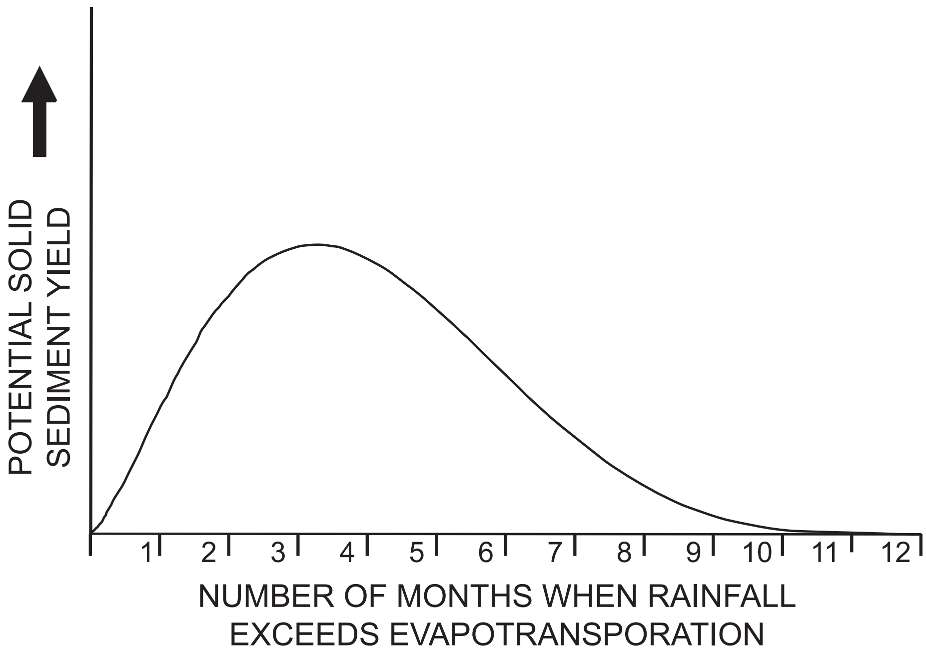
CLIMATE CONTROLS ON STRATIGRAPHY



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OBSERVATIONS ON CLIMATE AND SEDIMENT DISCHARGE IN SELECTED TROPICAL RIVERS, INDONESIA

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Abstract: Factors that influence fluvial sediment discharge in warm climates (catchment-basin size, relief, gradient, tectonic setting, bedrock lithology, and rainfall) can readily be evaluated in fluvial systems of Indonesia. In equatorial Sumatra and Seram, rainfall, catchment-basin size, relief, and gradient are similar, whereas bedrock geology and tectonic setting differ. The relief and rainfall in equatorial Borneo is similar to that of Sumatra and Seram, but gradient, catchment-basin size, and tectonic setting differ. All factors, except rainfall, are very similar for Timor and Seram. A pronounced dry season in Timor and Java distinguish those islands from the wet climates of Seram and Sumatra, respectively.

The nature of stream channels (braided or meandering), stream bed materials, the degree of fluvial estuarine fill, deltas, and the nature of coastlines were used to evaluate sediment discharge. In addition, reconnaissance-level stream sampling was conducted for solid-suspended-sediment concentrations, solute concentrations, and pH in rivers in equatorial regions in Sumatra and Borneo, in Seram at 3° S, in Irian Jaya at 4° S, and in West Timor at 10° S. Rainfall in Sumatra, Borneo, and Seram exceeds evapotranspiration for all months of the year (> 100 mm/month and > 2.4 m/yr, perhumid climate). In contrast, in Timor 85 percent of all rainfall (1.4 m/yr) occurs during a four-month rainy season (dry subhumid climate).

The absence of a fluvially derived bed load, river-mouth deltas, the lack of fluvial fill of estuaries, and mud-dominated coastal zones in the perhumid regions are indicative of a very low fluvial sediment discharge. Very low sediment concentrations (10 mg/l suspended and 10 mg/l solute) in modern rivers in the perhumid equatorial region of Indonesia are consistent with this observation. In contrast, sediment discharge in dry subhumid climates of Indonesia is very high, as indicated by coarse-grained braided-stream bed materials with cobbles transported to the coast, the complete fluvial fill of estuaries, the formation of river-mouth deltas, and coarse-grained beaches. Very high sediment concentrations (2100 mg/l suspended and 340 mg/l dissolved) during rainy-season discharge in modern rivers in dry-subhumid regions of Indonesia (Timor) are consistent with this observation. The dominant variable affecting fluvial sediment discharge among the islands of Indonesia, therefore, appears to be the degree of seasonality in rainfall regardless of tectonic setting, relief, or catchment-basin size. Solute concentrations in humid and perhumid climates are indicative of bedrock geology. Chemical weathering of massive Miocene limestone thrust sheets in high mountainous areas of Seram and Irian Jaya results in solute concentrations that approximate the solubility of calcite (~ 50 mg/l). Humid and perhumid areas without significant limestone bedrock geology have solute concentrations that approximate that of rainwater (~ 10 mg/l).

INTRODUCTION

This study compares and contrasts the apparent sediment transport in some modern tropical river systems that may serve as analogues for sediment supply to ancient depositional systems, particularly those in ancient cratonic seas. Much of the information on sediment supply from modern tropical rivers has been derived from hydrological and geomorphological studies (e.g., Summerfield, 1991; Olive et al., 1994) rather than sedimentological investigations and the perspective of sediment supply. Modern analogues that can be used to interpret sediment supplies in ancient depositional systems are, therefore, underdeveloped. Modern large rivers of the tropics and subtropics, such as the Amazon, the Ganges/Brahmaputra, the Indus, and the Zaire (Congo), empty along passive continental margins. As a result, these rivers generally appear to be atypical of sediment-supply systems to most ancient cratonic depositional environments. Smaller river systems, such as those in Indonesia, may be representative of sediment supply in ancient cratonic seas and foreland-basin systems.

If cyclic variation in sediment supply (sedimentation) is related to cyclicity in paleoclimate (Huntington 1907; Wanless and Shepard, 1936; Cecil, 1990), then the rivers on the islands of Indonesia are ideal analogues because they span climate belts that range from perhumid at the equator (Cecil, this volume, Part 1) to dry subhumid at 10° S (Fig. 1). By studying sediment supply in these modern rivers, it may be possible to extrapolate results to ancient systems where the climate may have cycled between relative extremes in both seasonality and amount of annual rainfall. Climatic changes of large magnitude, and their

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effects on variation in sediment supply, are not well documented in the humid tropics (Verstappen, 1975) although there is a considerable body of evidence that is indicative of significant shifts in rainfall regimes during the Quaternary (Van der Karrs, 1988). There also appears to have been extreme climate shifts in the eastern Sahara Desert (dry tropics) where ground-penetrating radar has revealed at least two periods of major fluvial incision that underlie modern sand seas (see Summerfield, 1991, p. 359-360). Interpretations of lithostratigraphic relationships can be improved, therefore, as cyclic fluctuation in paleoclimate is further documented and related to cycles in sediment supply.

Considerable uncertainty persists regarding controls on sediment discharge (supply) in modern fluvial systems (Milliman and Meade, 1983; Milliman, 1997). Many studies suggest that tectonic uplift is the primary control on erosion and fluvial sediment discharge (Meade, 1996; Milliman, 1997). Catchment-basin size and provenance also are proposed to be important controlling factors on yield (Staub and Esterle, 1994; Walling and Webb, 1996; Milliman, 1997). In addition, rainfall is one of the primary controls on sediment yield from modern rivers (Langbein and Schumm, 1958; Fournier, 1960). Unless the level of uncertainty concerning the importance of the variables can be reduced or somehow quantified, it will always be difficult to use existing studies of modern environments as analogues for the interpretation of ancient depositional systems.

Comparison of Sediment Supply in Four Tropical and Subtropical River Systems

Although there have been studies in modern tropical environments, an understanding of fluvial sediment discharge as a function of climate remains ambiguous. Most studies generally have compared sediment discharge with annual rainfall (Milliman, 1997) rather than monthly rainfall amounts and monthly distribution throughout the year, as suggested by Fournier (1960) and Cecil and Dulong (this volume, Part 1). As a result, there has been a tendency to suggest that high annual rainfall results in high fluvial sediment discharge. Other studies point out that there is little (if any) correlation between sediment discharge and annual rainfall (Milliman and Meade, 1983; Milliman, 1997; Hooke, 2000). In western Indonesia, it is sometimes assumed that erosion rates and sediment loads must be high because the climate is perhumid (Keller and Richards, 1967; Milliman and Meade, 1983) or because the region is undergoing tectonic uplift, which in turn is believed to be the primary control on sediment discharge (Meade, 1996; Milliman, 1997). However, neither high mountainous areas nor perhumid climates necessarily equate to high sediment discharge. This is demonstrated by the exceedingly low sediment discharge from the western slope of the arid central Andes Mountains and by the very limited degree of sedimentary fill extending into the adjacent central Peru–Chile trench (Cecil and Edgar, 1994; Edgar and Cecil, this volume, Part 3). It is also demonstrated by the exceedingly low sediment discharge from rivers that debouch from the mountainous perhumid regions of equatorial Sumatra to the Sunda Shelf (Cecil et al., 1993) and the Zaire (Congo) River (Meade, 1996). Extreme conditions of rainfall, tectonic setting, or catchment-basin size compound the problem of understanding sediment discharge in rivers of the tropics and subtropics. Four previously studied tropical to subtropical river systems with headwaters in high mountainous areas (>5000 m) include the following: (1) the Fly River, New Guinea, which is in a humid climate setting, (2) the Amazon River, South America, whose huge catchment basin is in a humid to subhumid climate, (3) the Zaire, where the catchment is situated primarily in a humid to perhumid climate, and (4) the Ganges/Brahmaputra river system, where the catchment is situated mainly in a dry subhumid climate. In the humid climate of the Fly River, the sediment load is thought to be derived primarily from intense slope failure in high and very steep mountainous areas (Markham and Day, 1994). The combined effects of high mountains, high rainfall, and frequent earth tremors are conducive to extreme volumes of landslide debris (Markham and Day, 1994). The relatively high sediment discharge (derived from erosion of

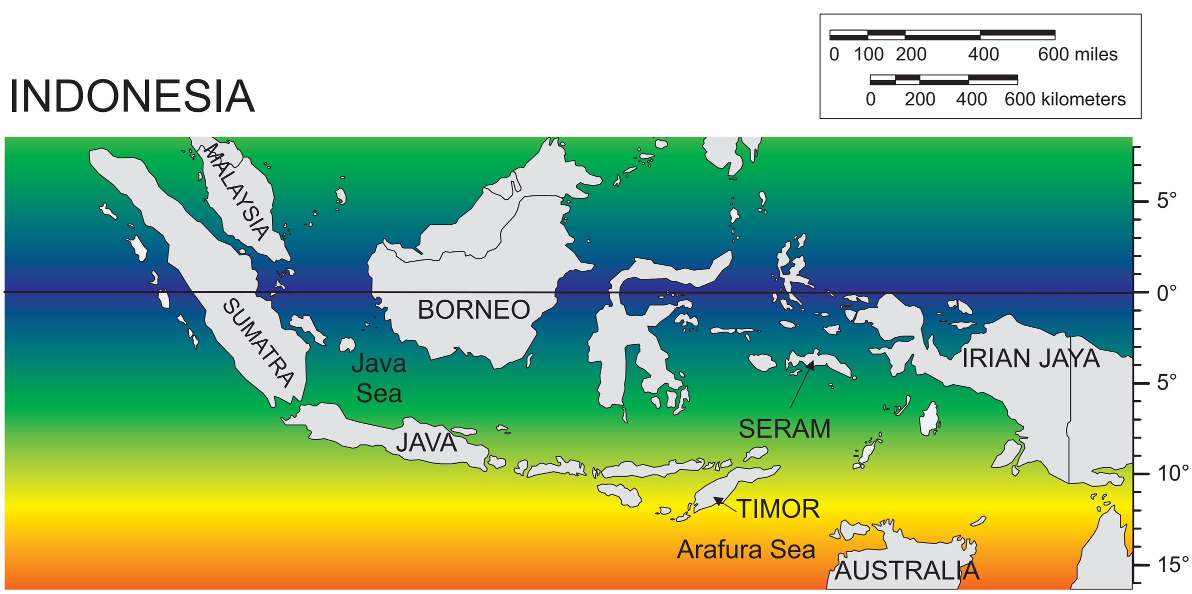


FIG. 1.—Climate belts in Indonesian study areas, which range from perhumid at the equator (dark blue) to dry subhumid in Timor at 10° S (yellow).

landslide debris in high mountains in a tectonically active area and a humid climate) has apparently contributed to the concept that high mountains and high annual rainfall always equates with high sediment discharge. The sediment discharge from the Amazon River to the Atlantic Ocean further contributes to the concept that high annual rainfall always results in high sediment discharge (Meade, 1996). It has been suggested that the sediment in the Amazon is derived principally from the vast catchment basins of the eastern slope of the Andes Mountains and that much of the sediment is stored in upstream portions of the Amazon (Meade, 1996). The sheer volume of the Amazon River discharge and the subhumid climates in the upper reaches of the Amazon Basin probably accounts for the relatively high annual sediment discharge to the Atlantic Ocean. On the basis of data from Meade (1996), the annual sediment discharges of the Amazon and Ganges/Brahmaputra are nearly equal even though water discharged from the Amazon is nearly six times that of the Ganges/Brahmaputra (Table 1).

When sediment discharges are normalized on a mass per unit volume basis (tons of sediment per km^3 of water discharge), sediment concentrations of the Ganges/Brahmaputra in the highly seasonal rainfall (dry subhumid climate) of southern Asia are approximately twice that of the Fly, six times that of the Amazon, and two orders of magnitude greater than that of the Zaire (Congo) (Table 1). The comparisons in Table 1 are indicative of the influence of seasonal distribution of rainfall on sediment supply in tropical and subtropical settings. Only the Fly River shows a distinct influence of tectonics on sediment discharge, apparently because of slope instability high in the catchment basin. The dominant control on the other rivers appears to be the degree of seasonality of rainfall regardless of tectonic setting, heights of mountains, or catchment basin size.

The data in Table 1 indicate that a significant climatic change within a given catchment basin also causes a major change in sediment supply. For example, if the climate of the Zaire Basin shifted from perhumid or humid to dry-subhumid conditions, sediment discharge would undergo a major increase even though annual rainfall would likely decrease.

River Systems, Climate, and Tectonic Setting of Indonesia

A primary objective of our study is to delimit and relate the perhumid to dry subhumid climatic conditions in Indonesia to fluvial sediment discharge, which we equate to sediment supply. Indonesia represents an ideal natural laboratory to test the role of climate as a control on fluvial sediment discharge in warm climates because many Indonesian islands have similarities in geomorphology and geology but significant differences in rainfall distribution. Similarities in the size of catchment basins, stream gradients, relief, and geology are due mostly to similarities in tectonic setting. For example, the islands of Sumatra and Java are both part of the Sunda arc–trench system but annual rainfall in Java is much less and more seasonal than in Sumatra. A similar situation exists with the islands of Seram and Timor, both of which are part of the Banda arc–continent collision zone of eastern Indonesia, but Timor is much drier and rainfall is more seasonal. In both the Sunda and Banda arcs, where tectonic and geologic settings are similar, the number of consecutive wet months per year is the primary variable that controls differences in sediment discharge (supply) among fluvial systems.

