Environmental Change in the Yangtze River Delta since 12,000 Years B.P.

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A 52-m core from Qidong at the tip of the Yangtze River (Chang Jiang) delta provides a history of sea-level change, deltaic development, and vegetational and climatic changes during the last 12,000 yr. About 12,000 yr ago, when sea level was about 60 m below the present level, the coring site was situated in the innermost part of the exposed continental shelf. The late-Pleistocene vegetation on the uplands of the Lower Yangtze River valley was a mixed forest of deciduous and broadleaved evergreen trees in which Betula, Ulmus, Tsuga, and Cupressaceae were slightly more abundant than at present. Abies and Picea were probably present as relict populations on mountains bordering the region. Rapidly rising sea level converted the Qidong area to a coastal or estuarine environment between 11,000 and 10,800 yr B.P., leading to widespread development of wetlands dominated by Gramineae and Cyperaceae. During the next 2500 yr coastal erosion due to marine transgression obliterated the sedimentary record. Deltaic sedimentation predominated from 8300 to 3800 yr B.P., as the Yangtze River delta prograded by successively building a series of estuarine sand bars. During the mid-Holocene, the climate was slightly warmer and more humid than at present, allowing the subtropical broadleaved evergreen trees to increase their populations. Pinus and Quercus became more abundant after 3800 yr B.P. in response to climatic cooling. The present deltaic plain in Qidong formed less than 200 yr ago. © 1992 University of Washington.

INTRODUCTION

The Yangtze River (Chang Jiang according to the Pinyin system) delta is situated in the subtropical monsoonal region of China. During the Quaternary it was subjected to repeated episodes of marine transgressions and regressions, corresponding to major glacial/interglacial climatic fluctuations. The last major marine transgression, called the Zhenjiang transgression (Lin et al., 1989), occurred during the early Holocene as a result of the postglacial sea-level rise. However, the detailed chronology and areal extent of this marine transgression in the Yangtze River delta region, including the adjoining Tai Hu lacustrine plain to the south, remains a matter of considerable debate among Chinese researchers (e.g., Guo, 1983; Han et al., 1987; Li and Min, 1981; Yan and Hong, 1988; Yang and Xie, 1984).

Equally controversial are questions concerning the late-Pleistocene and Holocene climate and vegetation history of the Yangtze River delta region, and of the Chinese subtropics in general. One scenario for the last glacial maximum suggests that a “cold trough” extended southward into the eastern Chinese subtropics, along which mean annual temperature was depressed by as much as 9–13.5°C, resulting in the development of boreal forest dominated by Picea (spruce) and Abies (fir) in the Lower Yangtze River basin (Yang and Xu, 1980). Other scenarios suggest a late-Pleistocene climate somewhat cooler and drier than now with a temperature depression of only 3° to 5°C; the inferred vegetation of the Yangtze River delta region varied from grassland and parkland on the exposed continental shelf to mixed coniferous forest dominated by Pinus (pine) and Cupressaceae (cedars) on the uplands (Wang et al., 1981, 1987).
In this paper, we present a radiocarbon-dated pollen and sediment stratigraphy from a 52-m core collected from the Yangtze River delta. The data are interpreted in the context of climatic and vegetation changes, delta development, and sea-level history of the Yangtze River delta region during the last 12,000 yr.

STUDY REGION

Modern Environment

The Yangtze River flows into the East China Sea at about 31.5° N and has built a delta about 51,800 km² in size, about 29,000 km² (56%) of which is below sea level (Fig. 1). The climate of the Yangtze River delta region is humid subtropical, or Cfa according to the Köppen system, and is strongly influenced by the East Asian monsoon. The mean annual temperature, July temperature, and January temperature are 15°, 28°, and 2°C, respectively. Precipitation averages about 1100 mm per year, about 40–45% of which falls in the summer (JJA) (Academia Sinica, 1985).

