Hemipelagic Sediment Accumulation Rates in the South China Sea Related to Late Quaternary Sea-Level Changes

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Sediments of 13 piston cores from opposite continental slopes of the South China Sea, off southern China and Sabah (northern Borneo), were analyzed by sedimentological methods and dated by oxygen isotope stratigraphy. Sediments mostly consist of hemipelagic clay with 20% carbonate off Sabah and 40% off China. We calculated terrigenous and carbonate accumulation rates for up to 11 time-slices from the Holocene to oxygen-isotope stage 6. Terrigenous accumulation rates generally increase with water depth and reach a maximum at the middle slope off Sabah and at the lower continental slope off China. During glacial and interglacial times this distribution pattern did not markedly change, despite an increase of accumulation rates for glacial periods by a factor of 2 to 5 compared to interglacial periods. Rates are negatively correlated with positions of sea level, which controls the partition of fluvial terrigenous material for deposition on shelf, slope, and abyssal plain. Carbonate accumulation rates are higher off China by a factor of 2 compared to Sabah, probably indicating higher calcareous plankton productivity. ©1993 University of Washington.

INTRODUCTION

Pleistocene climatic variations in combination with eustatic sea-level changes generally influenced the fluvial input of terrigenous material and its dispersal pattern on shelves, continental slopes, and abyssal plains. During glacial periods of low sea level, large parts of the shelves were subaerially exposed, weathered, and subjected to erosion. Consequently, the shelf was predominantly a source of material, whereas it has been the main sink for terrigenous material during the present and previous interglacial periods of high sea level (Vail *et al.*, 1977; Seibold and Berger, 1982; Nummedal *et al.*, 1987; Saito, 1991). Abyssal plains, especially near continents, received much more sediment by increased turbiditic transport during glacial periods as compared to interglacial periods (Nelson, 1976; Kuijpers *et al.*, 1984; Kuijpers and Duin, 1986; Soh *et al.*, 1990).

In contrast, the response of accumulation rates on continental slopes to sea-level changes is not well known, although a variety of slopes have been investigated (Diester-Haass, 1976; Thiede *et al.*, 1982; Ehrmann and Thiede, 1985). This lack of knowledge results from the

complex changes of dispersal patterns, which are induced by climatically controlled variations of subsurface currents, contour currents, and other local factors (e.g., bypassing of sediment in canyons or slumping). However, sediments from slopes should record sea-level oscillations most sensitively because the slopes are the closest depocenters to the shelves which are affected severely by sea-level changes.

Here we present sedimentological data from 13 cores recovered from the continental slopes of the marginal South China Sea. This marginal basin is more than 4000 m deep and is closely linked to the Western Pacific Ocean (Wang and Wang, 1990). It receives a high terrigenous input from its extended hinterland and from large islands. The resulting high sedimentation rates (e.g., Winn *et al.*, 1992) enable us to study in detail the interaction of Late Quaternary sediment accumulation and sea-level changes.

GEOLOGICAL SETTING AND HYDROGRAPHY

The tropical to subtropical South China Sea is the largest west Pacific marginal basin and originated by Oligocene to Miocene sea-floor spreading (Taylor and Hayes, 1980). Its passive continental margins are characterized by broad shelves to the northwest (southern China) and to the southwest (Sunda shelf) onto which large rivers such as the Si Kiang, the Hungho, and the Mekong build their deltas (Fig. 1). The shelf is very narrow off central Vietnam, probably caused by a transform fault. The moderately broad shelves along the islands of Luzon, Palawan, and Borneo are partly formed by accretion (Hinz *et al.*, 1987, 1989), which ended during the Pleistocene (Hamilton, 1979). Holocene vertical tectonic movements have not been reported in the parts of the South China Sea continental margins considered here (Yoshikawa, 1987, pp. 99 and 107).

Most of the cores were recovered along two profiles that cross the continental slope off southern China and the accretionary wedge off Sabah (Fig. 1). The slope off southern China gently lowers from the shelf break at approximately 120 m water depth to 1800 m, below which the inclination increases down to the abyssal plain (3800

FIG. 1. Map showing South China Sea and surrounding areas. The 50- and 100-m bathymetric isolines delineate the shelf, while dots show positions of cores. Terrigenous accumulation rates of four cores with encircled site positions are given in Figure 7. Bathymetric profiles A and B with core sites are shown in Figures 5 and 6, respectively.

m water depth) (Fig. 5). The outer part of the slope off Sabah is subdivided by several slope-parallel ridges and associated troughs, which are 200 to 300 m high and which are formed by accretionary processes (Hinz *et al.*, 1987, 1989). The shelf edge is defined by a rather gradual steepening near 200 m. At the seaward side of the slope, an abyssal plain lies at 2900 m water depth (Fig. 6).

