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9. BIOSTRATIGRAPHY AND GEOLOGICAL EVOLUTION OF THE SULU SEA AND SURROUNDING AREA[1]

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ABSTRACT

Biostratigraphic and lithologic data, obtained from Leg 124 in the Sulu Sea, are placed in the geologic context of the surrounding area: Palawan, north Borneo, and Zamboanga Peninsula. This comparison shows a consistent chronostratigraphic scenario for the evolution of the region throughout the Cenozoic: (a) the probable middle Eocene age for the emplacement of the ophiolites in Palawan and Sabah (north Borneo) and their remobilization during the early middle Miocene tectonic event, (b) the opening of the South China Sea since late Oligocene time linked with the subduction of the proto China Sea and initiation of the Cagayan volcanic arc, (c) the opening of the Sulu Sea at least since early Miocene time, (d) cessation of the volcanic arc activity in the Sulu Sea at early middle Miocene time (Zone NN5) as it is observed in Palawan, Sabah, and the Zamboanga Peninsula. This might be related to the collision of the Cagayan volcanic arc with the drifted Chinese continental margin. This event coincides with the end of spreading in the South China Sea; (e) subduction of the oceanic crust of the southeast Sulu Sea Basin to the south probably since latest Miocene time, and initiation of the Sulu volcanic arc.

INTRODUCTION

The Sulu Sea is bordered in the northwest by Palawan Island, to the south and southwest by Sabah, to the southeast by the Sulu Ridge and the Zamboanga Peninsula, and to the northeast by the Philippine Mobile Belt (Fig. 1).

Several interpretations have been proposed for the origin and age of the Sulu Sea: (a) entrapment of a piece of Eocene oceanic crust of the Sulu-Celebes-Banda Indian Ocean Basin (Lee and McCabe, 1986), (b) a back-arc origin related to northward subduction of the Celebes Sea below the Sulu volcanic arc in early Tertiary or post early middle Miocene time (Hamilton, 1979; Rangin, 1989), (c) a back-arc origin with northward drift of the Cagayan volcanic arc related to the opening of the South China Sea and southward subduction of the "Crocker Basin" below the Palawan accretionary ridge during late Oligocene to early middle Miocene time (Holloway, 1982; Letouzey et al., 1988). The age of cessation of the volcanism has been correlated with collision of this volcanic arc with the drifted Chinese continental margin (north Palawan-Reed Bank block). It corresponds to the end of spreading in the South China Sea during early middle Miocene time.

Biostratigraphic and paleoenvironmental data from the surrounding area will be compared with the results obtained from the Sulu Sea during Leg 124. The general geologic setting of this area is represented in four sections (Figs. 1 and 2).

Palawan

Palawan can be subdivided into two distinct terranes representing north Palawan and central and south Palawan. The north-south trending Ulugan fault has been considered longtime as boundary. However, according to Letouzey et al. (1988), this boundary lies further to the north. The main difference is the continental character of north Palawan where the series consists of upper Paleozoic to lower Mesozoic rocks. They are part of the Chinese continental margin drifted from mainland China during late Oligocene to early middle Miocene time (Taylor and Hayes, 1983; Holloway, 1982). Detailed studies of north Palawan have been published by Hashimoto and Sato (1973) and Fontaine (1979). Some additional results were given more recently by Wolfart et al. (1986). Results from offshore northwest Palawan were presented by Salvidar-Sali et al. (1981) and Kudrass et al. (1986). However, this part of Palawan will not be discussed in more detail. The stratigraphy of this area is summarized in Table 1.

Central and South Palawan

Central and south Palawan, with a general southwest-northeast trend, is considered to be an emerged imbricated thrust belt created by the early middle Miocene collision between the Cagayan volcanic arc and the drifted Chinese continental margin (Holloway, 1982; Taylor and Hayes, 1983; Letouzey et al., 1988). This accretionary wedge might have originated from the northwest Sulu Sea Basin thrusted onto the Dangerous Grounds-Reed Bank platform (Fig. 2). To the southwest, Balabac Island represents the prolongation of the accretionary prism into Sabah.

Mesozoic

South of Ulugan Bay large parts of Palawan and Balabac Islands are built up by the ophiolitic complex of oceanic crust. It is composed of peridotites, gabbros, metagabbros, amphibolites, pillow basalts and greenshists. In the southern part of the Ulugan Bay, Segama Point (Fig. 3) pillow basalts and their overlying radiolarites are exposed. Peridotites are cropping out as large masses at the northern end of the Ulugan Bay (Mount Bloomfield) along the coast southwest of the bay and in central and southeastern Palawan. They were encountered in the wells offshore northeast Palawan, and they are also exposed on Paly Island east of north Palawan. That means that the accretionary wedge extends further to the northeast into the northwest Sulu Sea Basin, and that it is not bounded by the Ulugan strike slip fault (Letouzey et al., 1988). Small imbricated slices of ophiolites and pillow basalt were found south of St. Paul's Bay and Ulugan Bay as well as in the region southwest of Quezon City (south Palawan) and on Balabac Island. Calcareous red clay associated with pillow lavas in

