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The characteristics of the China coastline

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Abstract—Evolution of China's coastline reflects the influence of geology, rivers, climate, typhoons, waves, tides, shelf currents, and sea-level changes. While tectonics control the broad-scale appearance of the coast (either bedrock-embayed in emergent regions or plains coast in subsiding regions), rivers dominate the supply of sediment to the shore and help control erosional/accretionary trends. The Yellow River (Huang He) is the world's largest in terms of sediment supply, while the Yangtze River (Chang Jiang) is the fourth largest in terms of water discharge. The size of these large rivers, combined with their instability over recent geological and historical times, accentuates their impact on coastal development in China. Since the migration of the Yellow River northwards from the Yellow Sea into the Bohai Sea in 1855, the north Jiangsu coast has eroded approximately 17 km inland, while the new delta near Lijin has encroached about 28 km into the Bohai Sea.

The coastal classification of WANG (1980, *Geoscience Canada*, **7**, 109–113) is applied to the coast of China, dividing China into four major sectors. Relative impact of rivers, waves and tides on coastal processes in each of these sectors varies widely, ranging from river-dominated in the Bohai Sea sector, to wave-dominated in the southern Guangdong/Guanxi sector. This classification and discussion summarizes major studies of coastal processes in China.

INTRODUCTION

CHINA'S coastline is approximately 32,000 km long, 18,400 km of which encompass the mainland from the Yalu River at the China–Korea border to the China–Vietnam border. The remaining 13,600 km or so of coastline belong to China's offshore islands, of which there are more than 6000. Both the sediment and water discharge of the major rivers dominate the evolution of China's coastline. Seasonal monsoon winds control the wave climate for the mainland China coast, while the marginal seas control the tidal characteristics.

In the recent historical past the coastline of China has undergone rapid change. Most notably, the two major rivers, the Huang He (Yellow River) and the Chang Jiang (Yangtze River), have migrated great distances during the past 4000 years. The present position of the Huang He, centered near Lijin (Figs 1 and 2), was established in 1855, when the river migrated approximately 420 km to the north from the north Jiangsu coast. Since 2278 B.C., the Huang He has changed position eight times, the last major change occurring in 1855 (Fig. 3; PANG and SI, 1979; WANG, 1983). At the present location of the Huang He, in southern Bohai Bay, major shoreline accretion has occurred during the past 130 years, the delta building seaward 20–28 km in this time period (WANG *et al.*, 1984).

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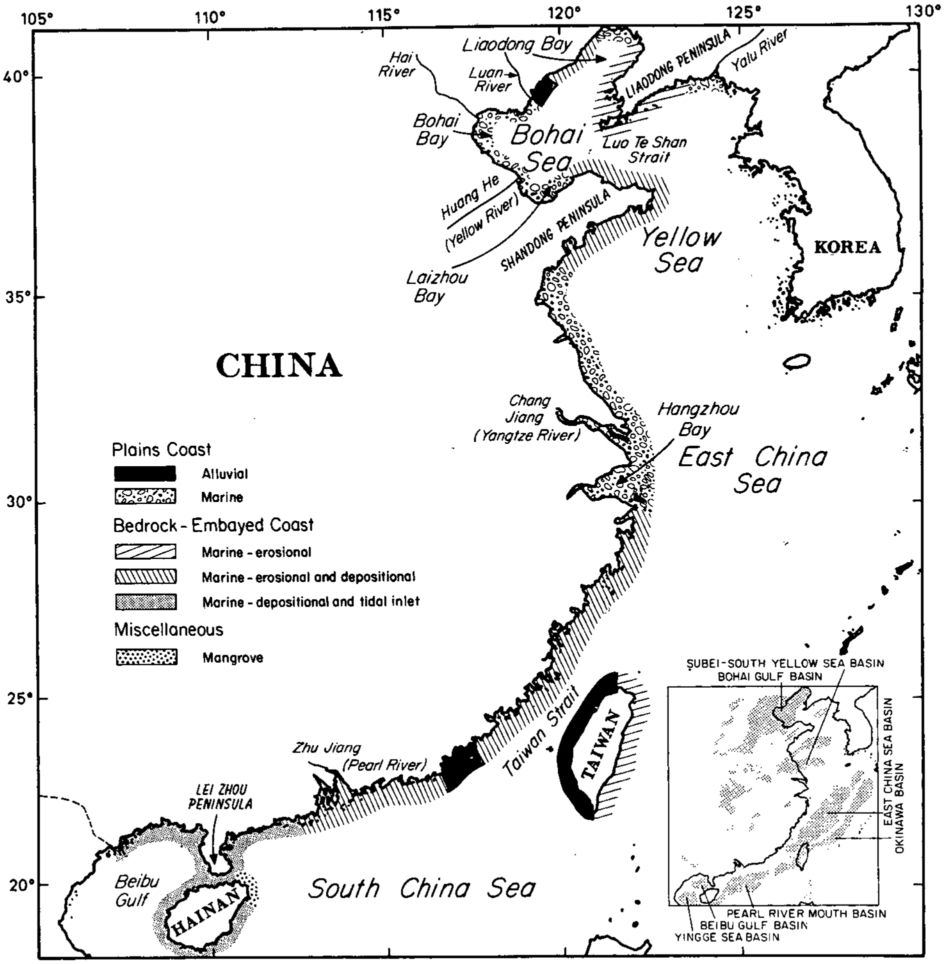

Fig. 1. Location map for China, incorporating major geographical names and features. Stippling indicates coastal classification, from this study. Insert: distribution of Cenozoic basins according to LI (1984) (after EMERY and AUBREY, 1986).

Along the north Jiangsu coast, where the Huang He emptied from 1128 to 1855, erosion has been extensive. The coast here has retreated about 17 km since 1855 (REN *et al.*, 1983a), with coastal retreat presently exceeding approximately 30 m y^{-1} along a 150 km coastal reach (WANG, 1961).

The Chang Jiang (Yangtze River) has steadily migrated southward and deposited five large sand bodies during the past 7000 years (LI, 1979). This southerly migration has exerted a major influence on coastal development in south Jiangsu and north Zhejiang province, with Shanghai itself built upon the raised former river delta. Clearly not only the sediment supply, but also the position of the major rivers of China influence coastal development to a significant degree.