The hydrography of the South China Sea is dominated by monsoonal changes. During summer, surface currents flow northeast and during winter monsoonal periods, they reverse to southwest (Wang and Wang, 1990). The pattern of subsurface circulation is only partly known (e.g., Shaw, 1991). The deep water corresponds to the Pacific Intermediate Water, which enters the 4000-m-deep South China Sea basin through the broad 2500-m-deep strait between Luzon and Taiwan (Wyrtki, 1961; Berger, 1987).

MATERIALS AND METHODS

Thirteen piston and gravity cores (Table 1, Fig. 1) obtained from various R.V. "Sonne" cruises (SO27 to

SO58, 1983 to 1988) were studied. Most of them are located on two transects across the northwestern (off Hong Kong) and southeastern (off Sabah) continental slopes of the South China Sea. In addition, one core (SO49 37KL) was recovered off southern China from the northern slope of the Xisha continental block, which is morphologically separated from the continental slope of South China by the erosional Xisha channel (Kudrass *et al.*, 1992). Another additional core was taken off Palawan (SO27 91KL) from the northwestern flank of the Palawan Trough, approximately 900 m above the deep-sea plain. Cores of the Sabah margin are mostly located on small elevated positions or narrow ridge crests.

Most of the cores are composed of bioturbated, calcareous to terrigenous hemipelagic mud with carbonate contents of up to 40% on the Chinese margin and up to 20% on the Sabah side. The sand fraction, generally varying between 2 and 10%, is dominated by planktonic foraminifera and fine-grained quartz. Several turbidities are encountered in abyssal plain sediments off Sabah (SO58 109KL). Two cores from the lower slope off Sabah (SO58 110KL and SO58 114KL) contain in their Pleistocene sections mottled, bioturbated, centimeter-thick, sandy layers with no primary laminations or grading, and are therefore interpreted as contourites.

Volume-defined subsamples were taken from hemipelagic sediments in 5- to 20-cm intervals using the syringe method. Samples were dried at 60°C and the salt-corrected bulk dry-density was calculated from weights before and after drying. The relative error of these determinations owing to laboratory procedures (Boyce, 1976)

TABLE 1
Coordinates, Water Depths, and Core Recovery of Piston and Gravity Cores from the South China Sea

Core No.	Latitude (N)	Longitude (E)	Depth (m)	Core length (cm)
(a) Continental slope of Southern China				
SO49 3SL	19°35.23'	114°11.64'	713	365
SO49 8KL	19°19.47'	114°20.84'	1040	965
SO49 12KL	19°01.20'	114°29.91'	1532	920
SO49 37KL	17°49.04'	112°47.09'	2004	1310
SO50 29KL	18°26.08'	115°39.22'	3766	993
SO50 37KL	18°54.60'	115°45.78'	2695	851
(b) Northern flank of Palawan Trough				
SO27 91KL	08°33.45'	115°41.48'	2060	1470
Continental slope of Sabah				
SO49 136KL	05°58.43'	114°41.85'	650	805
SO49 137SL	05°55.77'	114°47.78'	220	115
SO58 109KL	06°12.73'	114°03.89'	2792	1223
SO58 110KL	06°10.73'	114°06.30'	2238	1208
SO58 114KL	06°05.88'	114°14.37'	1929	1311
SO58 133KL	06°39.41'	114°43.24'	2136	1300

Note. These positions are also indicated in Figure 1.

is considered to be in the range of $\pm 2.5\%$. The carbonate content of the samples was assessed by gas-volumetric analysis with a relative error (σ -value) of $\pm 0.7\%$ according to 22 parallel measurements. The noncarbonate fraction is considered to be terrigenous material because volcanic ash particles, diatoms, radiolarians, sponge needles, and diagenetic minerals (i.e., pyrite) are rare.

Isotopic analyses were carried out with a Finigan MAT 251 mass spectrometer at the Institut für Kernphysik, Kiel University. We used 10 to 20 tests of the planktonic foraminifer *Globigerinoides ruber* (white variety), with a size range between 125 and 315 μm . From cores SO50 29KL and SO50 37KL *Globigerinoides sacculifer* (Winn *et al.*, 1992) and from core SO49 8KL *Uvigerina* div. sp. were used because of the greater abundance of these fo-

raminifera (Fig. 2). The isotope ratios are expressed in permil relative to the PDB standard (Craig, 1957). The relative accuracy of the measurements ranges from ± 0.01 to $\pm 0.07\text{‰}$.

Redeposition of foraminiferal tests is considered to be minimal as *G. ruber* (pink variety), which has its last occurrence at isotopic stage level 5.5, was not found in any sample above that level. In addition, only very well-preserved tests were used for the isotopic analysis, as damaged tests which were scarcely recorded in the residues are assumed to indicate redeposition. The analyzed grain-size fraction is also assumed to be not intensively transported by the slow near-bottom currents usually prevailing on the continental slope. Thus, negative effects on the isotopic curves are thought to be minimal.