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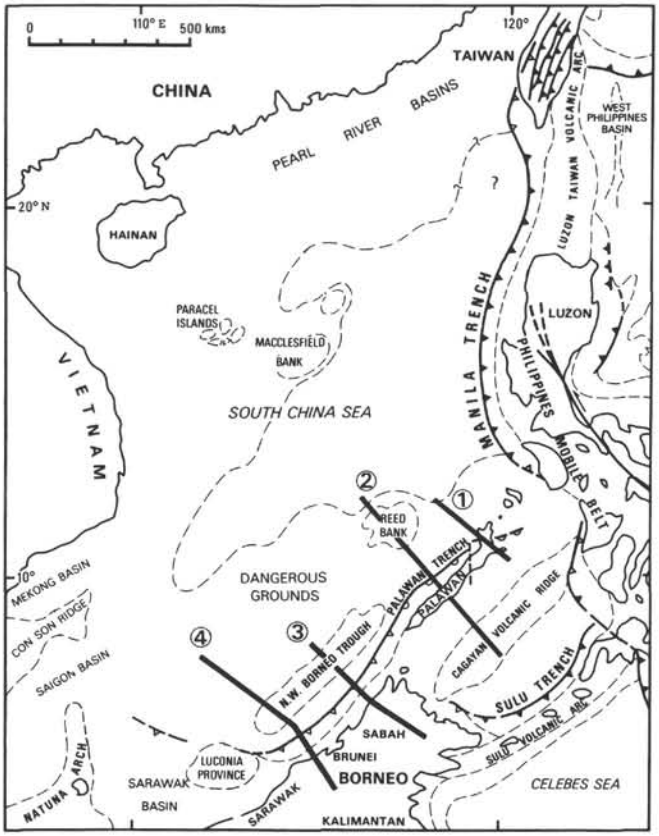

Figure 1. Map of the Sulu Sea and the surrounding area, indicating the location of the geological sections given in Figure 2.

south Palawan west of Brookspoint and from Balabac Island yielded common poorly preserved nannoplankton. Only resistant species of the genus *Watznaueria* were preserved that has a very long stratigraphic range. However, the absence of resistant late Cretaceous forms as well as the abundance of *Watznaueria* make an early Cretaceous age most likely. The same age was obtained by radiolarians from Sabah (Leong, 1977; Jasin et al., 1985; Rangin et al., 1990), where radiolarites associated with ophiolites occur in the same tectonic context. These ophiolites were imbricated most probably during middle Eocene time linked with the change in motion of the Pacific Plate at about 44–42 Ma (Letouzey et al., 1988). This is confirmed by the 40 m.y. K/Ar ages of the tectometamorphic parts of the ophiolites (Raschka et al., 1985).

A thick clastic series of turbidites with few conglomerates and intercalated red tuffaceous layers is widely exposed in central and northern Palawan. They are typical slope deposits with numerous slumps, debris flows, and dissociated sandstone layers. At the Underground River a middle-late Jurassic limestone block was found within this series (H. Fontaine, pers. comm., 1982). Plant fragments are common in several layers. The sediments are locally sightly metamorphosed, especially in the area of Barton and Roxas (Fig. 3). This series was dated at Ulugan Bay and in the Aborlan River (central Palawan) by nannofossils as the late Campanian-early Maestrichtian Quadratum trifidum Zone (Letouzey et al., 1988). The same age was obtained by Wolfart et al. (1986) from the area at Carugay near St. Paul's Bay (Fig. 3).

Nannoplankton are rare and restricted to some layers. The assemblages consist of the following species: *Quadratum trifidum, Ceratolithoides acutus, Watznaueria barnesae, Micula staurophora, Broinsonia parca, Cribrosphaerella ehrenbergii, Arkhangelskiella cymbiformis,* and *Eiffellithus turriseiffeli*. A late Cretaceous age was also obtained using palynomorphs from offshore wells east off north Palawan. This sequence is known from central and northern Palawan but not from the south (Table 1).

Tertiary

Paleogene deposits are present from south and central Palawan, Balabac Island, and can be followed to north Borneo (Sabah). They are represented by the strongly folded "Crocker formation" dated by nannoplankton as late Paleocene to late Oligocene in age. Previous age determinations were based mainly on arenaceous foraminifers or on larger foraminifers from included limestone lenses which, however, do not allow precise datings. It seems that the lower Paleocene and part of the middle Eocene are represented by hiatuses (Tab. 1), but it is difficult to confirm this assumption using the rare data obtained from the entire sequence. No middle Eocene was determined with exception of the uppermost part (Zone NP17). Most of these slope deposits are barren of nannoplankton probably due to the high input of detrital material. They consist of clay- and siltstone with bedded or massive slumps of quartz sandstone. Typical turbidite features are common. Plant fragments are more or less frequent throughout the sequence.

The upper Paleocene (nannoplankton Zones NP8 and NP9) has been determined in only one sample taken southwest of Quezon City (south Palawan) including following species: *Sphenolithus anarrhopus, Fasciculithus tympaniformis, Toweius craticulus, Coccolithus cavus, Ericsonia subpertusa, Cyclococcolithus robustus,* and *Chiasmolithus bidens*. Sediments of the same age were dredged from the Dangerous Grounds by Kudrass et al. (1986). The abundance of nannoplankton indicates deposition of these sediments in an open marine outer shelf to slope environment. Reworked nannoplankton species of Zone NP9 were found in middle to late Eocene sediments. Other samples taken in the area southwest of Quezon City yielded either poor assemblages of the lower Eocene (Zone NP12) with *Marthasterites tribrachiatus, Discoasteroides kuepperi,* and *Discoaster barbadiensis*, or of the upper middle Eocene (Zone NP17) characterized by the occurrence of *Sphenolithus obtusus, Sphenolithus moriformis, Cyclococcolithus formosus, Coccolithus eopelagicus, Reticulofenestra umbilica, Sphenolithus radians, Cribrocentrum reticulatum, Discoaster barbadiensis, Discoaster tani nodifer,* and *Discoaster saipanensis*. These species occur generally together with reworked nannoplankton from the upper Cretaceous, upper Paleocene to lower Eocene (uplift and erosion after the middle Eocene tectonic event).

The upper Eocene (Zone NP18) was recognized in one sample including the same assemblage plus Chiasmolithus oamaruensis and *Coronolithus germanicus*.