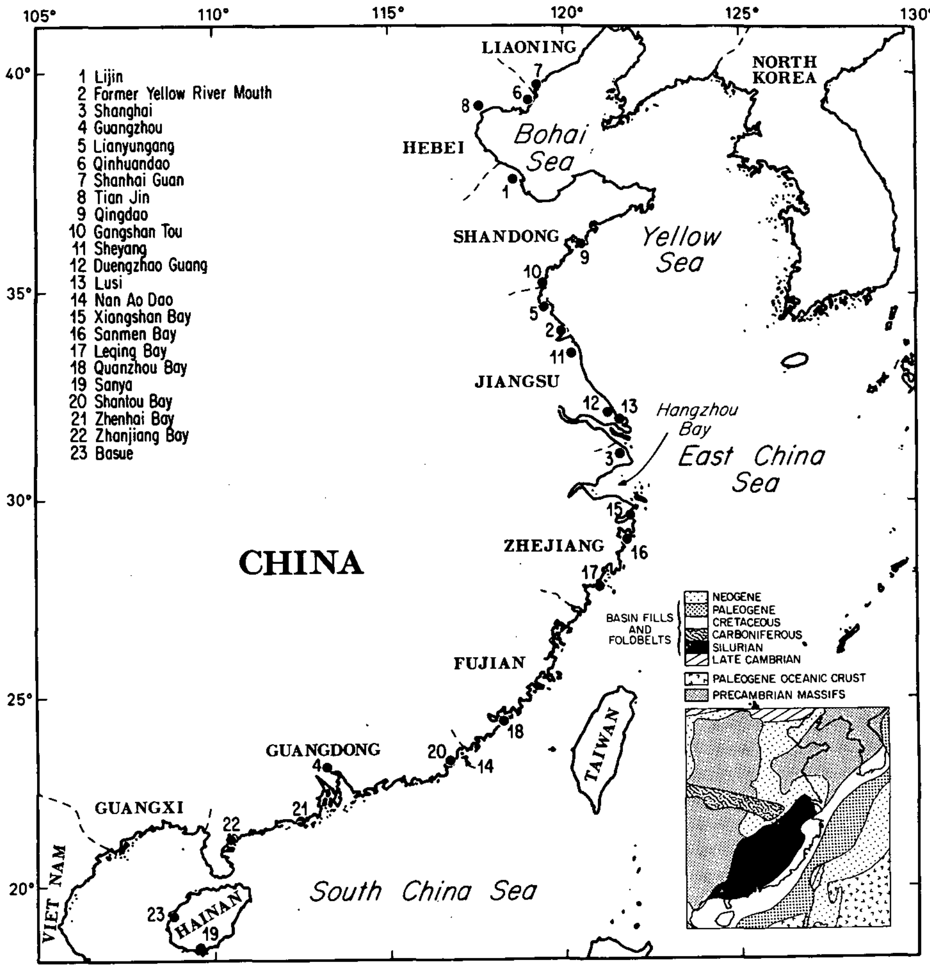

Fig. 2. Map of China with political boundaries and town locations referred to in text. Insert: massifs and foldbelts as interpreted by EMERY (1983) (after EMERY and AUBREY, 1986).

Besides these natural changes in river course, anthropogenic influence has impacted coastal evolution. For example, the sediment load of the Huang He increased dramatically as a result of human activities (WANG, 1983). In early historical times (prior to 11 A.D.) the Huang He entered northwestern Bohai Bay near the present Hai River. In 12 A.D. the river shifted to near its present position. Prior to and during the Western Zhou Dynasty (1100–771 B.C.) population was lower in the pasture-dominated Loess Plateau of northwestern China, the major source of sediment to the Huang He. The abundant forested land and grass (32 million hectares, 53% of the land) stabilized the soil, thus the sediment load in the Huang He was lower than present. Since then, especially during the Tang Dynasty (618–907 A.D.), settlers migrated to the west, cutting forests and cultivating the land, and causing rapid soil erosion. With only 3% of the land now

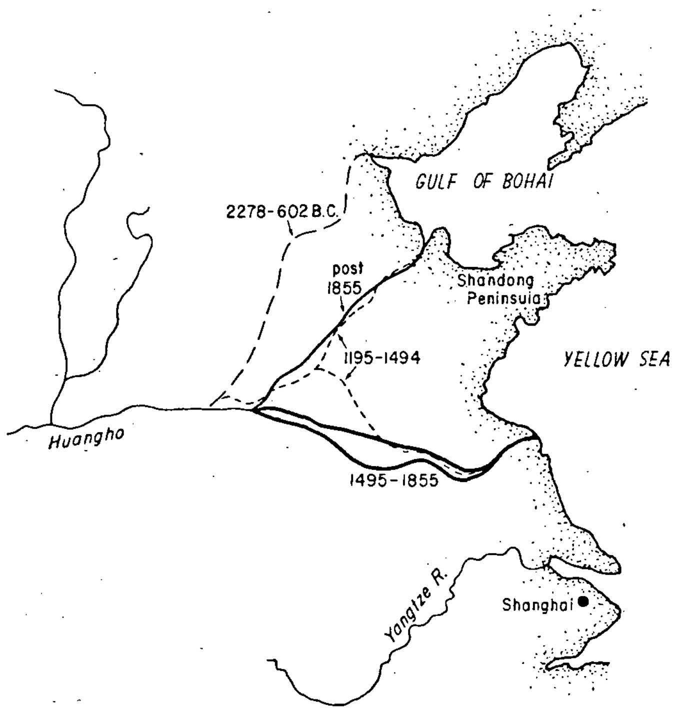

Fig. 3. Locations of the Huang He in the historical past.

forested, the sediment load has risen dramatically, with an average sediment concentration of 25 kg m^{-3} in the Huang He at present (WANG, 1983).

Also in the past, man has tried to tame the vagaries of the annual floods in the major rivers. As far back as the Song Dynasty (960–1127 A.D.), river bank dikes and other engineering methods of river control were constructed (WANG, 1983). More recently (during the 1950s) a series of dams was constructed in the estuaries of the North Jiangsu Plain, in an effort to harness the tidal currents and provide fresh river water for irrigation. The lower part of the estuaries silted rapidly because of reduced flood and tidal flow, requiring that all dams be opened to flush the silt and maintain the proper river channel depth (WANG, 1961). These and other human activities have influenced shoreline development in China and will continue to do so in the future.

The present paper is a classification and description of the China coastline, extending from the coastal plains or foothills out to the inner continental shelf. It is a synthesis of past Chinese and international research on China's coastline, with an emphasis on Chinese research during the past 20 years. In particular, it draws heavily on research performed in the Department of Geography at Nanjing University, Jiangsu Province, especially by the Marine Geomorphology and Sedimentology Laboratory. To the extent possible the work of many other Chinese coastal geoscientists is incorporated. This synthesis is more complete than those by SCHWARTZ (1982) and BIRD and SCHWARTZ (1985).

For consistency, local nomenclature is used where possible, but anglicized names that have become standard in the literature are retained. For instance, Bohai Sea has gained common acceptance even though it is redundant (hai in Chinese means sea). This redundancy is retained to distinguish the smaller Bohai Bay from the larger Bohai Sea that encompasses Bohai, Laizhou, and Liaodong bays (Fig. 1). Major rivers are represented by either their full Chinese names (Huang He, Chang Jiang, Zhu Jiang) or by their anglicized names (Yellow, Yangtze, Pearl rivers), but never by a mixture of the two usages. However, for the lesser known rivers where anglicized names have not gained general acceptance, the Chinese name is used with the English noun (Yalu River, Guan River, etc.). Redundancy in the Chinese and English words for river is avoided. City names are presented in their current Chinese form (Pinyin) with clarification provided where needed. The authors believe these conventions yield more consistency than is apparent in past Chinese and international literature.

