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Sea-Level Rise on Eastern China's Yangtze Delta

Zhongyuan Chen† and Daniel Jean Stanley‡

†Department of Geography
East China Normal University
Shanghai 200062, P.R. China

‡Deltas-Global Change Program
E-206 NMNH, Smithsonian Institution
Washington, D.C. 20560, U.S.A.

ABSTRACT

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The Yangtze delta is a densely populated, low-lying region highly vulnerable to flooding, high tides and typhoons. All previous studies indicated that relative sea level was higher from ~7500–4000 yrs. BP, then lowered and stabilized at about present msl during the past 3000 yrs. To the contrary, we find that sea level has been rising relative to the southern Yangtze delta plain based on new sea-level data derived from dated peats, reassessment of earlier sea-level curves and measurement of delta plain subsidence and analysis of prehistoric habitat bases from ~7000 to 3000 yrs. BP. Consequences of this relative rise include difficulty in expelling water from the low-lying delta plain to the coast and associated flood damage. Emplacement of the 3-Gorges Dam on the Yangtze will control flooding of the Yangtze river but decrease sediment accumulation on the delta plain that, in turn, is likely to accelerate saline inundation of this vital breadbasket.

ADDITIONAL INDEX WORDS: *Delta flooding, Neolithic sites, peat, radiocarbon dates, relative sea level, sea-level curve, subsidence, Taihu lake, Yangtze delta.*

INTRODUCTION

The Yangtze delta, agricultural and industrial center for nearly 100 million inhabitants in eastern China, is periodically inundated by floods, high tides and typhoons. Rapidly increasing human pressures are modifying this low (3–5 m above mean sea level, msl) region, and it is thus vital to accurately measure Holocene sea-level stands so as to monitor ongoing sea-level change and help implement protection measures. On the basis of pollen and microfossil records derived for the delta, all previous studies show a marked warming trend and corresponding high sea-level stands (3–5 m above present msl) from ~7000 to 4000 yrs. BP (YANG and XIE, 1984; YAN and HONG, 1987; HONG, 1990; ZHAO *et al.*, 1994).

Our ongoing investigation of the delta plain, however, indicates that relative sea level was not higher than present msl during the Holocene, as earlier proposed. This finding is based on two new sea-level curves, one compiled from dated peats, the other calculated from former curves. Both indicate that relative sea level in the Yangtze delta has risen, but was below present msl during the Holocene. This is further supported by assessment of subsidence rates in the central delta plain and of elevations of prehistoric habitat bases from ~7000 to 3000 yrs. BP. We propose here that the difficulty in expelling excess water from the low-lying vulnerable delta plain to the coast, the major cause of flood damage, results in large part from the long-term Holocene relative rise in sea level.

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BACKGROUND INFORMATION

Earlier studies of the modern Yangtze delta (Figure 1) depict sea level positioned near and, periodically above, present mean sea level (msl) since ~7000 yrs. BP. Relative sea-level curves established for the delta were based in part on radiocarbon-dated materials collected at or near the delta plain surface, in trenches, shallow cores, areas of topographic relief, and archaeological settings such as middens. Although hundreds of deep drill cores have been recovered on this delta plain (YAN and XU, 1987), only few sea-level curves showing actual age of radiocarbon-dated sections have been published (Figure 2).

Pollen in radiocarbon-dated samples, denoting an increase in temperature by several degrees from early to mid-Holocene, was used by most workers (YANG and XIE, 1984; YAN and HONG, 1987, YU *et al.*, 1994; ZHENG *et al.*, 1994) as primary evidence for proposing a sea-level rise from ~7000 to 4000 yrs. BP (Figure 2, insets II and III). Thus, high sea-level

