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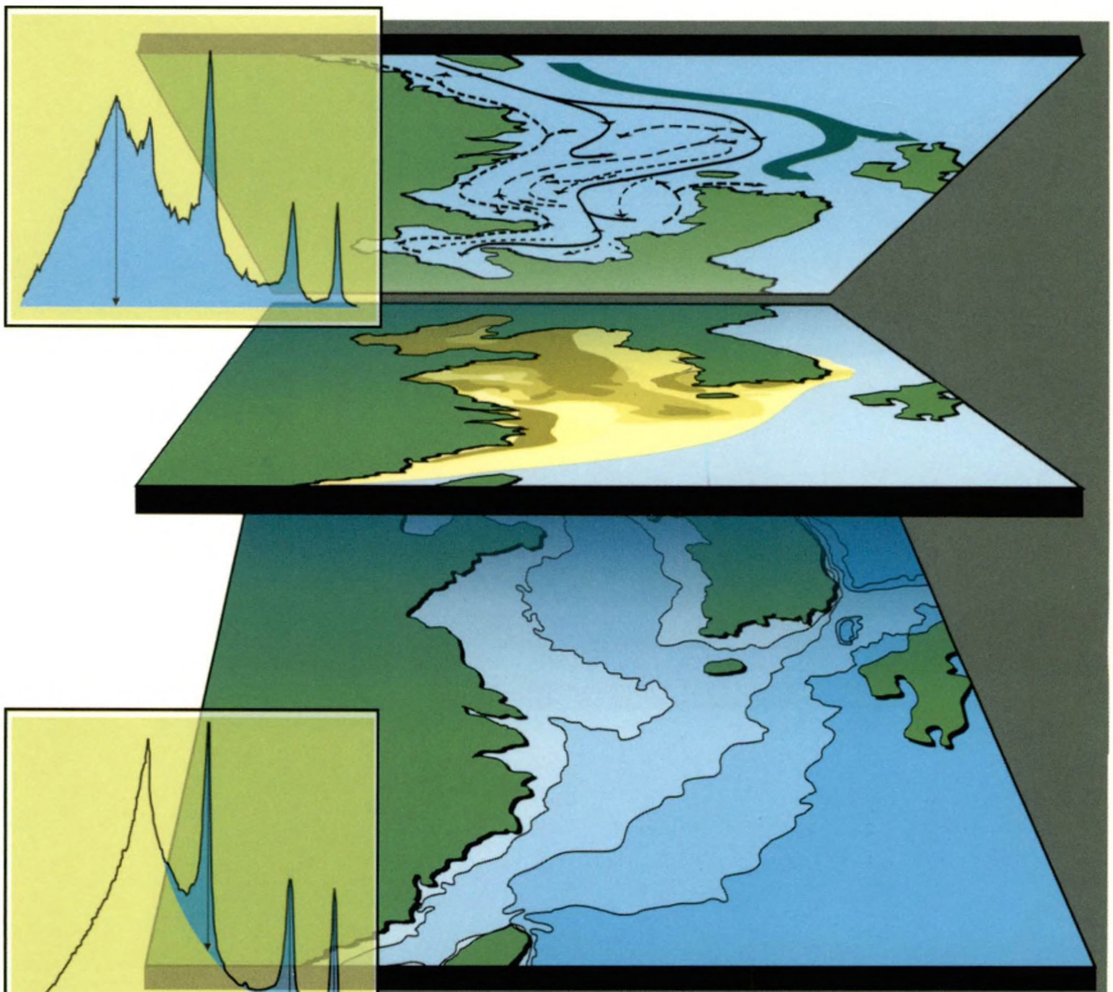

Nederlands Instituut voor Onderzoek der Zee

Netherlands Institute for Sea Research (NIOZ)
P.O. Box 59, 1790 AB Den Burg,
Texel, The Netherlands

ISSN 0923 - 3210

Cover design: H. Hobbelink

CLAY MINERAL COMPOSITION OF RECENT SEDIMENTS ALONG THE CHINA COAST, IN THE YELLOW SEA AND THE EAST CHINA SEA

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ABSTRACT

Analysis of the clay mineral composition of sediments along the China coast, in the Yellow Sea and the East China Sea indicates two principal sources: the Huang He and Chang Jiang rivers, including the old (now abandoned) mouth of the Huang He south of the Shandong peninsula. Some material (probably minor quantities) reaches the East China Sea shelf from the Taiwan west coast. Fine-grained sediment from these sources can be distinguished by the illite/smectite ratio. The dispersal patterns of material from the Chang Jiang to the Yellow Sea, where the fine-grained sediment is of mixed Huang He-Chang Jiang origin, is not clear and probably rather complex. Along the coast the Chang Jiang river outflow is a barrier for the transport of Huang He sediment coming from the north.

INTRODUCTION

The principal sources of fine-grained sediment along the Chinese east coast and the East China Sea are the large rivers, the Huang He (Yellow River) and the Chang Jiang (Yang Tze). The Huang He supplies approximately 1.2 x 10^9 tons of sediment per year, the Chang Jiang 0.5 x 10^9 tons·y^{-1}. The other rivers along this part of the Chinese coast supply much less: the six largest ones - the Liao He and the Luan He in the north and the Qiantangjiang, Qujiang, Minjiang and Hanjiang south of the Chang Jiang - supply together not more than 0.06 x 10^9 tons·y^{-1} (Li *et al.*, 1991; Fig. 1). The largest river in Korea, the Keum river, only supplies 0.006 x 10^9 tons·y^{-1} which are deposited along the Korean coast (Khim & Park, 1992).

The sediment supplied by the Huang He since 1976 for more than 90% has been deposited within 30 km from the mouth (Bornhold *et al.*, 1986). Because of the shallow depth of the Bohai Sea (mean depth 30 m) resuspension of bottom sediment during storms has an important effect. The transport in suspension of Huang He sediment largely goes along the coast to the northeast of the Bohai Sea (Qin *et al.*, 1982, in Ren ed., 1986) but the distribution of bottom sediment composition indicates that the main near-bottom transport follows the south side of the Bohai Sea and goes around the Shandong peninsula into the Yellow Sea (Qin & Li, 1983). Transport in suspension around the Shandong peninsula occurs mainly during the winter season (Milliman *et al.*, 1986). Estimates for suspended matter transport from the Bohai Sea into the adjacent Yellow Sea vary from 10^6 to 10^8 tons/y (Qin & Li, 1983; Wells *et al.*, 1983).

The Chang Yiang sediment supply is for more than half deposited on the inner shelf directly off the river mouth. The remainder is moved southward by the Jiang Su coastal current. Part of the sediment deposited off the river mouth is resuspended by the winter storms and also transported southward. Chang Jiang sediment is deposited in Hangzhou Bay and further south along the coast as on tidal flats and on the inner shelf far as Wenzhou Bay (Ren ed., 1986; Wang & Eisma, 1988; Cao *et al.*, 1989). A small part of the Chang Jiang sediment supply goes towards the east and northeast into the East China Sea, as is indicated by the distribution of suspended sediment and current measurements (Sternberg *et al.*, 1985). Eastward transport occurs during high river discharge in the winter season: Landsat images show a marked turbid flow from the river mouth to the northeast during that period (Yun *et al.*, 1981).