The potential natural vegetation of the Yangtze River delta region is northern subtropical mixed deciduous–broadleaved evergreen forest known for its high species diversity (Wu, 1980). Among the characteristic tree taxa are various deciduous species of Quercus (oak) (e.g., Q. variabilis, Q. serrata var. brevipetiola, Q. fabri, Q. acutissima, Q. chenii, Q. aliena), Castanea (chestnut), Liquidambar (sweetgum), Platycarya, Albizia (albizia), Dalbergia (rosewood), Tilia (linden), and broadleaved evergreen taxa like Castanopsis (chinkapin), Cyclobalanopsis, and Ilex (holly) (Wu, 1980). However, virtually all available land in the deltaic plains and alluvial lowlands is now under cultivation and remains unforested. Secondary or successional forests occur on isolated hills amid the deltaic

![Map of the Yangtze River delta region](image-url)

**Fig. 1.** Holocene coastlines and river-mouth sandbars in the Yangtze River delta region during the last 7000 years (after Xu et al., 1985). The coring site in Qidong is marked by a triangle.
plain, and on mountains flanking the south and west of the delta region.

**Late-Quaternary Geologic History**

Much of the continental shelf area bordering the Yellow Sea and East China Sea was exposed subaerially during the last glacial maximum (about 18,000 yr B.P.), when the sea level was about 155 m lower than at present (Wang and Wang, 1981). A buried gorge detected at −50 to −60 m underneath the modern delta suggests that the Yangtze River occupied an incised channel as it flowed across the exposed continental shelf (Xu et al., 1985). The postglacial sealevel rise was very rapid. By about 10,000 yr B.P. the sea level was at about −40 m (Yan and Hong, 1988). Continued sea-level rise resulted in a marine transgression that climaxed about 7000 yr B.P. (Yan and Hong, 1988; Yang and Xie, 1984) (Fig. 1). The lower reach of the Yangtze River was inundated, forming a wide estuary eastward from Yangzhou and Zhenjiang. This wide estuary provides the geological framework in which the modern Yangtze River delta was formed as a result of fluvial and deltaic sedimentation over the last seven millennia.

The Yangtze River delta prograded southeastward by building six subdelta lobes successively during the last 7000 yr (Xu et al., 1985) (Fig. 1). Each subdelta lobe is centered around an estuarine sand bar. The chronology postulated for the six phases of subdelta development is as follows: Hongqiao phase (7500−6000 yr B.P.); Huangqiao phase (6500−4000 yr B.P.); Jinsha phase (4500−2000 yr B.P.); Haiming phase (2500−1200 yr B.P.); Chongming phase (1700−200 yr B.P.); Changxing phase (700−0 yr B.P.). A new subaqueous sandbar is being initiated at Jiuduansha to the southeast of Changxing Island (Xu et al., 1985).

**METHODS**

The 52-m core was taken at the northern tip of the Yangtze River delta about 2.5 m above sea level in the Xiangyang Commune just north of the county seat of Qidong (31°50'N, 121°40'E). Coring was undertaken by a local construction engineering team using an electric-powered mechanical corer mounted on a tripod. The sediments were cored in 0.5-m segments and were extruded from the 8.9-cm-diameter core barrels. Each core segment was then described, photographed, and sampled in the field. One hundred bulk samples were sealed in plastic whirlpack bags and shipped to Louisiana State University for sedimentological and pollen analyses and radiocarbon dating.

Small subsamples (4–6 g) of all 100 samples were heated at 105°, 550°, and 1000°C to determine the contents of water, organic matter, and carbonates in the sediments, respectively (Dean, 1974). Thirty subsamples of 0.9 ml each, mostly at intervals of 1.5 m, were selected for pollen analysis. Fine-grained sediments (clay or silt) were used for pollen analysis whenever possible. They were processed according to a procedure slightly modified from Faegri and Iversen (1975), involving treatments with hydrochloric acid, potassium hydroxide, sodium pyrophosphate, hydrofluoric acid (HF), glacial acetic acid, acetolysis solution, and tertiary butyl alcohol. For many samples, the hot HF treatment was extended to 1 hr to digest the silicates more thoroughly. One tablet containing 12,077 ± 200 exotic *Lycopodium* spores was added to each sample at the beginning of processing to permit calculation of pollen concentration values. The residue was suspended in silicone oil and mounted on slides for microscopic examination at 400× magnification. Pollen identification was aided by the use of published works with illustrations (Institute of Botany and South China Institute of Botany, 1982; Huang, 1973) and the modern pollen reference collection housed in the Department of Geography and Anthropology, Louisiana State University. Except for two sandy samples (10.15 and 15.10 m) with low pollen counts, the
pollen sum consists of at least 200 grains of all terrestrial pollen taxa; aquatic pollen, including Cyperaceae, and pteridophyte spores are excluded from the sum.

