

Storm deposits in the coastal region of Shanghai, the Yangtze Delta, China

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Abstract

In the nearshore area along the coast of Shanghai, from the marsh-lowland to the prodelta, a series of storm deposits is found that is relatively coarse-grained and interbedded with fine-grained fair-weather deposits. In a vertical section the proportion of storm deposits is up to 35%. The storm deposits are well preserved above normal wave base mainly due to abundant supply of sediment from the river. The storm-deposit series is characteristic of the mouth of a large river, such as the Yangtze River, having high sediment supply and accumulation rates.

Introduction

Since the 1960s a large number of papers concerning storm deposits has been published. Knowledge and understanding of sedimentary structures, sedimentary sequences and models of storm deposits are mostly obtained, however, from research on ancient deposits (Harms et al. 1975, Dott & Bourgeois 1982) rather than from studies on modern ones. The reason is that studying modern storm deposits is fraught with difficulties, such as encountered with

1. *in situ* observations and measurements under storm conditions,
2. acquisition of large-scale undisturbed box-core samples, and
3. subsequent destruction of such deposits by wave and tidal currents and by bioturbation.

In fact, observations on storm deposits under storm conditions are scarce (Smith & Hopkins 1972, Ew-

ing 1973, Lavelle et al. 1978, Butman et al. 1979). Furthermore, hummocky cross-stratification, which is considered to be characteristic of storm deposits, has hardly been successfully simulated in laboratories (Carstens et al. 1969, Lofquist 1978). It is therefore still necessary to establish distribution and characteristics of storm deposits in modern coastal depositional systems and to determine the physical backgrounds and hydrodynamics for the formation of hummocky cross-stratification. For that reason we studied an area around the Yangtze River mouth including the following sub-zones: marsh-lowland, sandy and shelly chenier, tidal flat, delta front and prodelta (Fig. 1). In the last 10 years we have surveyed the area, 26 trenches have been dug in the marsh-lowland and chenier area, 300 box cores ($25 \times 16 \times 8 \text{ cm}^3$) were taken from 18 sites on the intertidal flats, and 100 vibro-cores from the delta front and prodelta (Fig. 1). In 1981 the study area was swept by a strong typhoon

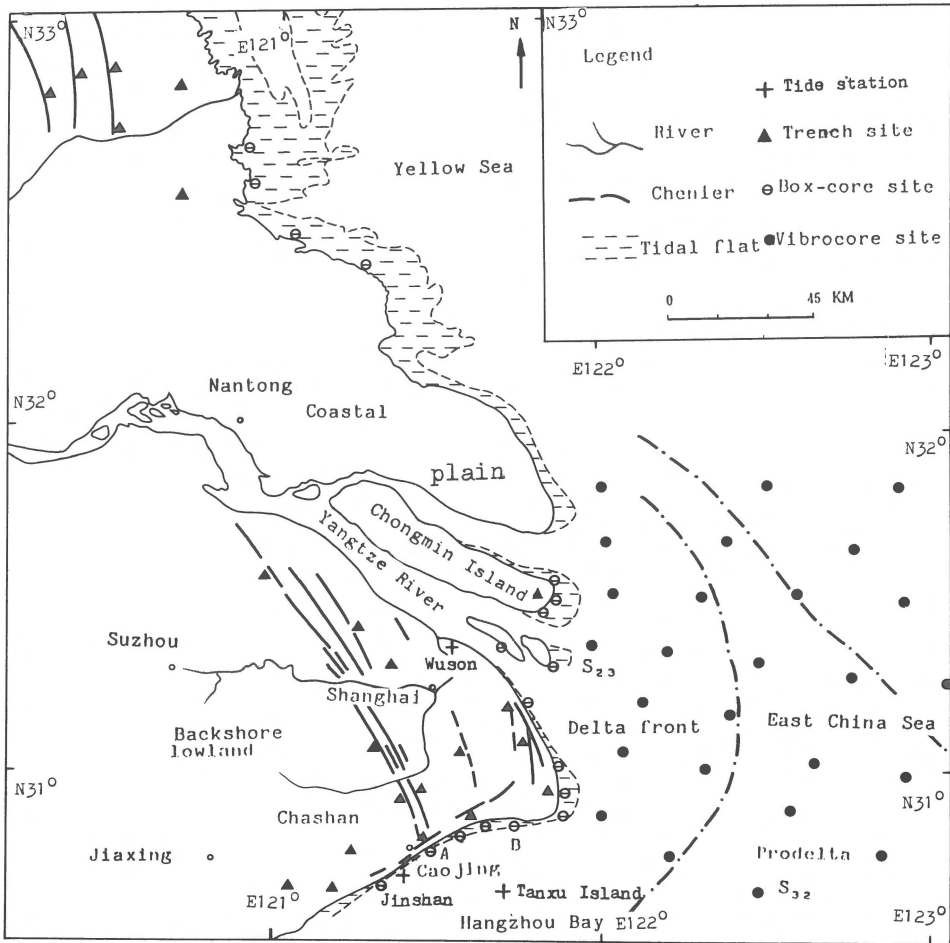


Fig. 1. Sketch map of the study area showing the geomorphological zonation and the sampling sites.

numbered 8114 (Fig. 2). Before during and after the typhoon, *in situ* observations were carried out across the Caojing tidal flat, Shanghai (Fig. 1), including repeated levelling and repeated sampling of surface sediments by box cores. Tidal current measurements were tried during the typhoon, but recording current meters couldn't work properly due to the rough sea. Measurements on fair-weather tidal currents were carried out by the recording current meters at the mean low water level on the tidal flat and in the subtidal zone. The meters were mounted on tripods installed on the tidal flat in the way shown in Fig. 3. The bottles were fixed on a pole for water-sampling. Wind and wave parameters were collected from nearby stations. Large numbers of resin peels were taken from box cores

and undisturbed vibrocores. This paper discusses the characteristics of storm deposits formed during Typhoon No. 8114 in tidal flat, marsh-lowland, delta front and prodelta. Storm-related sedimentary characteristics of the cheniers have been discussed by Yan et al. (1989b).