Middle to late Oligocene sediments (Zones NP24-NP25) were not found in Palawan with exception of the St. Paul limestone occurring as slices within the accretionary prism. These limestones are part of the large carbonate platform encountered in wells offshore northwest Palawan (Nido limestone) and dredged from the Dangerous Grounds (Kudrass et al., 1986). This platform plunges southward below the allochthonous wedge (Hinz and Schlüter, 1983; Fricaud, 1984).

Few pebbles of late Oligocene marls (NP24-NP25) are included in the lower Miocene sandstone exposed along the southwest coast of south Palawan. Those pebbles were also observed in west Balabac (Taripit Point) where they occur in shelfal limestones rich in larger foraminifers (Lepidocyclines). These hemipelagic Oligocene sediments are rich in nanno-

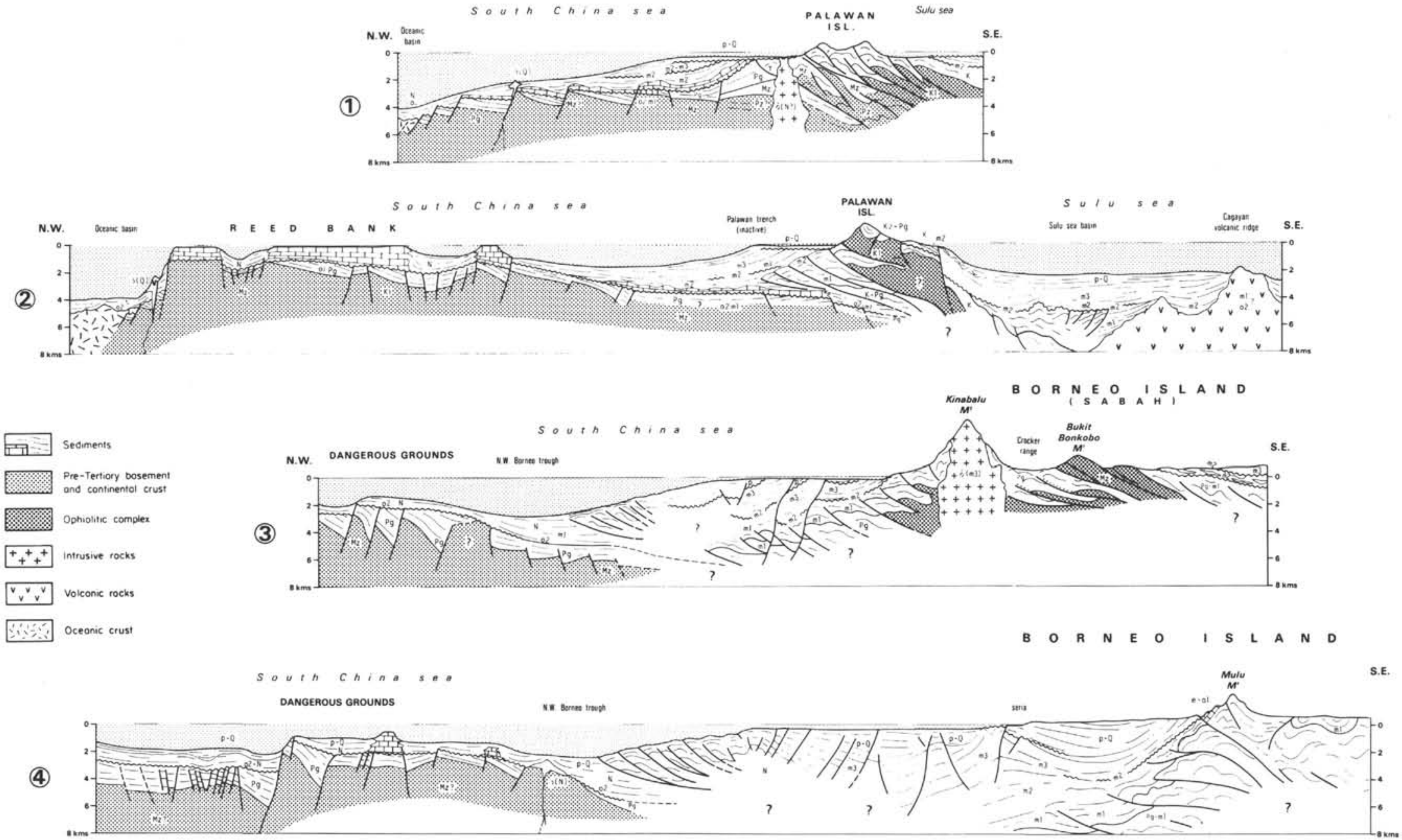

Figure 2. Geological sections through Reed Bank, Dangerous Grounds, Palawan, Sulu Sea, and north Borneo (Letouzey et al., 1988).

Table 1. Stratigraphy of Palawan.

AGE	REED BANK	OFFSHORE NW PALAWAN	NORTH PALAWAN	ULUGAN BAY CENTRAL PALAWAN	SOUTH PALAWAN BALABAC
PLIOCENE		limestone and calcarenite (shallow water)			marl and limestone
LATE MIOCENE		clay–and siltstone calcareous sandstone (bathyal)			
MIDDLE MIOCENE					turbiditic silt–and sandstones tuffaceous marls and claystone
EARLY MIOCENE	sandstone, siltstone conglomerates with metamorphics, chert, volcanics (shallow water)	limestone (shelf)		limestone (shallow water)	calcareous silt–and sandstone (shallow water)
LATE OLIGOCENE	limestone,				
EARLY OLIGOCENE	carbonate turbidites in depressions sandstone, siltstone				
EOCENE		clastics and limestone (shallow water)	limestone (shelf)	turbidites, silt–and sandstone (slope deposits)	
LATE PALEOCENE	turbiditic sand–and siltstone claystone				turbidites, silt–and sandstone (slope deposits)
EARLY PALEOCENE	limestone (shelf)				
LATE CRETACEOUS				turbidites, tuffaceous claystones slightly metamorphosed (slope)	
EARLY CRETACEOUS	sandstone, conglomerates, tuff siltstone, claystone (shallow water)	tuffaceous shales, silt–and sandstone limestone, volcanic' rocks		radiolarites pillow basalt, ultramafics	radiolarites pillow basalt, ultramafics
LATE-MIDDLE JURASSIC			silt–and sandstone (slope)		
EARLY JURASSIC					
LATE TRIASSIC	sand–and siltstone plant fragments (shallow water)		limestone, shales, sandstone (shallow water)		
MIDDLE TRIASSIC			chert, shales (bathyal)		
EARLY TRIASSIC					
LATE PERMIAN			limestone (shallow water)		