FIG. 2. Oxygen isotope records of 13 cores from the South China Sea; the isotopic events according to Pisias *et al.* (1984) and Prell *et al.* (1986) which were used for the determination of accumulation rates are marked. *Globigerinoides ruber*, white, was analyzed in all cores, except cores SO50 29KL and SO50 37KL, in which *G. sacculifer* was used (Winn *et al.*, 1992). In core SO49 8KL, the isotopic record of the benthic foraminifer *Uvigerina* is used. ▽, last occurrence of *G. ruber* (pink variety).

We applied the oxygen isotope stratigraphy as a chronostratigraphic tool to calculate accumulation rates. A detailed taxonomy of isotopic fluctuations was established by Pisias *et al.* (1984) and Prell *et al.* (1986). Oxygen isotopic events were identified by graphic correlation with the composite record of Prell *et al.* (1986, Table 3) as indicated in Figure 3. The absolute age of the late Pleistocene and Holocene oxygen isotopic record was determined by conventional and Accelerator Mass Spectrometer (AMS) ^{14}C analyses (Duplessy *et al.*, 1986; Bard *et al.*, 1987; Broecker *et al.*, 1988), and the ages of older fluctuations were estimated by orbital tuning methods (Imbrie *et al.*, 1984; Martinson *et al.*, 1987). The ^{14}C timescale was recently calibrated with parallel $^{230}\text{Th}/^{234}\text{U}$ measurements (Bard *et al.*, 1990; Fairbanks, 1990; Sarnthein and Tiedemann, 1990, p. 1043). The absolute accuracy is ± 100 yr for the U/Th ages and ± 5000 yr for the rest of the events. The oxygen isotopic events and their absolute ages, as considered in this paper, are given in Table 2.

Rates of accumulation for terrigenous and carbonate material were calculated using the following equations (Van Andel *et al.*, 1975):

$$AR_{\text{carb.}} = (LSR * DD) * CC/100 \quad (1)$$

$$AR_{\text{terr.}} = (LSR * DD) * (100 - CC)/100, \quad (2)$$

FIG. 3. Oxygen isotope record of core SO49 37KL and the composite record of Prell *et al.* (1986; Table 3). The isotopic events 1.1 to 6.2 as defined by Pisias *et al.* (1984) and given by Prell *et al.* (1986; Fig. 10) were identified at our record by graphic correlation.

TABLE 2
Oxygen Isotopic Events, Absolute Ages, and Isotope Stages

Oxygen isotopic event	Age [10 ³ yr]	Isotope stage
1.1	9.8	1
2.0	13.9	—
2.2	18.3	2
3.1	29.5	—
3.3	50.2	3
4.0	59.0	—
5.0	73.9	4
5.2	91.0	—
5.4	110.8	5
5.5	123.8	—
6.0	129.8	—
6.2	135.1	6

Note. Isotopic events are designated according to Prell *et al.* (1986). Events 1.1 to 3.1 are based on Th/U calibrated radiocarbon ages (after Sarnthein and Tiedemann, 1990), while the ages of Events 3.3 to 6.2 have been determined by orbital tuning methods (Martinson *et al.* 1987).

where AR is the accumulation rate in $\text{g/cm}^2 * 1000$ yr, LSR is the linear sedimentation rate in $\text{cm}/1000$ yr, DD is the dry density in g/cm^3 , and CC is the percentage of carbonate content. The LSR is an estimation between age-control points defined as oxygen isotopic events and thus yields a constant value over the time interval regarded. Mean values of dry density and carbonate content were calculated for these time intervals and were used to calculate accumulation rates. The accumulation rate for terrigenous material is a maximum estimate because it is calculated by subtracting the carbonate fraction from the total sediment. By this calculation, terrigenous accumulation rates are slightly enlarged by negligible amounts of siliceous plankton, volcanic ash, and diagenetic minerals. Turbidites were excluded from the calculation of hemipelagic accumulation rates. Contourites in cores SO58 110KL and SO58 114KL, however, were included. These contourites are mud contourites *sensu* Faugeres *et al.* (1984) and their sand content varies from 3 to 7% and differs only slightly from that of the hemipelagic sediments (0.5 to 2%). Thus, they were probably formed by local winnowing of hemipelagic sediment on top of the small ridges in which the cores were recovered and do not indicate long-distance lateral transport.

For a comparison of accumulation rates with sea-level oscillations, we used Shackleton's (1987) sea-level curve (Fig. 4). This curve, which was calculated from the oxygen isotopic record and calibrated by U/Th-dated reef terraces extending back 135,000 yr before present, was tuned with the oxygen isotopic ages (Table 2) of the South China Sea cores. We assessed five periods of fairly constant high, low, or rapidly changing sea level: the Holocene (Events 0 to 1.1), the Termination I (Events 1.1 to 2.2), the last glacial age (Events 2.2 to 5.4), the last in-

FIG. 4. Sea-level changes as deduced from oxygen isotopes and calibrated by U/Th-dated reef terraces (Shackleton, 1987). The indicated five times slices are used to calculate accumulation rates for all cores (Figs. 5 and 6).

terglacial age (Events 5.4 to 5.5), and the Termination II (Events 5.5 to 5.2).