General setting

The discharge of the Yangtze River is 924 billion m^3/a , and the silt discharge is up to 500 million tons/a. Most of the sediments carried by the river are deposited in the river mouth area and the Hangzhou Bay. They form a gentle submarine slope with a gradient of 0.15‰ to 0.39‰, which is

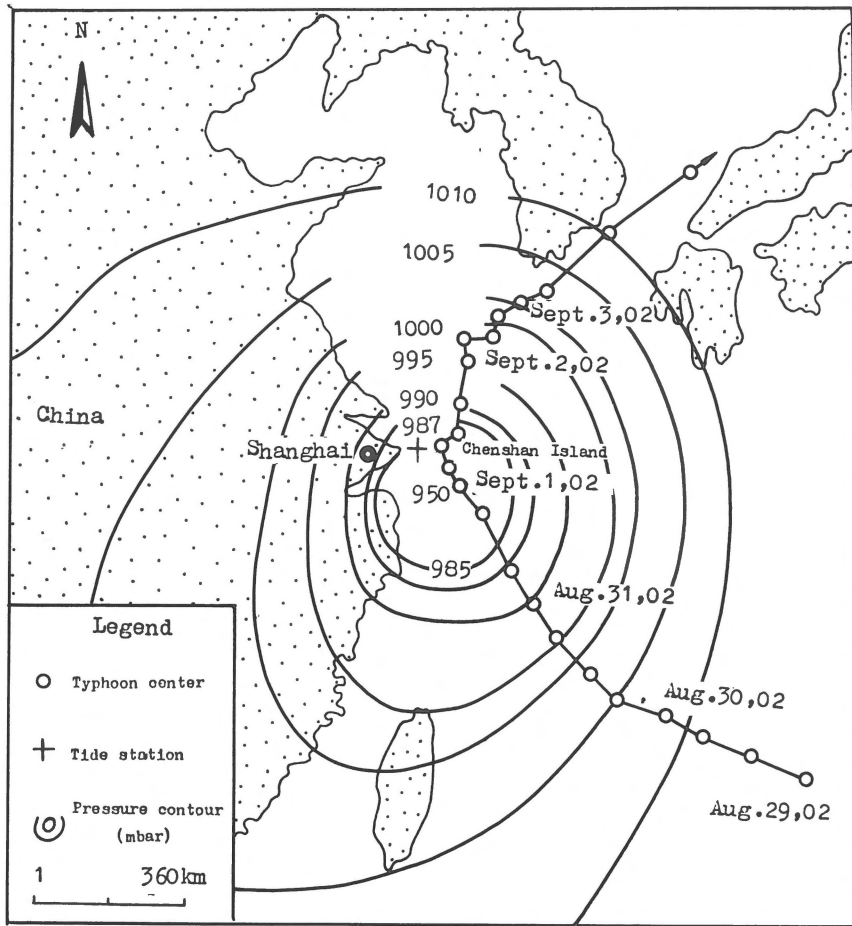


Fig. 2. Sketch map showing the path, evolution of the Typhoon No. 8114 and the pressure field at 02:00 Sept. 1, 1981.

covered mainly by silts. Formation of the coastal plain in this area began about 7000–6400 Y.B.P., and since then it has been prograding rapidly from west to east (Yan & Shao 1989a). Historical records show that the delta plain on the southern side of the

Yangtze River Mouth progrades with an average rate of 45 m/a (Xu, et al. 1987).

The study area is predominated by tidal currents. The mean regular semi-diurnal tide range is 2.5 to 4 m. For instance, near the Caojing tidal flat (Fig. 1) the mean tidal range is up to 4 m, and the maxi-

Table 1. Spring tide current velocity measured on the low-tidal flat and subtidal shallow of Chaojing, Shanghai on Oct. 18, 1986 (printing current-meters were arranged at 20 cm above the bed surface)

Location	Flood current				Ebb current			
	Maximum velocity (cm/s)	Mean velocity (cm/s)	Current direction	Duration	Maximum velocity (cm/s)	Mean velocity (cm/s)	Current direction	Duration
Low tidal flat	0.96	0.61	225–305°	5 h 20'	0.51	0.47	55–180°	7 h 00'
Subtidal shallow	1.26	0.60	227–238°	5 h 24'	1.11	0.48	50–57°	7 h 01'

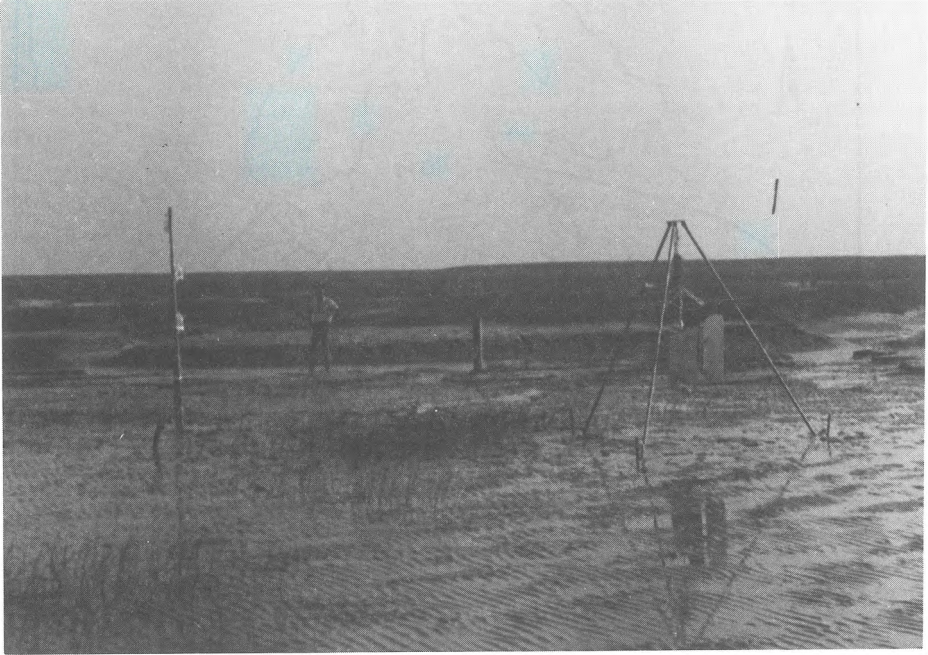


Fig. 3. A recording current meter mounted on a tripod and bottles fixed to a pole for water sampling during tides on the Caojing tidal flat.

imum flood-current velocity measured during the spring tides at the mean low water level and subtidal zone is up to 0.96 m/s and 1.26 m/s respectively (Table 1, Fig. 4). The duration of the ebb is one hour and 40 minutes longer than that of the flood. The mean velocity of the ebb is only 78% of the flood's one. The change in tidal current directions is relatively complicated. Firstly, the flood current is approximately opposite to the ebb current. Also, the flood- and ebb-currents are shifting in direction within a flood phase and an ebb phase, respectively, especially in intertidal flats. For instance, the tidal current on the low tidal flat shifts from 225° to 305° within a flood phase and from 55° to 180° within a ebb phase (Table 1, Fig. 4).