MAJOR INFLUENCES ON COASTLINE MORPHOLOGY

Geology

The two primary geological controls on coastal morphology are the positions of the massifs and foldbelts, and the position of the major sedimentary basins (Wang, 1980; Emery and Aubrey, 1986). Primary basins of the China region are the Bohai Sea, the Subei-South Yellow Sea, the East China Sea, the Okinawa, the Pearl River delta, the Beibu Gulf, and the Yingge Sea basins (Fig. 1, insert). Of these, the Bohai Sea, the Yellow Sea, and the Beibu Gulf basins exert the most direct influence on coastal morphology. Tectonics of the region can be simplified into a series of massifs, basin fills, and foldbelts (Fig. 2, insert; Emery and Aubrey, 1986). Precambrian massifs occur along the western margin of Guangxi Province, the Shandong Peninsula, and the Liaodong Peninsula. Much of the rest of the coast has bedrock of Mesozoic or Neogene basin fills and foldbelts. Combined, the basins and foldbelts form a series of northeast or north-northeast trending belts that intersect the coastline obliquely (Wang, 1980).

Basins contain 2.5–9.5 km of Cenozoic sediments that are dominated by continental (42%), transitional (22%), neritic (31%), and marine (5%) sediments (Emery and Aubrey, 1986). These sediment thicknesses, deposited in regions of restricted elevation range, exceed those expected from compaction alone; tectonic subsidence must be responsible for much of this accumulation.

The massifs are dominated by Precambrian rocks. The alternation of massifs and foldbelts (with ophiolites along many boundaries) is interpreted by Emery (1983) as repeated breakup of continental crust by plate divergence and translation, followed by deposition of thick sediment sequences in the new seaways, and ending with plate convergence that produced foldbelts. These same distributions of massifs have also been interpreted as massifs from other continents that were added to Asia (Ben-Avraham, 1979). Regardless of the interpretation, the intervening foldbelts represent thick sediment accumulations that subsided after plate convergence.

Rivers

Five rivers, the Yalu, Luan, Yellow, Yangtze and Pearl, discharge 90% of China's total annual contribution of 2.0×10^9 tons of sediment to the marginal seas (Table 1).

Table 1. Annual water–sediment discharge for rivers in China

	Water (m^3)	Sediment (tons)
Yellow River (Huang He)	4.9×10^9	1.2×10^9
Yangtze River (Chang Jiang)	930×10^9	4.9×10^8
Pearl River (Zhu Jiang)	370×10^9	1.0×10^8
Luan River	4.6×10^9	2.4×10^3
Yalu River	28×10^9	4.8×10^6
Liao River	6×10^9	41×10^6
Daling River	1×10^9	36×10^6
Hai River	2×10^9	81×10^6
Huai River	–	14×10^6
Total	$1.2–1.4 \times 10^{12}$	2.0×10^9

Sources: MILLIMAN and MEADE (1983), GUAN (1983), TONG and CHENG (1981), WANG (1980), WANG *et al.* (1984), QIAN and DAI (1980).

The Yellow, Yangtze, and Pearl rivers supply most of the total freshwater discharge to the marginal seas (Table 1). Estimates of annual freshwater discharge range from 1.2×10^{12} m^3 (GUAN, 1983) to more than 1.4×10^{12} m^3 (WANG, 1980). This discharge controls the character of the Continental Coastal Water (CCW), which in turn influences sediment dispersal from the major rivers. Sediment supply and freshwater influx distinguish the riverine from other coastal environments of China.

Yellow River. The Yellow River (Huang He) carries the largest sediment load of any river in the world. Although its freshwater discharge is modest (Table 1), reaching an average of 49×10^9 m^3 y^{-1}, its sediment discharge is immense, averaging 1.2×10^9 tons y^{-1} (TONG and CHENG, 1981). Sixty-four percent of the sediment is deposited on the delta and mudflat, while the remaining 36% is transported into the Bohai Sea (PANG and SI, 1980; WANG, 1983). The Yellow River sediment, composed primarily of coarse silt, is deposited as finger bars along the river mouth. Progradation of these finger bars is rapid, depositing as much as 10 km in 1964 alone (WANG *et al.*, 1964). To either side of the river mouth fine silt and clay collect in bays that are protected by coarser bars. Seaward of these muddy bays erosion of former deltas occurs, as the river changes its position every 6–8 years, although not in as drastic a fashion as a few centuries earlier. Since 1855, a delta has covered a distance of 160 km alongshore near Lijin, prograding seaward 20–28 km (WANG *et al.*, 1984). This progradation represents an average annual accumulation of 23.5 km^2 in plan view.

Yangtze River (Chang Jiang). The Yangtze River with its large estuary (CHEN *et al.*, 1979, 1985; MILLIMAN *et al.*, 1984) is the largest river in China, having the fourth largest water discharge in the world (MILLIMAN and MEADE, 1983). It's annual freshwater runoff is 9.3×10^{11} m^3, 70% of which occurs in the months from May to October. It is the main source of sediments to the East China Sea, with an average annual sediment discharge of 4.9×10^8 tons. Although it discharges more water than the Yellow River (by a factor of 18), its concentration of sediment is much less (0.5 kg m^3; WANG *et al.*, 1984), and its total sediment load also is lower by a factor of 2.5. The sediments of the Yangtze reach 122°40′E longitude at its distal margin. The spring tidal prism is 5.3×10^9 m^3 during the wet season, and 3.0×10^9 m^3 during the dry season (WANG *et al.*, 1984). The large freshwater discharge contributes to the dynamics of the CCW (see later section on low-frequency currents).

Sedimentation offshore of the Yangtze River is rapid, taking the form of a submarine delta, sand shoals, and sand bars at the mouth of the river. Five major sand bodies have been left by the Yangtze River since 7000 B.P. (Li, 1979) that either have merged into the north fluvial plain or form extensive sand ridges offshore of Jiangsu Province. Since the river mouth shifted continuously to the south, all of these former sand bodies are north of the present Yangtze River mouth. The sand ridge field is 160 km long, from north to south, encompassing more than 70 minor sand ridges. Individual ridges are 10–100 km long and 5–10 km wide. The top of the highest ridge is 5 m above low tide (Zhu and Xu, 1982). Sediments of the Yangtze River are largely silts, but include a significant fraction of fine sand, in contrast with the sediments of the Yellow River. The Yangtze has extensive offshore bedforms, particularly along it former river mouth positions, whereas the Yellow River lacks these extensive shoals (they are also missing in the eroding former Yellow River mouth in north Jiangsu). Present Yangtze River sediments are advected towards the south by coastal currents in the inner shelf and only a smaller part is carried to the north (Wang *et al.*, 1984).

Pearl River (*Zhu Jiang*). The Pearl River is in southern China, where a tropical climate influences its water and sediment discharge. With its abundant precipitation and lush vegetation, the water discharge is high, while sediment discharge is relatively lower. The annual runoff of the Pearl River is about 3.7×10^{11} m^3, while its annual sediment discharge is about 1.0×10^8 tons (Wang, 1980).