In order to test the influence that climate may have on sediment supply, Indonesian rivers were evaluated in the regions of northeastern Sumatra, western and south-central Borneo, Timor, Seram, and the southern coast of Irian Jaya (western New Guinea) (Fig.1). Rainfall for these areas ranges from perhumid in equatorial islands to dry subhumid in the more southern islands of Java and Timor (Ahrens, 1991). Rainfall throughout the study areas is strongly affected by the seasonal movement of the intertropical convergence zone (ITCZ), where the Hadley circulations of the northern and southern hemispheres meet and rise in response to a low-pressure system that is generated by equatorial solar heating (Verstappen, 1975; Ahrens, 1991). As the moisture-laden air of the ITCZ rises, the air cools and precipitation occurs. Wherever the ITCZ is stationary, or nearly so, rainfall is high and evenly distributed throughout the year. Because of the nearly continuous influence of the ITCZ, rainfall conditions in the equatorial areas of Indonesia are humid to perhumid. In contrast, the islands of Timor and Java are outside the influence of the ITCZ for much of the year. As a result, the climate of these two islands is dry subhumid, and their wet months are generally concentrated into a three- to four-month period.

All the islands in this study have experienced identical glacioeustatic histories. For the purposes of evaluating modern fluvial sediment discharge, the amount of tectonic movement probably did not significantly affect variation in either sea level or fluvial sediment discharge since the last eustatic rise in sea level about 8000–12,000 yr B.P. (sea-level history is summarized in Hanebuth, 2000).

The present tectonic setting of these areas appears to be analogous to conditions in eastern North America during the Carboniferous and in western North America during the Jurassic–Cretaceous. Many of the intracratonic basins of North America formed during episodes of crustal loading from continental accretion and extension, conditions that exist today in the Java and in the Arafura and Timor Seas of Indonesia (Hamilton, 1979; Silver and Smith, 1983). The Java Sea separates the Sunda arc–

TABLE 1.—Annualized sediment concentrations (mass/unit volume) for four tropical to subtropical rivers. Data are average annual water and sediment discharge.

River system	Approximate Mean Number of wet months	Water discharge, 10^9 m^3/y	suspended sediment discharge, 10^6 t/y	Annualized sediment concentrations (10^6 t/km^3 of water discharge)
Zaire (Congo)(2)	11	1250	43	0.034
Amazon(2)	8–10	6300	1000–1300	0.21
Fly(1)	9	150	81	0.54
Ganges/Brahmaputra(2)	5	970	900–1200	1.2

Data sources: (1) Markham and Day (1994), and (2) Meade (1996). Approximations of mean seasonality of rainfall for each catchment basin are based on data from EARTHINFO (1966).

trench system from the stable craton of Borneo, which is a modern analog for the Jurassic–Cretaceous seas and basins that formed between the Sierra arc–trench system and stable North America. Rivers along the northeastern coast of Sumatra and northern coast of Java drain from the high volcanic mountains of the Sunda Arc and empty into the shallow epeiric Java Sea of the cratonic Sunda Shelf. The rivers in southwestern and central Borneo drain a craton of granitic and sedimentary rocks that are primarily siliciclastic. The Arafura and Timor Seas represent foreland basins forming astride active fold–thrust belts produced by collision similar to the collisions that formed the Appalachian and Sevier belts of North America. The islands of Timor, Seram, and Irian Jaya represent the emergent parts of a fold–thrust belt forming on the northern edge of the Australian continent. Drainage basins in these islands consist primarily of sedimentary rock, particularly thick carbonates in the high mountains.

FIELD INVESTIGATIONS

Reconnaissance field investigations were conducted in rivers, estuaries, and offshore environments in the Indonesian provinces of Sumatra, West and Central Kalimantan (Borneo), Timor, Seram, and Irian Jaya (Fig. 2). These studies were conducted to determine the relative effects of tectonic, eustatic, and climatic variability on supply of fluvial sediment to epeiric seas and continental margins. Specific parameters evaluated included the average monthly amount and distribution of rainfall throughout the year, heights of mountains, stream type, degree of estuarine fill, and, where possible, the nature of bed load and of solid and solute concentrations in rivers, estuaries, and offshore. Water samples were collected for the determination of pH, specific conductivity as a measure of solute concentrations, and suspended-solids concentrations. At selected sites, a modified Pfleger corer and/or dredge were used to collect bottom samples to determine whether the bottom was erosional or depositional. The nature, composition, and size of any bed-load materials or lag deposits were also determined. Our analyses of sediment supply also considered the average monthly amount and distribution of rainfall throughout the year.

The climate of the study region varies from perhumid in equatorial Indonesia to dry subhumid in southern Indonesia. The climate of the river catchment basins we studied in Sumatra, Borneo, Seram, and Irian Jaya were either perhumid or humid. In contrast, the climate of the river catchment basins in our study areas in Java and Timor ranged from subhumid in Java to dry subhumid in Timor.

Studies in Perhumid and Humid Climates

Sumatra.—

The climate of the Sumatran equatorial study region is perhumid, on the basis of averaged monthly rainfall data that were collected at Pakenbaru on the Siak River approximately 100 km inland from the coast (EARTHINFO, 1966) (Fig. 3). The perhumid climate of the region is the result of a maritime influence combined with movements of the ITCZ over the equatorial region of Sumatra (Ahrens, 1991).

In the Sumatra study region, the Siak and Kampar Rivers (which drain from volcanic mountains in excess of 1600 m in elevation before crossing the eastern coastal plain of Sumatra) were evaluated for pH, solute concentrations, suspended-sediment concentrations, and the nature of bottom sediment. Particular attention was paid to the Kampar because interpretation of satellite imagery prior to field investigations indicated the following characteristics: (1) minimal anthropogenic disturbance in the catchment basin, (2) sediment filling the lower reaches of the Kampar, and (3) a sediment plume off the mouth of the river in the Sunda Sea.

Field investigations revealed that high suspended-sediment concentrations (1700 mg/l) are present at the mouth of the Kampar estuary but decrease upstream to approximately 40 mg/l at 80 km inland, and finally to 8 mg/l in the middle estuary 150 km from the coast (Cecil et al., 1993). Maximum bed load occurs in the lower estuary from the mouth of the estuary to approximately 85 km upstream, then it rapidly diminishes and is gone at 180 km upstream. The lower 85 km is exceedingly shallow and difficult to navigate even in small boats of very shallow draft. At

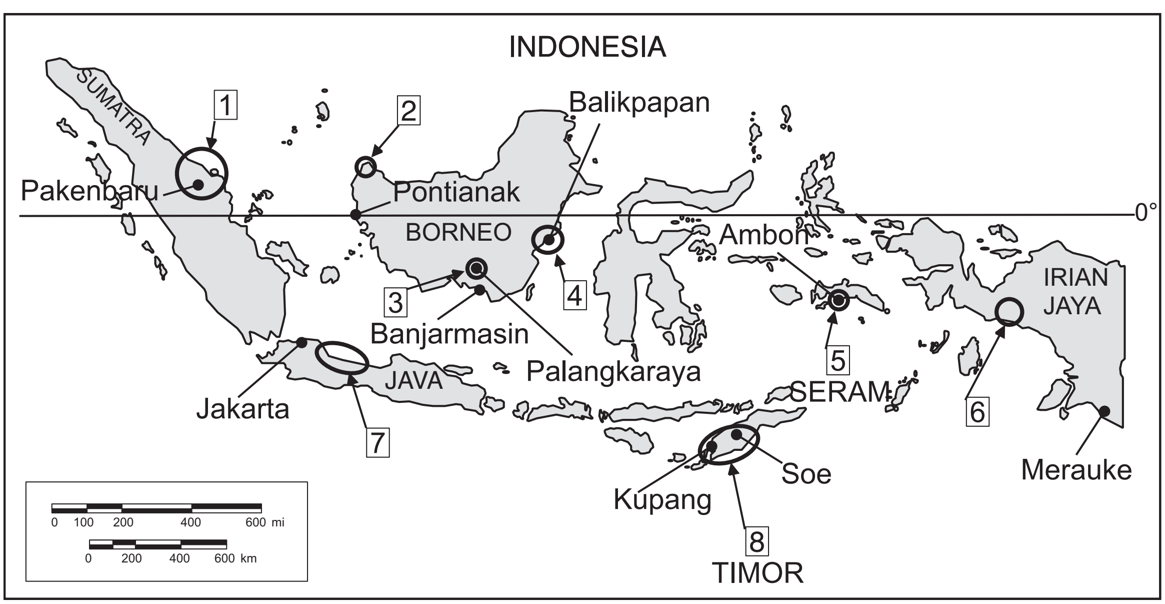


FIG. 2.—Study areas (circumscribed and numbered) and cities (dots) where rainfall data were collected.

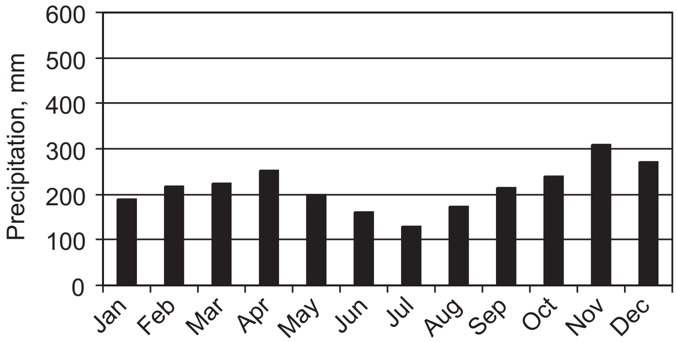


FIG. 3.—Average monthly rainfall, Pakanbaru, Sumatra.

approximately 180 km inland bottom sediment is not detectable by dredging or bottom profiling, and water depths are over 20 meters. The estuary bottom at 180 km inland is erosional and consists of a sparse channel lag on partially indurated preexisting sediment of the Tertiary Minas Formation. It is possible that the 20 m depth at 180 km inland is the result of incision during the last glacial lowstand. The solute content of the Kampar River estuary has a distribution analogous to that of the suspended solids. Maximum solute concentrations (23,000 mg/l) occur at the mouth as a result of mixing of river water with sea water. At approximately 35 km inland, concentrations decrease to 6000 mg/l, and finally to 10 mg/l at 85 km upstream and beyond. Both suspended-solids and dissolved-solids concentrations in the upper estuary and fluvial portion of the Kampar system are approximately equivalent to solids and solute concentrations in rainwater. The pH of the system above the region of salt-water influence averaged 4.5. Conditions of the Siak River and estuary are similar to those of the Kampar, except for the absence of bottom sediments in the lower Siak estuary, where water depths are fairly consistent at 20 m. This estuary is devoid of bottom sediment except at the mouth, where there is a mud-dominated estuary mouth bar, apparently deposited by tidal processes. Both dissolved solids and suspended sediment exhibit a dramatic decrease in concentration upstream. The pH of the Siak River upstream of salt water influence is also 4.5. The water in both rivers is tea colored (such coloration is generally referred to as "black water").

Satellite imagery had revealed the presence of both a sediment fill and a sediment plume in the lower reaches of the Kampar and offshore, respectively. This imagery was suggestive of high sediment supply from the Kampar River. Field investigations in the Kampar system, however, revealed that the lower reaches of the Kampar were flood-tide dominated and that suspended and bottom sediments were unrelated to fluvial processes. Instead, these sediments were derived from tidal processes. Tidal influence was estimated to extend upstream for approximately 180 km, with the lower 100 km being flood-tide dominated. The bottom sediment and plume observed on the satellite image were determined to be the result of strong bank erosion and redeposition by tidal currents in the lower estuary, and not the result of fluvial supply.

Bottom sampling revealed that the entire coastal and offshore marine environments in the Straits of Malacca and the Sunda Sea are sediment starved, probably as a result of the lack of fluvial sediment supply. Much of the coastal zone consists of tidal mud flats colonized by mangroves. Because of low-velocity surface winds and rare tropical storms within the low-pressure belt of the ITCZ, wave energy is exceedingly low and wave-dominated coastal beaches do not occur except where coastlines are exposed to waves generated in the open ocean outside the ITCZ. The very limited amount of modern sediment in coastal and offshore areas is derived entirely from bottom scouring and coastal erosion by strong tidal currents (Cecil et al., 1993). Conductivity measurements in coastal and offshore areas revealed diminished salinity (~ 22 ppt), probably as a result of high water discharge and the mixing of river water draining into the marine environment of the Sunda Shelf. Shallow Pfleger cores (generally < 0.5 m) retrieved in offshore areas commonly contained partially indurated red-mottled, gray-brown mud that appeared to be a paleosol, probably developed during the last glacial lowstand of sea level (Hanebuth, 2000). At locations where recent sediment was encountered, this sediment consisted of soft mud that was easily penetrated by the Pfleger corer.

The mineral soils in the Sumatra study area are composed largely of kaolinite and contain a spodic horizon. These soils most closely resemble Spodosols, which belong to the suborder of Aquods. Extensive Histosols (domed peat deposits) are present between the Kampar and Siak estuaries, and on offshore islands. Vegetal matter in the peat is generally well preserved and the soil suborder is Fibrist. These Histosols consist of domed low-ash peat (< 10 percent ash), are up to 13 m thick, and have accumulated during the last 5000 years (Neuzil et al., 1993: Supardi et al., 1993; Neuzil, 1997).

The high mountains and perhumid climate of central Sumatra do not result in high fluvial sediment supply as has been previously inferred (Keller and Richards, 1967; Gupta, 1996). Instead, solute and solid sediment concentrations in undisturbed fluvial systems are exceedingly low. The low pH and black water of fluvial systems are the result of acidic drainage from extensive deposits of domed peat (Histosols). Coastal and offshore areas are sediment starved, and most areas are undergoing erosion by tidal processes, except on the lee sides of islands, where deposition of recent sediment is occurring.

In addition to controlling sediment supply, the perhumid climate has been a primary control on formation of mineral soil and peat. Spodosol and Histosol genesis are the result of the perhumid climate and degree of soil drainage.

Gupta (1996) suggested that satellite images can be used to see sediment plumes off the mouths of rivers and infer fluvial sediment yield throughout the region. Our data indicate, however, that satellite images alone cannot be used to determine either sediment source, fluvial sediment discharge, or sediment yield from tropical rivers. Sediment sources specific to estuaries and estuary mouth bars must be determined by field investigations.

West Kalimantan (Western Borneo).—

The climate of West Kalimantan is perhumid (Fig. 4), as a result of maritime influences in combination with movement of the ITCZ over the equatorial region (Ahrens, 1991). The rainfall data were collected at Pontianak, on the equator, approximately 130 km south of our study area (EARTHINFO, 1966). The West Kalimantan study area (Fig. 2) included the Sambas River and shallow offshore areas of the cratonic shelf under the South China Sea (Fig. 5). Samples were collected from the Sambas River and estuary to evaluate pH, solute concentrations, suspended-sediment concentrations, and the nature of bottom sediment. As with the rivers studied in Sumatra, field investigations in the Sambas revealed that the lower reaches were tidally controlled and that suspended and bottom sediment is derived from tidal processes. On the basis of salinity measurements and the tidal range observed along the banks of the system, tidal influence was estimated to extend upstream for approximately 40 km from the estuary mouth. The highest suspended-sediment concentrations

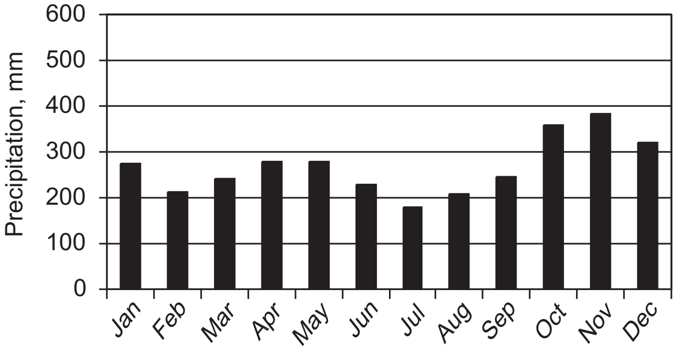


FIG. 4.—Average monthly rainfall, Pontianak, West Kalimantan.

were detected at the mouth of the estuary (170 mg/l; Fig. 6) but decreased up-stream to 3 mg/l at 57 kilometers inland (Fig. 6). Sediment fill was restricted to an estuary mouth bar. This sediment is likely derived from tidal erosion and redeposition along the coast and in the lower estuary. Bed load is present only in the lower estuary and is derived from tidal processes and not from fluvial processes.