Usually, the area experiences weak wave action, but it is swept over by strong typhoons about once a year in summer or autumn. Strong typhoons greatly change the hydrodynamic conditions of the coastal zone. Typhoon-induced high tides could be 1.3 to 2.2 m above the mean high water and promote the development of rip currents. Wave action on the tidal flat and nearshore is strengthened due

to the strong wind and high water level, and becomes the leading process on the tidal flat during the peak of a strong typhoon. For instance, the wave height near the mean low water level at the

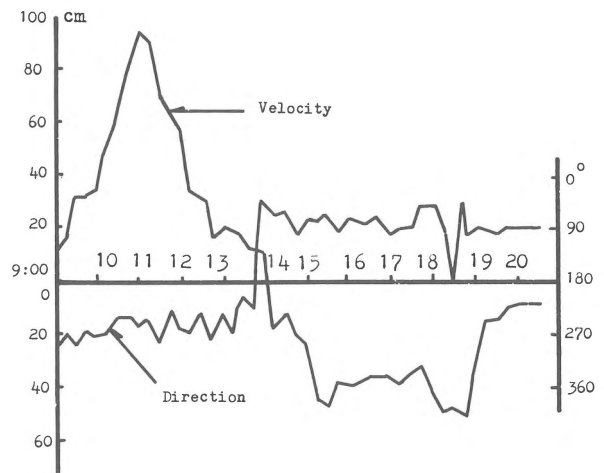


Fig. 4. Spring tide current velocity and direction measured on low-tidal flat, Chaojing, Shanghai on Oct. 18, 1986 (current-meters were positioned 20 cm above the bottom).

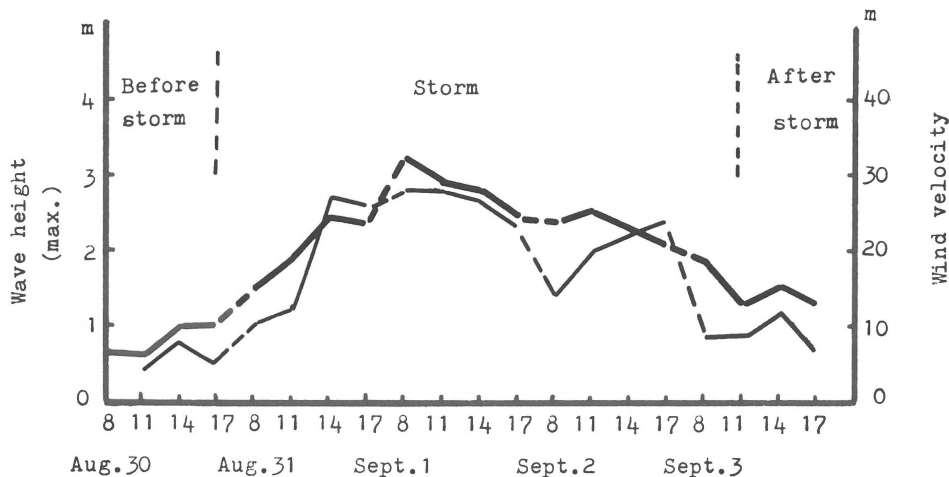


Fig. 5. 3 Hourly wind velocity (heavy line) and wave height (thin line) recordings during 5 consecutive days before, during and after passage of Typhoon No. 8114. Note that no measurements were made at night (dashed intervals).

Jinshan station increased from 0.4 m before typhoon No. 8114 to 1.4–2.80 m during the typhoon. The wave height was up to 2.8–3.8 m near Tanxu Island during Typhoon No. 8114 (Table 2, Fig. 5), and 13 m near the Chenshan Island (Fig. 2). The wind direction during a typhoon changes. For example, it changed in the range of 90° (from NNE to NNW) or more during the peak of Typhoon No. 8114 (Table 2, Fig. 5). It is inferred that wave direction correspondingly changes during a typhoon.

Outside the Yangtze River mouth, the mean normal wave base is located at about 10 m water depth and the mean storm-wave base about – 30 m (Chen 1987).

The silt which is the major component of the sea

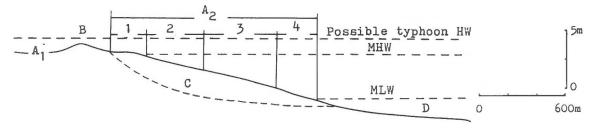
bed sediments in the area (Table 3) can be easily resuspended and transported by the tide/wave currents. Table 4 shows that the sediment content in the near-bed horizon is up to 95.6 kg/m³ in a spring flood-tide and the vertical gradient of the sediment content in the tidal current is quite large. During a strong typhoon the bed sediments are stirred up, and form silt clouds in the water. In such a case even the surface water also carries a large quantity of sediment. The vertical gradient of suspended-sediment concentration is low. The total amount of sediments transported by tidal currents, especially flood-tidal current, is surprisingly high.

Table 2. Wave and wind records at the Tanxu Island Station (Fig. 1) during the Typhoon No. 8114

Date	Wind										Wave											
	08:00		11:00		14:00		17:00		Period(s)		Wave-height (m)				Maximum wave-height							
	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	Vel.	Dir.	08:00	11:00	14:00	17:00	Mean	08:00	11:00	14:00	17:00	Mean				
1981																						
Aug. 30	6	ENE	6	NE	9	NE	10	NE	–	2.7	2.8	3.3	2.2	0.4	0.7	0.4	0.4	0.4	0.8	0.5		
Aug. 31	15	NNE	19	NNE	25	NNE	24	NNE	3.6	4.1	4.6	4.6	4.2	0.9	1.1	2.6	2.5	1.8	1.0	1.2	2.7	2.6
Sept. 1	32	N	29	NNW	28	NNW	24	NNW	4.7	4.8	4.1	4.0	4.4	2.6	2.7	2.4	2.2	2.5	2.8	2.8	2.7	2.3
Sept. 2	24	WNW	25	WNW	23	WNW	21	WNW	3.3	4.1	4.3	4.6	4.1	1.4	1.8	2.0	2.2	1.9	1.4	2.0	2.2	2.4
Sept. 3	19	WNW	13	WNW	15	WNW	13	NW	3.1	3.4	3.6	2.9	3.3	0.8	0.7	1.1	0.6	0.8	0.9	0.9	1.2	0.6