The distribution of muddy sediments in the East China Sea, the Yellow Sea and the Bohai Sea is given in Fig. 2 (compiled by Lee & Chough, 1989). A large mud area extends through the Bohai Sea into the Yellow Sea and reaches the East China Sea. Smaller mud areas are present off southern Korea, off the old Huang He river mouth (abandoned in 1855), off the Chang Jiang river mouth extending southward along the Chinese coast, and on the central shelf of the East China Sea south of Cheju island. A $CaCO_3$ content higher than 10% has been used to indicate supply from the Huang He, which transports eroded loess with $CaCO_3$ contents of up to 15% (Qin *et al.*, 1983). As during or after transport marine biogenic $CaCO_3$ is added to the sediment (foraminifera, coccoliths, mollusc shell fragments), a high $CaCO_3$ content can only be used as a very general indication. Fig. 3 (from Li *et al.*, 1991) gives the distribution of the $CaCO_3$ content in the bottom sediments. The two source areas of carbonate-rich Huang He sediment — the present river mouth and the old abandoned one — show up clearly with percentages above 10% with the content dropping to less than 5% in the Yellow Sea. Away from the source areas the carbonate content is influenced by grainsize effects as well as by supply of marine carbonate which may largely explain the decrease as well as the variations in carbonate content (Zhang, 1988; Zhu & Wang, 1988).

Besides the carbonate content the clay mineral composition has been used to distinguish Huang He river sediment (with 9 to 24% of smectite) from Chang Jiang sediment which contains only 2 to 14% smectite but more illite, kaolinite and chlorite. These compositional data have been obtained by different authors using different techniques, which has

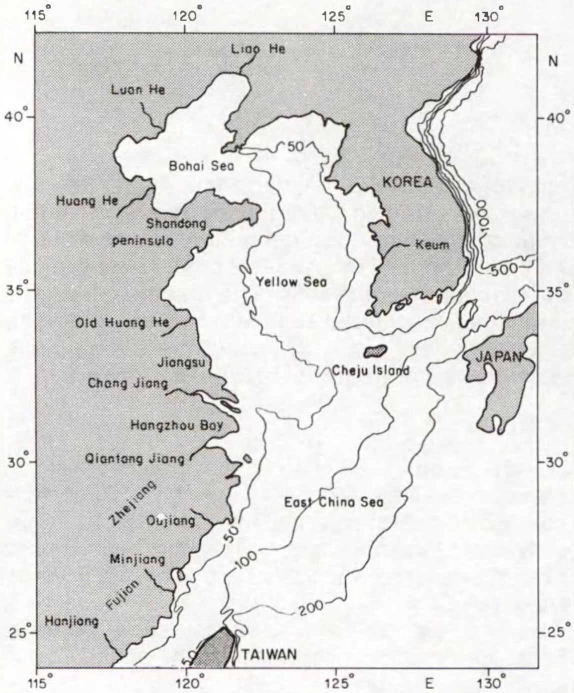

Fig. 1. Sketch map of the China east coast.

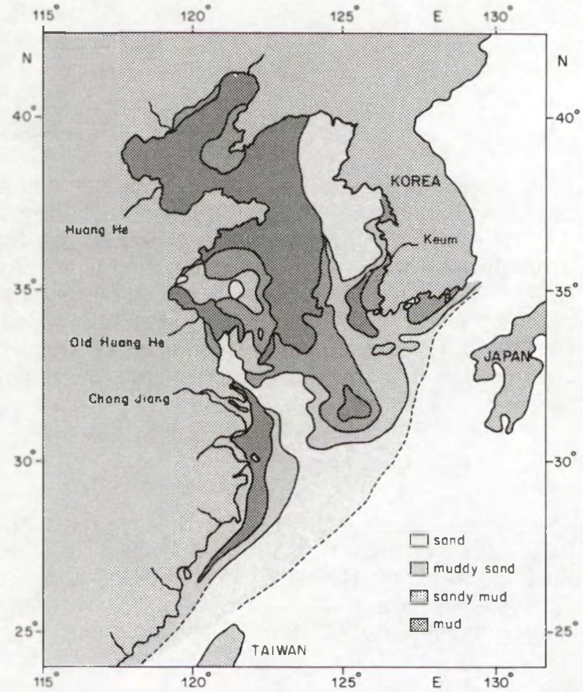

Fig. 2. Sediment distribution on the eastern China shelf (mainly after Chin, 1979 and Lee & Chough, 1989).

resulted in large variations in the clay mineral compositions. Therefore a series of samples from the Chinese coast, the Yellow Sea and the East China Sea was analysed using a high-precision technique (Van der Gaast, 1991) that allows determination of the clay mineral percentages to ± 2% of the value found.

Four other (possible) sediment sources are to be considered besides the present Huang He and the Chang Jiang: the old (pre-1855) river mouth of the Huang He, the west coast of Taiwan, resuspension of older deposits and, for the Yellow Sea, the Korean rivers.

The old Huang He river mouth, after it was abandoned and sediment supply stopped, was — and continues to be — eroded so that about 1400 km^2 of deltaic deposits have disappeared (Wang & Aubrey, 1987). Assuming that an average thickness of 4 meter of sediment with a density of about 2 has been removed, this means a supply to the coastal sea of 112 x 10^8 tons since 1855, or about 1 x 10^8 tons per year. This is of the same order of magnitude (or more) as the present Huang He supply to the Yellow Sea. Another (possible) sediment source is the eastern Taiwan coast. The sediment supply from Taiwanese rivers was estimated by Milliman & Meade (1983) to be in the order of 3 x 10^8 $t \cdot y^{-1}$. New data from Milliman & Syvitzki (1992) indicate 2.5 x 10^8 $t \cdot y^{-1}$. Not all of this sediment will reach the coastal waters, but the flow in the sea off western Taiwan, where most of the river discharge is located, may transport material from Taiwan to the north. Off northwestern Taiwan, where fine-grained bottom sediments and coastal sediments are present, the current along the coast is to the north in all seasons with a velocity of 0.4 to 1.8 knots (Chen *et al.*, 1988). As can be seen from the general water circulation over the shelf of the East China and Yellow Seas (Fig. 4), a large gyre is situated over the mud patch south west of Cheju island. This gyre is made up of water coming from the Yellow Sea as well as of water supplied from the south (the Taiwan current), which makes it likely that some material from Taiwan ends up in the central part of the East China Sea.

The supply from the Korean rivers to the eastern part of the Yellow Sea, which is relatively small, will be discussed below (p. 10 to p. 11).