The solute concentrations in the Sambas estuary have a distribution analogous to the suspended solids. Maximum solute concentrations (23,000 mg/l) occur at the mouth as a result of mixing of river water with sea water. At approximately 35 kilometers inland, concentrations decreased to 6000 mg/l, and finally to 10 mg/l at 85 km upstream and beyond. As with the rivers in Sumatra, both suspended-solid and dissolved-solid concentrations in the fluvial part of the Sambas system are approximately equivalent to the concentrations of rainwater (Figs. 6, 7A, B).

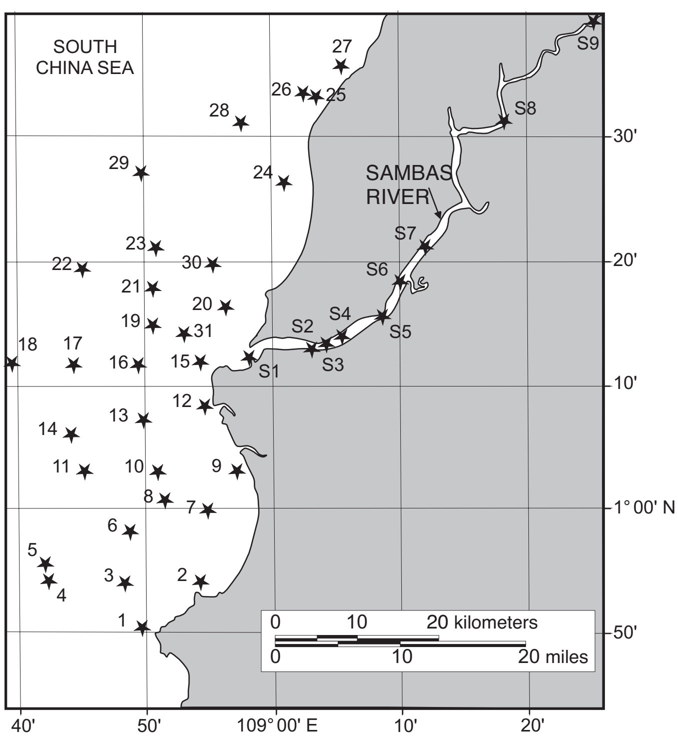


FIG. 5.—West Kalimantan study area with sample locations.

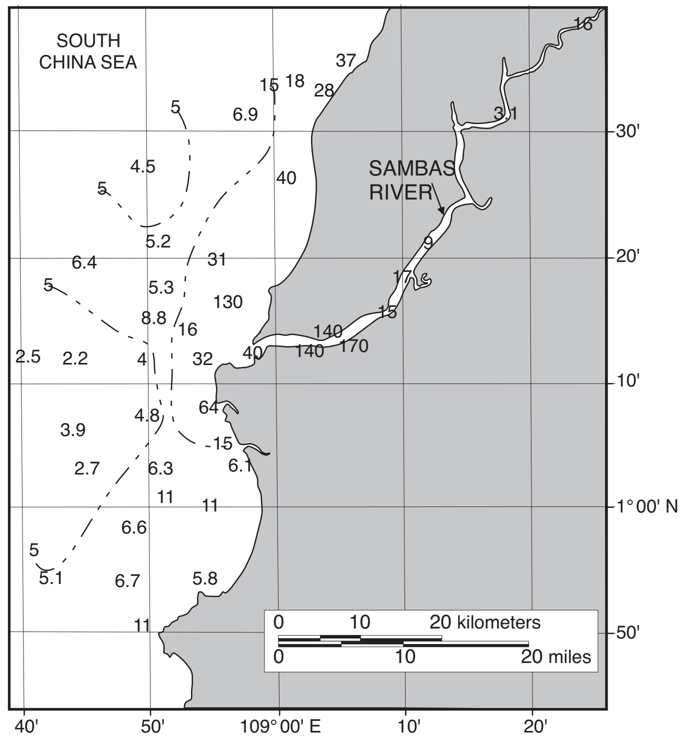


FIG. 6.—Suspended-sediment concentrations (mg/l) in the river, estuarine, and marine environments, West Kalimantan. Isoconcentration lines are shown at 5 mg/l and 15 mg/l.

Conditions of the Sambas River and estuary are analogous to those of the Siak River in Sumatra. As in the Siak, the Sambas estuary is devoid of bottom sediment except at the mouth, where there is an estuary-mouth bar, apparently the result of tidal processes. Both dissolved solids and suspended sediment decreased dramatically upstream.

In coastal areas of the West Kalimantan study area, sedimentation is restricted to fine-grained material that is being deposited along the coast north of the mouth of the Sambas. Suspended-sediment concentrations in offshore areas are very low (approximately 5 mg/l) (Fig. 6), even though the bottom is relatively shallow ($\leq$ 20 m) and tidal currents are quite strong. Depth profiling revealed a hummocky bottom surface. Pfleger cores retrieved in offshore areas commonly contained partially indurated red-mottled, gray-brown mud. Dredging revealed a bottom lag, consisting primarily of shell fragments resting on the partially indurated silty clay. The lag appeared to be confined to the swales,whereas the hummocks are scoured. The hummocky surface may be a relict soil catena (surface), which was probably developed during the last glacial lowstand of sea level. The lack of recent offshore bottom sediment results from the lack of fluvial sediment supply and from strong tidal currents that scour and remove any fine-grained material from the bottom. The very limited amount of modern sediment that occurs along the coastal area is derived from bottom scouring and coastal erosion by strong tidal currents, and perhaps also by wave energy that comes from the open ocean of the South China Sea. Salinity values offshore were somewhat below normal salinity for sea water (Fig. 7A).

Mineral soils in the West Kalimantan were not evaluated because of logistical considerations. However, extensive Histosols have developed over the last 5000 years in response to the

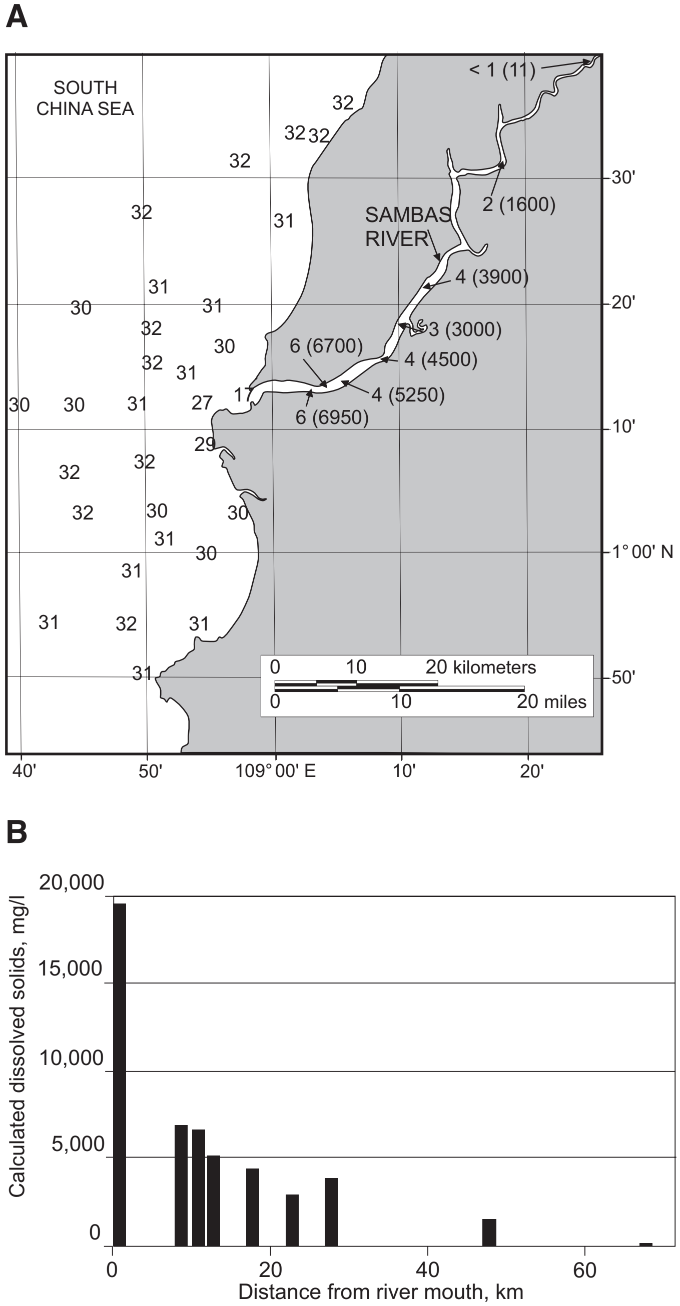


FIG. 7.—**A)** Solute concentrations as salinity in ppt and mg/l ( ), in the estuarine and marine environments, West Kalimantan, Indonesia. **B)** Solute concentration (mg/l) in the Sambas River estuary versus distance from the mouth.

perhumid climate of the region (Neuzil et al., 1993; Supardi et al., 1993; Neuzil, 1997).

The highlands of interior Borneo and the perhumid climate of the region do not result in a high sediment supply by rivers such as the Sambas. Instead, fluvial sediment supply, both solid and solute, is exceedingly low, as demonstrated by the absence of esturine fill, the absence of offshore sediment, and low sediment concentrations away from tidal disturbance. The partially indurated hummocky bottom in offshore areas may be a relict soil that developed during the last glacial lowstand of sea level.

Central Kalimantan (South-Central Borneo).—

The Central Kalimantan study locality is in the vicinity of Palangkaraya (Fig. 2), which is located at 2° 12' S latitude and is approximately 130 km north of the southern coast of Borneo. The climate data were collected closer to the coast at Banjarmasin on the Barito River, which is located at 3° 20' S and approximately 1° 10' (130 km) S of Palangkaraya (EARTHINFO, 1966) (Figs. 2, 8). Climate data were not available for Palangkaraya, but rainfall may not exceed 100 mm/month during the annual dry season in the study area (June through August), and, therefore, the climate at Palangkaraya may be slightly drier than the southern coast. Thus the climate of the study area is estimated to be marginally perhumid or humid, given the inland setting. The humid climate is partly the result of rainfall associated with movement of the ITCZ over the equatorial region (e.g., Ahrens, 1991) and, to a lesser extent, maritime influence.

Reconnaissance investigations were conducted along the Kahayan River and the Rungan River, and in the Histosols north of Palangkaraya (Figs. 9, 10). The Kahayan flows into a very large estuary that extends to the Java Sea approximately 130 km south of the study area. The Kayahan estuary is typical of several large estuaries along the coast of southern Borneo. There appeared to be a minor tidal range of approximately 0.5 m on the Kahayan River at Palangkaraya 130 km inland. We were not able, however, to document tidal influence at this locality unequivocally. Logs floating in the Rungan indicated the presence of a significant timber operation upstream of the study area. We did not attempt detailed studies of suspended-sediment concentration, in part because upstream anthropogenic activities such as logging may affect erosion and suspended-sediment concentrations. However, logging is unlikely to accelerate weathering at a rate sufficient to affect pH and specific conductivity.

A cursory evaluation of water in the Kahayan and Rungan Rivers revealed differences in pH and conductivity (Fig. 10). The Rungan is characterized by values of pH 5 and solute concentrations of 8 mg/l, whereas the Kayahan has pH values of 6.6 and solute concentrations of 21 mg/l. These differences may be partially related to drainage of acidic black water with low dissolved solids from extensive Histosols in the Rungan drainage. Both the Kayahan and Rungan are meandering streams within the study area. They both contain a bed load that is sufficient to develop point bars that are composed almost entirely of quartz sand. The bed load diminishes downstream of the confluence of these two rivers and is nearly gone upon reaching the upper estuary. Maps of southern Borneo that include fluvial systems, estuaries, and coastal zones indicate that both meanders

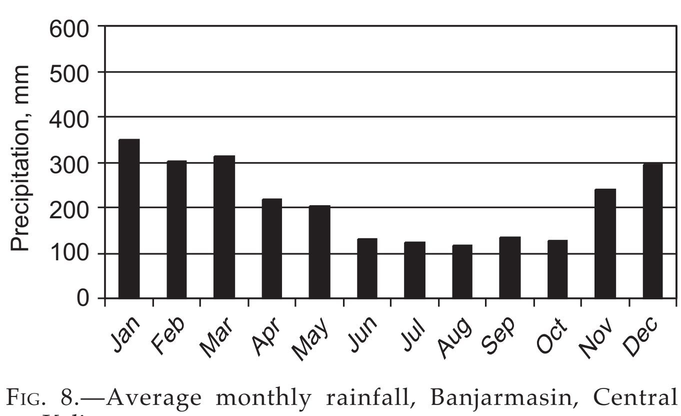


FIG. 8.—Average monthly rainfall, Banjarmasin, Central Kalimantan.

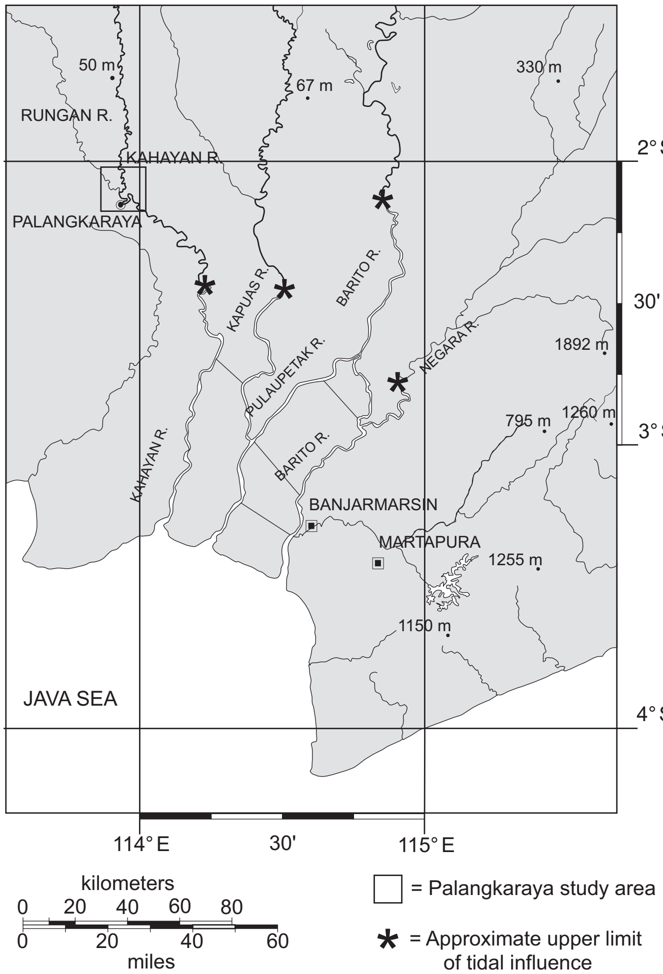


FIG. 9.—Central Kalimantan study area.