Table 3. Textural parameters of intertidal bed-load sediments (5 cm thick) sampled before, during and after Typhoon No. 8114 and in winter season, 1981

Item Time	Mean grain size (Mz)(ϕ)		Mud content (%)		Inclusive graphic standard deviation (σ)		Inclusive graphic skewness (SK)		Inclusive graphic kurtosis (Kg)												
	before typhoon	after typhoon	before typhoon	after typhoon	before typhoon	after typhoon	before typhoon	after typhoon	before typhoon	after typhoon											
High tidal flat	5.20	4.74	4.88	5.59	6.79	6.79	2.33	2.01	11.08	0.91	0.56	0.38	1.42	0.25	0.06	0.02	0.48	1.67	1.34	1.09	2.31
Middle tidal flat	5.05	4.54	4.64	5.30	7.21	7.21	1.99	4.07	10.46	0.83	0.63	0.82	1.38	0.20	0.26	0.71	0.57	1.25	1.51	1.59	2.83
Low tidal flat	4.71	4.34	4.64	4.60	4.65	4.65	1.52	4.57	1.97	0.74	0.61	0.56	0.54	0.20	0.26	0.53	0.24	2.38	1.65	2.77	1.86



- A_1 = Marsh-lowland A_2 = Tidal flat
 B = Chenier C = Inferred beach surface
 D = Subtidal zone 1 = Salt marsh
 2 = High tidal flat 3 = Middle tidal flat
 4 = Low tidal flat

Fig. 6. Sketch map showing the zonation in morphology of the tidal flat of Shanghai coast.

Storm deposits on the tidal flat

The tidal flats in this area are 800–2500 m wide, with a gradient of 1‰–3‰. The sediments in the tidal flats are mainly clay and silt and generally become finer landward (Table 3).

In this area, the high tidal flat (Fig. 6) is characterized by horizontal lamination with a laminae thickness of 0.2–3 mm; the middle tidal flat by an alternation of silt and clayey silt layers and the low tidal flat by ripple cross-laminae with an average ripple wavelength of 7 cm and a height of 1 cm.

Erosional features (Fig. 7a) and other distinctive storm deposits were clearly found on all parts of the tidal flat during field observations in the Caojing tidal flat 6 hours after the exceptionally high tide of Typhoon No. 8114. On the high tidal flat, small, low mound-like silt piles occurred (Fig. 7b). On the middle tidal flat, many ellipse-shaped silt piles were present (Fig. 7c). The storm increased the gradients of the low tidal flat and produced well-developed runoff marks and scattered sheet-like silt accumulations. The surface ripples were mostly replaced by dentritic rills. Planometric observations made on the Caojing tidal flat before and after Typhoon No. 8114 revealed that 10–20 cm of sediment was deposited on the salt marsh and high tidal flat, whilst about 10–30 cm of sediment had been removed from the middle and low tidal flat. After the passing of Typhoon No. 8114 these features were covered by newly-settled tidal deposits or reworked by normal tide/wave action.

However, the fair weather tidal deposits themselves were extensively reworked or removed dur-

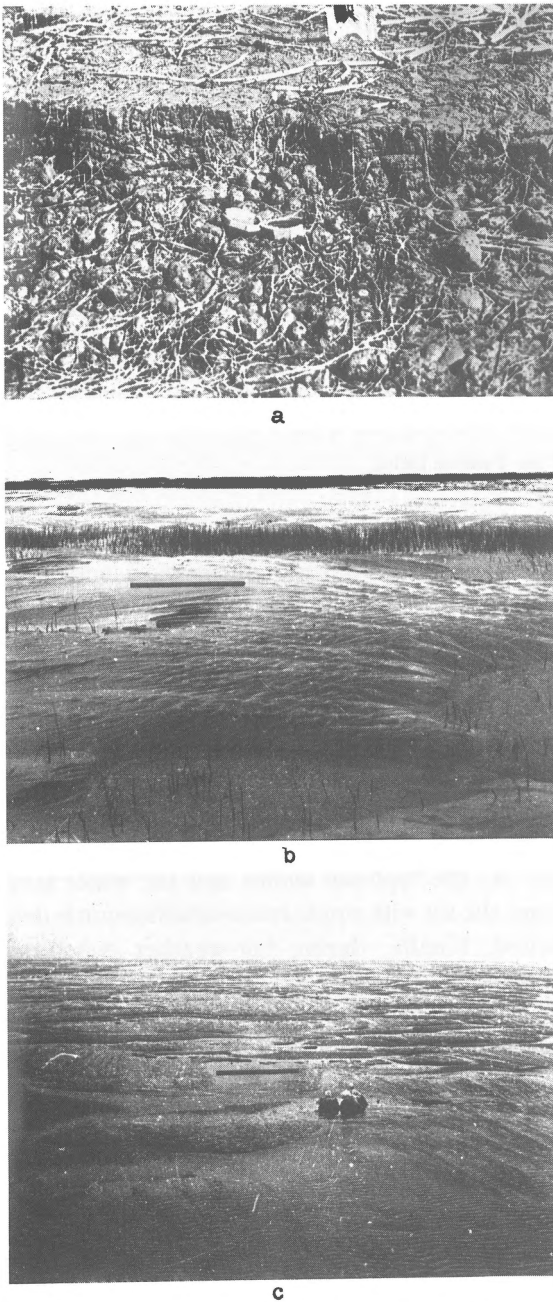


Fig. 7. Geomorphic features of tidal flat after the Typhoon No. 8114. The bar scale shown is 50 cm. a. The erosional scarp near high tidal water level. Mud-ball, shells and remains of reed-roots accumulated at the foot of the scarp (Caojing Tidal Flat). b. Low mound-like silt accumulations, with wave lengths of 1.5–3.5 m and a maximum height of 30 cm, on the high tidal flat which are generally oriented parallel to the shoreline and have small ripples superimposed on their surface. *Scirpus planiculms* were buried beneath these accumulations (Caojing Tidal Flat). c. Ellipse-shaped silt piles with long axes of 3–4 m and short ones of 1–2 m on middle tidal flat. The piles strike approximately parallel to the shoreline. The relief, through to crest, of these silt bodies is 20–30 cm (Caojing Tidal Flat).

ing Typhoon No. 8114. They were replaced by storm deposits of a generally cleaner, coarser and better sorted nature. The characteristic sedimentary sequence of storm deposits on the tidal flat is fining upwards and shows the following sequential development of sedimentary structures from bottom to top (Fig. 8, Fig. 9a): (1) A basal erosion surface (Fig. 9a, b, d); (2) horizontal lamination (Fig. 9a, c); (3) hummocky cross-stratification (Fig. 9a, b, c); (4) wavy cross-lamination or climbing ripple lamination (Fig. 9a, b, c); (5) normal tidal deposits.