Finally, resuspension and reworking of older deposits on the shelf may have influenced the composition of the surface sediment. Based on radiochemical measurements of ^{234}Th, ^{137}Cs and ^{210}Pb, DeMaster *et al.* (1985) found that in the offshore mud area between 31°N and 33°N particles at the sediment-water interface are reworked down to a depth of 25 cm on a 100 year time scale, and in the muddy sands offshore from the inner shelf between 29°N and 33°N to a depth of 16 cm. In the Yellow Sea and the adjacent parts of the East China Sea ^{137}Cs penetrates deeper into the sediment than ^{210}Pb (Alexan-

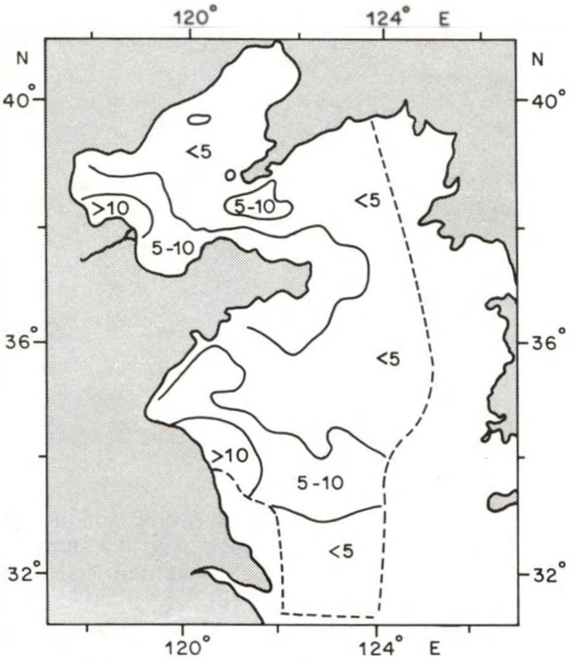

Fig. 3. Distribution of calcite content in bottom sediments of Bohai Sea and the Yellow Sea (from Li *et al.*, 1991).

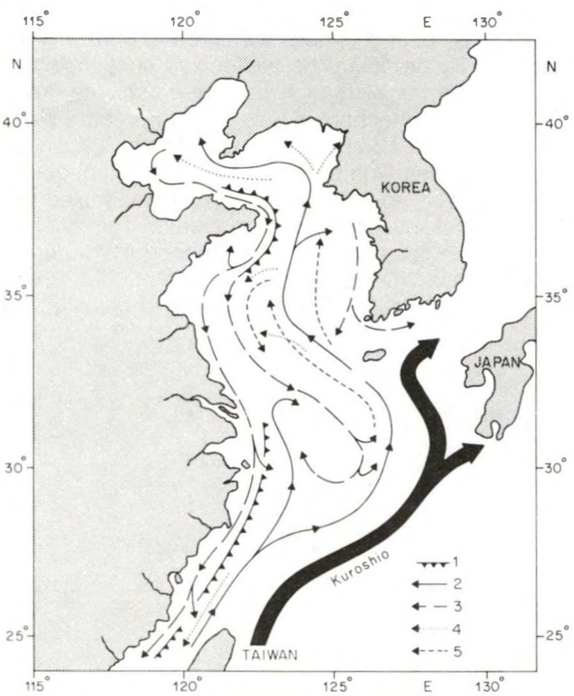

Fig. 4. General circulation pattern over the eastern China shelf (after Beardsley *et al.*, 1985, Butenko *et al.*, 1985 and Milliman *et al.*, 1985a, b) 1 = frontal zone; 2 = warm current; 3 = cold current; 4 = summer differences (warm current); 5 = summer differences (cold current).

der *et al.*, 1991; Chen, 1990b) which, besides to possible remobilization and downward diffusion of Cs (through the interstitial water), indicates the possibility of appreciable reworking of the bottom sediment. The distribution of relict sediment on the China continental shelf is given in Fig. 5 (after Liu, 1987). It shows large areas, particularly in the East China Sea, where recent sediments are absent or only form a thin veneer on top of older sediments. Recently supplied material may have become admixed into the top layer of the older deposits.

CLAY MINERAL ANALYSIS

Bottom samples were collected along the Chinese coast in 1988/1989 from the Huang He delta in the north to the tidal flats along Wenzhou Bay in the south (Ji, 1989; S. Chen, 1990a; Fig. 6). Some addi-

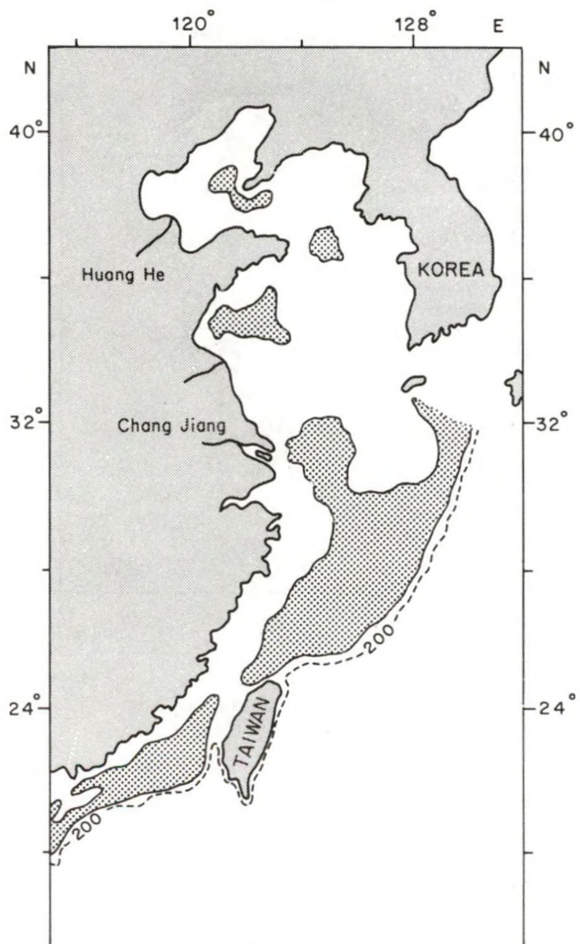

Fig. 5. Distribution of relict sediments on the eastern China shelf (from Liu, 1987).

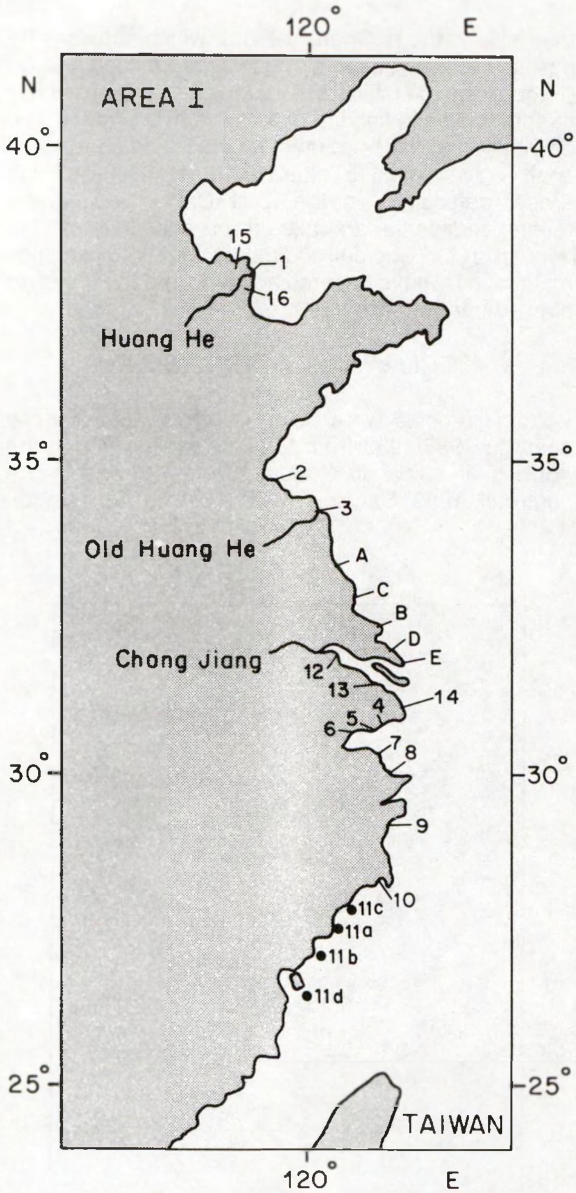

Fig. 6. Sampling stations along the China east coast. Numbers and capitals correspond with those in Table 2.

tional samples of loess from the Lanzhou region in northern China and Huang He sediment were obtained from J. Zhang (Qingdao). Samples from the Yellow Sea (Fig. 7) were obtained from C.R. Alexander (Savannah, Ga, USA) and had been used in a study on sediment accumulation in that area (Alexander *et al.*, 1991). In the East China Sea (Fig. 8) samples were collected in 1985 during cruise No. 50 of the RV 'Sonne' as part of a Chinese-German cooperation programme. Samples from the shelf west of Taiwan (Fig. 9) were collected in 1987/1988 with the RV 'Ocean Researcher' and had been used in a study on acoustic and physical properties of surface sediments in that area (M. Chen *et al.*, 1988).