Three tributaries enter the estuary (the Si, Dong, and Bei rivers). Most sediments are deposited within the embayment, forming the Pearl River delta. Eight inlets from the Pearl River tributaries connect the estuary to the South China Sea. Offshore, two belts mirror the sediment influx. The inner shelf deposit (35 km wide) continues to derive its sediments from the Pearl River, grading from sand nearshore to mud offshore. The outer shelf has relict sands. A coastal current carries river sediments to the southwest throughout the year, serving as a source of mud for tidal inlets along the downdrift coastline (Wang *et al.*, 1984). Zhongshan University (Guangzhou) has studied the geology and sedimentation of the Pearl River and its tributaries for the past 20 years. Most publications are in Chinese only, with a few exceptions (see Ying and Chen, 1984; Institute of Coast and Estuary, 1984; Li and Wang, 1985).

Many other smaller rivers locally influence sedimentation and coastal morphology. Wang *et al.* (184) discussed the Yalu and Luan rivers that have smaller freshwater and sediment discharges. Approximately a thousand smaller rivers contribute both freshwater and sediments to the nearshore. As an example of the many small rivers, Hai Nan Island in southern China alone has 154 rivers, 38 of which contribute significantly to the coastal evolution of the area. Altogether, the small rivers of the mainland of China contribute about 2.1×10^8 tons of sediment per year to the coast and marginal seas (Wang *et al.*, 1984).

Climate

A major influence on China's coastal processes is the monsoon wind pattern of Asia. In the winter, the Mongolian high-pressure system dominates the geostrophic winds. The anticyclonic gyre, beginning in January, yields northwesterly winds in the north, and northerly or northeasterly winds in the South China and East China seas. During the summer, the Indian Ocean low-pressure system dominates, creating a cyclonic (anti-clockwise) gyre. These winds are southwesterly in the South China Sea (south of latitude

15°N), changing northwards to southeasterly winds in the East China, Yellow, and Bohai seas. A transitional season exists during which winds fluctuate between the two dominant weather systems (WANG, 1980).

Winds at many coastal locations are summarized by the U.S. DEPARTMENT OF COMMERCE (1981) and more recently by SUN *et al.* (1981). Wind roses, monthly wind summaries, and dominant winds are provided by SUN *et al.* (1981) for 17 coastal sites.

Typhoons

Generated primarily from July to October, typhoons are destructive because of their large waves as well as their associated storm surges (reaching 5 m or so above MWL). Genetically, typhoons are tropical cyclones exceeding 64 kn (32 m s^{-1}) in windspeed. These typhoons normally develop in the northwestern Pacific, moving west or westnorthwest across the Philippines and South China Sea, dissipating rapidly when they reach the Asian continent. Typhoon frequency is higher for the South China Sea than for the other marginal seas of China (SUN *et al.*, 1981).

In the South China Sea, most tropical cyclones occur during August, September and October (Table 2). The annual average number of tropical cyclones exceeding winds of 17 m s^{-1} is 1.1, however the standard deviation about this average value exceeds the mean. Four typhoons were experienced in 1894 within 17 days, three within 10 days in 1887, but none for almost four years between 1932 and 1936.

Annual number of typhoons generated in the northwest Pacific is 28, with considerable year-to-year variability (all typhoon statistics are from SUN *et al.*, 1981). These data are monthly values, including maximum and minimum number of typhoons per month over the 21 year period of observation (1949–1969; Table 3). Of the total number of cyclones generated, only a small number reach the South China Sea. A compilation of monthly typhoon occurrence shows that on the average nine typhoons reach the South China Sea

Table 2. Number of tropical cyclones per month during 1884–1961 *that caused winds of* 17 m s^{-1} *and above. Data for Hong Kong* (WILLIAMSON, 1970)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	1	6	20	20	27	10	4	0

Table 3. Number of typhoons reaching South China Sea (includes storms with prolonged winds exceeding 11 m s^{-1})

	Month												
	1	2	3	4	5	6	7	8	9	10	11	12	Yearly total
A	–	–	1	4	10	15	29	30	45	24	27	11	196
B	–	–	0.05	0.19	0.48	0.71	1.38	1.43	2.14	1.14	1.29	0.52	9.33
C	–	–	0.51	2.04	5.10	7.65	14.80	15.31	22.96	12.24	13.88	5.57	100
D	–	–	1	2	2	2	3	3	6	4	4	2	

A, Total number from 1949 to 1969; B, yearly average; C, % in month; D, greatest number in single month over period of observation.

From SUN *et al.* (1981).

yearly, most of these in July–September, whereas the peak for the entire western Pacific is earlier. This difference in typhoon timing reflects the seasonal dependence of typhoon tracks in the Pacific. Of the typhoons reaching the South China Sea, there are four major tracklines. In September and October, 40% of all typhoons travel over Hai Nan Island on into Vietnam. In March–June, 22% of the annual typhoons travel north into Guangdong Province or Fujian Province. In spring and summer, another 20% of the total annual number of typhoons passes to the north–northeast, over Taiwan, or towards Japan. Finally, in winter, 10% of the typhoons pass to the west into Vietnam, missing the China coast.

In the period 1949–1969, the China coast experienced 77 strong typhoons (winds exceeding 32 m s^{-1}), 61 weak typhoons (winds of 17–32 m s^{-1}), and 65 tropical storms (winds from 11 to 17 m s^{-1}). This yields an average of 9.7 major storms per year reaching land, 6.6 of which are typhoons. Most of these storms occur in the period July–October. Typhoon landfalls are separated on a province-by-province basis, for months May–November. Most typhoons impact Guangdong Province; Taiwan is the next hardest hit, followed distantly by Fujian and Zhejiang Province.

Wind waves

Waves rarely have been measured during typhoons, and most accounts are anecdotal, quoting nearshore waves exceeding 20 m in height. ZHANG and LI (1980) compared calculations of typhoon waves with observations. They presented tables of wave height ($H_{1/10}$) and period for different fetches, wind speeds, water depths, and durations. For instance, a typhoon with wind speed of 32 m s^{-1}, blowing for 10 h over a fetch of 500 km with average water depth of 40 m, can generate a wave of 12 s period, and 13 m height. Most typhoons will generate waves less than this height, but some evidently can generate much higher waves, to 20 m. The recent failure of a drilling rig in the South China Sea during a storm accentuates the need to carefully consider typhoon waves.

Although there are exceptions, wave patterns along most of China are dominated by monsoon winds. Northerly waves prevail in the winter, their influence moving progressively southwards from the Yellow Sea, reaching Taiwan in September, latitude 10°N in October, and spanning the entire coast by November. In January, the wave directions rotate clockwise, with northwesterly waves in Bohai gradually swinging northerly to northeasterly in the East China and South China seas (WANG, 1980).

Southerly waves prevail in the summer, moving northward from the South China Sea. They appear first in February, and by May they dominate a wide area to the south of latitude 5°N (WANG, 1980). In June, southwesterly and southerly waves prevail in the South China Sea. In the Strait of Taiwan, northeasterly and southwesterly waves become equally frequent, while southerly waves prevail in the East China Sea and southern Yellow Sea. The northern Yellow and Bohai seas are dominated by southeasterly waves in June. In July, southerly waves prevail along the entire seaboard. Wave directions change anticlockwise, from southerly in the South China Sea (south of latitude 15°N), through southerly to southeasterly in the East China, Yellow and Bohai seas. During the periods of transition for the monsoons, wind directions fluctuate and there are no prevailing waves.