Variations from the idealized sequence are common, such as the absence of a basal erosional surface and/or hummocky cross-stratification or a dominance of horizontal lamination (Fig. 9d).

The hydrodynamics described above and the observations we have made provide important implications for the origin of hummocky cross-stratification and storm-deposit sequences on tidal flats. It is possible that the oscillatory flow induced by typhoon waves is shifting in direction and that, at the same time, flood- and ebb-currents are alternating in direction and are changing in intensity as well. These two processes usually intersect one another, and they are two main factors for the formation of hummocky cross-stratification. In addition, a rip current is apparent due to the set-up on the near-shore during typhoons, and it is also an additional factor for the formation of HCS. These three factors act together on the bed by scouring and filling. Under certain conditions, when the bed is affected by the shearing stress induced by the three factors with almost equal intensity in all directions then

Table 4. Silt contents in tidal currents measured on the middle tidal flat of Caojing, Shanghai, on Oct. 18 and Oct. 24, 1986

Water depth (above bed surface) (cm)	Spring tide (kg/m ³)		Neap tide	
	flood	ebb	flood	ebb
120	10.1		1.8	
70	22.3		1.8	
20	95.6	1.3	10.8	0.8

Note: Recording current-meters fixed at 20 cm above the middle tidal-flat surface using 3 bottles as sediment traps which were arranged at 20 cm, 70 cm and 120 cm above the surface.

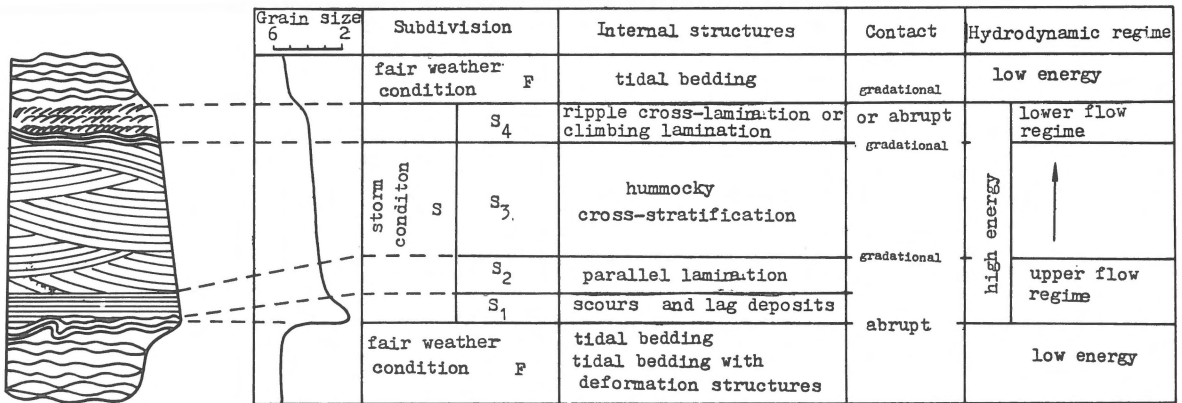


Fig. 8. Sedimentary structural sequence of storm deposits on tidal flat of the Yangtze Delta.

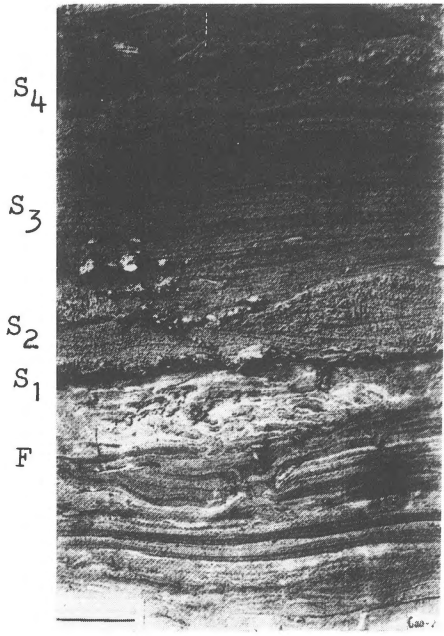
low mound-like piles are formed (see the Fig. 7b). This explanation is very similar to that of B. Greenwood's, stating that HCS (Allen's low-angle, undulatory lamination) is induced by combined oscillatory and alongshore 'steady' flows (Greenwood & Sherman 1986). If there is a relatively strong shearing stress in one direction, the silt piles are elliptical in plain view (see Fig. 7c). A flood-tidal current with a large quantity of sediment is the essential prerequisite for the formation of mound-like storm deposits. The rapid deposition of silt from the flood-tidal current with a large quantity of sediment results in the formation of mound-like silt piles 20–30 cm in thickness within a few hours. Horizontal lamination is also common in tidal-flat storm deposits (Fig. 9c, d), and the formation of the horizontal lamination is related to the rapid deposition of silt from the silt-saturated flood current on a less-eroded even bed surface. As a whole, the sequence of tidal-flat storm deposits (Fig. 8)

reflects the energy change in water body during a strong typhoon. At first, storm wave and flood currents scour the bed, forming the basal erosional surface and distorting/or disturbing the underlying fair-weather tidal deposits. Then, under upper flow regime, there follows the rapid accumulation of the silt with horizontal lamination. If deposition occurs under the influence of the oscillatory currents that shift in direction, tidal currents or rip currents, the silt is accumulated with hummocky cross-stratification. As the typhoon wanes and the water level drops, the silt with ripple cross-stratification is deposited. Finally, during fair-weather conditions normal tidal sediments cover the storm deposits.