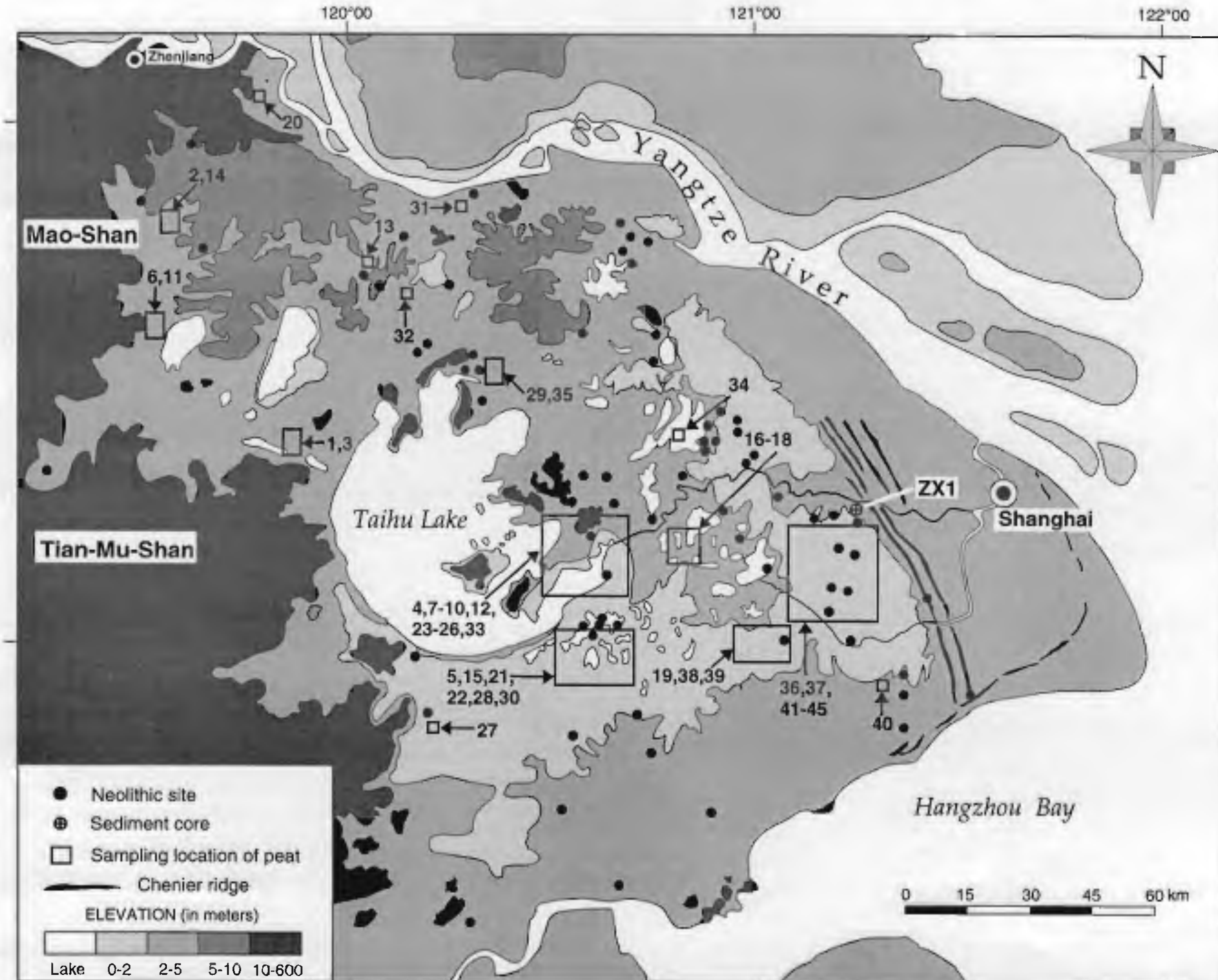

Figure 1. Topographic map of southern Yangtze delta showing the low saucer-like central plain, and positions of chenier coastal ridges, peat sample areas, some Neolithic sites and drill core ZX1.

stands during the Holocene are based, in large part, from indirect evidence collected in this region, i.e. interaction of regional climate warming and contemporaneous lowering of the delta plain surface by tectonic subsidence and sediment compaction (YAN and XU, 1987; ZHAO *et al.,* 1994).