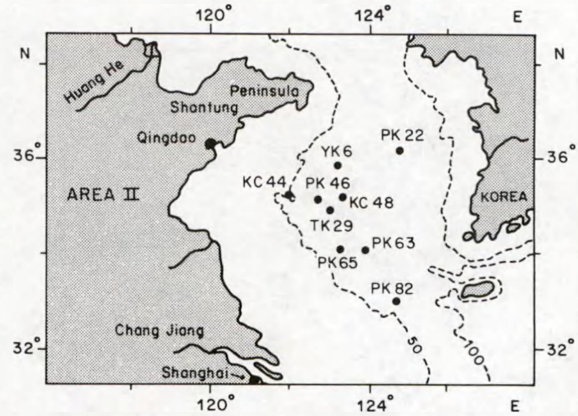

Fig. 7. Sampling stations in the Yellow Sea. Numbers and capitals correspond with those in Table 2.

For clay mineral analysis with XRD, the fraction < 2 µm of about 5 g sediment sample was separated by centrifugation after being suspended in distilled water. Calcium chloride was added to exchange other ions adsorbed to the particles with Ca. Then the suspensions were washed with distilled water until they were completely deflocculated. Oriented samples were obtained by dropping the well-mixed suspension on glass slides for XRD at high angles (chlorite, kaolinite). A suction technique was used to prepare slides on ceramic tile (Gibbs, 1965) for XRD at low angles (clay minerals). One percent of MoS_2 of 3 µm diameter (diffraction angle 16.7° 2θ CoKα) was mixed with the samples as an internal standard. The oriented samples on ceramic tile were scanned at 100% and 50%, relative humidity (r.h.) from 1° to17.5° 2θ to determine smectite, illite, kaolinite and chlorite. The

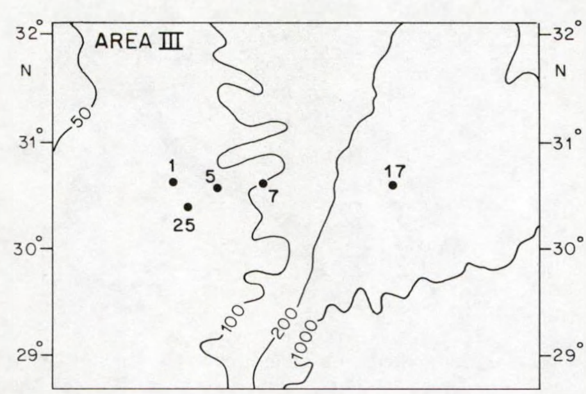

Fig. 8. Sampling stations on the East China shelf. Numbers and capitals correspond with those in Table 2.

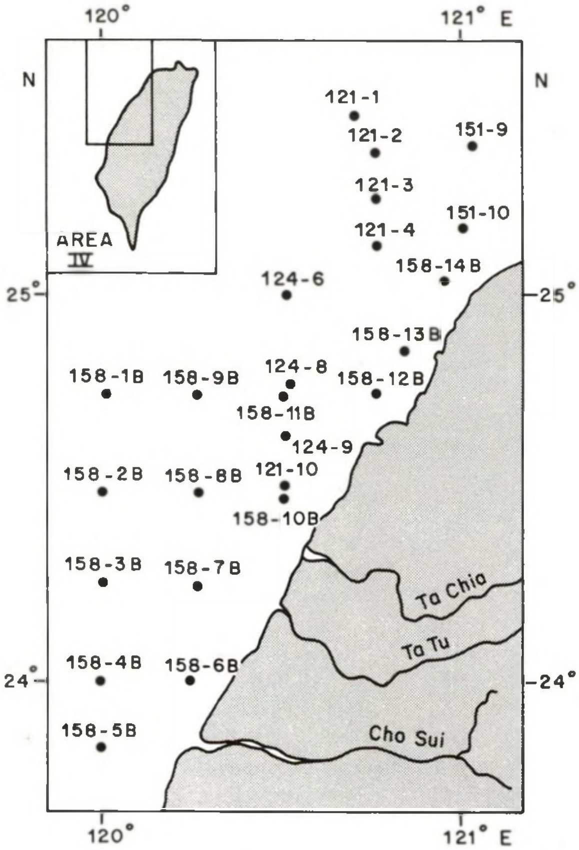

Fig. 9. Sampling stations off NW Taiwan. Numbers and capitals correspond with those in Table 2.

glass slides were scanned at 0% r.h. from 28° to 30.5° 2θ to determine the kaolinite and chlorite ratio from their (001) and (004) reflections, respectively. All XRD measurements were carried out on a Philips XRD system with a helium-vacuum attachment as described by Van der Gaast & Vaars (1981). All XRD results were corrected by using Lorentz-polarization (Cullity, 1967) and a volume factor to diminish the influence of the background in the measurements (Parrish & Wilson, 1965).

Smectite was measured from its (001) peak at 100% r.h., illite from its (001) peak, kaolinite from its (001) peak at 50% r.h. and its (002) peak, and chlorite from its (002) peak at 50% r.h. and its (004) peak (Fig. 10). To separate kaolinite and chlorite the method of Biscaye (1965) was followed. To estimate the relative clay mineral concentrations (in relative %) the ratio between the peak heights (corrected with the internal standard) were used and not the peak area ratios because influence of the background may result in a larger error in the peak area ratio than in the peak height ratio (Scape & Kunfe, 1971; Chen, 1973). By following this procedure for all samples in the same way comparable results were obtained which are reproducible within ±2% of the value found. By measuring at constant humidity at 100% r.h.

