deepest part of the basin (Figure 12). This pre-Miocene(?) basinal sequence is represented by a relatively thick, high-amplitude seismic facies unit that onlaps the paleoshelf edge, marking the onset of subsidence and the initiation of sedimentation in the modern forearc basin. Its stratigraphic position suggests that it is latest Oligocene or earliest Miocene in age. The contorted reflection pattern probably represents original stratal surfaces, still recognizable after minor compressional deformation along the western margin of the basin.

Tertiary unit 2 is onlapped by a restricted sequence of flat-lying, continuous, parallel reflections interpreted as onlapping fill (Sangree and Widmier, 1979). These basinal deposits pass upward into the distal facies of prograded slope deposits that thin by depositional downlap toward the center of the basin. We correlate these seismic facies units with Tertiary unit 3; hence, they may be mostly Pliocene in age. A small wedge of chaotic facies on the western side of the basin indicates that slumps occurred from place to place along the unstable slopes of the rising subduction complex.

Pleistocene basin deposits comprise Tertiary unit 4 and are generally characterized by an onlap-fill seismic facies unit (Figure 12). Flat-lying, parallel reflections fill the basin vertically and interfinger laterally with the distal edge of prograded slope deposits. Subsidence rates have exceeded sedimentation rates throughout the Neogene and Quaternary, and the basin remains unfilled.

Facies Maps

The seismic facies map of Tertiary unit 2 shows the distribution of the lower Miocene seismic facies units (Figure 13). The thin, high-amplitude, mounded seismic facies unit represents a transgressive carbonate sheet that pinches out eastward and southward across the shelf. The thickness of this unit is fairly constant over the shelf area, averaging about 100-200 m (330-650 ft). An additional 200 m (650 ft) of limestone is present in restricted localities where further buildups of detrital, reefal, and bank limestones occur.

The landward extent of the prograded mudstones that overstepped the lower Miocene limestone facies is shown on Figure 13. The position of landward pinch-out may mark an early middle Miocene regressive shoreline. The areal restriction of strata occupying the axial part of the basin suggests that sediments were deposited in a narrow trough between the shelf and the trench early in the history of the basin. This trough was probably a structural feature bounded on its seaward margin by an elevated trench-slope break.

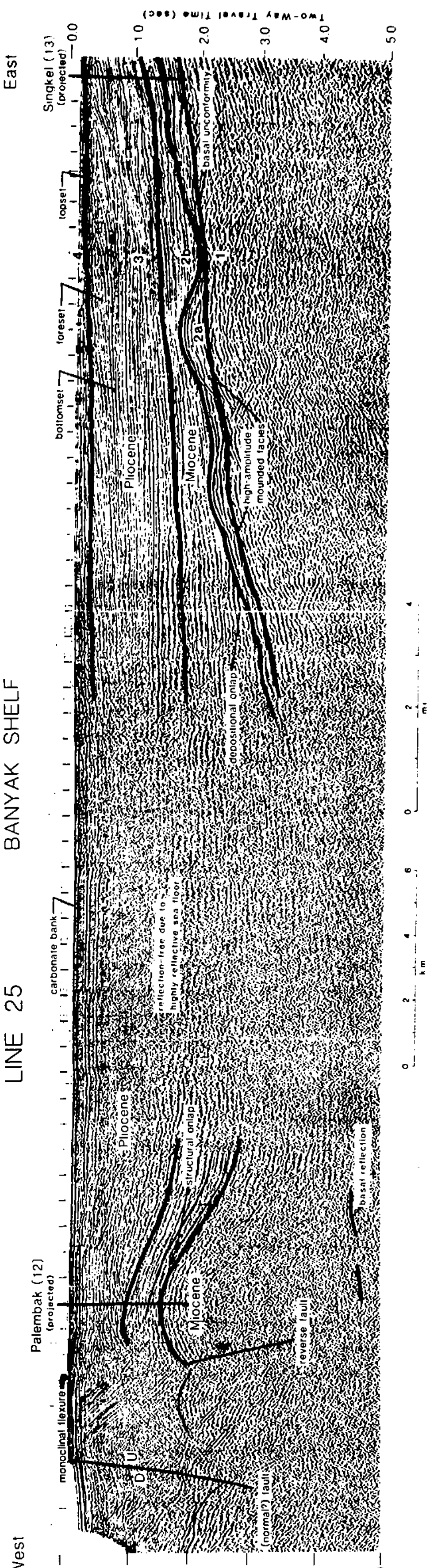

Figure 11—Multichannel seismic-reflection profile (line 25) across the Banyak Shelf. See Figure 2 for location of profile.