It is recognized that large marine Holocene deltas in low to mid-latitudes have been affected by a rapid rise in sea level from ~18,000 to 8000 years ago, followed by a decelerating rate of rise from ~8000–7000 yrs. BP to present (ZHU *et al.,* 1981; COLEMAN, 1988; STANLEY and WARNE, 1993). Most Holocene relative sea-level curves compiled for these deltas are positioned below present msl, and parallel various world curves (*cf.* LIGHTY *et al.,* 1982; FLEMMING and WEBB, 1986; FAIRBANKS, 1989). It is thus surprising that previous Holocene sea-level curves for the Yangtze delta commonly show long-term (to 1000 yrs.) fluctuations ranging from 3 to 5 m elevation above msl (YANG and XIE, 1984; ZHAO *et al.,* 1994; YAN and XU, 1987). These high elevations, most often depicted for ~7000 to 4000 yrs. BP (Figure 2), lie well above present msl, and even exceed the average high tide level of ~1.5 m above msl. Previous curves for this region also indicate that during the past 3000 yrs., high sea-level stands subsequently decreased, approaching present msl.

REVISED RELATIVE SEA-LEVEL CURVES

Analysis here of widely used sea-level data collected in various sectors of the Yangtze delta region helps us to comprehend the apparent differences between Holocene sea-level in this region versus other coastal plains (PIRAZZOLI, 1991) and major marine deltas (STANLEY and WARNE, 1994) at comparable latitudes. Earlier curves derived for the Yangtze are highly variable. Our calculated average relative sea-level curve, derived from data at 6 sites (Figure 2, inset I), is plot-