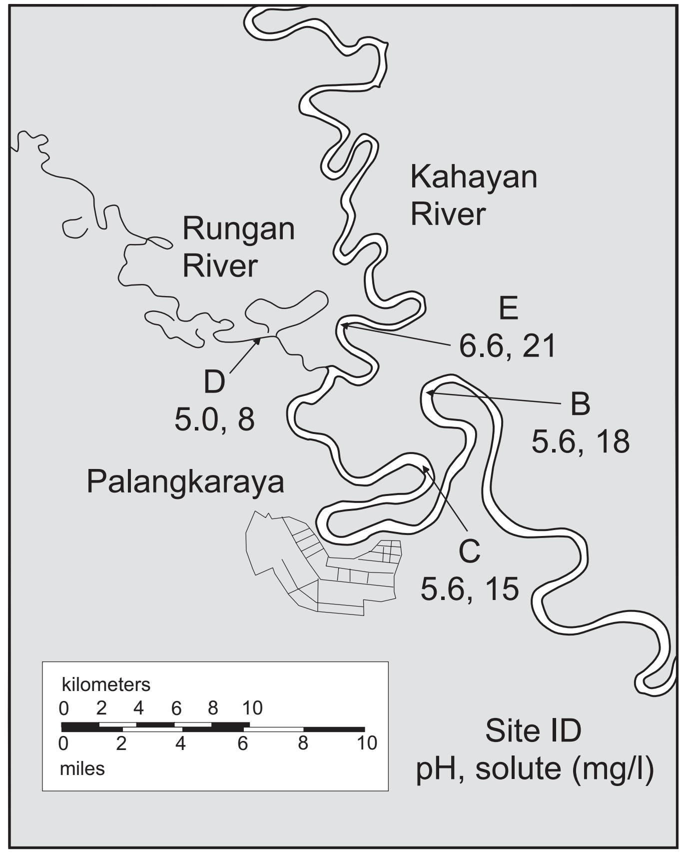


FIG. 10.—pH (left-hand value) and solute concentrations (right-hand value) in the Rungan and Kayahan Rivers, Central Kalimantan.

and point bars diminish downstream in the fluvial systems and are not developed in the estuaries. Gilmore (1996, and personal communication) pointed out that the sand content of the Barito River in South Kalimantan decreased downstream and gave way to mud in the estuary and offshore environments. Map bathymetry of the lower estuaries and nearshore environments suggests the presence of estuary-mouth bars that are analogous to the bars documented at our study sites in Sumatra and West Kalimantan. Coastal zones and offshore areas appear to consist primarily of mud (Gilmore, 1996), and coastal zones have been colonized by mangroves.

Soils in the study area are primarily Histosols and Spodosols. Histosols (domed peat) blanket much of the interfluve areas. Up to seven meters of peat were measured in the center of the peat dome north of Palangakraya. The peat began to form approximately 9000 yr B.P., on the basis of ^{14}C age dates from samples collected at the base of the domed peat deposits (Neuzil, 1997). Peat accumulation stopped approximately 2000 yr B.P. (Neuzil, 1997). Petrographic analysis of the peat revealed very high concentrations of fine-grained, highly carbonized macerals that are the result of aerobic degradation, probably over the last 2000 yr. The Histosols are degraded to the soil suborder of Saprists. The degradation is probably in response to a weak dry season, which allows the peat to drain partially and to undergo aerobic degradation. This type of peat may be a precursor to splint coal in the rock record.

The region, including the Histosols, is underlain by regionally developed Spodosols, suborder of Tropaquods. The Spodosols are up to 15 m thick, and they are composed primarily of quartz sand with a black spodic horizon that occurs deep in the soil profile. The spodic horizon commonly occurs 2–4 m above river level and is composed of amorphous organic material, Al, and Fe. This horizon is an aquiclude, or confining bed, that inhibits downward percolation of soil water in the otherwise highly porous quartz sand above and below the spodic horizon. The spodic horizon maintains a perched water table that sequesters water in the overlying horizons of the Spodosol and domed peat deposits.

The fluvial and esturine processes in Central Kalimantan are similar to those in the study areas in Sumatra and West Kalimantan. Differences in water chemistry in the Kayahan and Rungan may be related partially to drainage of acidic black water with low dissolved solids from extensive Histosols in the Rungan drainage. Values of pH 5 and solute concentrations of 8 mg/l in the Rungan, compared with pH 6.6 and solute concentrations in the Kayahan of 21 mg/l, are consistent with this interpretation. The estuaries and coastal areas of southern Borneo are sediment starved. The estuaries have not been filled since maximum sealevel was reached approximately 8000 to 5000 yr B.P. (sealevel history is summarized in Hanebuth, 2000). This indicates that sediment discharge has been insufficient to fill the estuaries since the last rise in sealevel.

The regionally extensive Spodosols are the source of quartz sand in the fluvial parts of the rivers as a result of erosion of cut banks in meanders (Fig. 11). The thickness and regional extent of the Spodosols document the importance of humid tropical weathering as a mechanism for the production of a quartz residuum. Such an accumulation of quartz sand represents a highly significant provenance for quartz arenites. Erosion and redeposition of such deposits could result in orthoquartzites that are mineralogically mature but texturally immature (such as Lower Pennsylvanian sandstones found in the Appalachian, Illinois, and Ouachita basins of the United States). The spodic horizon appears to have formed at a paleo–water table, and probably records a previous river or estuarine level linked to an earlier glacioeustatic highstand of sea level at 9 ka to 12 ka. The 9 ka estimate is derived from ^{14}C age dating of samples acquired at the base of the domed peat deposits (Neuzil, 1997).

East Kalimantan.—

The climate of the East Kalimantan study region is humid on the basis of rainfall data collected at Balikpapan (1° 16' S) (EARTHINFO, 1966) (Fig. 12). Rivers draining East Kalimantan from the highlands of central Borneo debouch into the Makassar Strait (Fig. 13). Data from maps and satellite images indicate that most of these equatorial rivers have well defined estuaries and are without deltas (e.g., Voss, 1983). The Mahakam River, however, is enigmatic because it has a large river-mouth delta. The delta is located where the Mahakam River empties into the Makassar Strait, less than one degree south of the equator. Allen et al. (1979) describe the delta as a mixed river- and tide-dominated system. They note the strong influence of tides on the distribution of modern sediments. They also point out that data on sediment discharge of the Mahakam River were unavailable at the time of their study. An uneven distribution in monthly rainfall is indicated in the headwaters of the Mahakam River by an annual rise and fall of about 8 m in water levels in the Kutai Basin (Diemont and Pons, 1992). The Kutai Basin (the Kutei Basin of Hamilton, 1979) is a very large depression and swampy region located approximately 120 km upstream of the Mahakam Delta (Fig. 12).

The Mahakam River and many of its tributaries have their headwaters in the highlands of central Borneo. The main stem of the Mahakam River and numerous tributaries flow in a general eastward direction into the Kutai Basin, located approximately 120 km upstream of the head of the distributaries in the Mahakam delta (Fig. 13). The Kutai Basin is a large Tertiary and Quaternary structural basin (Hamilton, 1979) that is situated between a Tertiary fold belt to the east and upland areas of Borneo to the west. The modern Kutai Basin consists of a vast swamp forest (Voss, 1988, p. 42), which is thought to contain extensive areas of topogenous peat (Voss, 1988, p. 38; Diemont and Pons, 1992; Supardi, personal communication, Directorate of Mineral Resources, Republic of Indonesia, 1990) (Fig. 13). On the basis of data from numerous map sources (e.g., Voss, 1982, p. 42), the mouths of the Mahakam River and its tributaries appear to be drowned as they enter the Kutai Basin. Swampy conditions appear to extend well up the main stem of the Mahakam and its tributary rivers as they enter the swamp (Fig. 13).

The apparent lack of prograding deltas at the mouths of the Mahakam and its tributaries (where they enter the western margin of the Kutai Basin) indicates that the modern rivers are sediment starved as they debouch from the highlands of central Borneo into the Kutai Basin. The lack of sediment entering the

FIG. 11.—Spodosol (~ 7 m thick) exposed in the cut bank of a meander in the Kahayan River. The Spodosol is composed entirely of quartz with trace amounts of accessory minerals. The Spodic horizon is the dark-colored zone (~ 1 m thick) approximately 2 m above river level.

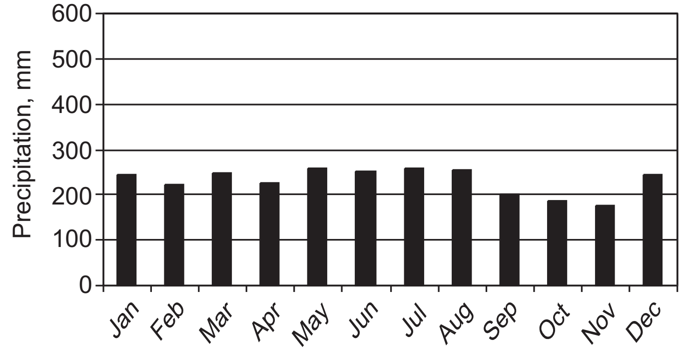


FIG. 12.—Average monthly rainfall, Balikpapan, East Kalimantan.

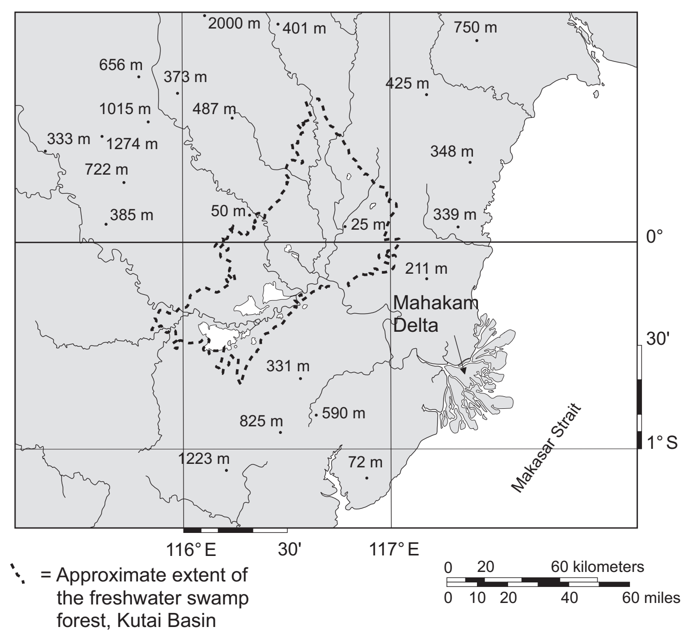


FIG. 13.—Mahakam River and delta, and modern Kutai Basin, East Kalimantan.

Kutai Basin (which in itself is a sediment trap) negates the possibility of significant sediment discharge from the highlands of central Borneo to the modern Mahakam delta and the Makassar Straits. It appears, therefore, that sediment supply from the highlands of central Borneo to the modern Mahakam delta is nil.

On the basis of ^{14}C dating, Diemont and Pons (1992) suggest that swamp conditions developed in the Kutai Basin about 5000 yr B.P. Their dates indicate that the modern swamp began to develop concurrently with the last high stand of sea level, which also occurred at about 5000 yr B.P. (Grossman et al., 1998; Hanebuth, 2000). It is unlikely that significant amounts of sediment have reached either the Kutai Basin or the modern Mahakam Delta since the inception of the swamp conditions in the Kutai Basin at 5000 yr B.P.

The available data indicate that the sediment discharge from the modern Mahakam River and its tributaries is exceedingly low. The delineations of kilometer-scale swampy conditions upstream of the central Kutai Basin strongly indicate that limited amounts of sediment have entered the Kutai Basin since the inception of swamp development, which began some 5000 yr B.P. (Demont and Pons, 1988). If large amounts of sediment were coming in from the highlands, there would be evidence of deltas prograding into the swamps of the Kutai Basin. The modern Mahakam Delta, therefore, is a relict feature that is being reworked by tidal processes. A strong tidal influence has been noted by Allen et al. (1979) and by Gastaldo et al. (1995). The modern subaerial and intertidal parts of the delta (as described by Allen et al., 1978) likely were deposited prior to 5000 yr B.P. Sea-level fall (Hanebuth, 2000) and tidal reworking during the last 5000 years probably accounts for the morphology of the modern subaerial and intertidal parts of the delta, rather than recent progradation as suggested by Allen et al. (1979).

Although the modern Mahakam River delta may be sediment starved, vast amounts of sediment have been delivered in the past. There are various explanations for the source of the sediment in the delta. It is possible that the Mahakam River is an antecedent stream that has cut and eroded the Tertiary fold belt as uplift progressed in the region between the modern Kutai depositional basin and the coast (Voss, 1988). This downcutting and lateral erosion over a downstream distance of 100 kilometers must have produced an enormous amount of sediment. Analyses of sedimentary rock fragments and quartz in cores extracted from the delta (Welton et al., 2000; Welton, personal communication, 2000) also indicate that sediment was supplied from the antecedent portion of the Mahakam River. Sediment supply from streams that are actively downcutting during uplift represents an interplay between tectonics and stream erosion, in which climate may have a secondary effect.

In addition to potential sediment supply from an antecedent stream, there may have been variations in fluvial sediment supply to the Mahakam Delta that were linked to variation in paleoclimate. Palynomorphs retrieved from cores in the delta indicate that a shift in vegetation from rainforest to grasses (savannah) occurred 18,000 yr B.P. (Caratini and Tissot, 1988). Other workers have suggested similar climate changes throughout the region (van der Kaars, 2000). A shift from rainforest to savannah vegetation correlates with paleoclimate cooling and an increase in detritus along with grass pollen, and a concomitant drop in sea level (Caratini and Tissot, 1988). We suggest that a drier and more seasonal climate may account for periods of savannah development and increased sediment supply.

There is general agreement on both sea-level and climate history during the Holocene in the equatorial Pacific, including the Mahakam Delta region (e.g., Verstappen, 1975; Stuijts et al., 1988; van der Kaars, 1988; Grossman et al., 1998; Hanebuth, 2000). During drier periods, rainforests were replaced by grasslands and the periods of grassland cover correlate with periods of increased sediment discharge. Coastal sedimentation and stratigraphy of the modern environments therefore need to be reassessed in terms of variations in sediment discharge as related to variations in paleoclimate.

Sediment supply by the modern Mahakam River and its tributaries is very low, as they flow from the highlands of central Borneo into the Kutai Basin. Because of the low sediment supply and the presence of the Kutai Basin sediment trap, it is unlikely that significant amounts of modern fluvial sediment are reaching the Mahakam Delta from the highlands of central Borneo. The presence of extensive estuaries at the mouths of other rivers along the east coast of Borneo are also indicative of low supply of fluvial sediment. Most of the sediment deposited in the Mahakam Delta may have been derived from erosion by the antecedent part of the Mahakam River. There remains a need, however, for detailed evaluation of the sediment source and sediment discharge variations of the Mahakam River and its delta.

Seram.—

The Seram study area is located approximately 3° S (Fig. 2). Rainfall data collected at Ambon indicate that the climate of Seram is perhumid (data from EARTHINFO, 1966) (Fig. 14). Unlike the other study areas, with a perhumid climate where monthly rainfall is rather evenly distributed, Seram has a four-month period (May through August) of exceedingly intense rainfall. The maximum rainfall of nearly 600 mm per month occurs in June and July (Fig. 14). This period of extremely high rainfall may be related partially to the movement of the ITCZ over the area. The overall climate, however, is controlled by the ITCZ plus maritime and orographic effects. Our investigations were conducted during July at the height of the period of most intense rainfall.

Reconnaissance investigations were conducted near the mouths of several rivers that drain the rugged southwestern coastal area of Seram (Figs.15, 16). All the streams in the study have a relatively straight course in response to rather steep gradients. These streams debouch into the Banda Sea. As a result of the tectonic setting in Seram, the coast line is rugged, the coastal plains are very narrow, and the estuaries generally are not extensive. Bottom sediment in the rivers consisted mostly of sand and pebbles with some cobbles. Water samples were collected to evaluate suspended sediment (Fig. 17, Table 2) and pH and conductivity (Fig. 18, Table 2). The pH values were relatively constant and ranged between 7.5 and 8.0. Conductivity was used to estimate solute concentrations, which ranged from a high of 125 mg/l to a low of 10 mg/l. Most solute concentrations, how-

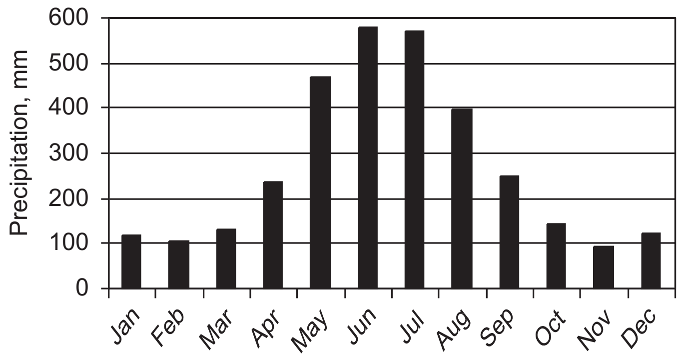


FIG. 14.—Average monthly rainfall, Ambon, Seram.