plankton with following assemblages: *Dictyococcites dictyodus, Sphenolithus ciperoensis, Cyclicargolithus abisectus, Cyclicargolithus floridanus, Discoaster deflandrei,* and *Coccolithus pelagicus*. Middle to late Oligocene red marls, including common displaced larger foraminifers, were also observed in a slump at Martinez Point (Balabac Island).

Neogene

The Neogene is well known from offshore wells. Onshore it is exposed only in south Palawan and Balabac Island, whereas it is unknown from onshore central and north Palawan indicating the strong uplift of the region since at least middle Miocene time (Fricaud, 1984).

Calcareous quartz sandstone exposed along the west coast of south Palawan are probably of early Miocene age. Locally they contain microconglomerates alternating with siltstone sometimes rich in plant fragments. Occasionally displaced larger foraminifers are present.

Early middle Miocene tuffaceous marl with some boulders of andesite is exposed along the Aboabo-Quezon road. It contains the typical assemblage of Zone NN5 with: *Cyclicargolithus abisectus, Cyclicargolithus floridans, Sphenolithus abies, Sphenolithus heteromorphus, Helicosphaera carteri, Discolithina japonica, Discoaster deflandrei,* and *Reticulofenestra pseudoumbilica*. These sediments are part of the Cagayan volcanic arc series thrusted onto the accretionary wedge.

A hiatus in south Palawan representing a part of the middle and upper Miocene might be related to the second tectonic event within the upper Miocene (uppermost part of Zone NN9 to Zone NN10), which is also recognized on seismic profiles (Fricaud, 1984). This event is well dated in other parts of the Philippines (Müller and von Daniels, 1981).

Tectonized early middle Miocene (Zone NN5) or older sediments are disconformably overlain by gently tilted reefal limestones (Quezon limestone) and marl of latest Miocene-early Pliocene age. They are exposed in the area of Quezon City and at the north coast of Balabac Island. The limestones occur often as small carbonate buildups interfingering with the marls. The nannoplankton assemblages within the marls are of low diversity with abundant *Sphenolithus abies* and few *Coccolithus pelagicus, Helicosphaera carteri, Cyclococcolithus leptoporus, Cyclococcolithus rotula,* and *Discoaster* sp., probably due to deposition in a very shallow environment.

Figure 3. Map of Palawan.

Table 2. Stratigraphy of Sabah (north Borneo).

		WEST SABAH	NORTH SABAH	CENTRAL SABAH	DENT PENINSULA	SEMPORNA PENINSULA
Quaternary	NN21–19	conglomerates siltstone				
Upper Pliocene	NN18–16					basalt
Lower Pliocene	NN15–12			clay, sandstone Sandakan formation		
Upper Miocene	NN11	Granodiorite Kota Kinabalu				?
	NN10			?		
	NN9				siltstone, sandstone	
Middle Miocenen	NN8			sandstone, siltstone	Sebahat formation	sandstone, siltstone
	NN7			Tanjong formation	conglomerates, volcaniclastics	Umas–Umas formation
	NN6		sandstone, conglomerates		Libong Tunku formation	
	NN5		shale with limestone breccias		tuffs, tuffaceous marls	tuffaceous marls
Lower Miocene	NN4–1				limestone andesite Kalumpang formation	andesite Kalumpang formation
Upper Oligocene	NP25–23	turbidites	marl, limestone sandstone Kudat formation	sandstone, siltstone Labang formation		
Lower Oligocene	NP22–21	sand–and siltstone ?	?			
Upper Eocene	NP20–18	West and East Crocker formation	sandstone, siltstone			
Middle Eocene	NP17–14	?	Crocker formation			
Lower Eocene		shale, siltstone Trusmadi formation	?			
Paleocene						
Upper Cretaceous						limestone •
Lower Cretaceous			chert, utramafics•	chert, ultramafics•	chert, ultramafics•	chert, ultramafics•

• blocks within the melange

Sabah (North Borneo)

Sabah is bordered to the northeast by the Sulu Sea and to the southeast by the Celebes Sea with a late middle Eocene oceanic crust (about 44–42 m.y., Rangin et al., 1989). The Sulu volcanic arc separating these two marginal basins is referred to the subduction of the Sulu Sea under the Celebes Sea Plate since latest Miocene time (Fig. 1). A detailed mapping of Sabah was done by the Geological Survey of Borneo. Recently the data were synthesized on a 1:5000,000-scale map (Yin Ee Heng, 1985). The biostratigraphic and lithologic units are summarized in Table 2.