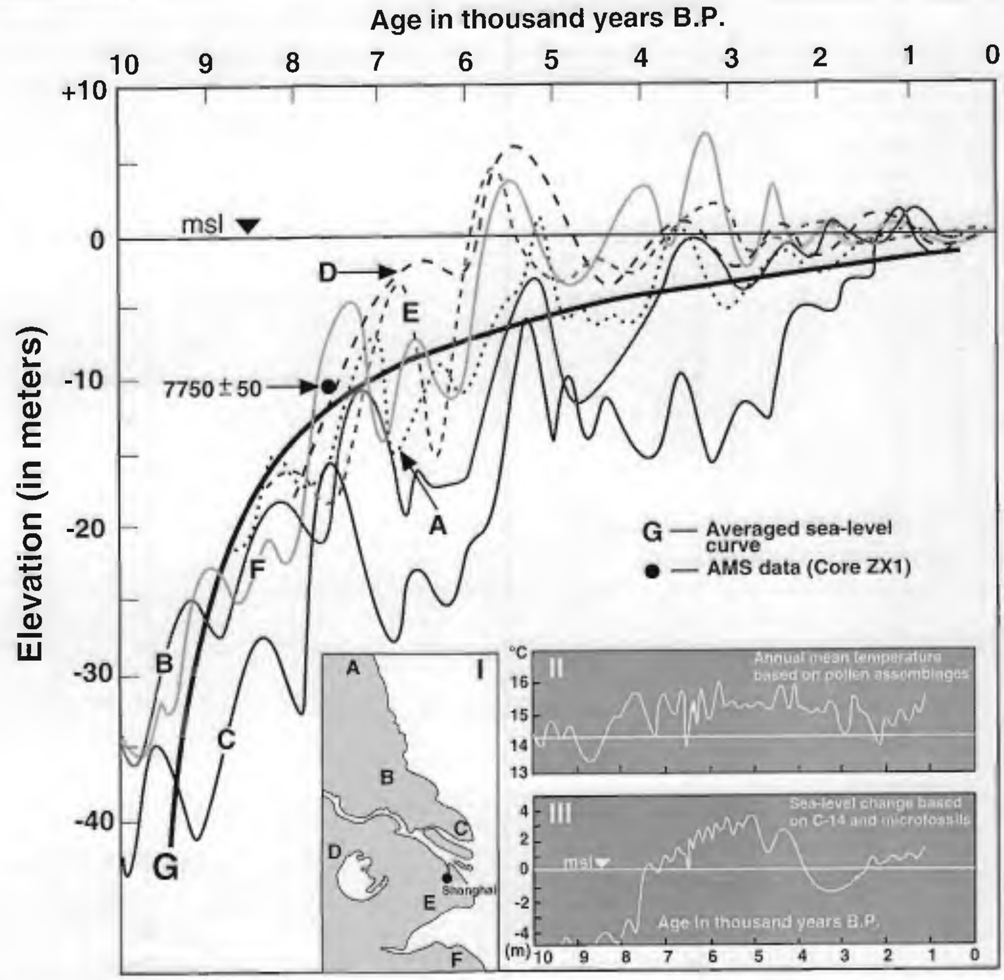

Figure 2. Selected relative sea-level curves A-F for the Yangtze delta region showing long-term high sea-level fluctuations from ~7000 to present (after YANG and XIE, and PIRAZZOLI, 1991). Curve G (heavy line) is calculated here from these data. Note position of basal Holocene marine section of delta core ZX1 relative to line G. Positions of A–F are shown in inset I. Also reproduced are curves (both after ZHAO *et al.*, 1994) depicting Holocene warmer climate (inset II) and higher sea-level stands (inset III).

ted as an exponential regression line (G, in Figure 2). This curve highlights the rapid rate of rise to a depth of ~10 m below present msl at ~8000–7000 yrs. BP, and since that time, the average curve shows a general deceleration in rate of rise to the present. This curve smooths long-term oscillations and, for the entire period considered, lies below present msl. Also plotted on this diagram is the recently dated (accelerator mass spectrometric, AMS, method) base of a Holocene marine delta section from one of many cores recovered on the southern plain (core ZX1, in Figure 1). The plotted age-depth position of this Holocene base (~10 m at 7750±50 yrs. BP) is proximal to our recalculated Yangtze curve.

As a primary method to determine Holocene relative sea-level change through time in the southern delta plain, we also plot ages of radiocarbon-dated peat samples and their depths (Figure 3). Most of these 45 samples (Table 1) were derived from the Taihu lake region (Figure 1), in the low-lying central part of the delta plain (data in DAI, 1987; HONG, 1990, 1991; SUN and HUANG, 1993). The peats are used as relative sea-level gauges inasmuch as they are formed by *in situ* preservation of woody plants, grasses and flora tolerant to fresh and brackish water conditions. These species, living at or near sea level, are listed in SUN and HUANG (1993). A two-step calculation calibrates peat age-depth information for plotting a relative sea-level curve (Figure 3). (1) The first step takes into account the elevations (ranging from 1 to 3 m above msl) of present delta plain surfaces where peats were recovered (Figures 1 and 3, inset). Thus for each sample, 2 m (mean elevation of the central delta plain) is subtracted from the total depth in m below the present ground surface below which the peat sample was collected (usually an elevation below msl). (2) A second step involves subtracting 1.5 m from elevation value (1), since plants forming the peat lived at or just above mean high sea level (~1.5 m above msl).

Although scattered at depths below msl, peat data show an overall positive trend: peat depth decreases as peat age be-