RESULTS

Stratigraphy

The oxygen isotopic curves (Fig. 2) can be correlated with the stacked isotope record (Pisias *et al.*, 1984; Prell *et al.*, 1986) as demonstrated for core SO49 37KL (Fig. 3). Sediments of five cores represent a period back to the last interglacial age. Although cores SO49 8KL, SO49 12KL, and SO27 91KL recovered older deposits back to isotope stages 6, 9, and 10, respectively, only the last glacial–interglacial cycle is considered here. Cores with a high sedimentation rate and closely spaced analyses (e.g., SO58 110KL) show high-frequency isotopic variations of $\pm 0.5\%$ which may be due to slight redeposition of sediment or local high-frequency variations of paleoceanographic conditions.

Isotope Event 5.5 coincides with the last appearance of *G. ruber* (pink variety) as in the adjacent Sulu Sea (Vollbrecht and Kudrass, 1990) and elsewhere in the Indo-Pacific Ocean (Thompson *et al.*, 1979). This was used as an independent test of our age model obtained from the oxygen isotope record.

Accumulation Rates on the Continental Slope Off Southern China

With the exception of core SO49 3SL at 713 m, terrigenous accumulation rates (Fig. 5) generally increase with

water depth and approximately double at depths beyond 2500 m as compared to those of the upper continental slope. This trend shows no change in time. The lowest accumulation rates were found at almost every core site during the Holocene or the last interglaciation. The Holocene section is missing in core SO49 3SL from the upper continental slope due to erosion. The highest rates were found during Terminations I and II, when sea level rose rapidly by more than 100 m in a few thousand years. On the upper slope, the glacial-age accumulation rates are similar to those during the terminations, with the exception of core SO49 12KL. They are lower, however, at greater water depths (SO50 37KL and SO50 29KL).

Carbonate accumulation rates, again with the exception of SO49 3SL, are fairly constant between 1040 and 2700 m water depth and decrease in greater water depths by a factor of 2, which is probably caused by dissolution (Wu *et al.*, 1991). Rates of terrigenous and carbonate accumulation are positively correlated in each core, indicating redeposition (see below).

Accumulation Rates on the Continental Slope Off Sabah

Holocene terrigenous accumulation rates (Fig. 6) considerably increase downward by a factor of up to 14, at 1930 m water depth, and slightly decrease to greater water depths at the outer accretionary wedge off Sabah. This regional pattern, with a depocenter between 800 and 2000 m water depth, did not change during the late Pleistocene, even though late Pleistocene accumulation rates were significantly higher by a factor of 2 to 5. The terrigenous accumulation rates during the last glacial age were higher by a factor of 1.2 to 1.6 than during Termination I. In cores SO58 133KL and SO27 91KL, the last interglacial age had an accumulation rate similar to the Holocene.

Carbonate accumulation rates vary much less in space and time. With the exception of core SO49 137SL at 220 m depth, they change during the various Pleistocene intervals by a factor of 2 at maximum. The highest carbonate accumulation rates are found in the same depth interval as those of terrigenous material, i.e., between 800 and 2000 m. Off Sabah, changes of carbonate accumulation rates with time are not correlated to changes of terrigenous rates. The carbonate rates had their maximum during Termination I, while the terrigenous accumulation rates were highest during the last glacial age, as observed in cores SO27 91KL, SO58 110KL, and SO58 and 133KL (Table 3, Fig. 6).

Terrigenous Accumulation Rates and Mean Sea Level

Terrigenous accumulation rates of selected cores and sea-level data were averaged for various Holocene and

FIG. 5. Bathymetric profile across the continental slope of southern China (for position, see Fig. 1A) with location of cores. The average accumulation rates in up to five time slices are shown for the terrigenous and carbonate sediment fraction. Cores SO49 37KL, SO50 37KL, and SO50 29KL are not lying on the profile, but are positioned on the profile according to their water depth.

Pleistocene time-slices (Table 3, Fig. 7). The highest accumulation rates are recorded on the continental slope off Sabah (SO58 133KL) and the lowest are found at the northwestern, seaward flank of the Palawan Trough (SO27 91KL). Terrigenous rates show significant fluctuations in time, but most of the maxima and minima appear synchronous and are negatively correlated with mean sea level. The highest flux of terrigenous material occurred from 29,500 to 18,300 yr B.P., when the sea level reached its lowest stand during the last glacial maximum. A second, smaller maximum is recorded from 59,000 to 50,200 yr B.P. and is only displayed by cores SO49 37KL and SO58 133KL. The lowest accumulation rates were recorded in all cores during periods of high sea level, i.e., during the Holocene and the last interglacial age.