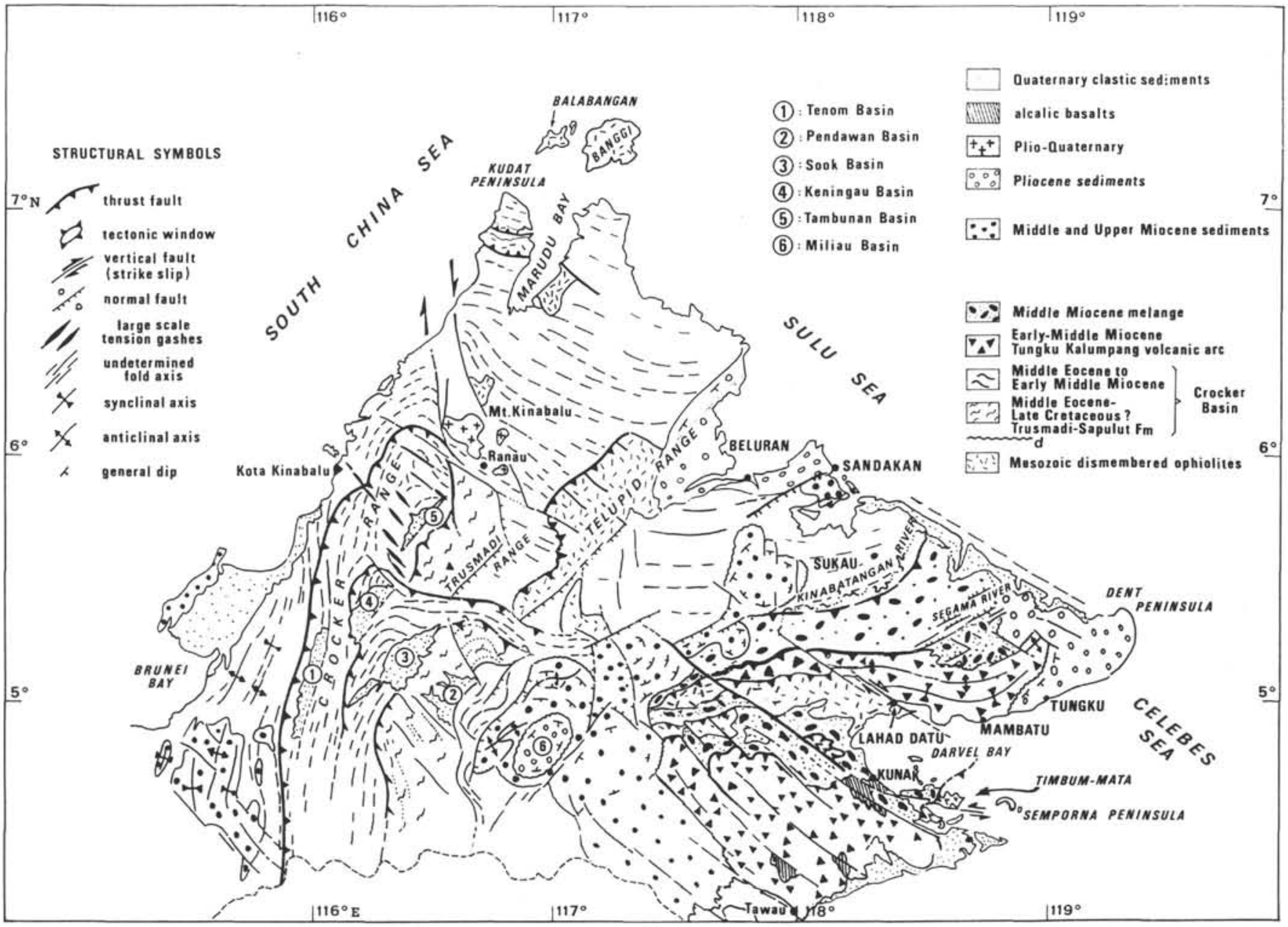

Figure 4. Geologic map of Sabah (Rangin et al., 1990).

West and Central Sabah

The Rajang-Crocker Range (Fig. 4), the main topographic feature in north Borneo, is considered to be an enormous accretionary prism related to the subduction of the proto China Sea (Taylor and Hayes, 1983). The prism extends northward into Banggii Island and south-central Palawan, where the series was dated late Paleocene to late Oligocene in age.

In Sabah only very few samples from the Crocker formation could be dated as late middle Eocene (Zone NP17) to late Oligocene (Zone NP25). The West Crocker formation consists of regularly alternating sandstone and siltstone. The thickness of the beds varies from a few centimeters to one meter.Slumps and channel infillings are common. This unit is strongly isoclinal folded. The East Crocker formation is represented by sandstones that react to deformation by broad folds and ramps. The Crocker formation of Sabah, with thick turbidites, is comparable with the time-equivalent sediments on Banggii Island and south Palawan. Calcareous microfossils and nannofossils are extremely rare and restricted to several layers. As in south Palawan, reworked nannofossils from upper Cretaceous to lower Eocene and microconglomerates with pebbles of chert and ultramafics have been observed since late middle Eocene time (Zone NP17), indicating a period of uplift and erosion following the middle Eocene tectonic event.

The Trusmadi formation is represented by dark siltstone and shale with minor sandstone. This series is strongly folded and occurs locally as "brocken formation." The sediments are slightly metamorphosed; they are assumed to be of Eocene age.

In the entire area, the carbonate content is increasing in the middle to late Oligocene sediments. At this time shallow-water limestones and carbonate buildups have a wide distribution in the Philippines, Borneo, and the Dangerous Grounds-Reed Bank areas. On Banggii Island and Kudat Peninsula (north Sabah) the Oligocene series is represented by marls with large slumps and intercalations of limestone breccias displaced from the shelf. Sediments of middle-late Oligocene age (Zones NP24-NP25) are exposed near Kota Kinabalu, in the northern part of the Kudat Peninsula, in the islands as well as in the Sapalut River, and the central part of Sabah. Rich nannoplankton assemblages are present in the marls with *Cyclicargolithus abisectus, Dictyococcites dictyodus, Sphenolithus distentus, Sphenolithus predistentus, and Sphenolithus ciperoensis*. A time-equivalent shallower facies (Labang formation) is exposed in central and eastern Sabah north of the Kinabatangan River and south of Sandakan. The sediments consist of bedded sandstone with thin intercalations of siltstone rich in plant fragments, coal lenses, and amber. At Batu Puteh, limestones are interfingering with clastic deposits of late Oligocene age (Zone NP25). Along the road to Sukau a series of silt- and sandstone shows locally transition to calcareous mudstone rich in branching corals and larger foraminifers. There are also carbonate buildups with head corals. A similar facies of the same age occurs in the Beluran area as blocks. Equivalent limestones were sampled along the Sapalut River in western Sabah.