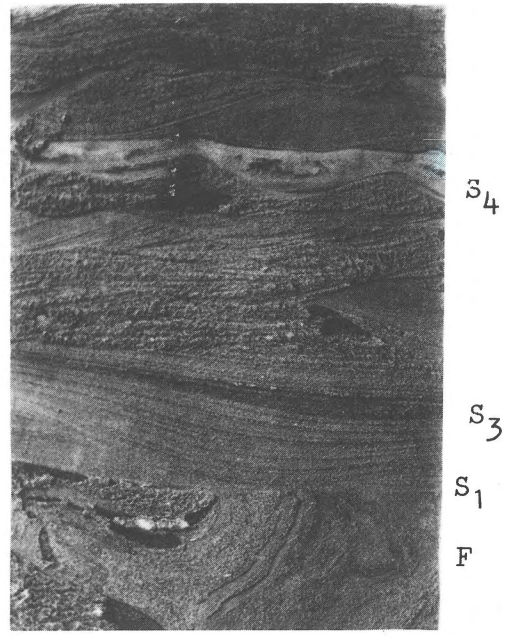
Storm deposits in marsh-lowland

The typhoon generates uncommonly high-water levels in the nearshore area which may be 1 to 2

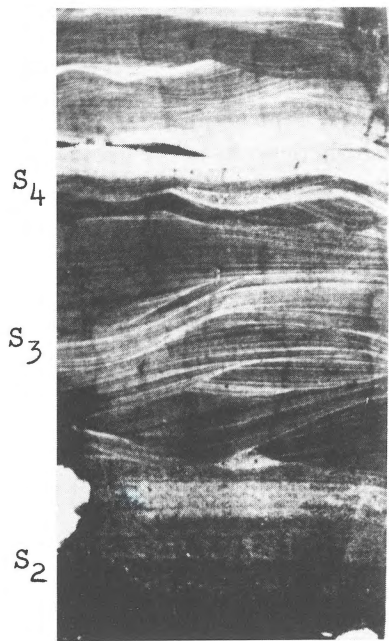
Fig. 9. Resin peels of box cores showing the storm-deposited sedimentary structures of tidal flat. The bar scale shown is 5 cm. a. Storm tide-emplaced layer (upper half) and the normal tidal layer (lower half) in erosive contact. In storm layer from bottom upward appear basal erosive surface, shells and mud-ball lag deposits, antidune cross-lamination and parallel lamination, hummocky cross-stratification and ripple cross-lamination and climbing lamination. In normal tidal deposits tidal bedding can be seen and deformational structures (Caojing Middle Tidal Flat, Fig. 1A). b. Storm tide-emplaced layer (upper and middle parts) and normal tidal layer (lower part) in erosive contact. In storm layer from bottom upward appear basal erosive surface, hummocky cross-stratification and ripple cross-lamination. In lower part the sedimentary structures are greatly deformed (from the middle tidal flat, Fig. 1B). c. Storm tide-emplaced layer (lower and middle parts) and normal tidal deposit layer (upper part). In the lower part of the storm tide-emplaced layer appears horizontal lamination of coarse silt. (Holocene tidal deposits of Shanghai Tidal Flat, Fig. 1C). d. Storm tide-emplaced layer (upper part) and normal tidal layer (lower part) in erosive contact, the normal tidal layer is greatly deformed. In storm layer from bottom upward appear basal erosive surface, horizontal lamination of coarse silt, disturbed layer (Holocene tidal deposits of Shanghai Tidal flat, Fig. 1C).



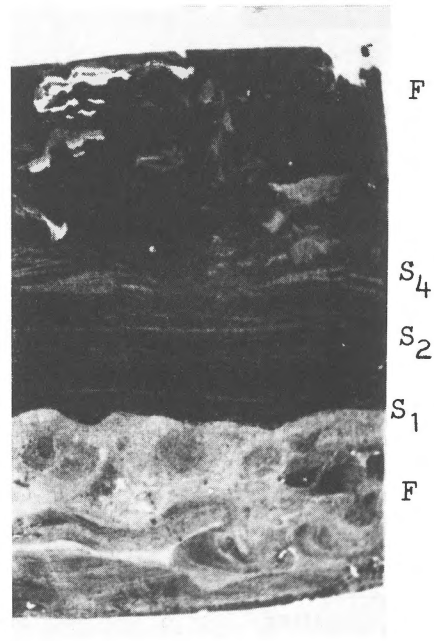
a



b



c



d

0 5cm

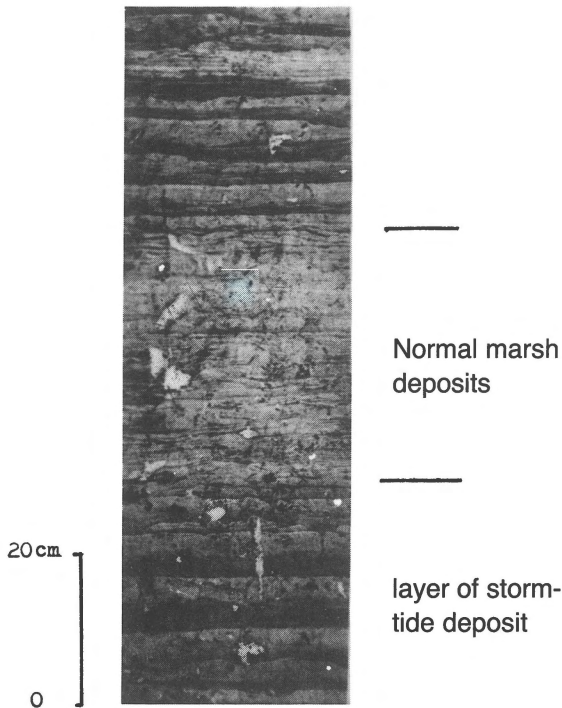


Fig. 10. Resin peel of Late Holocene marsh sediments. Storm deposits preserved in the former Late Holocene marsh in Chashan, Jinshan, Shanghai. Storm tide-emplaced layers (upper part and lower part) and normal marsh layers (middle part). Individual storm layer has a thickness of 4–6 cm and a basal erosive surface with a relief of 1–2 cm, horizontal lamination, massive silty clay in an upward sequence. It is generally fining upward. (Former Late Holocene marsh in Chashan, Jinshan, Shanghai, Fig. 1).

metres higher than the elevation of the coastal-plain surface (Table 5). Consequently, the storm-flood current overflows the beach ridges, cheniers or valleys and inundates the marsh-lowland, where