The terrigenous accumulation rates for each core are negatively correlated to the mean position of sea level. Correlation coefficients range from -0.536 to -0.906 for $n = 9$ to $n = 7$ data pairs, respectively. The coefficients are within the 5% confidence limits and are thus significant.

DISCUSSION AND CONCLUSIONS

Terrigenous Accumulation Rates

Terrigenous accumulation rates in the South China Sea show a complicated pattern of spatial and temporal variations. Although regional differences are recognized, the transects off China and Sabah display some resemblance. Terrigenous rates commonly increase with water depth down to the middle or lower continental slope. The highest accumulation rates are recorded in intermediate water depths off Sabah, whereas the depocenter on the continental slope off southern China lies at the lower-most slope. This distribution pattern primarily reflects differences in the intensity of downslope transport. Off China, the capacity of downslope transport is greater and more material is transferred to greater water depths than off Sabah.

Although sediment availability is at its maximum on the upper slope, because the continental source is nearby, most of the terrigenous material is not deposited in that area, but instead is transferred to deeper slope

FIG. 6. Bathymetric profile across the outer accretionary wedge off Sabah (for position, see Fig. 1B) with location of cores. The average accumulation rates in up to four times slices are shown for the terrigenous and carbonate sediment fraction.

sections. Transfer processes probably include gravity-driven transport in the near-bottom nepheloid layer as well as transport in suspension within large depth intervals of the water column.

As on other continental slopes (Bein and Fütterer, 1977; Aloisi *et al.*, 1982), transport in the near-bottom nepheloid layer, which is created by winnowing and bioturbational resuspension, is most probably the main conveyor of sediment from upper to deeper slope. However, accumulation rates in cores from morphological elevations on the slope and data from sediment traps (Jennerjahn *et al.*, 1992) indicate that in the northern South China Sea significant amounts of hemipelagic sediment are transported by suspension in the water column. For instance, core SO49 37KL is recovered from a position which is completely disconnected from the near-bottom transport on the Chinese margin: lying south of the erosional Xisha Channel (Kudrass *et al.*, 1992) and 750 m above the channel floor (Fig. 1). Nevertheless, accumulation rates of terrigenous material (Fig. 5) of this core are as high as those in cores from the neighboring continental slope, indicating long-distance lateral transport in suspension.

Data from a sediment trap (Jennerjahn *et al.*, 1992) confirm the conclusion that, off southern China, suspended terrigenous material is transported far beyond the shelf break. This trap anchored at 3750 m water depth

near coring site SO50 29KL and recorded 1000 m below sea surface approximately the same terrigenous flux as at 3350 m, i.e., 400 m above the sea floor. This flux of about $1.2 g/cm^2 \cdot 10^3 yr$ compares quite well with the Holocene accumulation rate of $2.7 g/cm^2 \cdot 10^3 yr$ as determined in the nearby core.

Hydrographic conditions off Sabah are different. The highest accumulation rates in the middle of the slope indicate active near-bottom downslope transport which is decelerated by accretionary ridges and associated basins at the outer slope. Suspension transport to the seaward, northern flank of the Palawan Trough is very low, as reflected in core SO27 91KL by accumulation rates an order of magnitude lower than those on the adjacent slope.

Based on the invariable distribution pattern of accumulation rates, the hydrographic conditions on the two continental margins have not changed essentially since the last glacial age. During interglacial ages, however, accumulation rates (Fig. 5) off China were very low, indicating that the fluvial supply of terrigenous material to the continental slope was significantly reduced. As carbonate accumulation rates (Fig. 5) were also significantly reduced, even in cores from shallow parts of the continental slope that were not affected by the increased interglacial carbonate dissolution (e.g., Thunell *et al.*, 1992), it can be concluded that the carbonate production was lower. Increased concentrations of foraminiferal sand in

TABLE 3

Linear Sedimentation Rates, Mean Dry Densities, Mean Carbonate Contents, and Terrigenous and Carbonate Accumulation Rates for Intervals between Isotopic Events