The seismic facies map of Tertiary unit 3 shows the distribution of upper Miocene through Pliocene sedimentary strata (Figure 14). Sedimentation rates were high and large volumes of terrigenous material derived from Sumatra were deposited in deltaic systems on the shelf, while turbidites were being ponded in the deep basin behind the outer-arc ridge. Stratigraphic relationships suggest that sediments initially prograded across the central Sumatra shelf and quickly filled the shelf to base level. Thereafter, progradation occurred along the entire length of the shelf, reflecting a reorganization of coastal drainages caused by late Tertiary activity along the Sumatra fault zone.

The deltaic deposits thin by depositional downlap toward the center of the basin. Along the western margin of the basin, slope sediments consist of tilted basin strata and slumps. A small delta was built basinward along the southeast coast of Nias, probably in response to uplift and erosion of the outer-arc ridge in latest Pliocene time.

CORRELATION OF FOREARC STRATIGRAPHY WITH REGIONAL STRATIGRAPHY AND GLOBAL SEA LEVEL

The correlation of forearc stratigraphy with regional stratigraphy and the Cenozoic sea level cycle chart of Vail et al (1977) allows us to integrate the tectonic history of the arc with the history of sedimentation and subduction, and to distinguish between orogenic and eustatic cycles of erosion and deposition. The regional correlation diagram (Figure 15) shows that an erosional hiatus separates Paleogene and older metamorphic basement rocks from a relatively continuous sequence of Neogene shelf deposits, indicating that a regional episode of tectonism occurred prior to subsidence and sedimentation. This episode of tectonism may correspond to a major change in relative plate motions approximately 44 Ma. At this time, the direction of spreading of the northeast Indian Ocean changed from north-south to northeast-southwest (Curray and Moore, 1974; Sclater and Fisher, 1974; Johnson et al, 1976), which increased the component of convergence along the western margin of Sumatra leading to deformation and uplift (Karig et al, 1980).

Throughout Sumatra, the Oligocene was a period of erosion or deposition in restricted marine and nonmarine environments (Koesoemadinata, 1969; Adinegoro and Hartoyo, 1975; Kamili et al, 1977). This interval coincides with a global lowering of sea level in the late Oligocene (Vail et al, 1977; Pitman, 1978). Upper Oligocene strata grade upward from coarse, nonmarine clastics at the base through nearshore sandstones and restricted shales (Figure 15). Restricted marine deposits include euxinic brown shales (Bampo Formation) of late Oligocene age (Graves and Weegar, 1973; Kamili and Naim, 1973).

The Miocene is widely represented by calcareous shales and reef limestones deposited in an open marine environment (Graves and Weegar, 1973; Kamili and Naim, 1973; de Coster, 1974; Mertosono and Nayoan, 1975). The depositional cycles observed correlate well with a global rising of sea level (Figure 15). Onshore basins also were significant depocenters during this rise of sea level.

In the late Miocene, the forearc basin remained marine, but the back-arc basins were filled with a fluvial-deltaic