RESULTS

Sediment Stratigraphy

The 52-m core from Qidong consists of clastic sediments with organic matter content of typically 1–2% for the sand and 3–4% for the silt and clay (Fig. 2).

The core comprises two distinct sedimentary units (Fig. 3). The lower 15 m (36.70–52.00 m) is alluvium consisting of predominantly nonlaminated or faintly laminated dark-gray silty clay or clayey silt, except that sand is prominent below 50.30 m. Ferromanganese concretions, yellowish-brown and ranging in size from several millimeters to >3 cm, occur amid mottled clay at 36.70–37.55 and 46.00–51.00 m. Fossils and casts of plant roots and stems, freshwater snails and clams, as well as small shell fragments, are present sparingly. Foraminifera and marine ostracods occur in the upper part of this sedimentary unit but disappear entirely below 43.5 m. The foraminifera assemblage has relatively low benthic species diversity and contains a significant proportion of planktonic individuals (B. Sen Gupta, personal communication, 1990).

A distinct lithological change, implying a hiatus, occurs at 36.7 m where a thin (0.5 cm) layer of peat is present. The upper 36.7 m of the core is characterized by alternating layers of sand, silt, and clay typical of prodeltaic and delta-front deposits (Coleman and Wright, 1975). Sand is generally predominant in the upper-middle part of
this sedimentary unit, especially from 7.14 to 12.8 m and from 14.5 to 18.05 m, whereas clay is predominant in the lower part, especially from 19.1 to 25.0 (Fig. 3). Burrows, tiny shell fragments, and some small shells of marine gastropods and bivalves are present in certain segments. Two shell layers occur at 32.0–33.7 and 36.50–36.67 m; the former contains well-preserved fossils of salt-water clams, snails, fish bones, crab shells, and shark teeth. Marine ostracods and foraminifera indicating a warm and shallow-water marine environment are present throughout this sedimentary unit above the hiatus (B. R. Huang and B. Sen Gupta, personal communications, 1987, 1990).

The upper 7.14 m of the core represents an intertidal zone or deltaic plain deposit. It consists of interbedded clay and sand, with dark-gray silty clay predominant toward the top. Organic laminae and plant roots are present above 4 m. The uppermost meter of the core is a disturbed cultivated horizon and was not sampled.

**Radiocarbon Dates and Sedimentation Rates**

The eight ¹⁴C dates and the calculated sedimentation rates are shown in Table 1 and Figure 4. The alluvial sediments in the lower 15 m of the core span ca. 12,000–10,800 yr B.P. This section includes three ¹⁴C dates that are in stratigraphic order, although overlapping at 1σ (11,110 ± 100, 10,970 ± 70, 10,810 ± 140 yr B.P.). Sedimentation rates calculated from these dates vary widely from 0.444 to 5.036 cm/yr (Fig. 4), but decreases in the pollen concentration values do not follow the trend implied by these calculated sedimentation rates unless pollen influx values were to fluctuate even more dramatically (Fig. 5). Possibly the 11,110 ± 100 yr B.P. date is too young by several hundred years due to sample contamination by roots of younger plants growing on a higher horizon. In any case, the mean sedimentation rate for the entire section of late-Pleistocene sediments is about 1.2 cm/yr.

Sediments immediately above the hiatus are dated to 8320 yr B.P., so that about 2500 years of sedimentation are missing in the hiatus. Among the four ¹⁴C dates in the deltaic sediments above the hiatus, the uppermost one, 7370 ± 90 yr B.P., is rejected because it is much older than the two below it. The reason for the anomalous date is unclear, but in a sediment sample with organic content of less than 5% only slight contamination with recycled carbon is sufficient to affect the date seriously (Harkness, 1975).