Core No.	Interval between isotopic events	Linear sedimentation rate (cm/10 ³ yr)	Mean dry density (g/cm ³)	Mean carbonate content (%)	Carbonate accumulation rates (g/cm ² * 10 ³ yr)	terrigenous accumulation rates (g/cm ² * 10 ³ yr)
SO49 3SL	1.1-2.2	41.71	0.97	18	7.28	33.17
SO49 8KL	0-1.1	2.24	0.65	36	0.53	0.93
	1.1-2.2	4.71	0.81	34	1.3	2.52
	2.2-4.0	8.12	0.76	28.1	1.73	4.44
	4.0-5.0	4.7	0.76	26.8	0.96	2.61
	5.0-5.4	1.9	0.84	32.7	0.52	1.07
	5.4-5.5	0.77	0.84	36.5	0.24	0.41
	5.5-6.2	5.31	0.84	30.6	1.36	3.1
	2.2-5.4	5.09	0.77	29.7	1.16	2.75
SO49 12KL	1.1-2.2	4.71	0.75	30	1.06	2.47
	2.2-5.4	2.27	0.84	34.1	0.65	1.26
	5.4-5.5	1.54	0.79	39.9	0.48	0.73
	5.5-6.2	4.42	0.82	35	1.27	2.36
SO49 37KL	0-1.1	5.1	0.61	31.2	0.97	2.14
	1.1-2.0	6.1	0.55	25	0.84	2.52
	2.0-2.2	12.5	0.47	19	1.12	4.76
	2.2-3.1	10.71	0.53	19.3	1.1	4.58
	3.1-3.3	5.31	0.53	25.3	0.71	2.1
	3.3-4.0	10.8	0.58	26.1	1.63	4.63
	4.0-5.0	4.7	0.67	18.6	0.59	2.56
	5.0-5.4	7.67	0.67	21.5	1.1	4.03
	5.4-5.5	2.46	0.54	27.1	0.36	0.97
	5.5-6.0	10	0.63	28.4	1.79	4.51
	6.0-6.2	7.55	0.64	19.7	0.95	3.88
	1.1-2.2	9.41	0.51	21.9	1.05	3.74
	2.2-5.4	7.64	0.61	22.1	1.03	3.62
	5.5-6.2	7.69	0.64	23.7	1.16	3.73
SO50 29KL	0-1.1	5.2	0.58	11	0.33	2.69
	1.1-2.2	17.65	0.47	10	0.84	7.52
	2.2-5.4	8.55	0.61	8.08	0.42	4.77
SO50 37KL	0-1.1	8.27	0.62	24	1.23	3.89
	1.1-2.2	15.29	0.5	17.4	1.33	6.32
	2.2-5.0	8.63	0.59	16.31	0.84	4.29
SO27 91KL	0-1.1	1.02	0.53	40.30	0.22	0.32
	1.1-2.2	3.53	0.57	33.85	0.68	1.33
	2.2-3.1	10.71	0.57	23.6	1.44	4.67
	3.1-4.0	2.71	0.47	24.1	0.31	0.97
	4.0-5.2	2.81	0.6	18.4	0.31	1.38
	5.2-5.4	6.06	0.56	29.6	1.00	2.39
	5.4-5.5	4.62	0.51	34.1	0.80	1.55
	5.5-6.2	5.31	0.57	28.00	0.84	2.16
	2.2-5.4	4.43	0.55	24.3	0.60	1.86
SO49 136KL	0-1.1	5.46	0.57	16.4	0.51	2.6
	1.1-2.2	20.00	0.66	7.29	0.96	12.24
SO49 137SL	0-1.1	0.66	0.77	19.1	0.10	0.41
	1.1-2.2	7.41	0.98	6.12	0.44	6.82
SO58 109KL	0-1.1	10.05	0.45	11.5	0.52	4.00
	1.1-2.2	14.13	0.48	8.5	0.58	6.21
SO58 110KL	0-1.1	8.21	0.46	14.4	0.54	3.23
	1.1-2.2	21.12	0.53	9.05	1.01	10.18
	2.2-3.3	27.57	0.65	3.08	0.51	16.11
SO58 114KL	0-1.1	14.54	0.45	14.6	0.95	5.59
	1.1-2.2	25.20	0.48	7.07	0.86	11.24
SO58 133KL	0-1.1	5.10	0.52	18.2	0.48	2.17
	1.1-2.0	14.63	0.50	16.7	1.22	6.09
	2.0-2.2	9.09	0.46	14.6	0.61	3.57
	2.2-3.1	33.93	0.52	6.2	1.09	16.55
	3.1-3.3	9.66	0.57	7.3	0.40	5.10
	3.3-4.0	15.91	0.60	5.8	0.55	8.99
	4.0-5.0	5.37	0.63	3.9	0.13	3.25
	5.0-5.4	6.50	0.64	5.7	0.24	3.92
	5.4-5.5	6.15	0.63	12.0	0.46	3.41
	1.1-2.2	11.76	0.48	13.5	0.76	4.88
	2.2-5.4	11.24	0.56	6.0	0.38	5.92

Note. The rates were calculated for hemipelagic sediments exclusively (turbidites were not included). For four cores, average accumulation rates are given for greater time slices.

the interglacial core sections indicate, however, that winnowing and downslope transport were generally more intensive in interglacial ages. In addition, a third variation should also be considered: even if winnowing and downslope transport rates were constant; i.e., a constant amount of sediment was transferred into deeper sections of the continental slope, a reduced supply rate of terrigenous material would have resulted in a reduction of carbonate accumulation rates. This is caused by a relatively increased portion of carbonate material in the sediment transported downslope, which then is not available for accumulation on the slope.