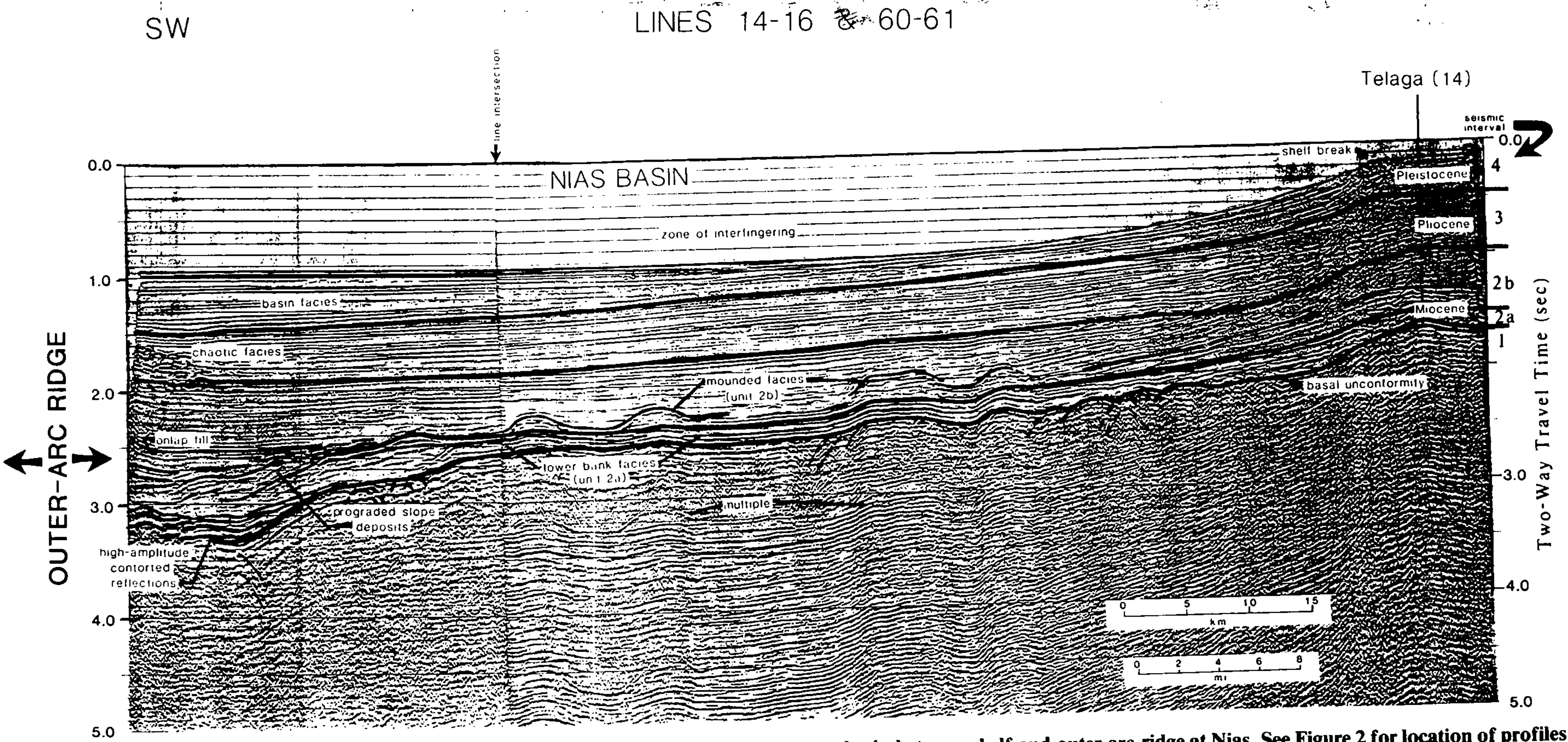

Figure 12—S.I.O. multichannel seismic-reflection profiles (lines 14-16 and 60-61) across forearc basin between shelf and outer-arc ridge at Nias. See Figure 2 for location of profiles.