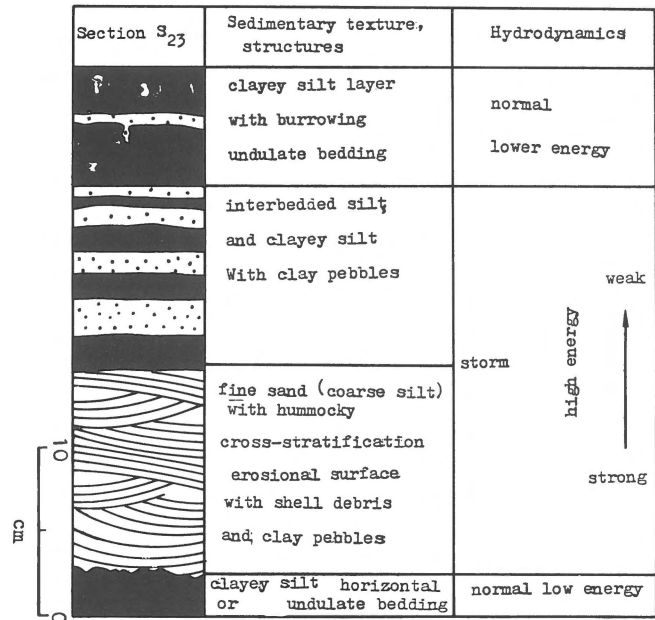


Fig. 11. Sedimentary sequence of storm deposits on the delta front (vibrocore S₂₃ in 8 m water depth, see Fig. 1). Total length of section is 33 cm.

it forms storm deposits. We have observed marsh-lowland storm deposits in the geological record of Late Holocene marsh in Chashan, Shanghai (Fig. 1) and in Dongxiang, Zhejiang Province (Fig. 10). The characteristics of storm deposits in marsh-lowland are as follows:

1. The storm deposits are finer than those of the nearby tidal-flat deposits;
2. the storm deposits fine upwards (Fig. 10);
3. the storm layer overlies a basal erosional surface with a relief of 1–2 cm (Fig. 10);
4. it consists of silt with horizontal lamination or

Table 5. Typhoon-induced storm high tide records at the Wuson tide station, Shanghai

Code no. of typhoon	Date	Measured high water level (m) (above Wuson Zero)	Depth above M.H.W. (m)
6001	Jun. 6, 1960	4.90	1.40
6008	Aug. 9, 1960	4.82	1.32
6207	Aug. 2, 1962	5.38	1.88
6911	Sept. 27, 1969	4.82	1.32
7413	Aug. 20, 1974	5.29	1.79
7910	Aug. 24, 1979	4.87	1.37
8114	Sept. 1, 1981	5.74	2.24

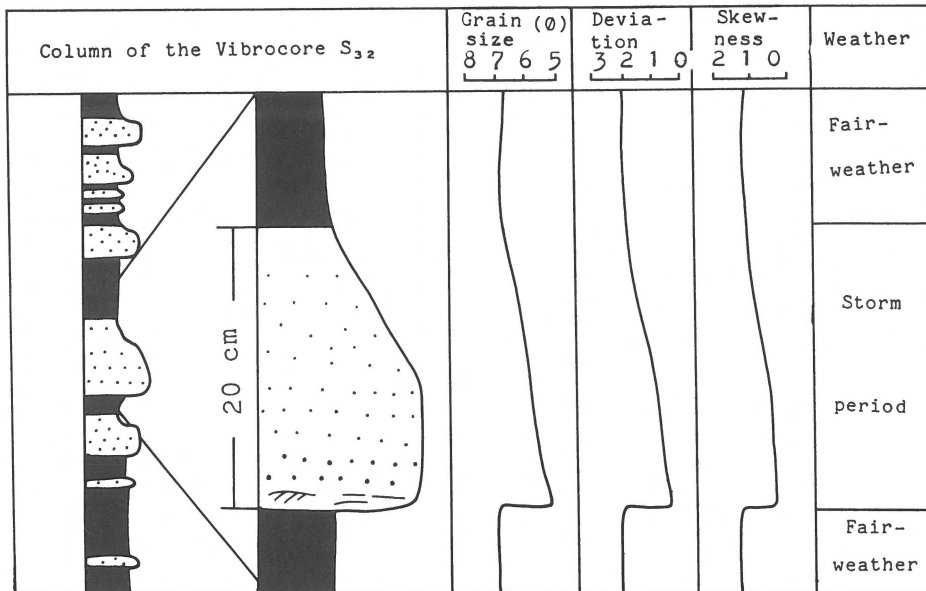


Fig. 12. Sedimentary sequence of the storm deposits on the prodelta (vibrocore S₃₂ in 30 m waterdepth, see Fig. 1).

ripple cross-lamination in the lower part of the layer, and without stratification in the upper part (Fig. 10);

- the remains of terrestrial plants, fresh-water fauna and foraminifera occur in the layers (indicating a marine origin).

These deposits are thought to have been formed by storm tides. During a storm the tide rises and violently floods the marsh-lowland at a relatively high velocity (accompanied by wave action), eroding the surface of the marsh sediments (Fig. 10). The fining upwards sequence is deposited during the waning of the typhoon as current-velocities gradually decrease (Fig. 10). A distinctive feature of the marsh-lowland storm deposits is the occurrence of marine foraminifera with the remains of terrestrial plants and fauna. This results from the similarity in hydrodynamic behaviour between fine silt and small-size foraminifera.

Storm deposits in the delta front

The topography of the delta front changes from place to place due to submarine distributaries of the Yangtze River. The sediment in the delta front

is dominated by fine sand and silt with small-scale ripple cross-bedding and other sedimentary structures (Xu Shiyuan et al. 1982). Based on the 2–4 m long vibrocores from this area, there are storm-deposited layers 20–30 cm in thickness interbedded with the normal deposits of the delta front. A typical sequence (Fig. 11) from bottom upwards is: (1) An uneven erosional surface with gutter or pot casts covered by mud pebbles and shell fragments. (2) The lower part (– 10 cm) of the storm deposit is relatively coarse (fine sand, average grain size of 2.8–3.0 φ) mostly with hummocky cross-stratification. (3) The upper part of the storm deposit (– 13 cm) comprises interbedded silt and clayey silt (couplets of silt and clayey silt). The silt laminae thin from 3 cm upward to 0.5 cm. (4) The storm deposit is topped by a clayey silt layer, which formed under fair weather, contains some vertical burrows and has no apparent stratification.

Moreover, the storm deposits in the delta front could be destroyed not only by normal wave/tide action, but also by the shifting of the submarine distributaries. The observation on 15 vibrocores taken from the delta front shows that the storm deposits were well preserved only in five vibrocores.