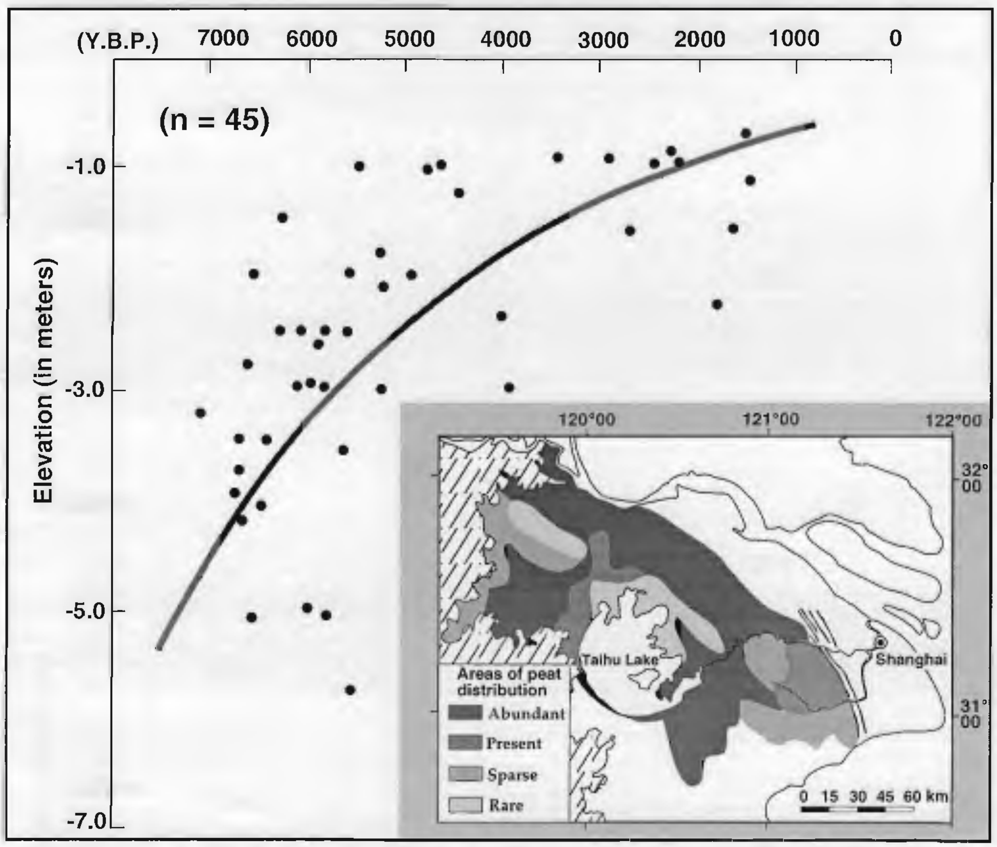

Figure 3. Holocene relative sea-level curve derived from dated peat in samples collected in the central southern Yangtze plain. Inset shows peat distribution pattern. Age and depth of peats are listed in Table 1.

comes younger. An exponential regression line was derived from peat sample data: this curve lies below present msl, and records a decrease in depth from −5 m at ~7000 yrs. BP to −1 m about 1000 years ago (Figure 3). Compaction of the peats is not measured here in the compilation. An overall rate of sea-level rise of 0.7 mm/yr is determined for this time span, and the curve is shallower by several meters than the averaged curve (G in Figure 2) and AMS dated core sample ZX1 (Figure 2). Both curves, while generalized, indicate that relative sea level in the Yangtze delta region, from ~7000 yrs. BP to the present, as in many delta plains of the world (STANLEY and WARNE, 1994), remained below present msl during the Holocene.

CORE STRATIGRAPHY AND SUBSIDENCE

Some isotopically-dated material, including wood and molluscs collected on or near the plain surface, were used to compile former Yangtze delta sea-level curves (YANG and XIE, 1984; YAN and XU, 1987; ZHAO *et al.*, 1994). In some cases, these are not *in situ*, but were displaced at times of flood and typhoon (ZHANG *et al.*, 1987). To minimize this phenomenon of reworking, we focus herein on drill core lithostratigraphy and early archaeological records. Together these do not support earlier proposed long-term stands higher than present msl and which then lowered from 4000 yrs. BP to present. Instead, our findings indicate that relative sea level has been rising in the delta region from the early Holocene to the present.

Moreover, pollen assemblages and petrologic changes from numerous drill cores examined in the delta are not synchronous with proposed climate fluctuations from ~7000 to 4000 yrs. BP as would be expected from earlier proposed sea-level fluctuations (LI *et al.*, 1986). Also, core stratigraphy indicates that, as in most of the world's large deltas, high rates of subsidence (to >4.0 mm/year) have lowered the seaward sector of the Yangtze plain, *i.e.* delta east of the chenier coastal ridge system (Figure 1) (YAN and XU, 1987; CHEN and STANLEY, 1993; STANLEY and CHEN, 1993). However, stratigraphic analysis of numerous drill cores recovered farther to the west (central Yangtze delta plain, including Taihu lake region), shows that the Holocene deltaic sediment cover above the Pleistocene is only 3 to 5 m thick (HONG, 1991; SUN and HUANG, 1993; CHEN and ZHANG, 1994). We find this thin stratigraphic section west of the chenier ridges, representing a time span of >7500 years, records minor subsidence rates (1.0 to <0.5 mm/year) in the central delta region where our peat-based relative sea-level curve is determined (Figure 3). This subtle lowering of the central plain would not account