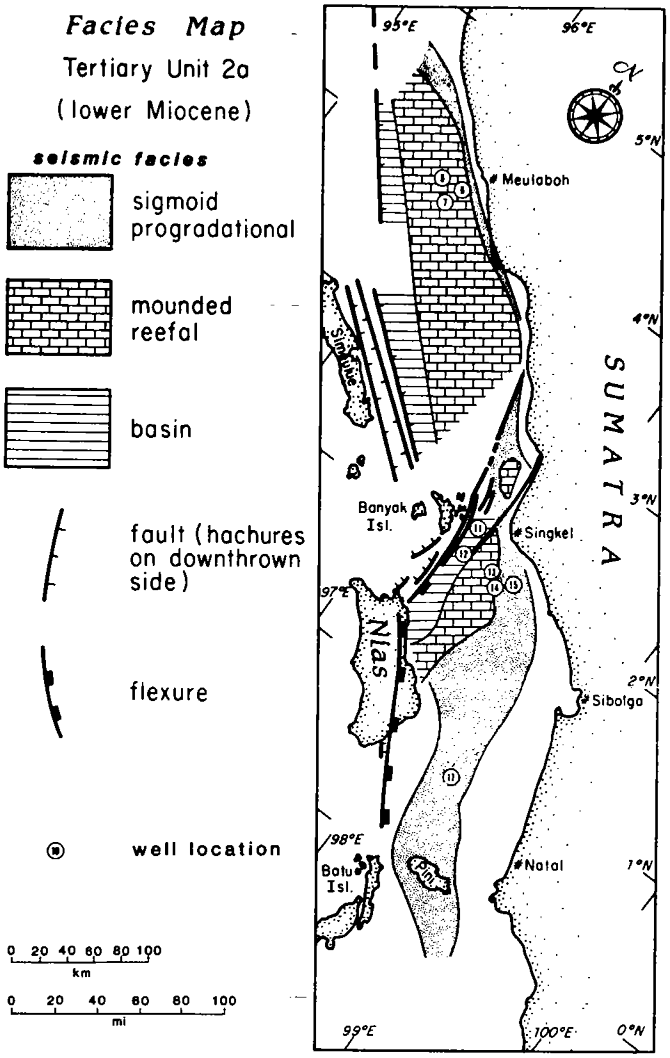

Figure 13—Facies map of Tertiary unit 2a, lower Miocene.

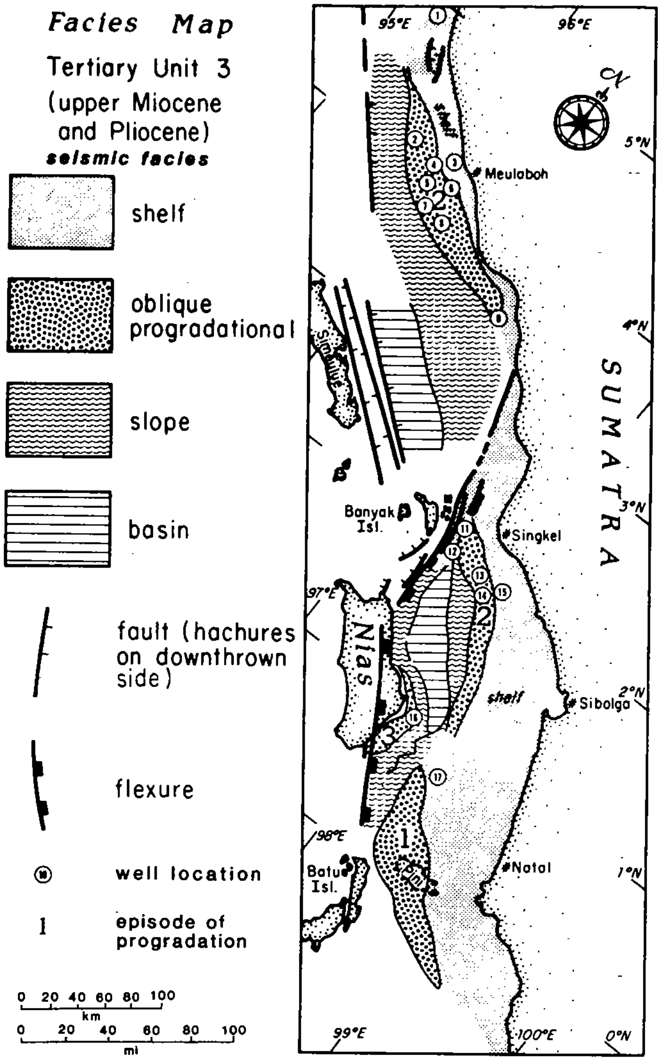

Figure 14—Facies map of Tertiary unit 3, upper Miocene and Pliocene.

sand complex, partially derived from Malaysia (Mertosono and Nayoan, 1975). This progradational cycle of sedimentation correlates with a lowering of sea level, which may be partly responsible for the hiatus in sedimentation in basins along the western flanks of the Barisan Ranges (Figure 15). Patch reefs of late Miocene and early Pliocene age developed on the outer continental shelf where siliceous detrital sedimentation rates were relatively low.