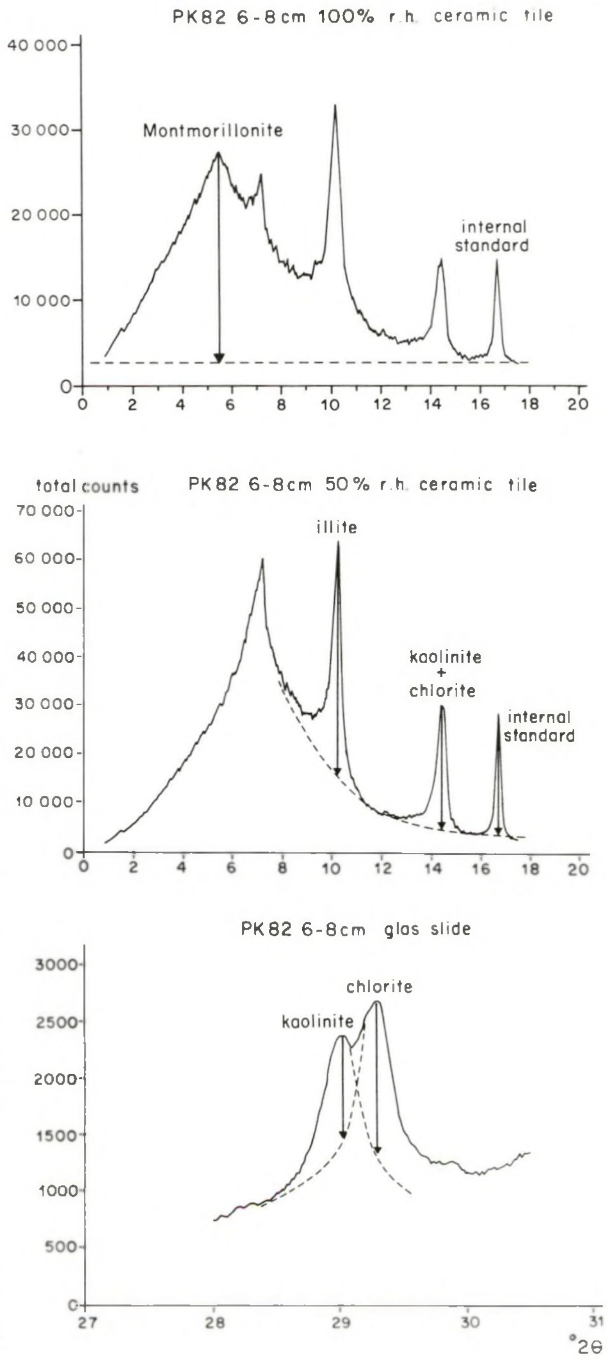

Fig. 10. X-ray diffraction patterns of sample PK82 6-8 cm. A: at 100% r.h. after correction (Lorentz-polarization, volume factor). B: at 50% r.h. after correction. C: on glass slide (A and B were made on a ceramic tile).

TABLE 1

Clay mineral composition (in %) of sediments along the China east coast, on the shelf and along the west coast of Korea, as obtained by different authors.

	Illite	*Smectite*	*Kaolinite*	*Chlorite*	*References*
Loess (China)	60-68	9-19	10-11	11-12	Ren & Shi (1986)
Huang He river	59.00	23.23	8.48	9.29	Xu (1983)
	60.60	10.06	19.20	9.60	He (1985)
	62	16	12	10	Yang (1988); Yang & Milliman (1983)
	59.0	23.2	8.4	9.2	Xie *et al.* (1983)
Off Huang He river mouth (bottom sed.)	67	13	8	12	Ren & Shi (1986)
Bohai Sea	58-62	8-12	15-20	11-13	He (1985)
	69.4-86.6	2.8-9.0	3.0-15.8	2.0-7.5	Shi *et al.* (1984)
East of Shandong Pen.	67-76	8-14	8-11	9-14	Qin & Li (1983)
bottom sediment					Khim (1988)
Old Huang He	63.7	20.50	7.70	8.30	Qin & Li (1983)
riverdelta	59.0	24.0	9.0	8.10	Xie *et al.* (1983)
	56-62	8.5-8.6	28.5-35.6		Xu (1983); Ren ed. (1986)
	71.7	11.2	8.6	8.5	Lin (1988)
Keum river (50 km from mouth)	59	1	10	30	Ren & Shi (1986)
Keum river	63.7	trace	17.0	19.3	Choi (1981)
bottom sediment off Keum river mouth	72-79	trace	8-14	12-16	Khim (1988)
	55-79	trace	8-20	13-16	Chough (1985)
	60-81	< 2	8-19	9-20	Park *et al.* (1986)
Yongsan river	63.9	trace	19.2	16.8	Kim (1980)
Coastal sea south of Korea	50	4	21	25	Park & Han (1985)
	45	5	23	27	Park *et al.* (1976)
	57	trace	21	21	Park *et al.* (1984)
shelf west Korea (< 50 km offshore)	52.6-81.3	0.5-3.2	9.3-19.5	8.1-28.2	Park *et al.* (1986)
Western Yellow Sea	70.2-73.7	5.5-9.0	8.1-9.5	8.5-13.6	Shi *et al.* (1989)
	68.4	6.0	25.6		Xie *et al.* (1983)
	72-78	4-11	4-10	8-13	Buckley *et al.* (1983)
Central Yellow Sea	64.97	22.90	5.93	6.20	Ren ed. (1986)
	72.34	6.52	10.57	10.57	Ren ed. (1986)
	65.72	5-17	6-12	6-15	Khim (1988)
Changjiang	67.97	5.52	13.86	12.65	Xu (1983)
	70-77	2-8	5-11	12-16	Shen *et al.* (1983)
	67.70	5.95	14.29	13.06	Ren ed. (1986)
	74.6	5.0	10.3	10.1	Lin (1988)
	73.1	6.7	10.2	10.0	Lin (1988)
	64.65	10.14	14.16	11	Yang (1988)
Changjiang river mouth	75-79	2-4	19-21		Ren & Shi (1986); Ren ed. (1986)
	58	6	13	23	Wang & Eisma (1988)
	72.3	6.4	10.8	10.7	Xie *et al.* (1983)
	71.4	5.0	9.5	14.5	
Qiantangjiang estuary	55-58	4-10	13-22	18-24	Ren ed. (1986)
	65-68	8-13	7-14	10-15	Yang & Milliman (1983)
Hangzhou Bay	76.8	5.8	8.7	8.7	Lin (1988)
	52	11	16	21	Ren ed. (1986)
Zhejiang coast	63-64.5	4.5-6.3	32.0		Xie *et al.* (1983)
East China Sea	65	4	6	25	Chen (1978)
	49-74	0-15	0-15	14-49	Aoki *et al.* (1983)
	61-64	3-5	0-9	27-31	Wang & Eisma (1988)
	65	4	6	25	Chen (1978)
Taiwan north shore	60.5-65.0	5.0-9.0	5.0-8.0	23.0-26.58	Chen (1973)

higher percentages for smectite were found than by most other authors (Tables 1 and 2). We consider these higher values, measured at maximum swelling and under constant conditions, corrected as indicated above, to be more realistic than the (uncorrected) values found at lower —usually uncontrolled— humidity.

CLAY MINERAL COMPOSITION

The data available from the literature on clay mineral composition of sediments in the Huang He river, the old Huang He river delta, the Chang Jiang, the Qiantang Jiang river estuary, the principal Korean rivers, Bohai Sea, the Yellow Sea, Hangzhou Bay, the Zhejiang coast, the East China Sea and the north shore of Taiwan are compiled in Table 1. The clay mineral composition of the sediments in the Huang He river, the old Huang He river delta and the Yellow Sea are characterized by high concentrations of illite and lower concentrations of smectite, kaolinite and chlorite. The differences between the percentages found by different authors, however, are rather large, in particular for smectite. Sediments from the Korean rivers and on the shelf along the Korean coast are also characterized by high concentrations of illite, but also by a very low (or almost undetectable) concentration of smectite and sometimes high concentrations of kaolinite and especially chlorite. Sediments from the Chang Jiang river and off the Chang Jiang river mouth, from Hangzhou Bay, the Qiantang Jiang estuary, the Zhejiang coast, the East China Sea and the north shore of Taiwan also have a high illite content, but a somewhat lower smectite content. In the East China Sea and off northern Taiwan also the chlorite content can be rather high.