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**TABLE 1. Radiocarbon Dates from the Qidong Core**

<table>
<thead>
<tr>
<th>Core depth (m)</th>
<th>¹⁴C date (yr B.P.)</th>
<th>Lab. number</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0–20.5</td>
<td>7370 ± 90</td>
<td>Beta-24638</td>
</tr>
<tr>
<td>24.2–24.4</td>
<td>4460 ± 90</td>
<td>Beta-24639</td>
</tr>
<tr>
<td>32.5–33.1 (shells)</td>
<td>5960 ± 110</td>
<td>Beta-20757</td>
</tr>
<tr>
<td>36.5–36.7</td>
<td>8320 ± 170</td>
<td>Beta-21099</td>
</tr>
<tr>
<td>37.0–37.5</td>
<td>10,810 ± 140</td>
<td>Beta-20758</td>
</tr>
<tr>
<td>40.0–40.5</td>
<td>10,970 ± 70</td>
<td>Beta-20211</td>
</tr>
<tr>
<td>47.2–47.4</td>
<td>11,110 ± 100</td>
<td>Beta-20759</td>
</tr>
<tr>
<td>50.8–51.0</td>
<td>11,920 ± 160</td>
<td>Beta-20760</td>
</tr>
</tbody>
</table>
Block slumping or redeposition of older sediments is unlikely to be the cause because the sample comes from pure clay with undisturbed microlaminations. The other three dates are stratigraphically consistent and seem to suggest very slow sedimentation between 8320 and 5060 yr B.P. (0.117 cm/yr), followed by more rapid sedimentation for the next 600 yr (1.417 cm/yr) and an intermediate rate (0.545 cm/yr) after 4460 yr B.P. (Fig. 4). However, pollen concentrations remain fairly uniform throughout this section and do not seem to corroborate these large fluctuations in sedimentation rates (Fig. 5); no drastic variations in real pollen influx are expected for this interval. It is likely that the 5060 ± 110 yr B.P. date, which is the only one from shells sieved from their matrix, is too young due to contamination from modern carbon. If this date is rejected, then the calculated sedimentation rate between 8320 and 4460 yr B.P. becomes 0.319 cm/yr, and the calculated pollen influx values for this section would then be about 3000–7000 grains/cm²/yr—quite comparable with those calculated for the deltaic sediments above (Fig. 5).

The higher sedimentation rate over the last 4500 yr, (0.545 cm/yr) is consistent with the progradation of the Yangtze River delta toward the coring site.

Pollen Stratigraphy

The pollen record for Qidong provides the first estimates of pollen concentration and pollen influx values in deltaic sediments from China. Total pollen concentration values are fairly uniform throughout the Holocene deltaic sediments, generally between 10,000 and 20,000 grains/cm², except in sand where the values are less than 10,000 grains/cm². Pollen concentrations are higher in the late-Pleistocene alluvium, about 20,000–30,000 grains/cm². This translates into pollen influx values of 2000–10,000 grains/cm²/yr for the Holocene deltaic sediments, and 20,000–50,000 grains/cm²/yr for the late-Pleistocene alluvial sediments (Fig. 5).

The pollen percentage and concentration diagrams are each divided into two pollen zones, each with two subzones (Figs. 6 and 7). Zone 1 (52.0–36.7 m; ca. 12,000–10,800 yr B.P.), corresponding to the late-Pleistocene alluvium, contains greater abundance of Cupressaceae, Tsuga (hemlock), Betula (birch), Ulmus (elm), Gramineae (grass), and Cyperaceae (sedge) pollen. Subzone 1a (52.0–43.5 m; 12,000–11,000 yr B.P.) is characterized by the presence of Abies and Picea pollen and high pollen frequencies of Cyperaceae and Potamogeton (pondweed). Subzone 1b (43.5–36.7 m; 11,000–10,800 yr B.P.) is characterized by a dramatic peak of Gramineae pollen, both in percentage and concentration values. It also contains increased pollen frequencies for Cupressaceae and Betula, as well as freshwater aquatic plants like Sparganium (bur-reed) and Cyperaceae.