By the Pliocene, all of the basins were receiving carbonaceous sand, silt, and clay derived from the eroding arc terrane. The change from carbonate to terrigenous deposition is largely due to the influx of clastics from the uplifted core of Sumatra. A thin cover of sands and gravels of Pleistocene age reflects extensive reworking of shallow-water deposits due to rapid sea level fluctuations during the Quaternary. Carbonate platforms are presently forming on shallow shelfal areas offshore.

EVOLUTIONARY MODEL OF NORTH SUMATRA ARC-TRENCH SYSTEM

By integrating the stratigraphic framework of the forearc basin with regional geologic and geophysical studies, we have formulated a model for the evolutionary sequence of events leading to the present configuration of the forearc basin (Figure 16). This reconstruction shows how regional tectonics and eustatic sea level fluctuations influence depositional systems in the forearc region. The tectonic evolution of the arc massif and the outer-arc ridge is adapted from the work of Cameron et al (1980) and Karig et al (1979, 1980). The overall tectonic setting is similar to that of a "ridged" or "constructed" forearc as described by Dickinson and Seely (1979).

Approximately 30 Ma, the shelf was exposed to subaerial erosion owing to a eustatic lowstand of sea level (Figure 16A). The trench was near the shelf edge (Karig et al, 1979), creating a "shelved" forearc (Dickinson and Seely, 1979). Forearc morphology was probably characterized by a broad shelf and a steep, inner trench slope. An elevated trench-slope break may have served as a restricting sill for offshore basin deposits identified on seismic reflection profiles. Data from the Pandjang well indicate that the area of emergence and erosion of the shelf extended out to the paleoshelf edge. This strongly suggests that sea level occupied a position below the shelf edge, cor-