Locally, large variations occur in both wave height and direction. Commonly a mix of waves having different sources occurs at any time, reflecting local fetches and local wind patterns, as well as distant swell. As an example, eastern Hai Nan Island is affected not only by monsoon winds, but also by distant South Pacific swell. The north Jiangsu coast is dominated by waves generated by monsoon winds acting on the Yellow Sea. In southern Jiangsu, by contrast, the wind waves are modified strongly by the offshore sand ridges, making its wave climate much more moderate than the relatively unprotected northerly counterpart.

Waves in the South China Sea are largest of those in all China marginal seas, because of the large fetch and greater water depths (SUN *et al.*, 1981). The shallow, extensive shelf of the East China and Yellow seas limits the size of the waves in this region. The waves of the Bohai Sea are the smallest, as the fetch is restricted. Wave periods are under 5 s, and since winter monsoons are northwesterly here the waves tend to be largest near the Luo Te Shan Strait separating Bohai Sea from the Yellow Sea. Water depths in the Bohai are also relatively shallow (the mean water depth is 18 m), so large waves are rare.

SUN *et al.* (1981) presented a wave compilation from various sources around China, including wind wave conditions (sea) for each of 14 locations around China, for the months January, April, July, and October, in the form of percent occurrence of waves from particular directions, and for swell conditions, again for the months of January, April, July, and October. Monthly average wave height for 13 of these same coastal stations are presented for the same months, and an annual average given. Annual average wave height is largest off Fujian Province, and the north part of the South China Sea (1.1 and 1.4 m, respectively; Table 4).

Wave period data for 14 Chinese stations document the shortest periods are in the north (from 1 to 4 s), with longer periods in Fujian Province and in the north part of South China Sea. According to these data, waves with periods exceeding 7 s are rare. Since typhoons occur for a small percentage of total time, they have little impact on the climatological summaries. These summaries do not reflect open ocean or open sea conditions, since waves have been measured only in shallow coastal waters where frictional attenuation is significant.

Average periods and average directions of wave propagation are available for 13 Chinese coastal stations, for the same four months of the year (eight of which are presented as Table 5). These data show the average wave period varies from 2.5 s up to 7 s, with maximum monthly wave periods ranging up to 14 s in the south. Maximum monthly averages reach 12.8 s in the north part of the South China Sea.

Table 4. Average monthly wave height (m) *for various China coastal stations*

	N. Jiangsu	Zhejiang	Fujian (Pingtan)	Fujian (N)	Guangdong	W. Hai Nan (Basue)	Guanxi (in Gulf)	(North) South China Sea
A	0.9	1.0	1.1	1.2	0.9	0.9	0.4	1.6
B	0.9	1.0	0.8	0.9	0.8	0.8	0.4	1.0
C	0.9	1.0	0.7	0.9	0.8	0.9	1.0	1.4
D	0.9	1.0	1.2	1.3	1.0	0.7	0.5	1.4
E	0.9	1.0	0.9	1.1	0.9	0.8	0.6	1.4

For 4 months (A, January; B, April; C, July; D, October) and yearly average (E). Data from SUN *et al.* (1981).

Table 5. Average wave periods (s) and directions for 4 months

		N. Jiangsu	Zhejiang	Fujian (Pingtan)	Fujian (N)	Guangdong	W. Hai Nan (Basue)	Guanxi (in Gulf)	(North) South China Sea
	II	4.4	6.0	5.8	4.0	3.8	3.7	4.5	5.1
A I	III	E	NW	E	SE	ENE ESE	SSW	SW	NW
	IV	8.6	11.2	8.7	9.6	5.8	6.8	5.2	8.9
	II	4.8	6.0	5.5	5.1	3.9	4.0	4.9	3.8
B I	III	ENE	WSW	NE	SE	ENE	SSE	SW	SSW
	IV	9.7	10.0	7.7	6.5	5.9	6.9	7.0	8.1
	II	5.0	7.1	5.8	5.7	7.9	3.8	4.3	3.9
C I	III	E	SE	E	SE	WNW	SSW WSW	SSW	WSW
	IV	13.7	19.8	8.8	11.5	7.9	7.0	8.8	10.9
	II	4.7	5.6	5.8	4.9	4.0	3.3	3.8	3.9
D I	III	ENE	NE ENE	E	SE	SSE		SSW	NE
	IV	10.9	10.8	9.1	9.1	6.8	9.5	5.9	12.8

I, Monthly averages; II, average period (s); III, average direction; IV, maximum average period over years of observation.
Data from Sun *et al.* (1981).
A, January; B, April; C, July; D, October.

Tides

Tides in the Chinese marginal seas are variable in type and amplitude. Tides in the Bohai, Yellow and East China seas are semidiurnal, while the tides in the South China Sea are either diurnal or semidiurnal, having considerable geographic variability. Within the Bohai Sea, tides are predominatly semidiurnal although they can be irregularly semidiurnal or irregularly diurnal. Here tidal range averages about 3 m except near the mouth of the Yellow River (Huang He), where it is only 0.5–0.8 m (Wang *et al.*, 1984).

Tides of the Yellow and East China seas are semidiurnal, with a large variability in range. Near the Yalu River mouth, tidal range averages 4.5 m. Near the abandoned Yellow River mouth, tidal range is 1.6 m, while near Shanghai the range is 1.9 m. Larsen and Cannon (1983), Shan *et al.* (1983), Choi (1984) and Larsen *et al.* (1985) discussed the tides of this region in more detail.

Tides in the South China Sea are more complex, varying from diurnal to semidiurnal over its extent. The diurnal tides are locally amplified, particularly in the Gulf of Tonkin (Beibu Gulf) and Gulf of Thailand, where they are near resonance. Otherwise, tides are largely semidiurnal, with ranges of generally less than 2 m. Ye and Robinson (1983) modeled the M_2 and K_1 tides in the area, both in sea surface and in velocity. Tidal currents in the South China Sea exceed 50 cm s^{-1} in restricted locations, including the Strait of Hai Nan.

Sun *et al.* (1981) discussed the coastal tides of China, though showing no cotidal or corange charts. Wrytki (1961) published corange charts for the dominant semidiurnal and diurnal tides, as well as a chart of type of tide (semidiurnal, diurnal, or mixed), for the South China Sea. Larsen *et al.* (1985) provided cotidal charts for the Yellow, Bohai, and East China seas. Yin (1984) discussed tides near Taiwan.

MAJOR COASTAL TYPES OF CHINA

In this summary, the coastal classification of WANG (1980) has been adopted. Two major coastal classes have been identified: bedrock-embayed coasts and plains coast (Fig. 1).

Bedrock-embayed coast

Characterized by irregular headlands, bays, and islands, these develop where mountains meet the sea. Four subtypes are identified.