No lower Miocene series was identified, suggesting that there is a gap representing this time interval. This hiatus (Zone NNl to NN2) exists in many areas of the Philippines and it might be explained by the low sea-level stand at this time (Vail and Hardenbol, 1979; Müller and von Daniels, 1981).

Early middle Miocene sediments (Zone NN5) were found in Kudat Peninsula and the northern islands (Zone NN6). In a limestone quarry near Kudat, strongly altered calcareous grit with upper Eocene to upper Oligocene larger foraminifers, algae, and echinoids are exposed. Included pebbles and thin stringers of marls are very rich in nannofossils of Zone NN5 with *Sphenolithus heteromorphus*. These sediments also contain abundant reworked Eocene-Oligocene species. In another outcrop near Kudat the sediments of Zone NN5 are represented by a gray turbiditic sequence of predominantly siltstone and sandstone layers. Limestone breccias are intercalated locally that consist of eroded Eocene-Oligocene platform limestones.

On Molleangan Basar Island, southwest of Banggii Island, thinly bedded calcareous sandstones with cross bedding and layers of trace fossils indicate a shallow-water environment. Nannofossils are few, with *Helicosphaera carteri, Helicosphaera perch-nielseniae, Discolithina multipora, Discoaster exilis*, and *Cyclicargolithus floridanus* typical for nannoplankton Zone NN6 of middle Miocene age. The sediments also contain fragments of ultramafic rocks and chert indicating erosion of ophiolites that have been abducted during the early middle Miocene deformation.

Postdating the early middle Miocene tectonic event, sediments were deposited in circular basins bordered by normal faults (Fig. 4). No precise age determinations were obtained from these sediments. North of the Kinabatangan River along the road to Sukau, a series of sandy siltstone and fine-grained sandstones is exposed (Tanjong formation). They contain, besides reworked Oligocene nannofossils, *Cyclococcolithus macintyrei, Helicosphaera carteri, Cyclococcolithus leptoporus, Sphenolithus abies*, and *Reticulofenestra pseudoumbilica* that indicate at least a middle Miocene to Pliocene age. They are overlain unconformably by brackish shallow-water sediments of red and gray claystone and sandstone of channel infillings (Sandakan formation). The sediments are rich in plant fragments. Comparable sediments occur unconformably above the volcanic arc series at Sandakan.

East Sabah

Volcanic arc series are widely exposed from the Segama River in the north to the Dent and Semporna Peninsulas in the south (Fig. 4). The northernmost isolated exposure of this series was found at Sandakan. It consists predominantly of tuffaceous claystone, tuffs, and agglomerates. Massive andesitic flows and breccias are widely distributed in the area of Tawau, but minor flows are also present at Sandakan. Absolute datings using the K/Ar method gave an age ranging from 16.7 ± 0.83 to 11.2 ± 0.55 Ma (Rangin et al., 1990). Ages obtained by the Geological Survey of Borneo range from 70.7 to 13.6 Ma with distinct maxima between 13.6 and 21.4 Ma and between 30.0 and 35.6 Ma. They are in good agreement with the biostratigraphic data that gave a late Oligocene (Zones NP24-NP25) to early middle Miocene (Zone NN5) age.

The volcanic arc series is associated with melanges that are considered to be at the base of nappes and thrust sheets. These melanges were described as Kuamat and Ayer formation (Collenette, 1965). They are characterized by an undated shaly carbonate-free matrix including blocks of different size and lithology as late Cretaceous limestones (Madai Baturong limestone), ophiolites, cherts, diorites, gabbros, pillow basalts, and metagabbros. The youngest blocks are tuffs from the volcanic arc series of early middle Miocene age. That means that the formation of these melanges is related to the early middle Miocene collision.

The ultramafic rocks and associated radiolarites that are part of the ophiolitic complex of an oceanic crust had been described as chert-spillite formation (Fitch, 1955; Kirk, 1962) and were considered to be the crystalline basement. They are of early Cretaceous age (Rangin et al., 1990).

The volcanic arc series is overlain by the tectonically undeformed Libong formation (Table 2). It is well exposed along the Ladad Datu-Tungku road. It consists of conglomerates with well-rounded boulders of andesite and dacite interbedded in a pyroclastic sequence. Recently this series was dated as middle Miocene (Zones N11-N12) by foraminifers (Jasin and Tahir 1987) corresponding to nannoplankton Zones NN6-NN7. This result confirms the pre-Zone NN6 age for the deformation.

The overlying Sebahat formation is represented by thick shales and sandstones. These sediments, devoid of any sign of volcanic activity, were dated late middle Miocene to late Miocene (Zones NN8 to NN9) by the presence of *Catinaster coalitus* and *Discoaster hamatus*.

Late Pliocene basalts (3.0 ± 1 Ma) in the Semporna Peninsula are associated with 130°N trending faults. Younger volcanic activities (Pleistocene) in this area and the Sulu Islands are related to the Sulu-Zamboanga volcanic arc.