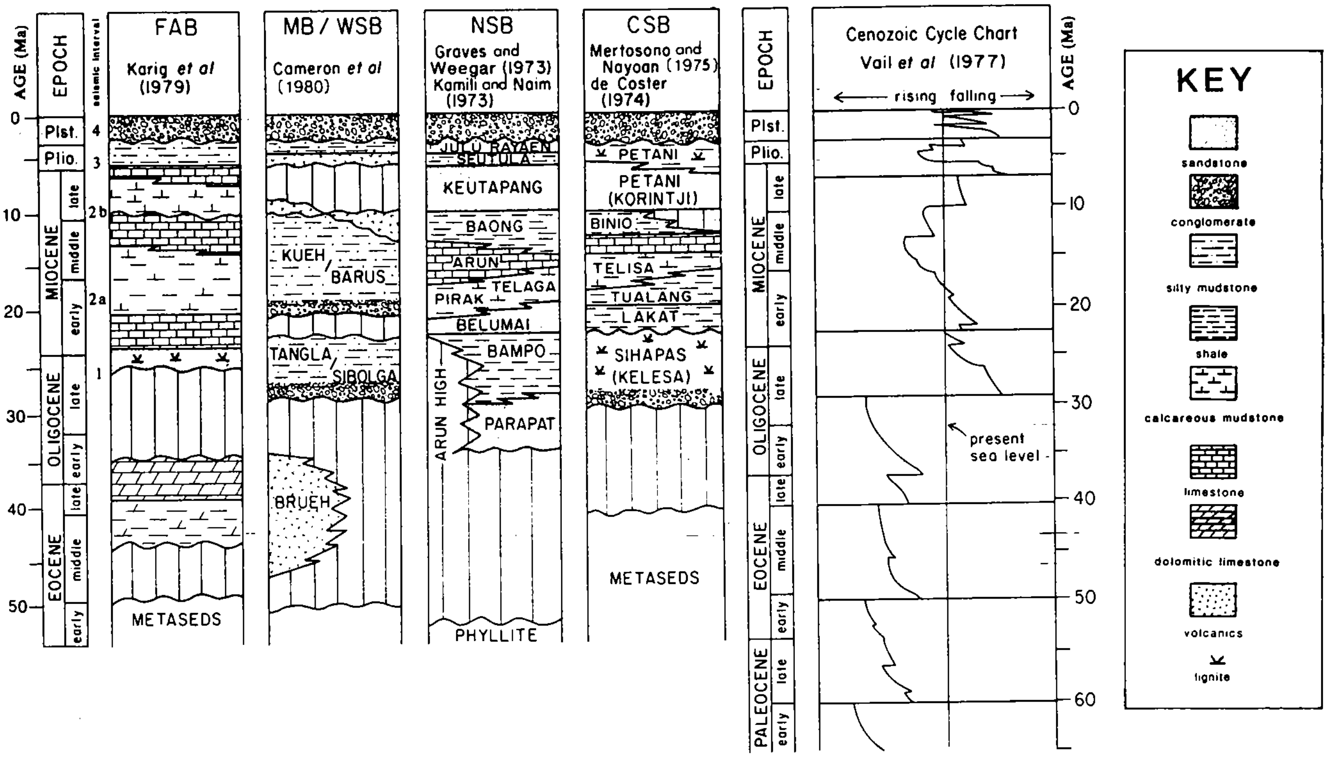

Figure 15—Correlation of forearc stratigraphy with regional stratigraphy and Cenozoic sea level cycle chart of Vail et al (1977). Schematic columnar sections were summarized from literature for several Tertiary basins flanking the arc: FAB = forearc basin, MB/WSB = Meulaboh basin/West Sumatra basin, NSB = North Sumatra basin, CSB = Central Sumatra basin. Lithologic key same as Figure 4.

responding to a major eustatic fall in the late Oligocene (Vail et al, 1977; Pitman, 1978). Karig et al (1980) suggest that the shelf unconformity is primarily due to regional uplift, but the evidence for this is unclear. Seismic reflection data document deformation of older sedimentary strata prior to cutting of the unconformity, but the exact timing and amount of uplift are poorly constrained.

Reflection profiles and well data attest to a general subsidence of the western margin of Sumatra since the early Miocene (Karig et al, 1980). Magnetic anomaly patterns in the Indian Ocean suggest that this interval coincides with a period of steady subduction (Liu, 1983). A widespread marine transgression at this time accompanied Neogene subsidence and created a marine environment of deposition in both forearc and back-arc basins (Figure 16B). This transgressive event corresponds to an overall rise of eustatic sea level approximately 15-20 Ma (Vail et al, 1977). Marine sediments overlapped the regional shelf unconformity in a landward direction, and limestone reefs were deposited on topographic highs and offshore in areas of relatively low sedimentation rates. Estimates of coastal onlap indicate a net transgression of the shoreline of nearly 90 km (56 mi).

The forearc basin continued to widen throughout the Miocene and Pliocene, and the bathymetric trench migrated westward relative to the shelf edge (Figure 16C). The outer-arc ridge was near sea level, forming a structural high that served as a dam and ponded sediment in a deep offshore basin. At this time, the configuration of the west Sumatra margin probably resembled that of a "narrow-ridged" forearc (Dickinson and Seely, 1979). Approximately 10 Ma, movement along the Geumpang thrust initiated uplift of the Barisan Ranges (Cameron et al, 1980). This episode of late Tertiary tectonism corresponds in time to an increase in the rate of subduction along the trench from 5 to 7 cm/year (2 to 2.8 in./year), as indicated by marine magnetic anomaly studies of the Indian Ocean (Liu, 1983). Erosion of the uplifted arc terrane supplied clastic sediment to the forearc region. Sedimentation on the shelf was characterized by prograding clinoforms. Thick sequences of turbidites that bypassed the shelf were deposited in the deep offshore basin behind the rising subduction complex.

By earliest Pleistocene time, strike-slip faulting was prevalent throughout Sumatra, the volcanic arc was displaced eastward relative to the paleoshelf edge, and the outer-arc ridge was uplifted above sea level (Figure 16D). Renewed uplift and erosion of the Barisan Ranges supplied large volumes of terrigenous material to the forearc basin, where it was deposited in deltaic systems on the shelf. Turbidites were delivered to the basin along structural lineaments that transect the forearc region. Along the seaward margin of the forearc, basin strata were uplifted and tilted landward to form a large monoclinal flexure while large growth faults developed along the crest of the outer-arc ridge in response to rapid uplift. The present configuration of the basin can be compared to that of a "broad-ridged" forearc (Dickinson and Seely, 1979).