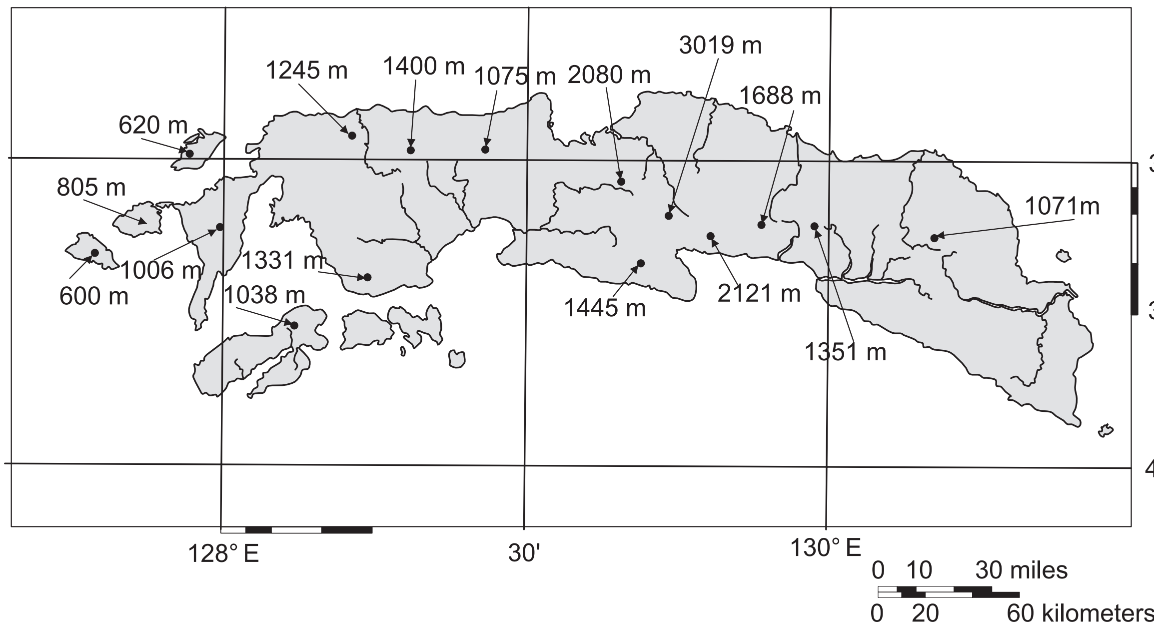


FIG. 15.—River locations and elevation of some mountains in Seram.

ever, approximated calcite saturation of 50 mg/l (Krauskopf, 1967).

Suspended-sediment concentrations clearly have a bimodal distribution directly related to the presence or absence of timbering operations in the various catchment basins. Catchments without timbering had very low suspended-sediment concentrations that ranged from a low of 7 mg/l to a high of 14 mg/l. Catchments with timbering operations have high suspended-

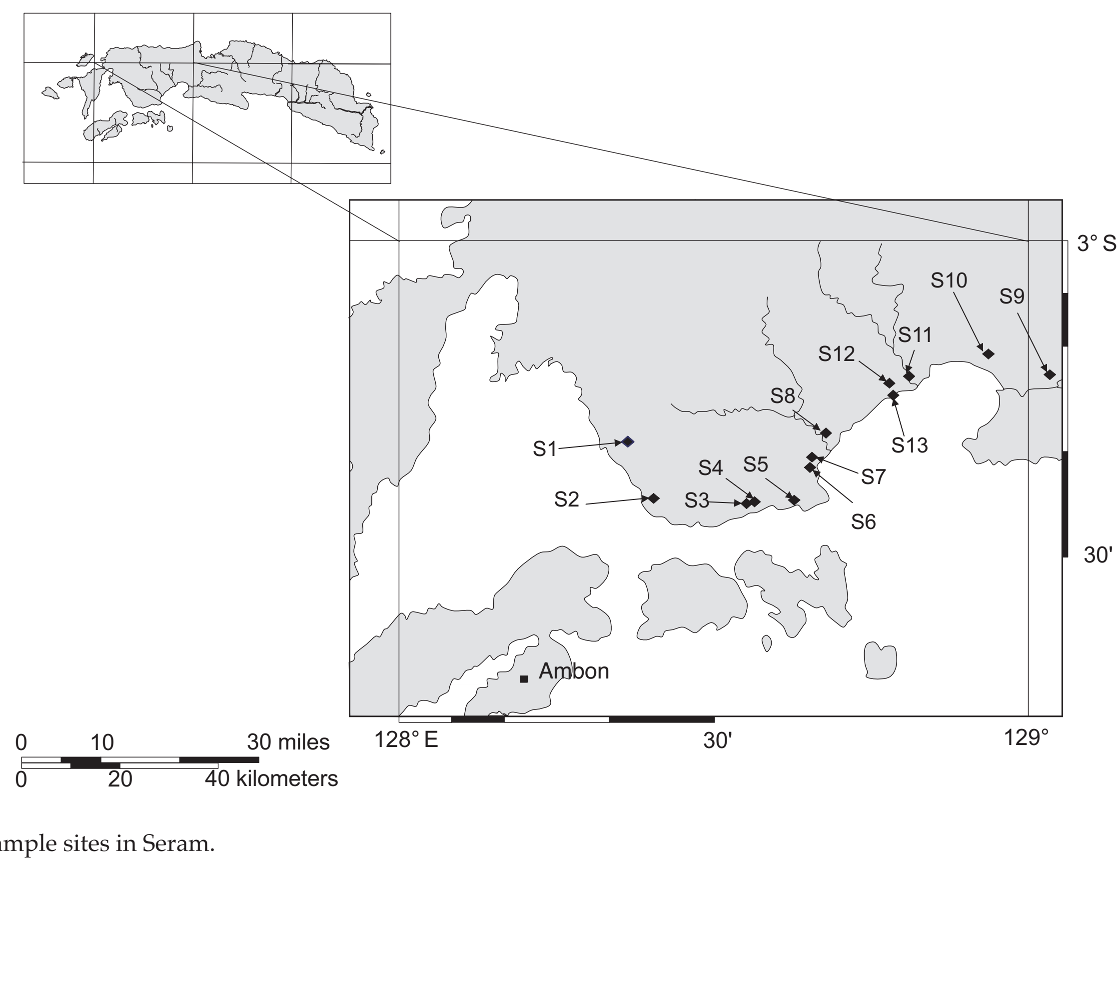


FIG. 16.—Sample sites in Seram.

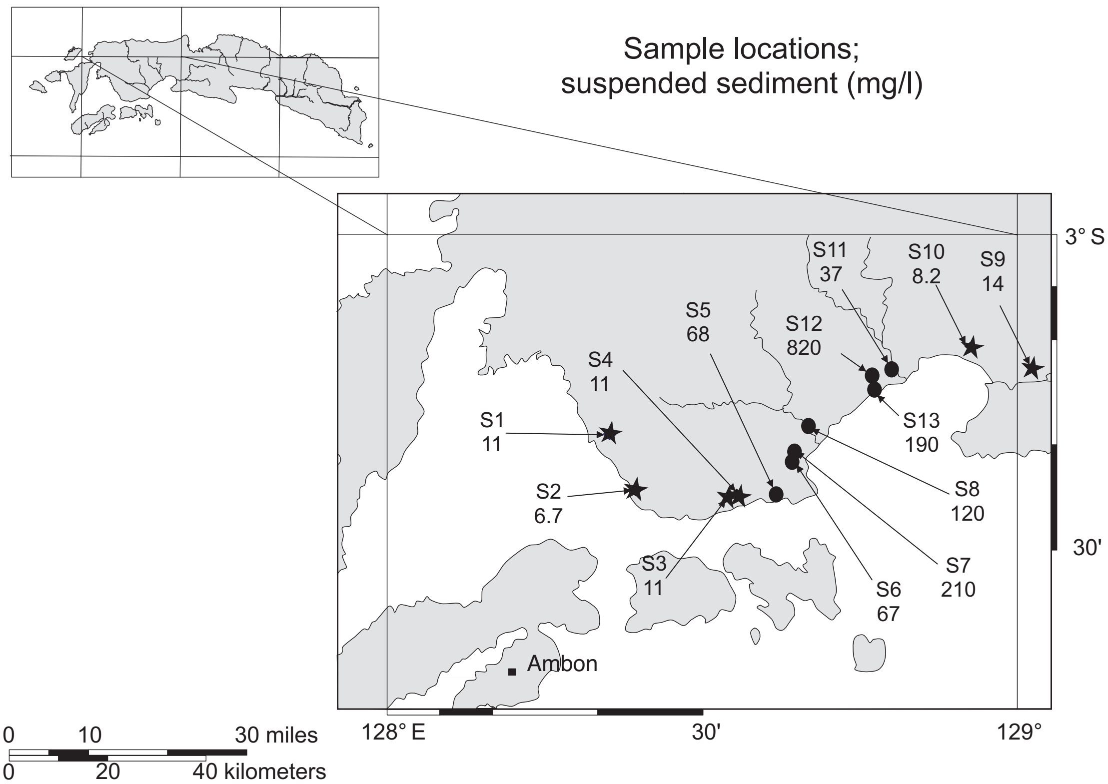


FIG. 17.—Suspended-sediment concentrations (mg/l) in pristine (star) and disturbed (dot) drainage sample locations in Seram. (Data are from Table 2.)

sediment concentrations that ranged from 190 to 820 mg/l (Fig. 17, Table 2).

Coastal zones consist of mud colonized by mangroves. Some sand beaches are present, but they are less common than mud-dominated coastlines. As in the other perhumid study areas, there is insufficient sediment coming down the rivers to fill the estuaries. Soils in the study area were not investigated.

The fluvial processes in Seram are similar to those in the study areas in Sumatra and in West, Central, and East Kalimantan. The solid-sediment and solute loads of the streams

TABLE 2.—pH, conductivity (μmohs), calculated solute concentrations, and suspended-sediment concentrations for selected rivers in Seram. Data were collected during the period of intense rainfall. Samples collected in river systems disturbed by logging operations contained suspended-sediment concentrations ranged from ≥ 200 mg/l ($\bar{X}$ = 430 mg/l = 0.43 x 10^6 metric tons/km^3 of water discharged). All other rivers had very low suspended-sediment concentrations ($\bar{X}$ = 26 mg/l = 0.026 x 10^6 metric tons/km^3 of water discharged).

ID	S Lat.	E Long.	Temp., °C	pH	conductivity μmohs	Solutes, mg/l	Solids, mg/l
S1	3° 20' 28"	128° 21' 45"	27°	7.7	203	130	11
S2	3° 25' 46"	128° 24' 25"	24°	7.3			7
S3	3° 26' 14"	128° 33' 43"	26°	7.3	58	37	11
S4-1	3° 26' 10"	128° 34' 30"	25°	6	13	10	11
S5	3° 25' 58"	128° 38' 32"	26°	7.3	61	39	68
S6	3° 22' 53"	128° 40' 03"	26°	7.3	23	16	67
S7	3° 21' 53"	128° 40' 18"	26.5°	7.4	192	120	210
S8-1	3° 19' 39"	128° 41' 41"	24°	7.6	86	54	510
S9	3° 14' 10"	129° 04' 08"	24°	7.9	78	49	14
S10	3° 12' 01"	128° 58' 01"	24°	7.5	120	75	8
S11	3° 14' 20"	128° 49' 55"	23°	7.9	90	56	37
S12	3° 15' 01"	128° 48' 02"	24°	8.0	105	65	820
S13	3° 16' 10"	128° 48' 18"	24°	8.0	89	56	190

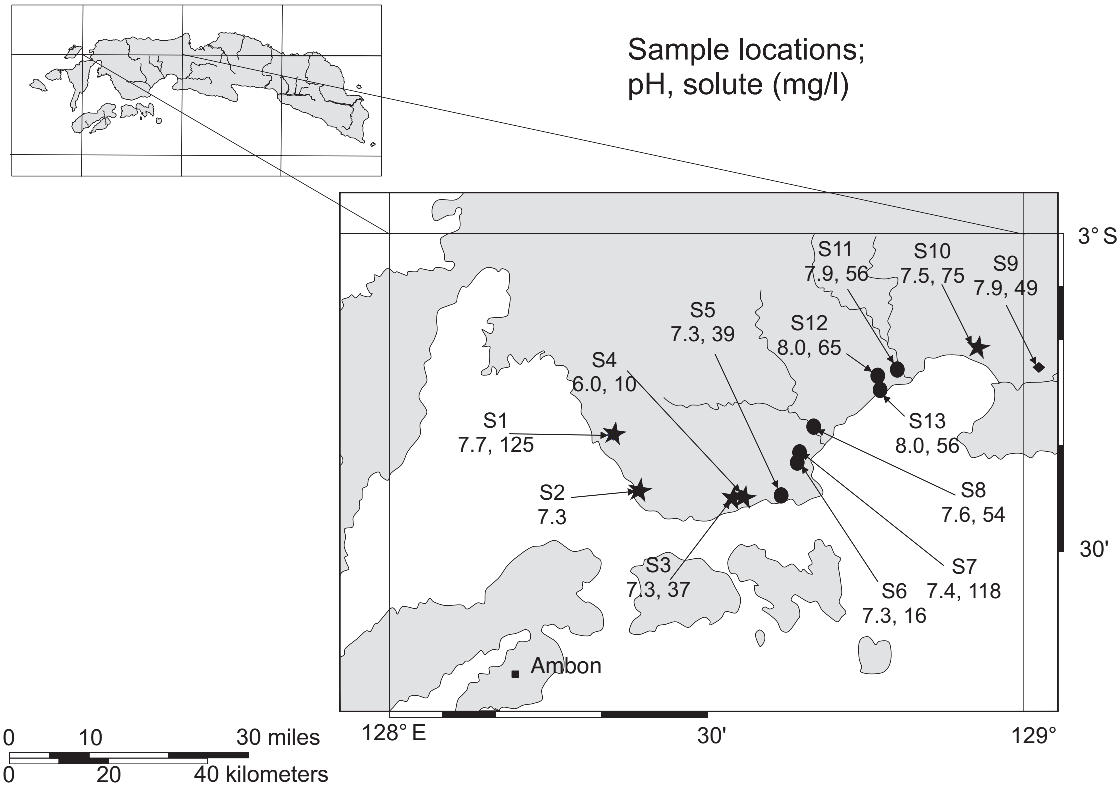


FIG. 18.—pH (left-hand values) and solute concentrations (right-hand values) in Seram. (Data are from Table 2.)

are highly restricted, except in those rivers with anthropogenic effects from timbering operations. The lack of esturine fill and prograding deltas is also indicative of the low sediment discharges. The coastal areas of Seram also appear to be sediment starved because of the lack of sediment coming down the rivers even though there is active tectonic uplift and heavy rainfall. The low sediment discharge persists in undisturbed catchment basins even during the period of extremely high rainfall. Some of the stream sampling was conducted during torrential rains, yet the stream waters were clear and free of suspended sediment. The nearly neutral pH and solute concentrations that approximate calcite saturation in the fluvial systems are probably the result of drainage from Miocene carbonates in the high mountains.