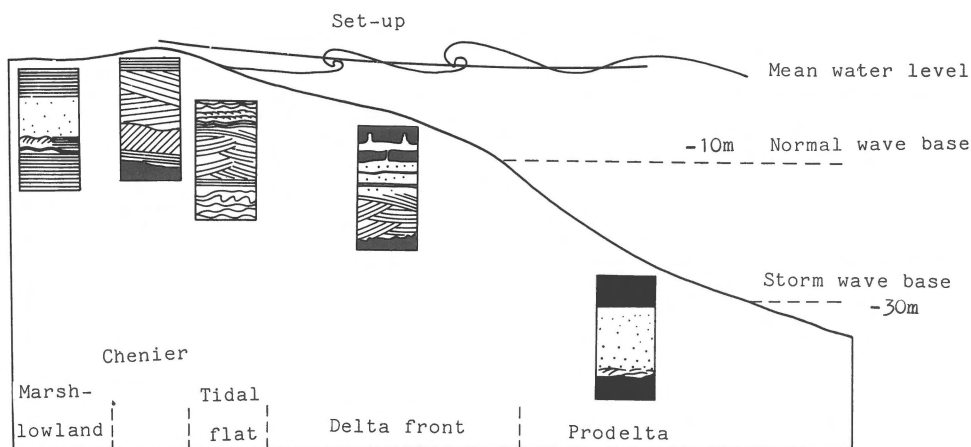


Fig. 13. Model of storm deposits of the yangtze delta coast.

Storm deposits in the prodelta

Vibrocores taken from the prodelta show that the sediments formed under fair weather are dominantly poorly sorted, organic-rich silty clay (average grain size 7.25ϕ), with apparent horizontal laminae and moderate bioturbation. The fair-weather deposits are interbedded with storm-deposited layers with thicknesses of 20 cm or less. Typical characteristics of the storm deposits (Fig. 12) are:

1. An erosional base;
2. silt with fining upward sequence, more poorly sorted upward, usually positive deviation;
3. horizontal laminae in the basal part and graded bedding in the main body of the layer, almost no biogenic structures;
4. the gradational or abrupt contact between the storm-deposit layer and the overlying (fair-weather) silty clay layer.

Vibrocores taken from the transition zone between the prodelta and continental shelf show that there are some storm-reworked relict sand layers. They are 1–3 cm thick with a mean grain size of 3.2ϕ , containing fragments of shells and indistinct internal structures, having a distinct contact surface with the underlying normal continental relict sand. Moreover, the surface of the relict sand layer on the continental shelf is also reworked by storms to some extent, thus showing that submarine-bottom sediments in the shallow sea outside the Yangtze

River mouth are also destroyed, reworked and re-deposited by strong wave action of storms. These results are consistent with the observations in the shallow seas of the continental shelf along the Gulf of Mexico, the North Sea and etc. (Hayes 1967, Reineck & Singh 1972, Butman et al. 1979).

Model of storm deposits in the delta

The intensive observation in the Yangtze Delta shows that storm-generated deposits are developed and are preserved in the marsh-lowland, cheniers, intertidal flats, delta front and prodelta (Fig. 13). In a vertical section these storm deposits are generally interbedded with fair-weather deposits. The base of the storm deposits is erosional. The storm-deposited layer is relatively coarse, its grain size fining upward. It consists of two parts: lower, coarse-grained deposits reworked from the underlying sediments, and an upper, very rapidly deposited main body. A typical vertical section of storm-generated deposits shows in sequence, from bottom to top, parallel lamination, hummocky cross-stratification or graded bedding and ripple-cross stratification or climbing lamination. The laminae in the sequence are usually thinning upward. In storm deposits, faunal remains are rare, bioturbation is not common, but escape traces may be found in the upper part of the storm deposits.

During a storm spring tide, the coastal zone is

usually strongly eroded, and more sediments are moved by the flood current landward. The effect of the storm therefore, is weakening with increasing water depth. Storm deposits occur more frequently in the nearshore area with a great amount of storm-deposit layers and sizable thicknesses of single storm-deposit layers in vertical sections. Storm deposits become thinner and occur less frequently seawards. For example, a single layer can be 30 cm in thickness on tidal flats and the delta front, and less than 10 cm the prodelta. As for the proportion of the storm deposits in vertical sections, there is no obvious difference among these subzones. The rate of accumulated thickness of storm deposits in the vertical section is 34.8% in Shanghai tidal flat (Shao & Yan 1982) and 37% in the prodelta (vibrocore S₃₂). This is due to the total, year-round, seaward decreasing sediment accumulation rate.

Discussion

Many authors have noted that it is difficult for storm deposits, and especially hummocky cross-stratification to be preserved in the shallow water area above normal wave base (Harms et al. 1975, Dott & Bourgeois 1982, Hamblin & Walker 1979, Walker 1984). However, the situation around the Shanghai coastal zone is different. The storm deposits developed intensively along the delta coast and are preserved in vertical section above normal wave base.

In the coastal area studied wave-induced oscillatory flows, the flood- and ebb-currents, and rip currents interact during storms and form an important hydrodynamic condition for the formation of the hummocky cross-stratification. Moreover, the Yangtze River carried a lot of fine-grained sediments, mainly silty clay, to the prodelta zone, and this material is too fine to form the hummocky cross-stratification. In the tidal flat and the delta front the sediments are relatively coarse (Table 3), which more favourable for the formation of hummocky cross-stratification. According to Duke (1987) hummocky cross-stratification is believed to form preferentially in fine sands.

The high sediment accumulation rate in the

study region is probably the major reason for the preservation of storm deposits in the area. Repeated levelling showed a vertical sediment accumulation rate of 12 cm/a on the intertidal flat east of Shanghai (Shao & Yan 1982). Based on the Pb²¹⁰ dating, the vertical sediment accumulation rate in the delta front is up to 5.4 cm/a (Cheng et al. 1985). Thus the typhoon-generated storm deposits are covered by newly settled sediments not long after the typhoon period, and are protected from destruction or reworking by succeeding waves, tidal currents or other coastal processes.

In addition, different sedimentary environments make a difference in the preservation potential for storm deposits. For example, the storm deposits in the delta front are easily destroyed due to the shifting of the submarine distributaries of the Yangtze River.

Conclusions

The present study of the storm deposits in the coastal region of Shanghai showed the following:

1. In the study area, typhoon-generated storm deposits are well developed and well preserved. In vertical sections storm deposits are interbedded with fair-weather deposits and the proportion of storm deposits is up to about 35%.
2. A distinctive feature of the storm deposit model of the region is that hummocky cross-stratifications are formed and preserved in the intertidal flats and subtidal zones above the normal, about 10 m deep wave base.
3. Wave-induced oscillatory flows, the flood- and ebb-currents and rip currents interact during storms generate important hydrodynamic conditions for the formation of HCS in this area.
4. The vertical sediment accumulation rate is about 5 cm/a in the delta front and about 12 cm/a on the tidal flat. The high sediment accumulation rate in this area is the major reason for the good preservation of storm deposits.

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