CONCLUSIONS

A detailed seismic-stratigraphic analysis of the west Sumatra forearc basin reveals that eustatic sea level and

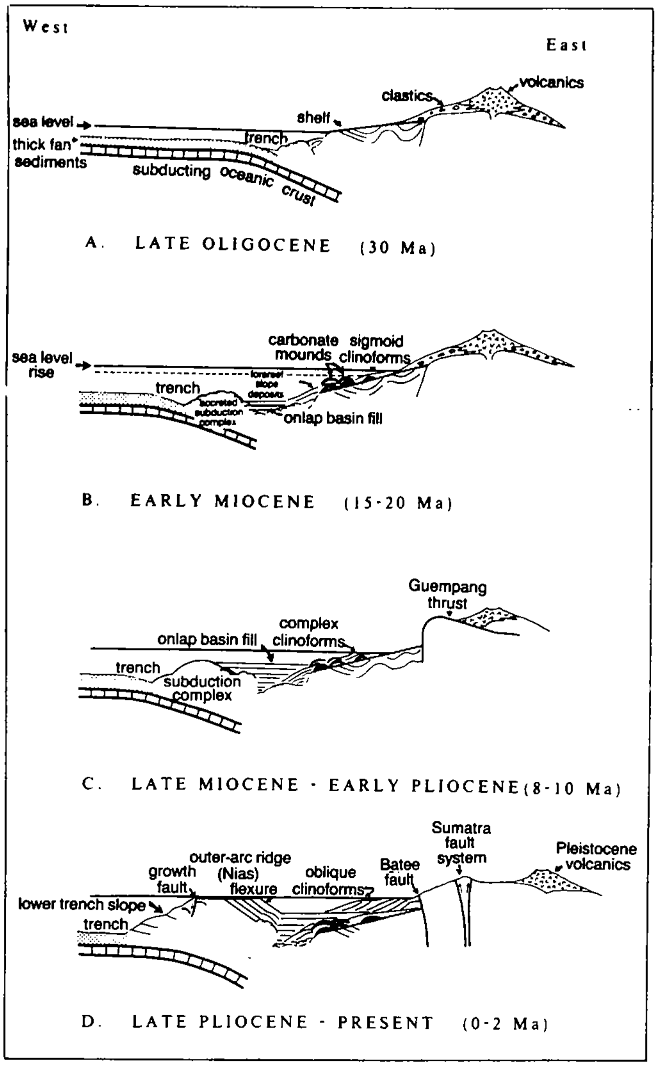

Figure 16—Schematic cross sections of north Sumatra depicting Cenozoic evolution of arc-trench system. Geology of north Sumatra modified from Cameron et al (1980). Not to scale.

regional tectonics are important controls on depositional systems in forearc basins. A major fall of sea level approximately 29 Ma exposed the continental shelf of west Sumatra to subaerial erosion. This event produced a regional unconformity observed in numerous basins throughout Indonesia and the western Pacific (Wood, 1980). A widespread transgression related to a eustatic sea level rise followed in the Miocene, and marine deposits overlapped the regional shelf unconformity. An abrupt change from carbonate deposition to clastic sedimentation in the Pliocene reflects an important change in provenance. Uplift and erosion of the arc massif, due to an episode of subduction-related tectonism, increased the supply of arc-derived clastics to the forearc region and produced a major depositional regression.

Significant long-term changes in the configuration of the west Sumatra forearc have occurred since the Oligocene. The evolutionary model put forth in this paper suggests that the west Sumatra margin evolved from a "shelved" forearc, with a steep inner trench slope, into a "ridged" forearc, with a well-developed outer-arc ridge. This evolutionary trend is typical of active continental margins characterized by large-scale lateral accretion and formation of a prominent subduction complex, e.g., the forearc basin south of Java and the Cretaceous Great Valley Sequence of California (Ingersoll, 1978; Dickinson and Seely, 1979).

New exploration ideas result from the detailed stratigraphic study of this basin. Restricted basinal deposits of Oligocene age are potential source rocks in this area. Any hydrocarbons produced there would tend to migrate updip into carbonate banks and prograded slope deposits that developed along the shelf edge in the Miocene. These relatively porous facies units were subsequently buried and potentially sealed by fine-grained calcareous shales and turbidites deposited in relatively deep water as the forearc region subsided.

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