A similar depth-distribution pattern of terrigenous accumulation rates is reported from the eastern North Atlantic by Ehrmann and Thiede (1985). They also assessed an increase of Pliocene and Quaternary terrigenous accumulation rates toward the continental rise and slope. However, differences in magnitude of time resolution, as well as different approaches (turbidites are included by Ehrmann and Thiede, 1985), restrict the comparability of both data sets.

Carbonate Accumulation Rates

Carbonate accumulation rates primarily record near-surface biological productivity (Rea *et al.*, 1991). The carbonate particle flux from the surface water differs from carbonate accumulation rates because carbonate particles are subjected to lateral transport, dissolution in the water column, and post-depositional dissolution. In the northern South China Sea, productivity and subsequent flux of calcareous plankton, as recorded by a sediment trap at 1000 m water depth, is highest during winter (northeast) monsoon (Jennerjahn *et al.*, 1982). As the northeast monsoon does not as strongly affect the southern parts of the South China Sea (Ramage, 1971), a lower productivity can be expected there. Carbonate accumulation rates, which are on average higher by a factor of 2 off China than off Sabah and off Palawan (Thunell *et al.*, 1992), clearly reflect this regional difference in productivity.

Extraordinarily low rates were recorded in core SO50 29KL at 3770 m depth off southern China. These low values are thought to be caused by carbonate dissolution, as the core site lies well below the lysocline which fluctuated between 2600 and 3600 m depth in the western Pacific during the Late Pleistocene (Rottmann, 1979; Wu *et al.*, 1991). Apparently, most of the carbonate dissolves during early diagenesis, for the carbonate flux of 1.2 g/cm² * 10³ yr (mainly foraminiferal tests), recorded in a sediment trap at 3350 m (Jennerjahn *et al.*, 1992), is an order of magnitude higher than the Holocene carbonate accumulation rate determined in nearby core SO50 27KL (0.3 g/cm² * 10³ yr). In contrast, terrigenous fluxes differ only by a factor of 2.

FIG. 7. Accumulation rates in time slices (Fig. 2) versus mean sea-level and correlation coefficients of both parameters for each core (locations of these cores are encircled in Fig. 1). Average accumulation rates were calculated for periods which could be reliably identified on the isotopic record.

Carbonate accumulation rates were generally low during the Holocene and last interglacial age in all of the cores from the Chinese continental slope. This reduction cannot be attributed only to solution, but, as already discussed, is also a consequence of decreased interglacial terrigenous sediment supply and increased winnowing and downslope transport equally affecting terrigenous and carbonate material.

In general, carbonate accumulation rates show only small temporal variations, with synchronous maxima during the Terminations I and II off Sabah and southern China. These maxima are related to improved carbonate preservation described for that period from the North Atlantic Ocean (Berger 1977), the Indian Ocean (Peterson and Prell, 1985), and the South China Sea (Rottmann, 1979; Thunell *et al.*, 1992).

Paleoenvironmental Factors Controlling the Terrigenous Supply

The flux of terrigenous material onto the continental slope is closely linked to fluvial discharge and possible

aeolian input, which may have changed with changing paleoclimatic conditions of the continental hinterland.

During the last glacial maximum, a dense vegetation of tropical moist forests persisted in northern Borneo and Malaysia. Tropical scrub and woodland covered the whole Mekong drainage area, and grasslands and temperate broad-leaved forests extended over northern Vietnam and southern China (Adams *et al.*, 1990, Fig. 1). This pattern indicates that precipitation was significantly lower during the last glacial maximum in Indochina and southern China. Denudation rates, however, were probably higher in these areas because grasslands are more erodible than soils covered by forests (e.g., Langbein and Schumm, 1958). These effects may well have balanced each other, so that the fluvial suspension input from southern China and Indochina during the last glacial maximum was approximately as high as it is today. The results of Pinet and Souriau (1988) confirm our assumption: they found, in a world-wide survey, that the amount of suspended material discharged by large rivers is mainly controlled by the average elevation of the drainage area rather than by climatic factors.

Eolian dust from arid source regions in Asia is a major terrigenous component of deep-sea sediments in the northern Pacific Ocean (e.g., Hovan *et al.*, 1991). During the last glacial maximum, arid regions in central Asia extended from 30° to 50° northern latitude (CLIMAP, 1976). Surface and high-altitude zonal winds (westerlies) blew eastward from these regions to the North Pacific, while the South China Sea was reached only by north-eastern near-surface winds from the western Pacific (Kutzbach and Guetter, 1986). Therefore, the influx of windblown dust to the South China Sea should have been negligible.