Irian Jaya.—

The island of New Guinea is one of the largest islands in the world, spanning nearly ten degrees of latitude and longitude. Irian Jaya, the easternmost province of Indonesia, covers the western half of the island. Many climatic zones occur because of the size of the island, the annual movement of the ITCZ across the island, and orographic and maritime effects. Cold and humid climates occur in the high mountains, where glaciers are present only three degrees south of the equator. In contrast, the hot climates of the coastal lowlands range from perhumid along the north coast to dry subhumid in the south. On the basis of rainfall data collected at Meruke (data from EARTHINFO, 1966) (Fig. 19), approximately 600 km to the southeast, we estimate the climate of the coastal lowlands of the study area to be moist subhumid or humid. Our reconnaissance investigation was confined to one area that ranged from the coastal plain up to near the crest of the mountains in the vicinity of 137° E, 4° S (Figs. 1, 20). The high alpine region (4000 m) is humid to perhumid and cold with remnant glaciers. Rainforests of the coastal lowlands give way to a fern-dominated vegetation in alpine areas.

The high mountains are exceedingly steep, and orographic precipitation in the form of rainfall and condensing fog is quite high. Landslides are common, and recent slides continue to partially block stream drainage. Slides probably occur at decadal time scales, and fresh landslide scars dot the alpine landscape.

Low-gradient alluvial fans occur where the rivers debouch at the foot of the mountains. Streams become braided on the fans but meander on the low-gradient coastal plain until they reach the upper estuary. The braided-stream beds consist mainly of small boulders and cobbles with lesser amounts of pebbles. The mod-

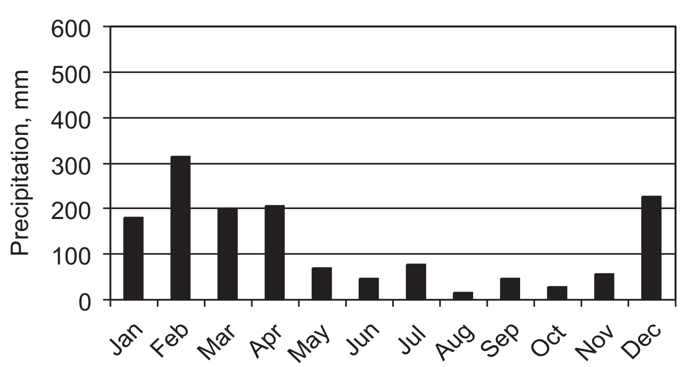


FIG. 19.—Average monthly rainfall, Meruke, Irian Jaya.

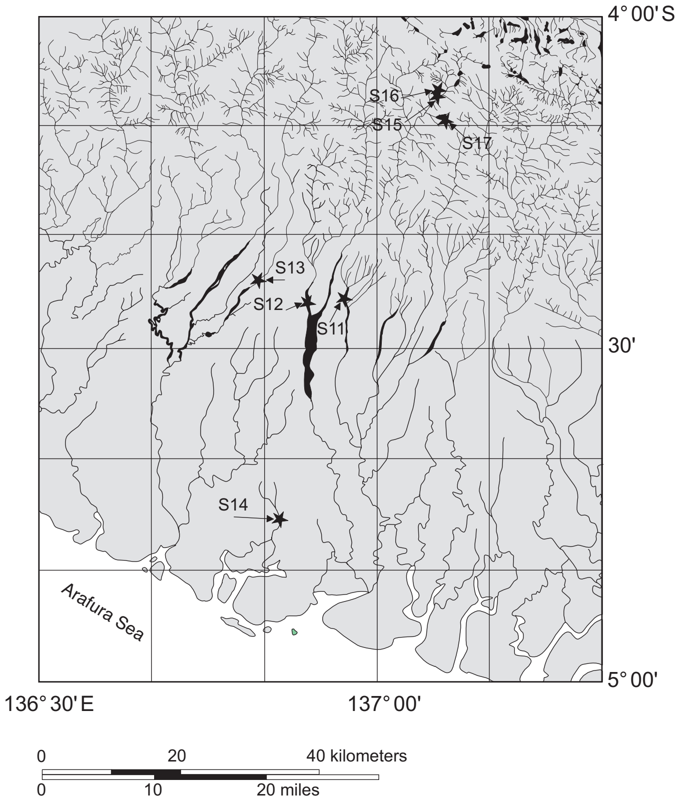


FIG. 20.—Sampling sites, Irian Jaya.

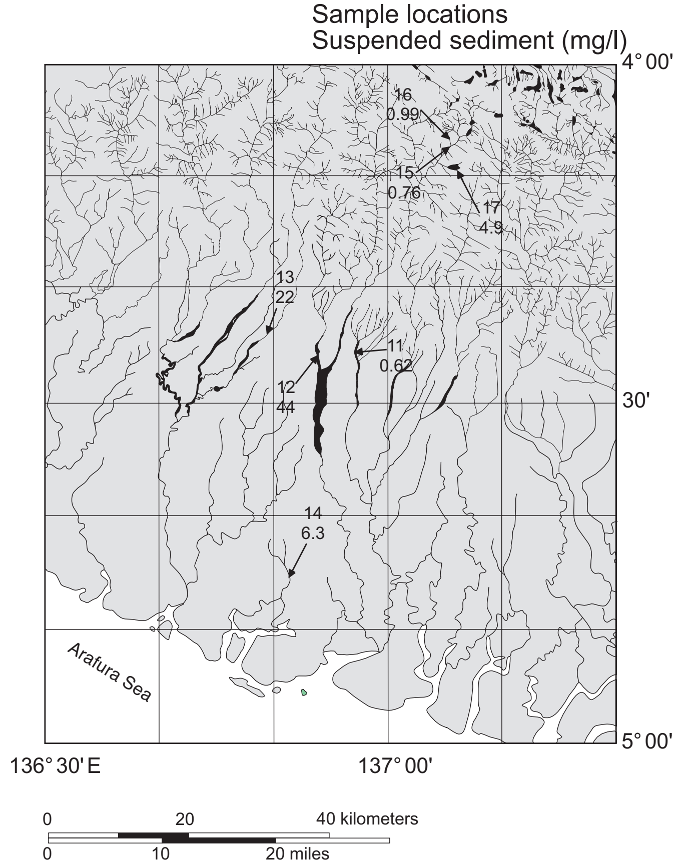


FIG. 21.—Suspended sediment, Irian Jaya. Data are from Table 3.

ern fans are vegetated with rainforest, and they do not appear to be aggrading.

The pH, conductivity, and suspended-sediment concentrations were measured in five closely spaced rivers (Figs. 21, 22; Table 3). Water from all sites had a pH of approximately 7. Conductivity measurements indicate that solute concentrations were low and near the solubility of calcite, except for station 14, which had a conductivity of 525 μmohs. The high conductivity at this locality is the result of salt-water influence in the estuary from which the sample was collected. Suspended-sediment concentrations were very low (< 50 mg/l), even in the high mountains (stations 15–17; Fig. 21, Table 3).

A low sediment discharge in the Irian Jaya study area is indicated by the presence of estuaries that extend across the coastal plain nearly to the toes of the low-gradient alluvial fans. If there were a significant sediment discharge, then we would expect the estuaries to be filled and deltas to be prograding into the Arafura Sea. On the basis of satellite imagery, filled estuaries and prograding deltas are rare. The apparent low sediment discharge in the study area in Irian Jaya is consistent with the low sediment discharges we observed in the other humid and perhumid study areas.

The alluvial fans at the base of the mountains may be the result of deposition caused by the sudden and major decrease in gradient. The very coarse material in the fans may be derived from landslides in the high mountains, or the fans may be relict features that were deposited under a more seasonal and drier climatic regime during glacial intervals.

TABLE 3.—pH, conductivity (μmohs), calculated solute concentrations, and suspended-sediment concentrations for selected rivers in Irian Jaya.

ID	E Long.	S Lat.	Temp, °C	pH	Conductivity, μmohs	Solutes, mg/l	Solids, mg/l
S11	136° 57' 12"	4° 26' 04"	25	6.9	20	14	0.62
S12	136° 53' 54"	4° 26' 13"	24.7	7.9	140	87	44
S13	136° 49' 14"	4° 23' 38"	24.7	7.7	130	81	22
S14	136° 51' 49"	4° 45' 16"	28	7.1	525	320	6.3
S15	137° 05' 46"	4° 07' 18"	15	6.9	20	14	0.76
S16	137° 05' 44"	4° 06' 44"	14	7.0	29	20	0.99
S17	137° 05' 58"	4° 09' 37"	13.5	6.7	2	3.0	4.9

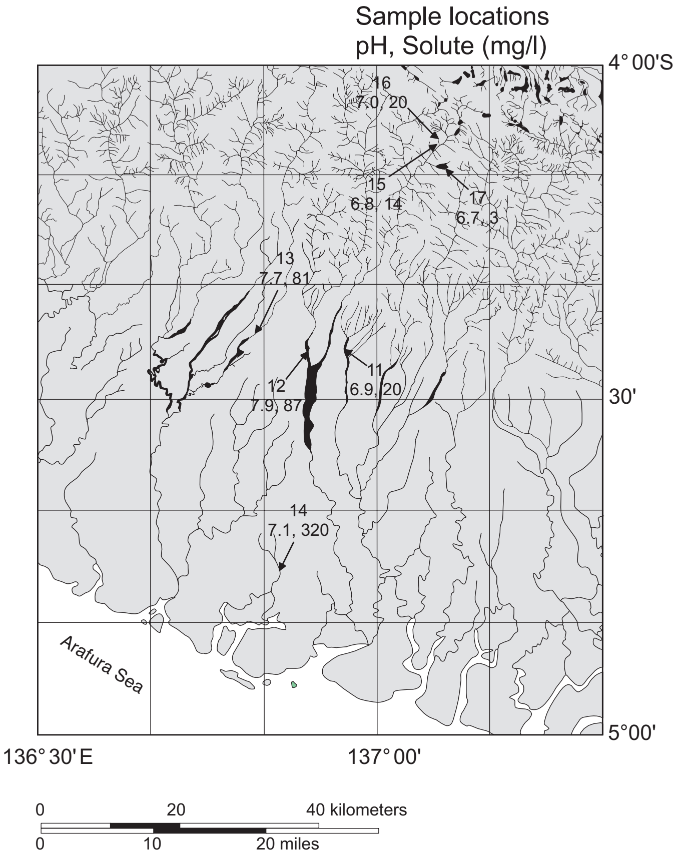


FIG. 22.—pH (left-hand values) and solute concentrations (right-hand values), Irian Jaya. Data are from Table 3.

Studies in Dry Subhumid Climates

North Coast of Java.—

The climate of northern Java (Fig. 2) is dry subhumid, on the basis of averaged monthly rainfall data collected at Jakarta (EARTHINFO, 1966) (Fig. 23). Northward-draining rivers originate in the high volcanic mountains of Java and debouch into the shallow epeiric Java Sea. Rivers along the north coast of Java are muddy and sediment laden, in contrast to the rivers in humid and perhumid areas, where the rivers are commonly black but free of sediment. Estuaries do not occur along the Java coast. If estuaries existed since the last rise in sea level, they have since been filled by sediment.

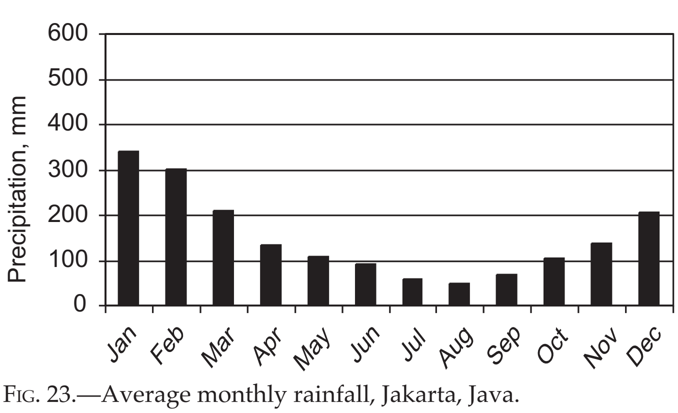


FIG. 23.—Average monthly rainfall, Jakarta, Java.

The geomorphology of the drainage basins and coastal plains of Java and Sumatra appear to be very similar. Rivers from both islands drain into the shallow epeiric Sunda Sea. Unlike the coastal plain of equatorial Sumatra, where extensive deposits of thick domed peat have formed, there are no significant amounts of peat in Java.

The similarities in catchment-basin size, heights of mountains, and stream gradients in Java and Sumatra preclude these variables as the primary control on differences in sediment delivery to the Sunda Shelf from these two islands. Sediment in the rivers in Java could be the result of anthropogenic effects, although this seems unlikely because major anthropogenic effects have not existed for a long enough period to account for the sediment fill of any estuaries. Instead, it appears that the dry subhumid climate of Java results in high sediment discharges, and also precludes peat formation. In contrast, the humid and perhumid climates of Sumatra result in highly restricted fluvial sediment discharge, unfilled estuaries, extensive deposits of peat, and sediment-starved coastal and marine environments.

West Timor.—

The West Timor study region is located between 9° and 12° S latitude (Fig. 2), and the climate of the region is dry subhumid, on the basis of averaged montly rainfall data collected at Kupang and Soe (EARTHINFO, 1966) (Fig. 25A, B). Kupang has four wet months and eight dry months, whereas Soe has four wet months plus two months where the average monthly rainfall marginally exceeds evapotranspiration and six dry months (Fig. 25A, B). The rainy season partially coincides with the passage of the ITCZ over Timor. The minor differences in rainfall between Kupang and Soe are probably related to orographic effects as a result of differences in elevation. Our field investigations were conducted during a dry season and a wet season.

Fluvial systems, both north and south of the east–west trending drainage divide in West Timor, were evaluated (Fig. 24). Rivers in the study area are braided from the mountains to the coast (Fig. 24), and bed sediments are dominated by cobbles and pebbles, with lesser amounts of sand-size material. These sediments are transported across the coastal plain to both the northern and southern coasts. The beaches are composed of cobbles and pebbles with subordinate amounts of sand near the mouths of the Mina and Benain Rivers along the southern coast (Fig. 24). Beaches near the mouth of the Tona River on the north coast (Fig. 24) were composed of sand. In contrast to mangrove forests along the sediment-starved, mud-dominated coasts in humid and perhumid regions, mangrove forests were not observed on either coast of Timor.