Marine erosional-embayed coast. Developed on hard crystalline rock, erosion is slow and the coast is modified slowly. Sparse sediment supply limits coastal deposition, leaving a dominance of erosional geomorphic features.

Marine erosional–deposition type. Most commonly developed where Miocene granites are overlain by weathered deposits, these coasts are easily eroded. Erosional features (rock benches and terraces) and depositional features (bays bars, tombolos, sand spits) develop here.

Marine depositional type. With relatively erodable bedrock, marine erosion supplies large quantities of sediment for prograding shorelines. This bedrock-embayed coast eventually matures to a plains coast, and is common in South China.

Tidal inlet-embayed coast. Common again in South China, the northeast–southwest trend of the coast is interrupted by northwest-trending inlets along faults with the same orientation. Tidal inlets are formed with sand spits, creating lagoons and estuaries in many cases suitable for harbors.

Plains coast

Based on genesis, these are classified into two types.

The alluvial plains coast. Located generally seaward of mountain ranges, plains are built of fluvial sediments. Plains continue seaward with low gradients, resulting in a wide breaker zone and active sediment movement. Barrier bars, sand spits, submarine bars, and extensive beaches are typical features of this coast.

Marine depositional plains coast. Flat and very extensive, these are located on the lower parts of large rivers in areas of subsiding basement. Coastal slopes are extremely gentle (1:1000 to 1:5000), leading to wave breaking well offshore; the nearshore commonly is dominated by tidal processes. Sediment from rivers is deposited either offshore, or high on the extensive tidal flats.

Both the bedrock-embayed coast and the plains coast may incorporate two minor types of coast. The first, the river mouth coast, is limited to the major rivers (the Yellow, the Yangtze, the Pearl), containing both delta and estuarine features. The second type is biogenic, found in the south of China, incorporating coral reef and mangrove coasts. Mangroves are limited south of latitude 27°N, while coral reefs occur as far north as Taiwan.

REGIONAL SUMMARY OF CHINA COASTAL CHARACTERISTICS

Following is a brief summary description of China's coast, separated into four regions. The Bohai Sea (sector 1) is a river-dominated environment. The Yellow Sea (sector 2) is tide-dominated, with waves playing a secondary role, along with the former and present river processes. The third sector (the East China Sea coast) is wave-dominated, having large tidal range in some tidal inlets and estuaries. The Yangtze River (Chang Jiang) contributes to coastal development. The fourth sector (the South China Sea coast) is largely wave-dominated.

Bohai Sea

The Bohai Sea coastline extends from the southern tip of the Liaodong Peninsula to the northern tip of the Shandong Peninsula, having its eastern border at the straits of Lao Te Shan. The tides in the Bohai Sea, though generally semidiurnal, are complex, varying from irregularly semidiurnal to irregularly diurnal, having a tidal range of 3 m except near the Yellow River mouth. Because of its geometry, Bohai Bay has its greatest fetch to the northeast; the observed value of $H_{1/10}$ is 4.8 m, with a period of 7.8 s. Average maximum wave height is 1.9 m. Mean and low-frequency flows are complicated by the geometry of the bay, which has an average water depth of 18 m and a total area of 78,000 km^2. Much low-frequency water motion is due to storms, with the resultant flow similar to that of the tides. As discussed by CHOI (1984), the low-frequency flow generally is cellular, with one eddy moving clockwise to the north, the second moving anticlockwise to the south.

The dominant control of sedimentation in the Bohai Sea is river influx, contributing 1.21×10^9 tons of sediment each year. The two major rivers are the Yellow River (discharging 1.2×10^9 tons) and the Luan River (2.4×10^3 tons). Other rivers, including the Liao and the Hai, discharge the remainder of the sediment to the sea. As discussed by WANG (1980) and EMERY and AUBREY (1986), most of the Bohai Sea is a subsidence basin, with up to 9 km of sediment. This subsidence must be tectonic, since sediment accumulation exceeds that expected from sediment compaction alone. The Liaodong and Shandong peninsulas are regions of uplift, as is the northwest corner of Bohai Sea. These patterns have resulted in most of the Bohai being classified as plains coast, with part forming bedrock-embayed coasts.

The west coast of the Liaodong Peninsula is a bedrock-embayed coast of marine erosional type. Locally in the heads of the bays, modern mud from the Bohai Sea overlies the sparse material from erosion of the peninsular mountains. The Liao River, adjacent to Liaodong Peninsula, carries mainly fine sediment (silts and fine sands) to the shore. Stretching to the west of the Liaodong Peninsula about 100 km is a plains coast, dominated by delta processes.

The west Shandong coast is also a bedrock-embayed coast, of mixed erosional depositional type. The highly weathered granitic material provides sediment to the coast, forming sand spits and other accumulating forms. This section of coast begins in the east part of Laizhou Bay, beyond the influence of the modern-day Yellow River.

In the Luan River region, south of Qinhuandao, the shore is a plains coast, backed by extensive sand dunes. The Luan River also provides sediments to the inner shelf. To the south of the river, there are narrow sediment belts distributed parallel to the shoreline: fine sand, coarse silt, fine silt, then muddy clay. Pyrite in the muddy offshore area in water depths exceeding 9 m suggests quiet reducing bottom conditions. North of the Luan River sandy deposits dominate the inner shelf, persisting in the 20-km wide band out to water depths of 13 m. The fine-and-medium sands have textures of former beach dunes, now submerged (WANG *et al.*, 1984).

Most of the inner shelf sediments of this region are supplied by the Luan River, which has migrated in the past. Many sand bodies such as point bars, river mouth bars, and sand shoals, left in the area of ancient river mouths, have undergone wave erosion. The influence of the modern river delta extends both to the north (15 km) and south (20 km), responding to waves and tides.

North of the Luan River the coast is an alluvial plain coast, from Qinhuandao to approximately Shan Hai Guan. From Shan Hai Guan north to the plains coast near the Liao River, the coast is classified as bedrock-embayed of mixed erosional–depositional type.

Near the former Yellow River mouths the coast is eroding and cheniers have formed, while near the present river mouth the beach is prograding rapidly. Much of this coastal region is classic mudflat coast, up to 6 m wide. The mudflat zonation here is the typical salt marsh plain, intertidal flats (with four subzones), and submarine coastal slope (WANG, 1963). The salt marsh plains are the main marine depositional features. There are four old coastlines of chenier formed during the erosional periods of the mudflat when waves dominated. Presently, tidal currents dominate this region so cheniers are not forming actively. On the inner shelf, sediments change from sandy silt at the low tide level, to very fine mud at depths exceeding 10 m. The submarine coastal slope is gentle, ranging from 2:10,000 in the stable or slightly eroding coastal sections, up to 5:10,000 in the sand bar region of the 1965 river mouth position (WANG, 1983).