From these data and from data on the dispersal of suspended matter Park *et al.* (1986) concluded that off the Korean coast and in the mud patch that extends from southwest Korea over the shelf towards Cheju Island, the mud consists of sediment supplied by the Keum river: this river is the principal source of suspended matter to the coastal sea in Korea and its sediment is largely dispersed towards the southwest, with less significant amounts going towards the north and northwest. As can be seen in Fig. 2, in the area where only small amounts of suspended matter are supplied, the seafloor consists predominantly of sand. Lee & Chough (1989) concluded that Huang He sediment is deposited in the Bohai Sea and is moving southward to the central Yellow Sea. Sediment from the old Huang He delta is deposited on the large mud patch on the central shelf off the Chang Jiang river mouth southwest of Cheju Island. Chang Jiang river mud is deposited in the southern Yellow Sea and the northern East China Sea, as well as along the coast south of the river mouth. Khim & Park (1992) argued that in the Yellow Sea smectite content can be an indication of provenance since the Huang He sediment contains much smectite and the Korean rivers only minor quantities.

The results of our clay mineral analyses are given in Table 2. These are generally more precise and comparable than those given in Table 1, which are from different authors using often different methods. Although the smectite percentages for the Huang He and Chang Jiang sediments in Table 1 are much higher than found by earlier authors, the same characteristic difference between the two rivers is found: lower illite and higher smectite percentages in the Huang He and the reverse in the Chang Jiang. Also the loess is characterized by high illite percentages, which indicates that there are other sources of clay minerals in the Huang He that supply high concentrations of smectite, unless the illite is preferentially deposited before the Huang He material reaches the river mouth. In the old Huang He river mouth sediments that date from before 1855 when the river mouth was displaced to north of the Shandong peninsula, the smectite percentages are somewhat lower and the illite percentages somewhat higher. A similar composition is found on the tidal flats south of the old Huang He river mouth down to Yingang just north of the Chang Jiang river mouth, but the differences between the composition of the recent Huang He river sediment, the old Huang He river mouth sediment and the sediments on the Jiangsu coast are hardly significant. At Jingang the clay mineral composition becomes more similar to the composition of Chang Jiang sediment and can be seen as a mixture of sediments from the old Huang He and the Chang Jiang. From the Chang Jiang river mouth to the south a similar clay mineral composition as in the Chang Jiang is found in Hangzhou Bay and along the Zhejiang coast down to south of Wenzhou.

In the Yellow Sea the clay mineral composition of the bottom sediment is somewhat different from the composition in the Huang He. Two samples (PK22 and YK6) have a composition very similar to Chang Jiang sediment. Further to the south, in the East China Sea, the sediment at the westernmost stations (C1, C5, C25) also is similar to the Chang Jiang sediment, while at the easternmost station on the continental slope (C17) the composition is similar to the old Huang He and the tidal flats at stations A to D on the Jiangsu coast. One sample (C7) is characterized by high illite percentages and low smectite percentages combined with high chlorite percentages. This composition is not similar to the Huang He or the Chang Jiang composition, but sediments with a similar clay mineral composition are found on the shelf off northern Taiwan (*e.g.* 124-08, 151-9, 158-118). There, next to these sediments also sediments occur with a clay mineral composition similar to the Chang Jiang (121-1, 151-10), and further south (south of Hsin Chu) sediments with even lower smectite percentages and higher chlorite percentages, which probably have their origin on Taiwan.

The samples can be grouped neatly by their ratio of

TABLE 2
Illite/smectite ratio in the sediments listed in Table 2.

		Illite	*Smectite*	*Kaolinite*	*Cnlorite*	*% Illite* *% Smectite*	
Zhejiang coast	9	41	37	9	13	1.11	(Ch.J.)
	10	43	35	10	12	1.23	(Ch.J.)
	11a	41	37	9	12	1.11	(Ch.J.)
	11b	45	32	10	13	1.41	(Ch.J.)
	11c	42	36	10	12	1.17	(Ch.J.)
	11d	40	38	9	13	1.05	(Ch.J.)
Yellow Sea	PK22 0-6 cm	43	37	8	12	1.16	(Ch.J.)
	YK6 8-10 cm	42	39	8	11	1.08	(Ch.J.)
	KC44 0-2 cm	38	41	8	11	0.92	(X.T.)
	KC48 0-2 cm	39	42	7	12	0.93	(X.T.)
	PK46 0-6 cm	39	39	8	12	1.00	(X.T.)
	TK29 6-7 cm	38	41	8	13	0.93	(X.T.)
	PK65 0-3 cm	39	40	9	12	0.98	(X.T.)
	PK63 0-2 cm	39	41	8	12	0.95	(X.T.)
	PK82 6-8 cm	38	42	8	12	0.91	
Shelf East China Sea	C1-1	42	37	8	13	1.14	(Ch.J.)
	C1-3	41	40	7	12	1.03	(Ch.J.)
	C5-1	43	37	7	14	1.16	(Ch.J.)
	C5-4	43	38	6	13	1.13	(Ch.J.)
	C7-1	49	27	6	18	1.89	(x.T.)
	C7-2	49	26	6	18	1.89	(x.T.)
	C17-1	35	47	7	11	0.75	(H.H.)
	C17-3	38	44	7	11	0.86	(H.H.)
	C25-1	40	41	7	11	0.98	(Ch.J.)
	C25-7	42	38	7	13	1.11	(Ch.J.)
Taiwan shelf	121-1	43	36	7	14	1.19	(Ch.J.)
	121-2	58	12	9	21	4.83	(C.T.)
	151-9	49	28	7	16	1.75	(x.T.)
	121-3	50	25	7	17	2.00	(x.T.)
	121-4	53	23	7	17	2.30	(x.T.)
	151-10	43	40	7	10	1.08	(Ch.J.)
	124-6	51	25	7	16	2.04	(x.T.)
	124-8	49	25	9	17	1.96	(x.T.)
	124-9	58	18	7	17	3.22	(C.T.)
	158-10B	52	24	7	8	2.17	(x.T?)
	158-11B	49	25	7	19	1.96	(x.T.)
	121-10	55	17	7	21	3.24	(C.T.)
	158-14B	61	10	7	22	6.10	(C.T.)
	158-13B	52	19	9	20	2.74	(x.T.)
	158-12B	60	10	8	21	6.00	(C.T.)
	158-9B	56	18	7	19	3.11	(C.T.)
	158-1B	50	26	8	16	1.92	(x.T.)
	158-8B	55	21	5	19	2.62	(C.T.
	158-2B	62	10	8	19	6.20	(C.T.)
	158-7B	62	9	7	22	6.89	(C.T.)
	158-3B	56	16	6	22	3.50	(C.T.)
	158-6B	58	16	4	22	3.63	(C.T.)
	158-4B	62	11	7	21	5.64	(C.T.)
	158-5B	58	12	8	22	4.83	(C.T.)

TABLE 2 corrected %
Clay mineral composition of sediments along the China east coast and shelf as obtained in this study.