Pollen Zone 2, occurring in the Holocene deltaic sediments, is divided into two subzones. Subzone 2a (36.7–20.9 m; ca. 8300–3800 yr B.P.) is characterized by increased pollen frequencies of Cyclobalanopsis, Castanopsis, Castanea, Liquidambar, and
Fig. 6. Pollen percentage diagram for the Qidong core.
Fig. 7. Pollen concentration diagram for the Qidong core.
Pterocarya (wing nut). Gramineae pollen frequencies decline sharply, and Abies pollen is absent. Subzone 2b (20.9–1.0 m; 3800–0 yr B.P.) is characterized by a decrease in the pollen frequencies of Cyclobalanopsis, Castanopsis, and some other hardwoods, and an increase in Quercus, Pinus, and Gramineae pollen. Pollen concentrations increase sharply toward the top of this subzone.

POLLEN PROVENANCE IN YANGTZE RIVER DELTA SEDIMENTS

Questions about the source of pollen in the Qidong core are vital to the interpretation of the pollen diagrams. Pollen in deltaic or alluvial sediments, particularly those of large rivers such as the Mississippi or the Yangtze, are derived from a huge drainage basin that may encompass different vegetation zones (Chmura and Liu, 1990). For example, isolated grains of Abies and Picea pollen found in modern fluvial sediments along the Yangtze River channel in the deltaic plain (Wang et al., 1982) must have been fluvially transported over 2000 km from the upper reaches of the Yangtze River in southwestern China (see discussion below). However, surface sample studies from the Yangtze River delta region and the continental shelf of the East China Sea (Wang et al., 1979, 1982) suggest that pollen taxa exclusively attributable to long-distance fluvial transport are only a minor component and do not mask the more abundant pollen input from the regional upland vegetation. Modern pollen assemblages from the Yangtze subaqueous delta and continental shelf sediments typically contain 40–70% arboreal pollen and 10–30% terrestrial herb pollen. Predominant among the arboreal pollen taxa are Pinus, Quercus, Cyclobalanopsis, and Castanea, along with Betula, Myrica (waxmyrtle), Cunninghamhamia (China fir), Ulmus, Castanopsis, and Ilex; Gramineae, and to some extent Artemisia (sage), Compositae, and Chenopodiaceae are common nonarboreal pollen taxa (Wang et al., 1979, 1982). All of these taxa are important components of the modern vegetation growing in and around the Yangtze River delta. Wang et al. (1979, 1982) conclude that the pollen in the Yangtze River deltaic and continental shelf sediments are mostly transported, by both wind and river water, from the regional vegetation of the Yangtze River delta and the surrounding hills and mountains.

The overall pollen assemblages contained in our 52-m core from Qidong are dominated by Pinus, Quercus, Cyclobalanopsis, and Gramineae, along with Castanea, Salix (willow), Castanopsis, Myrica, Rhus (sumac), and Carpinus (hornbeam). They are remarkably similar to the modern pollen assemblages described above, and are consistent with the floristic composition of the modern vegetation in and around the Yangtze River delta. We, therefore, conclude that changes in the pollen stratigraphy of the Qidong core broadly reflect vegetational changes in the Yangtze River delta region.

ENVIRONMENTAL RECONSTRUCTION

12,000–11,000 yr B.P.

During the Wisconsin–Würm glacial maximum much of the continental shelf along the Chinese coast, including the Qidong area, was subaerially exposed. At 12,000 yr B.P. sea level was 60 m below the modern level, but rose rapidly to about 50 m by 11,000 yr B.P. (Zhao et al., 1979). The lowest sediments (43.5–52 m) in the Qidong core, spanning 12,000 to 11,000 yr B.P., were therefore an alluvial deposit formed well above sea level, an interpretation supported by the absence of marine microfossils. The coring site at that time was probably in the Yangtze River alluvial valley situated in the innermost part of the exposed continental shelf.

The regional upland vegetation inferred from pollen Zone 1a was a mixed deciduous–broadleaved evergreen forest domi-
nated by various species of deciduous and evergreen Quercus, Pinus, Ulmus, Betula, Castanea, and Carya (hickory). It was probably broadly similar in floristic composition to the one prevailing today, except that it contained more temperate deciduous trees such as Betula and Ulmus, and conifers more tolerant of cool summers such as Tsuga and Cupressaceae (e.g., Platycladus, Sabina, Juniperus). Abies and Picea were probably present as a minor forest component on mountains bordering the Lower Yangtze River valley (discussed below). The vegetation in the lowlands was probably more open, but forest development was limited by hydrological and edaphic factors rather than climate. Gramineae and Cyperaceae were abundant in riverine wetlands and on floodplains.