Yellow Sea Coast

This sector has two parts: a northern sector extending from the east Liaodong Peninsula to the Yalu River on the China–North Korea border, and a sector from the southern Shandong Peninsula extending south, including north Jiangsu Province. Waves in this area are generally small, since they are generated locally in the shallow Yellow Sea (Tables 4 and 5). Recently, the Yellow Sea tidal behavior has been clarified by both theoretical and observational work (LARSEN and CANNON, 1983; CHOI, 1984; LARSEN *et al.*, 1985). There are few observations of low-frequency and mean flows in this region, and theory has not advaced far in describing this fequency band. The extensive freshwater inflow dominates the coastal circulation in a gravitational sense, coupled at least indirectly to the Kuroshio. A few current meter and hydrographic observations of this area are described by BEARDSLEY *et al.* (1983, 1985), and LIMEBURNER *et al.* (1983).

The bedrock-embayed coast near the Yalu River mouth differs from the remainder of the Liaodong Peninsula. The Yalu River drains 64,000 km^2 of the Changbai Mountains in northeast China. Eighty percent of the annual discharge reaches the Yellow Sea during summer flood, from June to September. Tides here are irregularly semidiurnal, with an average range of 4.5 m, and a maximum range of 6.9 m. Tidal currents both within and outside the estuary are strong, and exert strong control over sediment distribution. Sediments within the estuary are coarse sands, with occasional pebbles and shingles (WANG *et al.*, 1984). Outside the estuary, an extensive area of fine-to-medium sands is distributed on the inner shelf, out to a water depth of 10 m (a distance of 20–30 km away from the river mouth). Strong tidal currents transport the sediment seaward from the estuary, where linear sand ridges are formed parallel to the direction of the estuarine tidal currents. Relief of these sand ridges is 15 m about 1 km from the river mouth. Sediments of these sand ridges are mainly fine sand with some coarse silt. These sand ridges migrate slowly to the west, under the influence of tides and waves (WANG *et al.*, 1984).

The second bedrock-embayed coast of this sector extends from the east Shandong Peninsula southwards towards Lianyungang, including the region near Qingdao. This extensive bedrock-embayed coast is of marine erosional–depositional type, with waves eroding the coast and small rivers transporting sediment to the coast. Erosional features, such as sea cliffs and rock benches, and depositional features, such as sand spits and bay-mouth bars, coexist.

The mudflat coast of the north Jiangsu Province is the most extensive in China. Extending south from near Lianyungang to the Yangtze River, this fluvial-marine depositional plains coast has undergone considerable change in recent historic time. The north Jiangsu mudflat coast is located along an area which has been receding in recent years. EMERY and AUBREY (1986) show the region from the Yangtze northward to about the former Yellow River mouth to be submergent, at rates of 2 mm y^{-1} near the south, to near zero in the north. North of the former Yellow River mouth the coast is emergent, as suggested by EMERY and AUBREY (1986) from recent tide-gauge records, and supported by observations of raised seacliffs near Lianyungang (found at elevations of 5, 15–20, 40, 60–80, 120, 200, 320, 450, and 600 m; WANG, 1983). These raised terraces suggest relative sea level here has been lowering not only recently but also in the geological past, a result of eustasy and tectonism. Unfortunately is is not possible to compare quantitatively recent trends in relative sea levels by using tide-gauge records in that area to those of the past combining seacliff elevation with radiocarbon dating. Thus, although this section of coast from Gang Shan Tou south to the Yangtze is a plains coast, the northern part is emergent, while the southern part is submergent.

This coastal sector is strongly influenced by tides, while to the north near the former Yellow River mouth waves are also important. Sediment eroded from mudflats by waves is transported primarily to the south, having some minor transport to the north towards Lianyungang. The erosional zone extends approximately 118 km, with intertidal mudflats only 0.5 to 1 km in width (ZHU and XU, 1982), consisting of very fine sand and silt. In the 700 years during which the Yellow River discharged sediment here, approximately 15,000 km^2 of delta was built (WANG, 1983). Since 1855, the old delta has eroded 1400 km^2 due to lack of sediment supply; present-day land loss is 2.4 km^2 y^{-1} (WANG, 1983). The counties of north Jiangsu are building dikes along the coast to protect valuable farmland from erosion as the tidal flats diminish under wave action.

In the region from Sheyang to Dueng Zhao Guang, the mudflats are rapidly prograding. Sediment comes directly from the eroding former Yellow River mouth through longshore transport in the nearshore, and indirectly through onshore transport of eroded sediment, which has been transported alongshore by the coastal currents, and subsequently moved onshore primarily by tidal action. Mudflats reach 10–13 km in width, having a slope of 1:5000, and are divided into four zones: supratidal zone (grass flat), mudflats, mud-sand flats, and silt-sand flats (ZHU and XU, 1982). These mudflats are protected from wave action by the extensive offshore sand ridges, many of which are intertidal.

From Dueng Zhao Guang south to approximately the north bank of the Yangtze River, the mudflat coast is eroding (REN *et al.*, 1983b). Near Lusi, the mudflat is narrow, eroding under the combination of larger waves and swift tidal currents. Mudflats represent the result of a conflict between tidal sedimentation and wave erosion, with sediment supply serving as a third factor. When waves are large, mud flats cannot accumulate. When waves are small and there is an adequate source of sediment, mudflats can prograde under the influence of tides.

East China Sea

The third sector extends from the Yangtze River mouth south to Nan Ao Island, near the border between Fujian and Guangdong provinces. Coastal evolution here is strongly influenced by the Yangtze River, both from its modern sedimentation and reworking of its ancient deposits. Tides are generally strong in this region, as are waves that are generated across large fetches of the deeper East China Sea. The lee (west) side of Taiwan differs in having only low waves.

There are three major coastal areas within this sector. The northern region extends from the Yangtze River mouth south to Hangzhou Bay. It is a delta plain coast, prograding steadily under the continued sediment supply from the Yangtze River. Coastal morphology is characterized by two major esturaries: the Yangtze estuary in the north, and the Hangzhou estuary in the south. The Hangzhou estuary, with its 9 m tidal range, is perhaps best known for its tidal bore, which has considerable historical significance. Predictions of the time and magnitude of the tidal bore date back more than 1000 years. Several cheniers testify to the progradation of the shoreline.

The second coastal region is a bedrock-embayed coast extending from Hangzhou Estuary south to Nan Ao Island, just south of the northern border of Guangdong Province. This bedrock-embayed coast is of mixed erosional–depositional type, having erosion near the major headlands and marine deposition within the bays. The many coastal embayments here trend northwesterly, in the interior of which mud deposits overlie rock platforms. This mud is supplied primarily by the Yangtze River, as the Yangtze material is moved seaward, then transported to the south under the influence of inner shelf currents, and finally moved shorewards by tidal currents. Many islands protect the bay mouths, the islands also following the general northeasterly trend of the Zhejiang–Fujian fault zone. These islands serve as sources for sediment to the bays, but more importantly shelter the bays from waves so fine sediments can be deposited within the upper reaches of the bays.

This region also has some tidal inlet bedrock-embayed sections, which are more typical of the southernmost sector (sector 4). For example, Xiangshan Bay, Sanmen Bay and Leqing Bay (Zhejing Province), and Quanzhou Bay (Fujian Province) are all tidal inlet coasts. Even these tidal inlet coasts accumulate mud inside, through tidal processes. Whereas the bays in this section tend to be depositional (mud in the upper reaches, sand in the lower reaches), most headlands are erosional.