		Illite	*Smectite*	*Kaolinite*	*Chlorite*	*% Illite / % Smectite*	
Loess (Lanzhou area)	L-1	63	25	5	7	2.52	
	L-2	69	21	3	7	3.29	
	L-3	57	26	4	13	2.19	
	L-4	66	24	3	8	2.75	
	L-5	56	30	6	8	1.87	
Huang He delta	1	29	56	7	8	0.52	
	15	32	48	9	11	0.67	
	16	30	52	8	9	0.58	
Old Huang He delta							
Lienyungang	2	35	49	7	10	0.71	
	3	33	49	8	10	0.67	
Tidal Flats Jiangsu coast							
Changdong	A (upper flat)	34	49	9	9	0.69	(H.H.)
Jinggang	C (upper flat)	32	52	7	9	0.62	(H.H.)
Changsha	B1 (upper flat)	36	47	8	10	0.77	(H.H.)
	B2 (middle flat)	36	47	7	9	0.77	(H.H.)
	B3 (lower flat)	34	52	6	9	0.65	(H.H.)
Lusi	D (upper flat)	34	50	7	10	0.68	(H.H.)
Yingang	E1 (upper flat)	39	43	9	10	0.91	(H.H.)
	E2 (middle flat)	39	43	9	10	0.91	(H.H.)
	E3 (lower flat)	41	41	7	11	1.00	(X.T.)
Chang Jiang							
river mouth	12	42	37	11	10	1.14	
	13	41	36	9	13	1.14	
	14	43	32	9	15	1.34	
Hangzhou Bay	4	44	34	7	15	1.29	(Ch.J.)
	5	47	30	9	14	1.57	(Ch.J.)
	6	42	34	11	13	1.24	(Ch.J.)
	7	42	37	9	11	1.14	(Ch.J.)
	8	43	34	9	13	1.05	(Ch.J.)

Ch.J.= similar to Chang Jiang sediment
H.H.= similar to Huang He sediment
X.T.= mixed origin
C.T.= from/at coastal shelf west of Taiwan

the illite percentage to the smectite percentage (Table 3). The Huang He river (both recent deposits and older deposits from before 1855), the tidal flats along the Jiangsu coast (samples A-D) and sample C17 on the slope off the East China Sea have ratio's between 0.52 and 0.86. In the Chang Jiang river, Hangzhou Bay, along the Zhejiang coast, two samples in the Yellow Sea (PK22, YK6), three stations in the East China Sea (C1, C5, C25) and two stations off northwestern Taiwan (121-1, 151-10) the ratio is between 1.03 and 1.57. The sediment off the Taiwan west coast has a ratio between 3.11 and 6.80. The ratio's of sediments that can be considered to be of mixed origin, fall between those ranges: the Jiangsu tidal flat sediment at station E (0.91 - 1.00), most of the samples in the Yellow Sea (0.91 - 100) and C 25-1 in the East China Sea (0.98) and Chang Jiang sediment, and the mixed sediment off northwest Taiwan (1.75-2.30; 2.62 and 2.74 at stations 158-8B and 158-13B respectively and C17 in the East China Sea (1.89).

SUSPENDED SEDIMENT DISPERSAL IN THE YELLOW SEA AND THE EAST CHINA SEA

Sediment from the Huang He is present in Bohai Sea and along the coast down to the Chang Jiang river mouth. There is a slight change in composition from Lienyungang to Yingang: the illite content tends to

TABLE 3
Summary of Illite/Smectite ratio's.

Loess	1.87-3.29
Huang He sediment	
Huang He delta	0.52-0.67
Old Huang He delta	0.67-0.71
Tidal flats Jangsu A-D	0.62-0.77
East China Sea slope C17	0.75-0.86
Chang Jiang sediment	
Chang Jiang river mouth	1.14-1.34
Hangzhou Bay	1.05-1.57
Zhejiang coast	1.05-1.40
Yellow Sea PK22, YK6	1.08, 1.16**
East China Sea C1, C5, C25	1.03-1.16**
NW Taiwan shelf 121-1, 151-10	1.08, 1.19**
Taiwan west coast	3.11-6.89
Huang He - Chang Jiang mixtures	
Tidal flats Jiangsu coast E	0.91-1.00
Yellow Sea	0.91-1.00
East China Sea C25-1	0.98
Taiwan-Chang Jiang mixtures	
NW Taiwan shelf	1.75-2.30, 2.62, 2.74
East China Sea C7	1.89, 1.89

**=possible admixture from other sources

increase and the smectite content to decrease. At Yingang there is probably some admixture of Chang Jiang river mud. Chang Jiang sediment is present south of the Chang Jiang river mouth along the coast to (at least) south of Wenzhou, probably as far as Fuzhou. The dispersal of sediment along the coast is in agreement with the general southward direction of the coastal currents (only interrupted by the eastward outflow of the Chang Jiang), and with the inflow into Hangzhou Bay from the Chang Jiang.

In the Yellow Sea the clay mineral composition seems to be intermediate between the composition of Huang He and Chang Jiang sediment. The illite/smectite ratio in sediment of the Huang He river, the old Huang He river mouth, and the Jiangsu tidal flats is 0.52 to 0.91 (average 0.70) with a tendency to increase towards the south. Chang Jiang sediment (Chang Jiang river mouth, Hangzhou Bay, Zhejiang coast) has a ratio of 1.05 to 1.57 (average 1.21), whereas the Yellow Sea sediments in the ratio is between 0.91 and 1.16 (average 0.98).

To account for the clay mineral composition of the Yellow Sea sediment four alternatives are considered. Mixing of Huang He and Chang Jiang sediment in about equal amounts would give the observed composition of the Yellow Sea sediments, but an admixture from the Chang Jiang, does not seem very likely, even when in the winter a certain amount of sediment flows to the northeast. The general circulation over the shelf shows that this outflow tends to be dispersed already over a wide area in the East China Sea before reaching the Yellow Sea (which includes an area with relict sediments; Figs 4, 5). About 0.1 x 10^9 t·y^{-1} or 20% of the supply from the Chang Jiang should be transported to the Yellow Sea to obtain the mixed composition sediments found there, which seems unlikely, as about 40% (0.2 x 10^9 t·y^{-1}) of the Chang Jiang supply is already deposited directly off the river mouth, about 5% is deposited on the shores of the estuary and about 5% on the mud patch on the central shelf southwest of Cheju Island (Milliman *et al.*, 1985b; DeMaster *et al.*, 1985). This would leave only 30% to go south. To this, however, is added an unknown amount that is yearly resuspended off the mouth and also is transported southward.

More likely, because the transport distance is much shorter, would be an admixture supplied from the Korean rivers. No samples from Korea could be analysed by the authors, but the data given in Table 1 clearly show the virtual absence of smectite. An admixture of sediment from Korea in Yellow Sea sediment therefore would lower the smectite content. The data in Table 2 show that indeed the Yellow Sea sediment has a lower smectite content and a higher content of illite, kaolinite and chlorite. This makes an admixture of Korean sediment likely.