The occurrence of Abies and Picea pollen in the late-Pleistocene sediments of Qidong is an intriguing problem. Abies and Picea are characteristic components of modern subalpine forests between 1500 and 4000 m in northeastern, southwestern, and western China, and between 2300 and 3300 m in Taiwan (Hsu et al., 1980); they are absent in the intervening lowlands. Their pollen, however, has been reported from Pleistocene core samples from the Yangtze River deltaic plain (Liu and Ye, 1977; K. Wang et al., 1984, 1986; Song and Wang, 1961), the Lower Yangtze alluvial valley (Xu and Zhu, 1984), the Taihu lacustrine plain (Han et al., 1987), and the continental shelf offshore from the Yangtze River delta (Wang et al., 1979, 1981). A plausible explanation is that these pollen were fluvially transported from the Upper Yangtze River basin, where Abies and Picea are present in the subalpine forests today and were likely to have been more widespread during the Pleistocene. However, the fairly consistent occurrence of Abies pollen in Zone 1 of Qidong, and the common occurrence of both Abies and Picea pollen in Pleistocene sediments at other core locations, favor the interpretation that they were derived from late-Pleistocene populations growing in upland forests in the Lower Yangtze drainage basin itself, rather than from extraregional sources. This scenario is deemed more likely in view of the recent discovery of a relict population of Abies, consisting of only six individuals and assigned to a new species, A. beshanzuensis, on a south-facing slope at 1700 m elevation on Beishanzu Mountain (27°45'N, 119°11'E), about 500 km southwest of Qidong (Hsu et al., 1980; Wanli Forestry Station, 1976). Moreover, abundant Abies and Picea pollen have been found in Pleistocene deposits at 400 m in Siming Shan and at 920 m in Tianmu Shan (Liu and Ye, 1977); both are sites on mountains in the southern reaches of the Yangtze River delta region, where the pollen source must have been local. Thus, it is quite conceivable that Abies and Picea had much wider ranges during the late Pleistocene and might have been present as minor components in the mixed deciduous–broadleaf evergreen forest south of the Yangtze River delta region prior to 11,000 yr B.P. Their distribution ranges contracted substantially during the early Holocene, presumably in response to climatic warming, when spruce became locally extinct in the eastern Chinese mainland and fir only survived as relicts in Beishanzu. The climate in East China at 12,000 yr B.P. was probably only slightly cooler than the present, perhaps only 2°C cooler, as suggested by climate-model simulations (Winkler and Wang, in press).

11,000–10,800 yr B.P.

Sea level rose rapidly from −50 m to ca. −35 m in the millennium after 11,000 yr B.P. The occurrence of Gramineae- or Cyperaceae-like plant remains and freshwater shells, along with marine ostracods and benthic foraminifera at low diversity, between 36.7 and 43.5 m probably suggests that at 11,000–10,800 yr B.P. the coring site was situated in a brackish or freshwater environment with some marine influence, rather than in a truly marine environment.
Although planktonic individuals constitute a significant proportion of the overall foraminiferal assemblage in this section, it has been documented from modern Yangtze River sediments that planktonic foraminifera tests can be transported by tidal waters as far west as Nantong, about 150 km upstream from the river mouth, during high tides in the low-flow season (P. Wang et al., 1986). During this interval the coring site was probably a coastal or estuarine wetland subject to tidal influence, perhaps only several meters above sea level.

The pronounced increase in the pollen of Gramineae in Zone 1b, and to some extent Cyperaceae and freshwater aquatic plants, reflects the widespread development of coastal or estuarine marshes in the vicinity of Qidong. These vegetation changes were mainly a function of sea-level rise and not directly related to climate.