Response of Terrigenous Accumulation to Sea-Level Changes—A Conceptual Model

The amount of terrigenous material being deposited during different glacial and interglacial ages on the continental slopes of the South China Sea is highly variable, despite the probably constant fluvial supply rate from the continental hinterland. The invariable distribution pattern of accumulation rates on the continental slope indicates that dispersal processes have not significantly changed during the late Quaternary, but that the glacial to interglacial decrease of accumulation rates is caused by a profound change in the amount of terrigenous material being delivered for dispersal on the continental slope. This change is closely related to variations in the Quaternary sea level (Figs. 4 and 7). For a better understanding of this relation, we designed a conceptual model with one scenario for the interglacial high sea level and another for the glacial low sea level (Fig. 8).

During interglacial periods of high sea level, most of the fluvial supply accumulated on the shelf. In particular, the extended area of the Sunda Shelf between Bor-

neo and Malaysia/Vietnam (Fig. 1) was fringed by coastal mangrove swamps and acted as a very effective trap for terrigenous sediment. As a consequence, the amount of terrigenous material reaching the continental slope and the abyssal plain was small. In comparison to glacial periods, accumulation during interglacial times was lowered by a factor of 2.6. Off China, the supply of terrigenous material for the upper parts of the slope was not even large enough to prevent erosion by winnowing.

During glacial periods of low sea level, the Sunda Shelf and the broad shelves off Sabah and northern China were largely or completely emergent and probably covered by lowland mangrove forests and swamps. As today, most of the fluvial terrigenous supply was deposited near the coastline, which had moved to the present outer shelf. These shallow water deposits formed a reservoir, which could be eroded by changing currents, hurricane-induced lowering of wave base, and slumping. These processes supplied suspended fine-grained terrigenous sediment for the subsequent deposition on the continental slope. Compared with interglacial high sea-level conditions, a greater proportion of the fine-grained fluvial material directly reached the continental slope by transport in suspension. Rivers which built their deltas near canyon heads or close to the shelf break may have fed sediment directly by turbidity currents onto the deep-sea fans. Thus, especially sand-sized terrigenous sediment and a considerable amount of silt and clay bypassed the continental slope and were deposited on the adjacent abyssal plains.

The good, negative correlation of sea level and terrigenous accumulation rates (Fig. 7) indicates that the position of sea level, which determines the distance from the coastline to the shelf break, largely controls the partition of terrigenous material for deposition on shelf, slope, and abyssal plain. This control not only has been effective during its extreme low and high positions but also during intermediate sea-level positions.

In contrast to our expectations, terrigenous accumulation rates during the last glacial regression did not increase significantly (Fig. 7). Apparently this regression was slow (Fig. 4), and by gradually adjusting the deltaic system to the successive lowering of sea level, rejuvenated linear erosion along river beds had no marked effect on the terrigenous supply on the continental slope. In contrast, the much faster transgressions mobilized, probably reinforced by the downslope transport process, large amounts of terrigenous material from formerly outer-shelf deltaic deposits off China for redeposition on the slope.

An Approach to the Partition of Terrigenous Material in the South China Sea

The present function of continental shelves as a very effective trap for the suspended sediment supplied by

FIG. 8. Conceptual model for the changing pattern of terrigenous accumulation rates: during interglacial high sea level most of the sand (·) and clay (—) supplied by rivers remained on the shelf; during glacial low sea level the depocenter shifted toward the outer shelf and continental slope.

ivers is shown by a simple mass-balance calculation. The three main rivers (Mekong, Hungo, Si Kiang) annually discharge 360×10^6 tons of suspended material into the South China Sea (Pinet and Souriau, 1988). With additional inputs from coastal rivers along East Vietnam and Borneo, the total annual amount of terrigenous sediment available for distribution in the South China Sea is estimated to be 460×10^6 tons. A homogenous distribution on the entire area of the South China Sea (2.318×10^6 km²) would result in an average accumulation of $20 \text{ g/cm}^2 \times 10^3 \text{ yr}$. Holocene terrigenous accumulation rates on the continental slopes are much lower, however, $2.7 \text{ g/cm}^2 \times 10^3 \text{ yr}$ on average. They are even lower in the basinal areas further away from the slopes where core SO27 91KL indicates a Holocene rate of $0.3 \text{ g/cm}^2 \times 10^3 \text{ yr}$.

Slopes and basins comprise 1.66×10^6 km², or 72% of the South China Sea. If an average accumulation rate of approximately $2 \text{ g/cm}^2 \times 10^3 \text{ yr}$ is assumed for continental slopes and the basins, the continental shelves would receive $65 \text{ g/cm}^2 \times 10^3 \text{ yr}$ on average. Thus, today the overwhelming amount of fluvial sediment delivered to the South China Sea is deposited on the continental shelves, in particular near the river mouths and in estuaries.

A comparable mass balance for the glacial age is not possible with the present data set, mainly because we do not know the amount of terrigenous material transported by turbidity currents into the basins during the last glaciation.

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