Zamboanga Peninsula

Compared with Palawan and north Borneo the stratigraphic column of Zamboanga Peninsula seems to be very simple. The metamorphic basement (phyllites, greenshists, micashists, metagrauwackes) of unknown age is overlain by a thick early middle Miocene (Zone NN5) volcanic arc series with andesites, tuffs, and tuffites. Predominantly limestone breccias of reefal limestones are intercalated. Locally the volcaniclastic deposits overlie slices of ophiolites that in some places are included within the series. The upper part of these sediments was deposited in a very unstable environment as shown by large slumps and thick intercalated breccias and conglomerates of andesites, ultramafics, and cherts. That shows the fast destruction of the volcanic arc after deformation.

The Sulu Sea

The Sulu Sea is located between two marginal basins: the South China Sea to the north and the Celebes Sea to the south (Fig. 1). It is separated from the South China Sea by the Palawan continental block and the Palawan accretionary wedge, and from the Celebes Sea by the Sulu volcanic arc. The volcanic Cagayan Ridge divides the Sulu Sea into a northwest basin and a southeast basin. Seismic reflection data indicate that the northwest Sulu Sea Basin is underlain by a relatively thick crust (Murauchi et al., 1973), whereas the southeast Sulu Sea Basin has an oceanic basement (Mascle and Biscarrat 1979).

The Sulu-Negros Trench and the associated accretionary complexes form the southern and eastern margin of the southeast Sulu Sea. They are linked with the oceanic basement subduction underneath the Sulu volcanic arc and the Philippine Mobile Belt.

The northwest Sulu Sea Basin is an elongated basin between Palawan and the volcanic Cagayan Ridge, filled by more than 700 m of strongly deformed Mesozoic to lower Miocene sediments, overlain by gently folded or undeformed middle Miocene to Quaternary strata (Fig. 2). The older unit represents the southern extension of the thrusted turbidites and ophiolitic Cretaceous to Paleogene series that are exposed onshore Palawan (Letouzey et al., 1988). The northeast-trending Cagayan Ridge extends from southern Panay to the Cagayan Sulu Island. It is characterized by a flat northwestern slope, but has a steep southeast flank dissected by southeast-facing normal faults. According to seismic data volcanic lava flows interfinger with deeper sedimentary horizons. They were tentatively identified as pre-middle Miocene sequences, unconformably overlain by flat-lying series that could correspond to the upper middle Miocene and upper Miocene (Letouzey et al., 1988). These interpretations were confirmed by results obtained during Leg 124 and by exploration wells located south of Cagayan Island.

The small southeast Sulu Sea Basin consists of relative flat oceanic crust covered by about 1 to 2 km of sediments. Toward the Sulu Trench, the sedimentary cover becomes thicker and the oceanic basement dips gently toward the trench (Hinz and Block, 1990).

LEG 124 RESULTS

During Leg 124 of the Ocean Drilling Program, three sites were drilled in the southeast Sulu Sea Basin (Fig. 5). Site 768 is located in the deep part of this basin. The basaltic basement at 1047 mbsf is overlain by pelagic brown clay dated by radiolarians as early Miocene (*Stichocorys wolffii* Zone). It follows a series of 200 m of pyroclastic rhyolitic flows and coarse tuffs that are most probably deposited during a very short time and that can be correlated with the upper volcanic arc series known onshore from north Borneo (Sabah), south Palawan, and Zamboanga Peninsula. They are again overlain by 30 m of red clay of early middle Miocene age (*Calocycletta costata* Zone). The red clay is replaced upsection by greenish gray clay with altered ashes. This sequence is barren of nannofossils except the distinct turbidite layers in Core 124-768C-42R. They contain rare nannofossils typical for Zone NN5. However, it is not clear if they are displaced and indicate the real age of these sediments or if they are reworked. These turbidites contain also the first land-derived material (quartz sand) that becomes common at late middle Miocene time (Zone NN8) dated in Core 124-768C-40R. These turbidites are rich in well-rounded quartz grains, plant fragments, and some reworked nannofossils from older strata (Eocene, Oligocene to lower middle Miocene). The greenish gray clay continues as background lithology. This means that at this time older deformed series had been exposed to erosion. The terrigenous material originates most probably from north Borneo, where thick Paleogene series (Crocker formation) have been exposed after the early middle Miocene deformation.

Layers of carbonate turbidites are intercalated with the terrigenous sediments. Number and thickness of these turbidites are increasing during latest Miocene-early Pliocene time. They contain displaced marls from a shallow environment. The early Pliocene layers are characterized by the high input of sheital material as shown by the abundance of shallow-water benthic foraminifers and tunicate spines. This might be related to tectonic movements as also recognized onshore on the surrounding areas.

The input of terrigenous material is replaced by the occurrence of volcanic ashes during latest Miocene time to Holocene. This change took place at the boundary between nannoplankton Zones NN11a/NN11b at about 6.3 m.y. This lithologic change might indicate the function of the Sulu-Negros Trench connected with the initiation of the Sulu-Zamboanga-Negros volcanic arc. A comparable lithologic sequence was encountered at Site 769 located on the flank of the Cagayan Ridge.

At Site 771, situated on a fault block of the southeast flank of the Cagayan Ridge above the carbonate compensation depth (CCD), it was possible to date a complete series from nannoplankton Zone NN3 of early Miocene age, included in the volcanic rocks, to the Quaternary. The middle and late Miocene sediments of this sequence are devoid of land-derived material due to its high topographic position.

The cessation of the volcanic arc activity was recognized within nannoplankton Zone NN5 of early middle Miocene age, in good agreement with data from sections in north Borneo and Zamboanga Peninsula.

DISCUSSION

Biostratigraphic data obtained on land from the surrounding area of the Sulu Sea were summarized to come up with a quite coherent scenario of the geodynamic evolution of this region. Because the Sulu Sea is a young basin, only the late Cenozoic history is reflected in the sedimentary sequences encountered during Leg 124.