Two sets of samples were collected in Timor. One set of samples was collected near the middle of the eight-month dry season (August) and a second set was collected in the middle of the four-month rainy season (February). The suspended-sediment concentrations, pH, and solute concentrations are illustrated in Figures 26A and B and 27A and B, respectively, and Table 4. Water samples collected during the dry season were alkaline, and solute concentrations were one to two orders of magnitude higher than in fluvial systems in Sumatra and Borneo. Solute concentrations in water samples collected during the rainy season were also an order of magnitude higher than in samples from fluvial systems in Sumatra and Borneo and six times higher than the mean value for Seram. In contrast to the high solute concentrations, dry-season suspended-sediment concentrations were generally less than 5 mg/l (Table 4), whereas the mean value

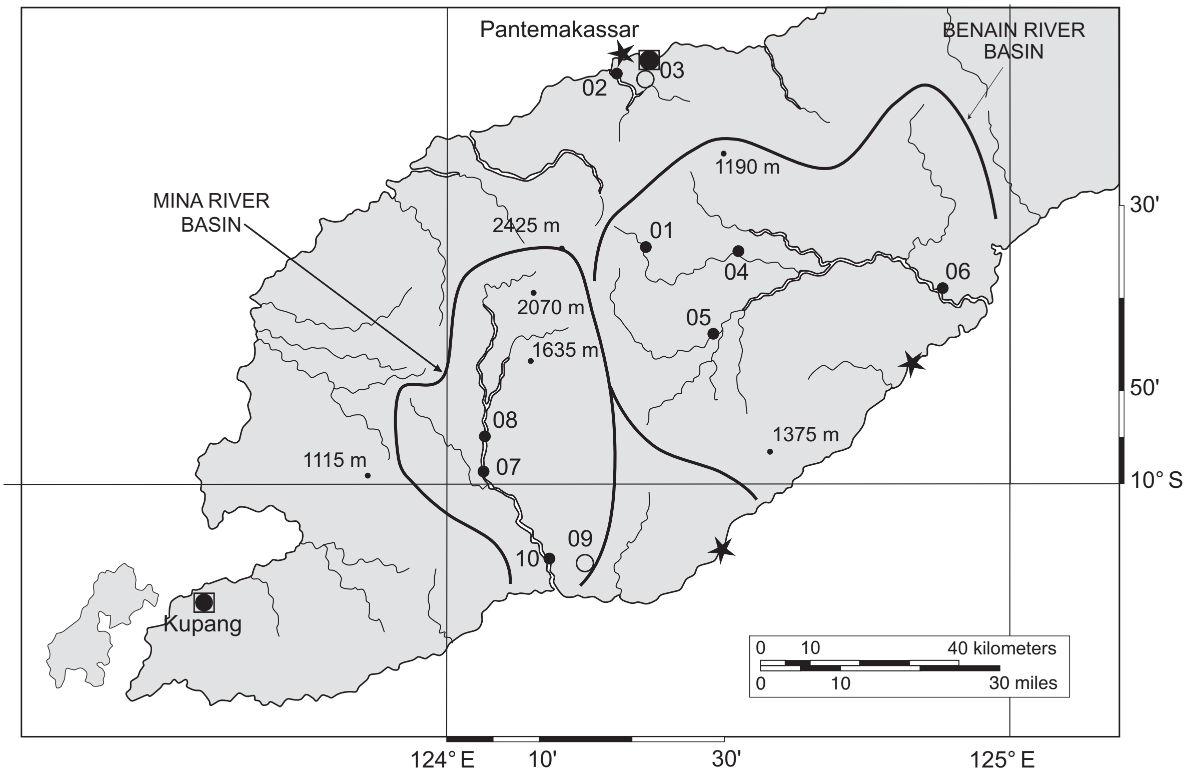


FIG. 24.—Sampling sites in fluvial systems in West Timor (○= wells, ● = rivers, and ★ = beach observation sites).

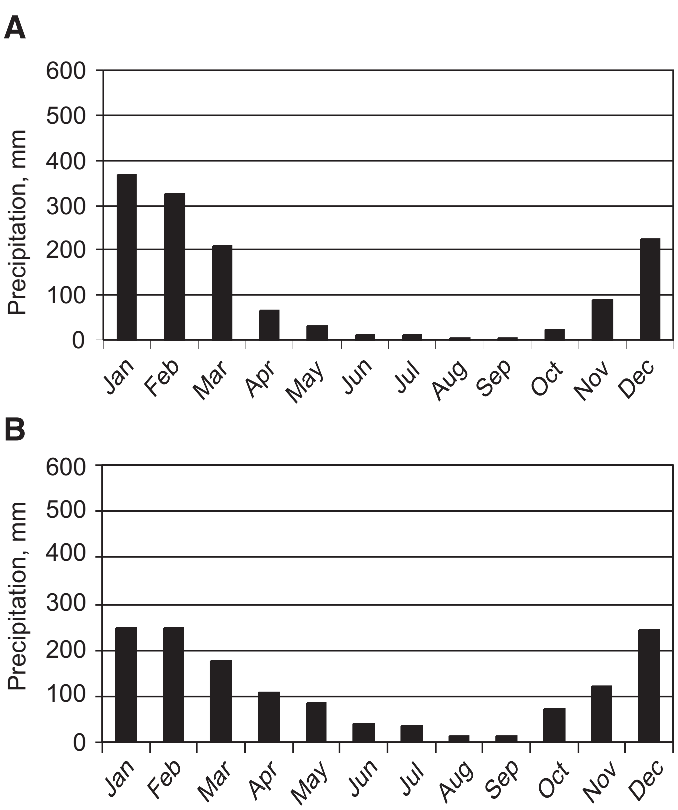


FIG. 25.—**A)** Average monthly rainfall, Kupang, West Timor. **B)** Average monthly rainfall, Soe, West Timor.

for suspended-sediment concentrations in samples collected during the rainy season was 2100 mg/l.

Samples collected in the dry season had very low suspended-sediment concentrations ($\bar{X}$ = 4.4 mg/l), consistent with the low-flow condition of the rivers. Very high suspended-sediment concentrations ($\bar{X}$ = 2100 mg/l) confirm very high sediment discharge during the four-month rainy season. All streams were braided under low flow conditions. The bed material of the braided streams and high-water marks resulting from abrasion on outcrops are indicative of a very high bed load and suspended load during rainy-season high-flow conditions. A further indication of high sediment load in the rivers of Timor is the common occurrence of river-mouth deltas and complete absence of estuaries along the coasts.

Alkaline pH values of 8 and high solute concentrations (200–500 mg/l) in samples collected during the dry season indicate that stream waters exceed calcite saturation of 50 mg/l (Krauskopf, 1967, p. 65). High solute values during the dry season indicate that streams and groundwater contain dissolved salts in addition to calcium carbonate. These high values are consistent with a high solute load in a dry subhumid climatic setting where solutes are concentrated by evapotranspiration (Cecil and Dulong, this volume, Part 1, their Figure 2).

Coral reefs, quite common in offshore areas along the southern coast of Timor, also belie major differences in sedimentology between Timor and the study areas in Sumatra and Borneo, where coral reefs were not observed. The absence of coral reefs in Sumatra and Borneo may, in part, be the result of high water discharge and low sea-water salinity (20 ppt and 30 ppt, respectively) relative to a salinity of 35 ppt for normal sea water. In coastal Timor the salinity was measured at 39 ppt during the dry season. The coarse-grained materials in fluvial and coastal sys-

TABLE 4.—pH, conductivity (μ mohs), solute concentrations (calculated from conductivity), and suspended-sediment concentrations for selected rivers in West Timor. Stream samples were collected during low-flow conditions in the dry season and moderate-flow to flood conditions in the rainy season.

ID	River	S Lat.	E Long.	Season & relative flow	Temp ., °C	pH	Conductivity, μmohs	Solutes, mg/l	Solids, mg/l
02	Tona	9° 12' 24"	124° 18' 40"	dry, low	27.9	8.2	720	440	16
03	well water	9° 15' 30"	124° 20' 53"	dry, N/A	26.7	7.2	1600	970	3.9
	Mina Basin								
07	Besi	9° 58' 39"	124° 05' 38"	dry, low	23.1	8.1	550	330	1.7
107	Besi	9° 58' 33"	124° 07' 22"	rainy, ebb flood	27.3	7.6	520	320	3500
08	Besi	9° 54' 13"	124° 05' 24"	dry, low	26.8	8.2	525	320	2.3
108	Besi	9° 58' 08"	124° 04' 21"	rainy, unflooded	30.0	7.6	650	400	55
09	well water	10° 18' 04"	124° 18' 04"	dry, N/A	26.6	8.1	2900	1800	7.0
109	well water	10° 04' 10"	124° 13' 10"	rainy, N/A	29.5		5200	3100	8.0
10	Mina	10° 05' 01"	124° 12' 15"	dry, low	28.2	8.2	775	470	4.3
110	Mina	10° 05' 01"	124° 12' 15"	rainy, unflooded	30.0	7.4	600	360	470
	Benain Basin								
01	Noni	9° 33' 28"	124° 21' 57"	dry, low		8.2	360	220	0.13
101	Noni	9° 33' 28"	124° 22' 01"	rainy, flood	24.0	7.6	230	140	1800
04	Muti	9° 33' 38"	124° 30' 20"	dry, low	22.9	8.0	500	300	0.80
104A	Muti	9° 33' 29"	124° 30' 06"	rainy, not flooding	29.0	7.5	435	260	200
104B	Muti			rainy, flooded			285	170	7600
05	Benain	9° 42' 30"	124° 27' 52"	dry, low	24.3	8.4	450	270	3.0
105	Benain	9° 42' 26"	124° 27' 58"	rainy, flood	27.3	7.5	560	340	1100
06	Benain, near coast	9° 36' 16"	124° 52' 04"	dry, low	25.1	8.4	600	360	2.4

tems in Timor, in contrast to mud-dominated systems in humid study areas, indicate that delivery and dispersal of fine-grained sediment into offshore coral habitats are not significant. Coastal and peritidal sedimentation in Timor is, therefore, one of mixed carbonates and siliciclastics. This mixed system is primarily the result of the dry-subhumid climate.

Our observations on soils in Timor indicate that Histosols do not occur and that calcic Vertisols (suborder Usterts) are very common. The highly seasonal rainfall of the dry-subhumid climate of Timor is particularly conducive to the formation of calcic Vertisols but is not conductive to the formation of soils that form under humid and perhumid climatic conditions, such as Histosols (as low-ash peat), Ultisols, Oxisols, or Spodosols (Cecil and Dulong, this volume, Part 1, and references therein).

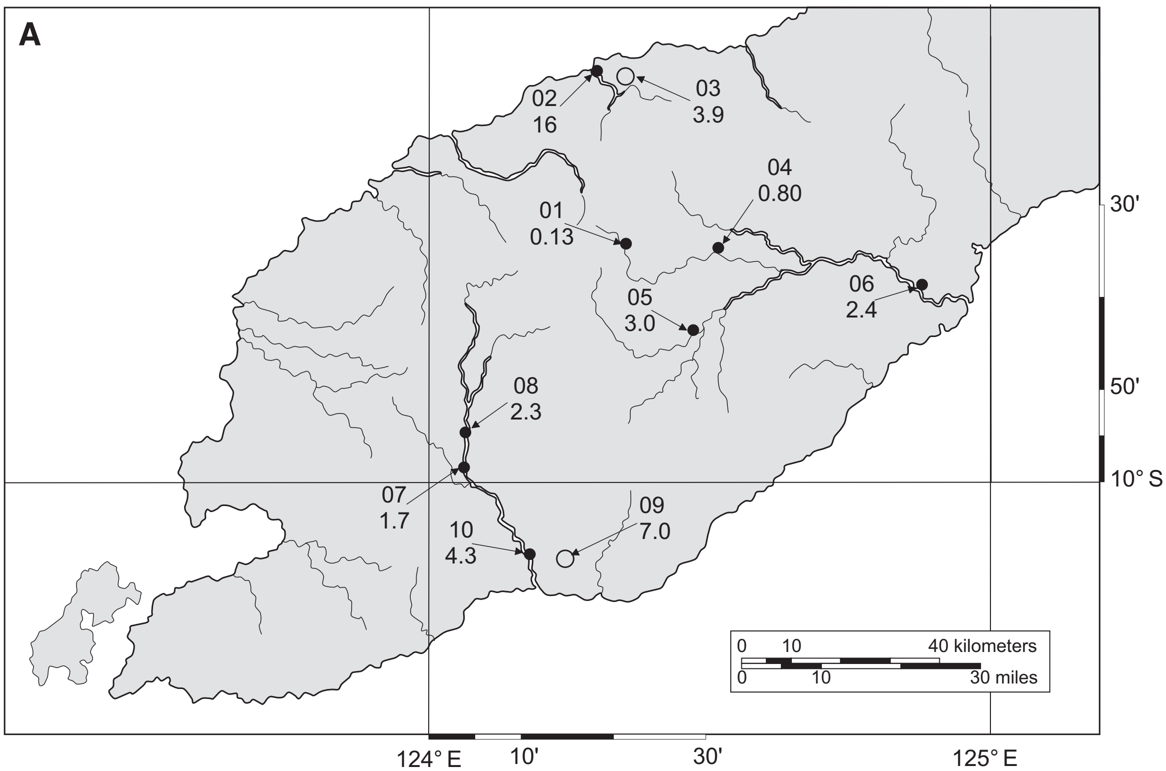
The dry-subhumid climate of Timor controls the solute load and the sediment load in rivers. Fluvial sediment discharge, both solid and solute, is especially high when compared to the perhumid study areas in Sumatra, Borneo, and Seram. The high sediment discharges are interpreted from grain size of the bed materials we observed during low-flow conditions, braided streams to the coast, the complete fill of estuaries, wave-dominated deltas and high solute concentrations throughout the year and high suspended-sediment concentration during the rainy-season high-flow conditions. The coarse-grained sediments of the Timor coasts are in sharp contrast to the mud-dominated coasts of Sumatra, Seram, and Borneo.

Given the similarities in height of mountains, stream gradients, and catchment basin-size among the various study areas, it is the difference in climate that accounts for the marked contrast in stream load and soil formation among the perhumid study areas of Sumatra, Borneo, Seram, and the dry-subhumid climate of Timor. The extensive development of calcic Vertisols and the absence of Histosols in the dry-subhumid climate of Timor are in marked contrast to the combination of extensive Oxisols, Ultisols, Spodosols, and Histosols that occur in the humid and perhumid equatorial study areas.

There are no estuaries in Timor, unlike Sumatra, Borneo, Seram, and Irian Jaya. Estuaries never developed because sediment supply kept pace with sea-level rise, or estuaries formed during early sea level rise but were subsequently filled because of the high supply of fluvial sediment. If we assume that rainy-season discharge accounts for all suspended sediment discharged by the rivers in Timor, then the annualized sediment concentration is 0.7 x 10^6 metric tons/km^3 of water discharged. The 0.7 x 10^6 metric tons/km^3 value is 60 percent of that of the Ganges/Bramaputra and 27 times that of the average value for the undisturbed rivers we sampled in Seram. The geology, including tectonic setting and geomorphology, of Seram and Timor is nearly identical. It is, therefore, the perhumid climate of Seram versus the dry-subhumid climate of Timor that best accounts for the sharp contrasts in annualized sediment concentrations and fluvial sediment supply.