Lee & Chough (1989) have estimated that the accumulation of mud in the Yellow Sea is in the order of 0.22 x 10^9 t·y^{-1}. The data for smectite and illite content in the Yellow Sea point to a possible admixture of 10 to 20% of Korean sediment, when the difference between the Yellow Sea sediment composition and the Huang He sediment composition has to be entirely accounted for by such an admixture, or 0.020 to 0.045 x 10^9 ton annually. This is about 3.5 to 7 times the annual supply of the Keum river (Lee & Chough, 1989; Khim & Park, 1992). Since most of the supply from Korea is deposited on the Korean coast and in the mud deposits extending from Korea to the southwest, the supply from Korea can not account for an admixture in the Yellow Sea.

A third alternative is selective transport and deposition of clay minerals. Differential flocculation in estuaries, resulting in deposition of more illite and kaolinite nearshore and more smectite offshore (as based on the experiments by Whitehouse *et al.* (1960), has been assumed to explain clay mineral distributions in river mouths and on the shelf. Such distributions, however, could also be explained by dispersal and mixing of sediment of different origin, while suspended matter is already flocculated in the river upstream of the estuary so that selective flocculation is not likely to take place in estuaries (summarized in Eisma, 1993). Selective transport of clay minerals may occur when flocs have already a different clay mineral composition in the source area, resulting in flocs of different transport and settling behaviour, but there are as yet no indications that this takes place off the Chinese coast. Also, differential transport would have resulted in a high smectite content, as smectite flocs have much lower settling velocities than illite flocs (Whitehouse *et al.*, 1960), and not in higher illite contents.

A fourth alternative is admixture of reworked older sediment, presumably of Chang Jiang origin, into sediment recently supplied from the Huang He river. Where samples from different depths in the sediment have been analysed (in the Yellow Sea down to 10 cm, in the East China Sea to 30 cm), the clay mineral composition deeper in the cores was found to be similar to the composition in the top sediment. Resuspension and mixing of surface material with material of different origin from a deeper layer is therefore likely to have occurred. Deposition rates in the Yellow Sea are in the order of 0.3 cm per year: this thin layer can easily be mixed with older sediment by waves in a sea of 40 to 80 meter waterdepth where storms of force 7 or more occur during the winter and typhoons with winds up to force 12 during the summer (China Pilot, 1968). This presupposes, however, the presence of older deposits of Chang Jiang origin, about which nothing is known. Where supply from the Korean rivers and selective transport of clay minerals can be ruled out, this leaves supply from the Chang Jiang: either directly or through an intermediate stage, or stages, of deposition and resuspension.

In the East China Sea most of the samples that were analysed, were of Chang Jiang origin. The one sample on the continental slope (with Huang He composition) probably is a relict sediment of which only the top few cm have been reworked, as unsupported ^{210}Pb was only found down to 2 cm depth (S. Chen, 1990b). At station C7 the clay mineral composition is similar to the composition of sediment found off western Taiwan and indicates some transport from that area to the north with the Taiwan current. Off Taiwan a clay mineral composition with high concentrations of illite and chlorite and low concentrations of smectite dominates that can easily be distinguished from the compositions of Chang Jiang and Huang He sediment (Fig. 11). A few samples are of Chang Jiang composition, while a group of samples of mixed composition can be regarded as a mixture of Chang Jiang and Taiwan sediment (Table 3).

CONCLUSIONS

Analysis with a precise XRD technique indicates that fine-grained sediment from the Huang He and the Chang Jiang as well as from the northwest coast of Taiwan, can be distinguished by the illite/smectite ratio. From samples collected between the Huang He river mouth and south of Wen Zhou, it could be concluded that along the Chinese coast the Huang He sediment is dispersed as far south as the Chang Jiang river mouth, whereas further south and at least as far south as Wen Zhou, the fine-grained coastal sediment comes from the Chang Jiang (except locally at river mouths). This agrees with earlier results obtained by other authors using different XRD techniques.

In the Yellow Sea the fine-grained sediment has illite/smectite ratios that are intermediate between those of the Huang He and the Chang Jiang sediment. Four alternatives were considered to explain these ratios: 1) admixture of about 20% of the supply from the Chang Jiang, which is transported to the north and in the Yellow Sea is mixed with material supplied from the Huang He; 2) admixture into material from the Huang He of material supplied by the Korean rivers which transport very little smectite; 3) differential transport of clay minerals resulting in a relatively higher illite content, and 4) resuspension of older sediment of Chang Jiang origin, which is mixed with recent Huang He material, or resuspension of an older sediment of mixed origin.

The first alternative leaves open how transport from the Chang Jiang to the Yellow Sea takes place, as most indications (flow distribution, presence of relict sediment) point to a predominant transport to the

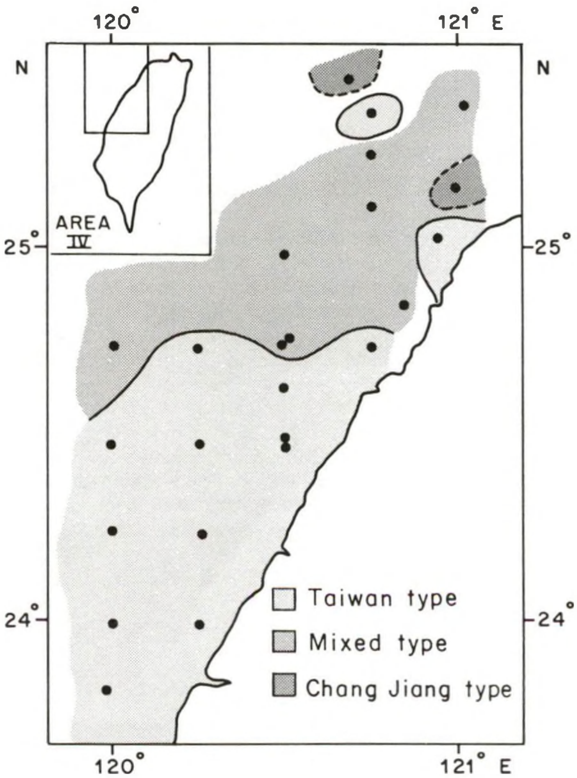

Fig. 11. Distribution of different sediment types characterized by different clay mineral assemblages off northwestern Taiwan (see also Fig. 10 and Table 2).

south and east. Supply from Korean rivers does not present this problem, but quantitatively the amount of sediment supplied by these rivers is not sufficient to account for the 10 to 20% admixture — or 0.020 to 0.045 x 10^9 $t \cdot y^{-1}$ — that is needed to give the observed illite/smectite ratios. For selective transport of clay minerals there is no indication; it would have resulted rather in a lower illite/smectite ratio than in a higher one. Resuspension of older sediment takes place considering the waterdepth and the regular occurrence of severe storms, but it is not known to what extent older sediment of Chang Jiang origin (or from Korean rivers) is involved. Therefore an admixture of Chang Jiang sediment is most likely, but the mechanism of the supply is not clear.

In the East China Sea most of the samples that were analysed contained material from the Chang Jiang. At one station the same illite/smectite ratio was found as in the sediment off northwest Taiwan, which indicates that some material from that area is transported to the East China Sea (presumably by the Taiwan current). One sample on the continental slope in the East China Sea contained Huang He sediment; ^{210}Pb data indicates that this is a relict sediment.

Acknowledgements.—We are very much indebted to C.R. Alexander (Savannah, Ga) for the use of samples from the Yellow Sea and to Th. Courp (Perpignan) and R. Gieles-Witte (NIOZ, Texel) for carrying out the clay mineral analyses.

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