New datings have shown that the ophiolites in Palawan and Sabah are of early Cretaceous age. They are part of an oceanic crust of the same basin. They were abducted and eroded in both regions since late middle Eocene time (Zone NP17) as shown by the occurrence of microconglomerates including pebbles of ultramafic rocks and radiolarites. It is supposed that their emplacement is related to the middle Eocene tectonic event connected with the change in motion of the Pacific Plate (Letouzey et al., 1988).

According to the results obtained from Leg 124, opening of the Sulu Sea started during early Miocene time at about 20 m.y.

Volcaniclastic series and andesites were dated in Sabah as late Oligocene (Zones NP24-NP25) to early middle Miocene (Zone NN5) in age. They represent an allochthonous unit thrusted onto the drifted Chinese continental margin during early middle Miocene time. In south Palawan, Sulu Sea, and Zamboanga Peninsula the volcanic arc series is of early middle Miocene age (Zone NN5). The cessation of the volcanic activity took place at the same time (within Zone NN5) throughout the entire region. This might be explained by collision of the volcanic arc system with the drifted Chinese continental margin. This event coincides with the end of spreading in the South China Sea. The early middle Miocene tectonic event is followed by uplift and erosion as it can be observed on land by the presence of eroded material from the volcanic arc, and in the Sulu Sea by the occurrence of land-derived material (quartz sand, plant fragments, reworked nannofossils from older strata since the upper middle Miocene).

The input of terrigenous material in the Sulu Sea is replaced, by latest Miocene time (about 6.3 m.y.), by the occurrence of volcanic ash probably related to the function of the Zamboanga-Negros Trench and the initiation of the volcanic activity of the Sulu arc.

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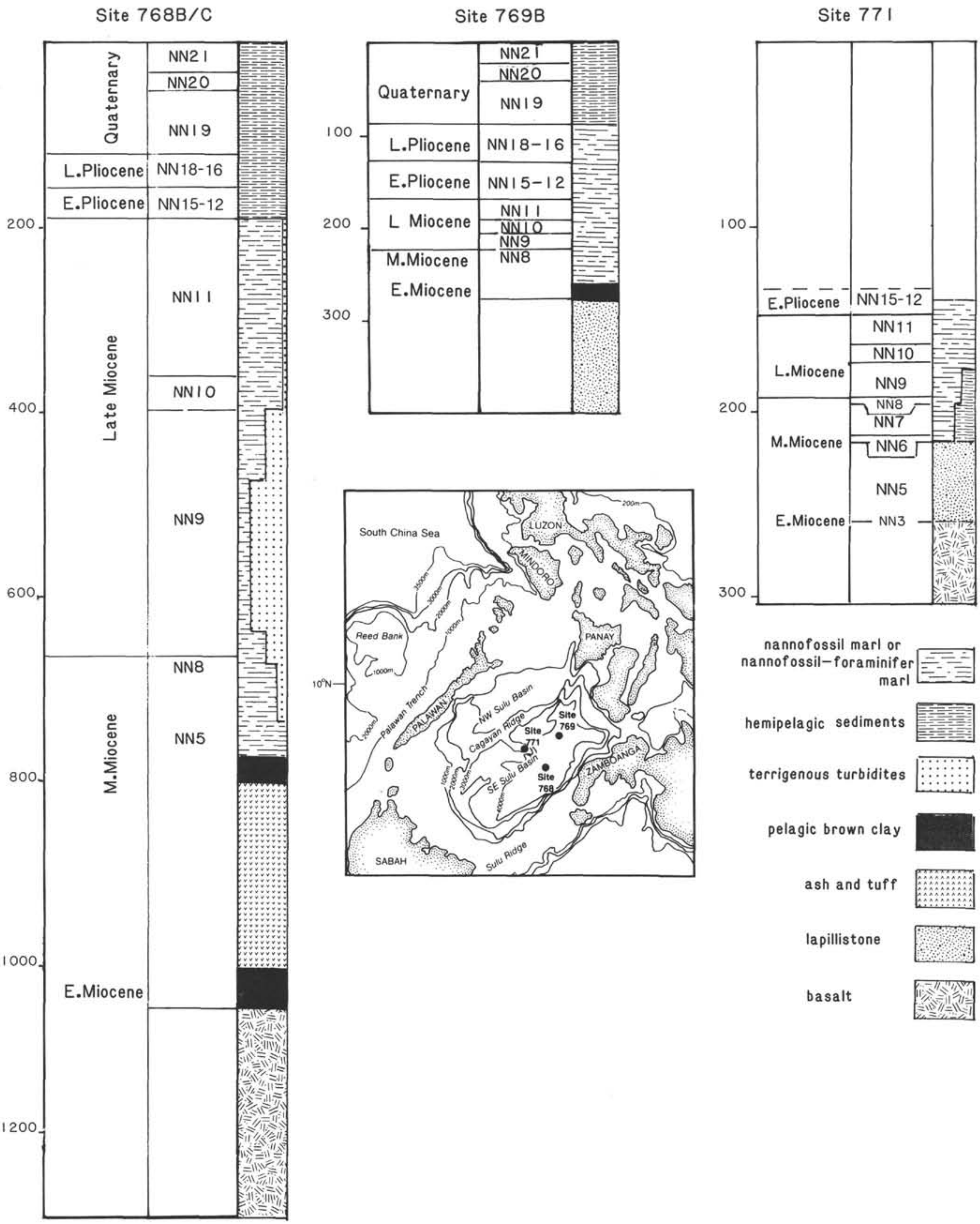

Figure 5. Location of the Sulu Sea sites drilled during Leg 124 (Rangin et al., 1989), and their biostratigraphic and lithologic columns.