SUMMARY AND CONCLUSIONS

Indonesia represents an optimal natural laboratory to study relations among allocyclic processes and fluvial sediment dis-



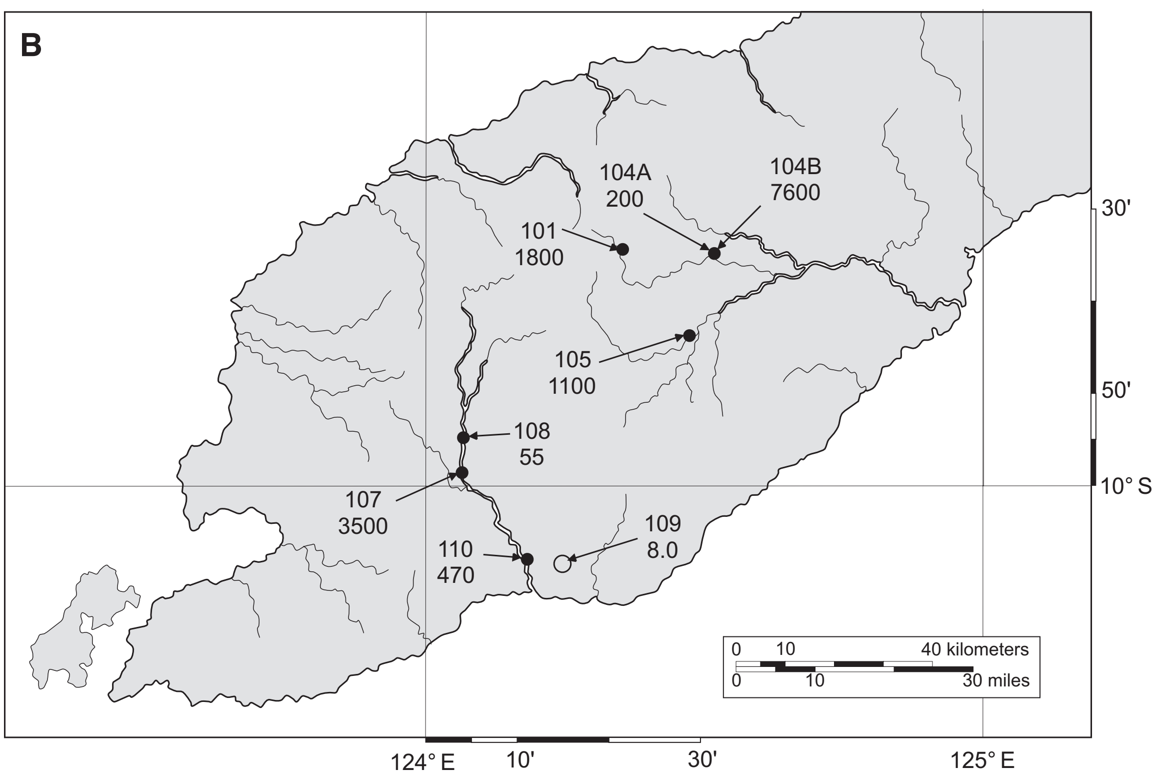
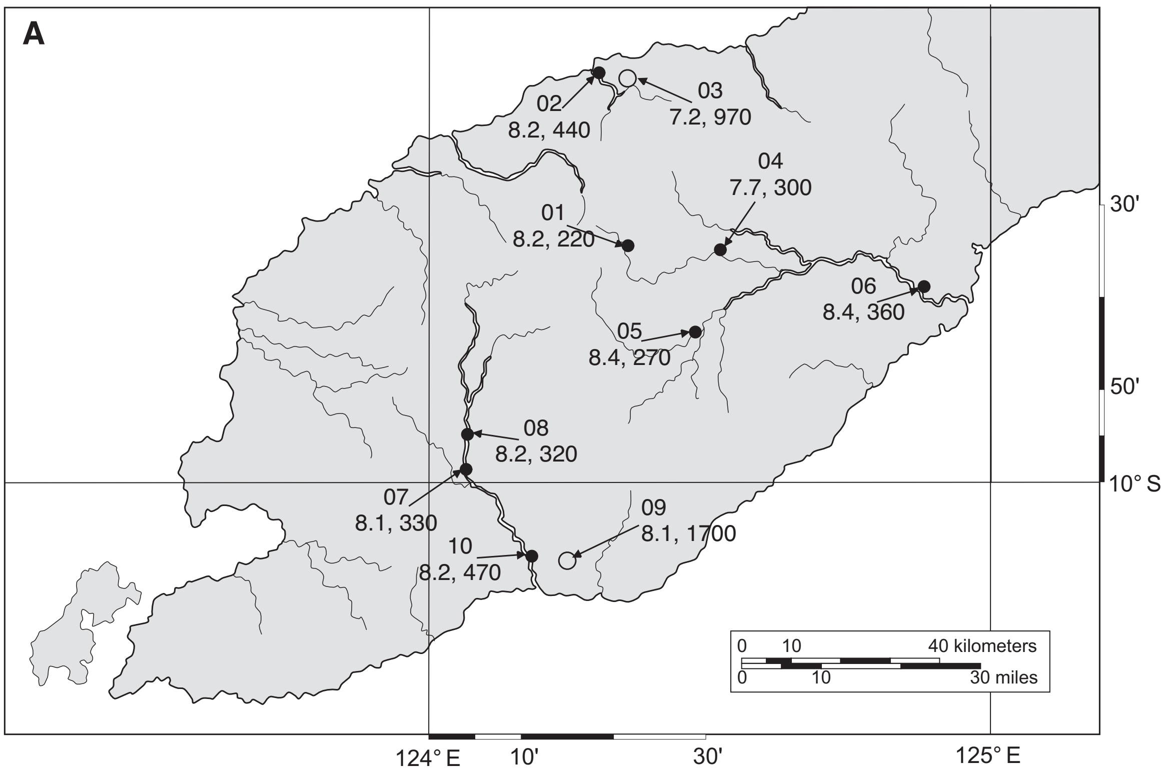


FIG. 26.—**A)** Suspended-sediment concentrations (mg/l) in West Timor, dry season (data are from Table 4). **B)** Suspended-sediment concentrations in West Timor, rainy season (data are from Table 4).



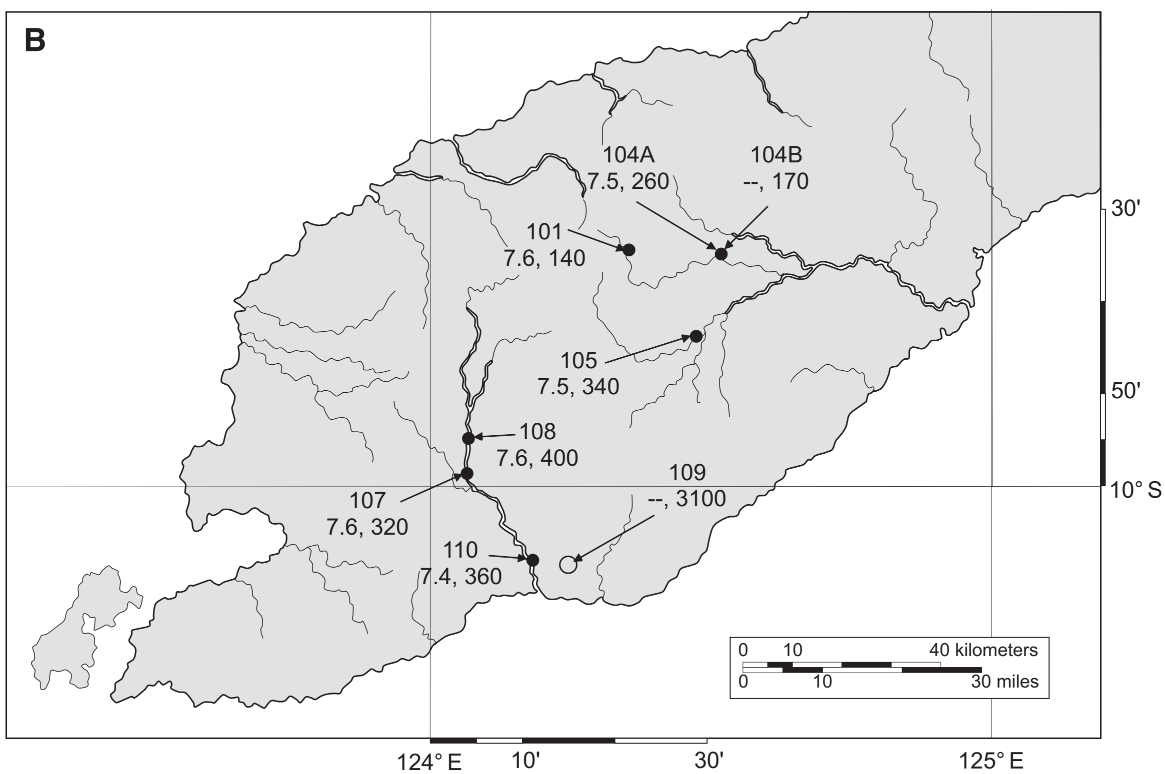


FIG. 27.—**A)** pH (left-hand values) and solute concentrations (right-hand values) in West Timor, dry season (data are from Table 4). **B)** pH (left-hand values) and solute concentrations (right-hand values) in West Timor, rainy season (data are from Table 4).

charge. Our study areas included climates that range from perhumid in Sumatra, East, Central, and West Kalimantan, and Seram, to humid in Irian Jaya, to dry-subhumid in Timor and Java, among which are settings that represent the same tectonic system in two different climates. Most Indonesian rivers in our study have similar-size catchment basins and stream gradients, and all rivers have identical glacioeustatic sea-level histories. The predominant allocyclic variable that controls variation in sediment discharge among Indonesian rivers is, therefore, climate (chiefly the amount and seasonality of rainfall).

Perhumid and Humid Climates

Rivers draining the perhumid and humid areas of Sumatra, West and Central Kalimantan, and Irian Jaya cross broad and flat coastal plains before debouching into shallow epeiric seas. The rivers evaluated in the humid climates of Seram and East Kalimantan cross a rugged coastal area with very narrow coastal plains before emptying into the deep Banda Sea and Makassar Strait, respectively. With the exception of Irian Jaya, characteristics of those settings with perhumid climates and extensive coastal plains that border epeiric seas include the following: (1) extensive Histosols and Spodosols, (3) meandering acidic blackwater rivers with exceedingly low solute and suspended-sediment concentrations but which may contain significant amounts of terrestrial organic matter, (4) limited fluvial bed loads, primarily as point bars, which diminish downstream and finally disappear before, or in, the upper estuaries, (5) extensive estuaries without sediment fill derived from fluvial systems, (6) mud-dominated, sediment-starved coastal and nearshore marine environments, and (7) the absence of nearshore coral reefs. The Irian Jaya study area differs because of the presence of low-gradient alluvial fans with braided streams between the base of the mountains and the proximal coastal plain. The active tectonic setting of Seram precludes the development of broad coastal plains, extensive estuaries, and extensive deposits of peat. The fluvial systems of Seram are, however, also sediment starved. The estuaries that do exist in Seram are not filled with sediment, and deltas have not developed. The rivers in East Kalimantan also appear to be sediment starved. Most have estuaries, except for the Mahakam River, which has a large delta. The predominant source of the sediment for the Mahakam Delta is probably from the antecedent part of the Mahakam River, which eroded the tectonically active 70-km-wide area between the delta and Kutai Basin during Neogene and Quaternary folding and uplift. Hamilton (1979) suggests that folding was concurrent with Neogene sedimentation.

Dry-Subhumid Climates

In contrast to the sediment-starved Indonesian rivers in perhumid and humid climates, river and coastal systems in the dry-subhumid climates of Timor and Java can be characterized by river-mouth deltas, sand and coarser-grained beaches, absence of estuaries, and absence of Histosols, Spodosols, Oxisols, and Ultisols. In addition, the island of Timor has characteristics that contrast with humid and perhumid regions as follows: (1) calcic Vertisols, (2) braided rivers with high annual solute loads, bed loads, and suspended loads, coarse-grained detritus in coast zones, and (4) coral reefs. Black-water rivers and mangrove forests were not observed in Timor.

The pedogenic and sedimentologic regimes of the study areas (Fig. 28) are consistent with the conceptual diagrams for soil formation and sediment supply of Cecil and Dulong (this volume, Part 1). The findings of our study reinforce the concept of climate as a primary agent of weathering, erosion, sediment transport, and sedimentation. Therefore, evaluation of paleoclimate and paleoclimate change should be included in genetic stratigraphic analysis, especially in terrestrial, coastal, continental-margin, and epeiric-seaway depositional sequences.

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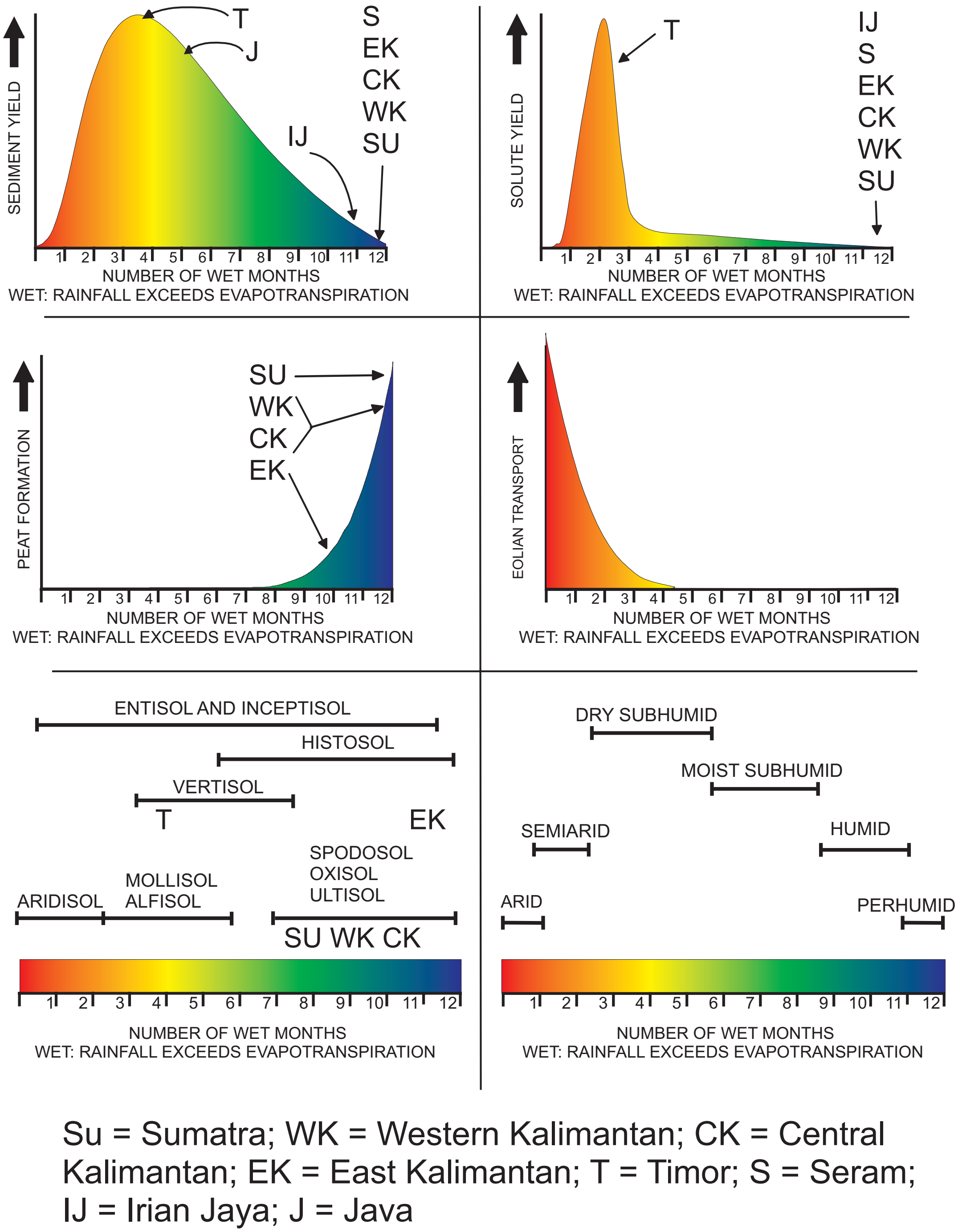

FIG. 28.—Schematic representation of sediment yield of tropical rivers and soils in Indonesia as a function of climate.

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Last Name, | First (Given) | Middle Initial | Date of Birth

Preferred Mailing Address

City | State/Province | Postal Code

Country | Phone Number

Fax Number | Citizenship | E-mail Address

Academic Record:

From	To	Institution	Major	Degree/Date

Professional Record:

From	To	Employer	Address	Nature of Work

Affiliations:

- ☐ AAPG
- ☐ PS
- ☐ IAS
- ☐ AGU
- ☐ GSA
- ☐ Other: ____________

References:

① ______________________
Name
____
Address

② ______________________
Name
____
Address

membership type:

☐ Sustaining Member $300
Financial support may be dedicated to a specific program.

☐ Voting Member .... see Journal Choice
Requires 3 years professional experience past bachelors degree.

☐ Associate Member .... see Journal Choice
Waives professional experience. May not vote or hold office.

☐ Spouse Member $30
Membership at same address without additional journal.

Journal Choice:

☐ Journal of Sedimentary Research
  ☐ Print: $75 ☐ Online: $70 ☐ Both: $85

☐ PALAIOS
  ☐ Print: $75 ☐ Online: $70 ☐ Both: $85

☐ Both Journals
  ☐ Print: $120 ☐ Online: $110 ☐ Both: $130

☐ Add $10 surcharge to defray mailing outside the USA

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☐ check/money order enclosed Total Amount:________________

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  ☐ Visa ☐ American Express ☐ MasterCard

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Fax this form with credit card information to:
918.621.1685

or mail with payment to:
SEPM Membership
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Tulsa, OK 74135, USA