The third coastal region in sector 3 is the Taiwan coast. The east coast is an erosional fault coast, where steep seacliffs drop off sharply into deep water of the Pacific Ocean. The west coast is more complex, consisting of an alluvial plain coast with marine deposition forming sand bars and lagoons. Marine processes are responsible for reworking the alluvial material into depositional features. In the south part of Taiwan Strait are fringing coral reefs, both along the main island and along the many small islands immediately adjacent.

The geological history of sector 3 shorelines is recorded in ancient deposits both onshore and offshore. The onshore evidence consists of raised terraces at elevations of 5, 10, 20, 40, 60, and 80 m above sea level (WANG, 1983). The age of these terraces has not been established. Offshore evidence for coastal submergence is extensive. Along the Zhejiang–Fujian coast, there are two submerged bedrock terraces (at 20–25 and 50–60 m depths). Paralleling the coast up to Hangzhou Bay, these terraces also have not been dated. They are in the region which EMERY and AUBERY (1986) determined from tide-gauge records to be subsiding, consistent with submergence of former terraces. North of Hangzhou Bay evidence for former coastlines is slightly different. Here accumulated coastal forms (such as deltas, sandy beaches) testify to lower relative sea levels. These must be dated to verify the chronology of coastal development. Perhaps the largest of these offshore accumulated features is the old Yangtze delta, known as the Great Yangtze Bank. In addition to these features on the inner shelf, there is also evidence of former north–south trending coastlines at depths of 100, 120, and 150 m (the latter dating 18,000 y B.P.; REN and TSENG, 1980).

South China Sea

Of all the coastal sectors, the South China Sea sector is perhaps the most diverse. It encompasses a large area of the China coast, from Nan Ao Island south to the Beilun River (the border between China and North Vietnam), as well as the many islands offshore, the largest of which is Hai Nan Island. The diversity of coastal types makes it difficult to summarize the coastline in a systematic fashion; instead this section provides specific examples of the major coastal types.

Tides are important locally, but since the South China Sea tides are generally diurnal, their associated currents are smaller. The high rainfall and higher temperatures of the tropics results in significant sediment supply. While the Pearl River contributes sediment to the south, many smaller rivers exert local control over sedimentation, separating the coast into a series of interacting coastal segments.

North Guangdong Province is characterized by granite Bedrock-embayed coasts of mixed erosional–depositional type. There are many small islands at the mouth of the bays, the latter which generally trend northwesterly. Besides eroding headlands, there are also large sand beaches. Heavy weathering which is typical of tropical climates allows higher erosion rates and greater supply of sediment to the beaches. An example of the poorly consolidated sedimentary material is the Zhan-Jiang formation, exposed along the mainland of Lei Zhou peninsula and in Hai Nan Island, composed of sand material with minor clay content. The combination of weathered igneous and metamorphic rocks and the easily eroded sandstone results in large accumulating forms on original bedrock-embayed coasts. In southern Hai Nan Island, which is genetically a bedrock-embayed coast, sections of the coast have built out extensively through a series of sand bars and lagoons. Near Sanya, there is a series of eight bars and lagoons which have built the coast out approximately 9 km. To the east of Sanya, the bedrock-embayed coast still has headlands actively eroding by wave action, accompanied by sedimentation in the bays. These forms are also common to the Guanxi Province, in southwest China.

Tidal inlet coasts are common in Guanxi Province and Hai Nan Island, as these embayments follow secondary east–west and northwest structural trends (superimposed on the dominant northeast fabric). On the mainland, the embayments follow this secondary structural fabric. Barriers generally trend northeasterly, crossing the mouths of the bays. There are abundant mudflats along the upper reaches of the embayments, the mud coming both from local sources and from the Pearl River to the northeast. Sandy beaches stretch along the barriers and the lower reaches of the embayments. Examples of tidal inlet coasts are Shantou, Zhenhai, and Zhanjiang bays. These tidal inlet coasts form good harbors, as they have good ebb flushing properties (WANG, 1980).

Submerged coastlines exist off this sector, with 8, 20, and 50 m deep terraces documented. They are generally of the accumulated form, rather than the bedrock platforms characteristic of the Zhejiang–Fujian area. Emerged terraces reflect smaller scale tectonics. An example is near the part of SanYa, Hai Nan Island, where marine terraces cut into bedrock.

Mangroves extend up to 27° north latitude along the South China Sea. They are mainly mangrove bushes (*Bruguiera conjugata*, *Aegiceras corniculatum*, *Rhizophora mucronata*, *Avicennia marina*) with a few jungles (*Bruguiera conjugata*, *Acanthus ilicifolius*) on Hai Nan Island. The mangroves are generally located in protected areas, such as lagoons and in the protected embayments behind sand barriers. Northeast Hai Nan Island has extensive mangrove development.

Fringing reefs are common on many of the islands as well as along part of the mainland. These fringing reefs are found in the embayments near the headlands, facing into the dominant waves, afforded some protection by the embayments.

Coral atolls are the dominant forms of most South China Sea islands whose basement is generally near 1200 m below sea level (CHEN, 1978). These atolls provide biogenic sediment for coastline morphology, and thus differ from the remainder of the beaches of China.

CONCLUSION

The development of the China coastline results from a complex interaction of tectonics, local geology, river processes, waves, tides and storms. With its broad north–south extent, ranging from latitude 42°N well into the tropics, varying climate dominated by monsoon conditions and typhoons impacts the coast to different degrees. With the active tectonism following a general northeast structural trend, coastal sectors can be divided into emergent and subsiding regions, reflected in the classification of bedrock and plains coasts. Net erosion in any of these sectors is dependent not only on vertical movement but also on sediment supply, primarily from rivers. For instance, the plains coast within Bohai Sea progrades rapidly as the Yellow River empties into this relatively shallow embayment. Conversely, the plains coast of North Jiangsu Province is rapidly eroding, losing the silt deposited here when the Yellow River occupied this coastal sector prior to 1855. Waves and tides combine to erode rapidly this unstable coast.

The sediment input of the historically unstable Yangtze, Pearl and many other smaller rivers, and the varying exposure of the coast to both locally generated seas and distantly generated swells, create considerable variability in coastal evolution in China. Superimposed on this natural variability is the strong influence of man, dating back more than 1000 years to the Tang Dynasty, as he settled and de-stabilized the extensive loess plains of China, accelerating the rapid local erosion and increasing heavy silt loads of the Yellow River. In more recent times this human impact continues as China dams many of its rivers for flood control, irrigation, and navigation. Offsetting these benefits have been the conflicting detrimental effects of increased siltation in the rivers (requiring periodic opening of the dams for navigation improvement) and reduced sediment supply to the rivers. Since riverine sedimentation is linked strongly to flood events which the dams are designed to tame, sediment input to the shore is reduced with consequent decline in coastal stability. With it population still growing and an increasing need for irrigation to sustain the food supply, man can be expected to continue to divert water from the rivers of China; diligent intervention by coastal scientists will be required to reduce the adverse impacts from this, and other, human activities.

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