Table 1. *Radiocarbon dates and depths of 45 peat samples in the southern Yangtze delta plain (data plotted in Figure 3). Code numbers refer to sampling areas shown in Figure 1.*

Code	C-14 date (uncalibrated) in years B.P.	Depth (in meters below msl)	Data reference	Code	C-14 date (uncalibrated) in years B.P.	Depth (in meters below msl)	Data reference
1	7064 ± 300	3.2	Dai (1987)	24	5530 ± ?	2.0	Hong (1990)
2	6680 ± 140	4.0	Sun and Huang (1993)	25	5470 ± 80	1.0	Hong (1990)
3	6670 ± 105	3.8	Sun and Huang (1993)	26	5260 ± 135	3.0	Dai (1987)
4	6670 ± 105	3.5	Dai (1987)	27	5260 ± ?	1.8	Sun and Huang (1993)
5	6600 ± 93	2.8	Sun and Huang (1993)	28	5210 ± 145	2.1	Dai (1987)
6	6580 ± 85	2.0	Sun and Huang (1993)	29	4901 ± 136	2.1	Sun and Huang (1993)
7	6510 ± 220	4.1	Sun and Huang (1993)	30	4750 ± 70	1.0	Hong (1991)
8	6500 ± 190	5.1	Dai (1987)	31	4660 ± 75	1.0	Hong (1991)
9	6365 ± 184	3.5	Dai (1987)	32	4470 ± 70	1.2	Hong (1990)
10	6275 ± 145	1.5	Sun and Huang (1993)	33	4000 ± ?	2.2	Sun and Huang (1993)
11	6227 ± ?	2.5	Sun and Huang (1993)	34	3950 ± ?	3.0	Sun and Huang (1993)
12	6008 ± 145	6.0	Sun and Huang (1993)	35	3407 ± 74	1.0	Sun and Huang (1993)
13	6000 ± ?	2.5	Sun and Huang (1993)	36	2950 ± 60	3.6	Dai (1987)
14	6000 ± ?	3.0	Sun and Huang (1993)	37	2720 ± 70	1.6	*
15	5960 ± 80	5.0	Hong (1991)	38	2393 ± 85	1.0	Dai (1987)
16	5930 ± ?	3.0	Sun and Huang (1993)	39	2285 ± 71	0.9	Dai (1987)
17	5845 ± 105	2.6	Sun and Huang (1993)	40	2180 ± 70	1.0	Hong (1990)
18	5845 ± 115	3.0	Hong (1990)	41	1790 ± 70	2.3	Dai (1987)
19	5790 ± 95	5.1	Sun and Huang (1993)	42	1780 ± 80	1.7	Hong (1990)
20	5780 ± 80	2.5	Dai (1987)	43	1691 ± 69	1.5	Sun and Huang (1993)
21	5640 ± 126	3.6	Dai (1987)	44	1530 ± 140	1.1	Dai (1987)
22	5600 ± ?	2.5	Hong (1991)	45	1510 ± 65	0.7	Dai (1987)
23	5530 ± 115	5.7	Sun and Huang (1993)	* From authors, unpublished			

for the high sea-level stands proposed for this sector in previous studies for the early to mid-Holocene.

ARCHAEOLOGICAL EVIDENCE

Prehistoric and dynastic archaeological records further support our postulate that relative sea level has been rising, not lowering, on the southern delta plain since the early Holocene. From ~7000 to 3000 yrs. BP, period of previously proposed long-term high sea-level stands, Neolithic settlements were widespread on the southern plain, especially in the Taihu lake region (STANLEY and CHEN, 1996). More than 300 of these early sites (some shown in Figure 1) are concentrated in this low-lying region (YI and ZHANG, 1962; CHANG, 1986; SUN and HUANG, 1993). Our survey of 28 dated habitat bases from this time-span indicates that most Neolithic settlements were positioned between −3 to + 3 m relative to present msl (Figure 4A). Habitat bases of the sites, averaged for 4 distinct early cultures, show these to be positioned between −0.3 to +1.4 m relative to msl (Figure 4B). At these elevations, settlements would have been inundated had sea level been higher, or even at the same, elevation as present (Figure 1). This finding is further supported by additional archaeological surveys in the southern and northern Hangzhou Bay plain (Figure 1), where sea level is estimated at 1 to 4 m below present msl for the ~7000 to 4000 yrs. BP period (WU, 1983).

DISCUSSION AND CONCLUSIONS

The Yangtze delta is highly populated in cities (>12 million in the Shanghai area alone) and in the countryside (250 to 1200 persons/km^2). The central plain is a large, low saucer-like depression (Figure 1) where the fresh-water table lies <1 m below present ground surface (HONG, 1991). The elevation difference between ground-water level in the central plain and msl has been markedly reduced since the early Holocene, and high tide at the coast can reach a level higher than that of the water table. This configuration causes difficulty in ex-

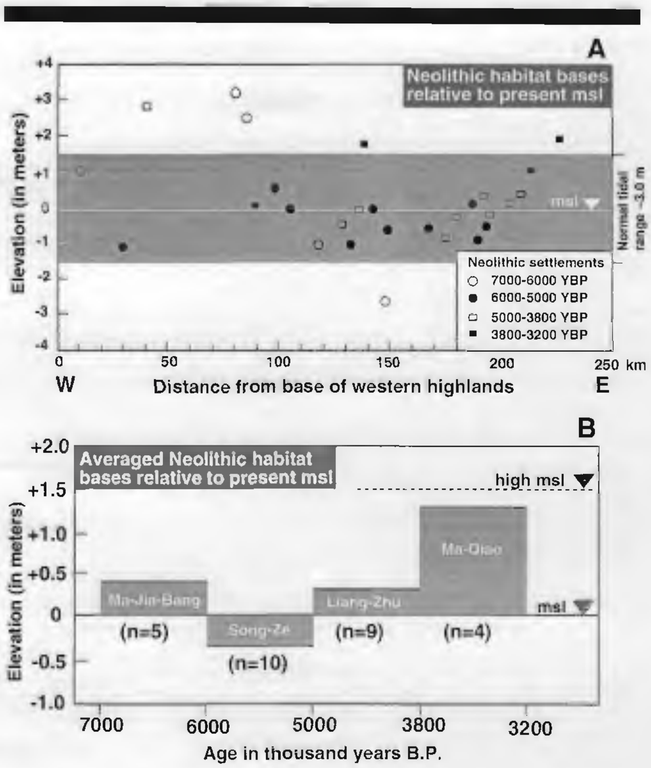

Figure 4. A, Elevation of habitat bases of early settlements relative to present msl and to distance east of the Mao-Shan and Tian-Mu-Shan highlands in the west (Figure 1). B, Habitat bases, grouped by 4 cultures, showing elevations between −0.3 to +1.4 m, or lower than present high msl.

pelling excess fresh water from the delta plain to the coast and is the major reason for flood damage (SUN and HUANG, 1993). In historic records, we find that this risk has increased with time due to progressive rise in sea level and land subsidence. In 1931, for example, >200,000 persons lost their lives when lower Yangtze reaches, including Taihu lake area, were inundated due to high precipitation coupled with river flooding and high tides. More recently, in June 1991, unusually high precipitation (>500 mm) during a short period caused a rise in water level of Taihu lake, to 4.8 m above msl, resulting in inundation of almost half of the southern delta plain (SUN and HUANG, 1993).

Our study shows that sea-level stands were not higher than present msl for long periods in the Holocene but, rather, relative sea level has generally been rising. The delta plain is now increasingly at risk as a result of interaction of sea-level rise and increasing human activity, including land reclamation, irrigation, municipal growth and industrialization. Of particular interest in this respect are large river engineering structures, especially the Three-Gorges Dam now under construction on the Yangtze, which will help control river flooding but also reduce sediment accretion on the delta plain early in the next century. We expect that further relative rise in sea level would be hazardous for this low-lying area, particularly at times of flood, high tide and typhoon. Developing an accurate base to measure sea-level stands in the recent past to the present is essential to monitor present and future rise in sea level and realistically plan protection measures against saline incursion into this vital, highly populated region.

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