The slight increase in Betula, Ulmus, and Cupressaceae pollen at 11,000 yr B.P. probably reflects vegetation changes in the upland. This coincides in time with the onset of the Younger Dryas interval, an episode of cooler climate very well documented from sites on both sides of the North Atlantic Ocean (Wright, 1989) but not evidenced unequivocally from China (Liu, 1988) or Japan (Heusser and Morley, 1990) in the northwest Pacific. Climate-modeling experiments simulating the global impact of the Younger Dryas climatic oscillation suggest a winter temperature decrease of about 2°C in East China, while summer temperature and precipitation remained essentially unchanged (Rind et al., 1986). The increase in these deciduous trees and conifers at 11,000 yr B.P. could have been a response to slightly cooler winters or increased climatic perturbations during the Younger Dryas. Nevertheless, this interpretation remains speculative without corroborative data from this region.

10,800–8300 yr B.P.

The hiatus at 36.7 m depth coincides with a period of very rapid sea-level rise from ~50 m at 11,000 yr B.P. to ca. ~10 m at 8000 yr B.P., which initiated the marine transgression of the Yangtze River delta region (Yan and Hong, 1988). During this interval the coring site was probably part of a shallow coastal bay or lagoon–estuary system near the mouth of the Yangtze River. It is conceivable that sediments deposited in the early part of this interval were subsequently removed by wave action or longshore currents, or by erosion caused by channel shifts of the Yangtze River.

8300–3800 yr B.P.

Sedimentation resumed at the coring site after 8300 yr B.P. Initially the water at the site was shallow, as shown by layers of shell debris in the lower part of this sedimentary unit. Variations in lithology and shell content are a function of the location of the coring site in relation to coastal geomorphic changes brought about by marine transgression and subsequent regression and deltaic sedimentation. Maximum water depth at the site likely occurred between ca. 4500 and 3800 yr B.P. as suggested by the deposition of very fine silt and clay.

The decline in total pollen concentrations and in the frequencies of Gramineae pollen in Subzone 2a is consistent with sedimentary change indicating a shift from a terrestrial depositional environment to a shallow-water marine or prodeltaic environment (Wang et al., 1982). The increased frequencies of Cyclobalanopsis and Castanopsis pollen between 8300 and 3800 yr B.P. reflect an expansion of subtropical broadleaved evergreen forest elements relative to temperate deciduous hardwoods, probably in response to a Hypsithermal climate that was warmer and more humid than the present. Similar changes in the mid-Holocene have also been noted in other pollen records from the Yangtze River delta region (K. Wang et al., 1984, 1986).

3800 yr B.P.–Present

Sand deposition in the lower part of Subzone 2b reflects the progradation of the
Yangtze River deltaic front to the proximity of Qidong. The climate also became cooler during this period, resulting in a decrease in subtropical broadleaved evergreen trees and an increase in trees of wider tolerances such as the deciduous *Quercus* and *Pinus*. The land in the Qidong area formed within the last 200 yr. The increase in grass pollen and fern spores and the increase in total pollen concentrations reflect the change from a marine environment to a terrestrial depositional environment where a significant portion of the pollen is derived from the local vegetation. Much of the deltaic plain in Qidong today is covered by herbaceous vegetation or is under cultivation. Evidence of anthropogenic vegetation disturbance is lacking in the upper part of this pollen record, partly because the uppermost meter of the core was not sampled. But such evidence has not been clearly documented in the pollen records from eastern China (Liu, 1988).

**CONCLUSIONS**

The late-Quaternary environmental change in the Yangtze River delta is a function of the dynamic interaction between postglacial sea-level rise, deltaic development, and regional climatic and vegetation changes. The 52-m core from Qidong provides the most detailed and well-dated pollen and sedimentary record of these environmental changes from the Yangtze River delta for the last 12,000 years. Toward the end of the Pleistocene, the Qidong area was situated in the innermost part of the exposed continental shelf, far from the mouth of the Yangtze River. The physical landscape in the lowlands was probably a mosaic of forests, swamps, marshes, and lakes; in the uplands it was a mixed deciduous—broadleaved evergreen forest broadly similar to the one existing there today except having somewhat greater abundance of temperate and cool-tolerant trees like *Betula*, *Ulmus*, *Tsuga*, and Cupressaceae. On mountains bordering the Lower Yangtze River valley *Abies* and *Picea* probably existed in small and diminishing populations in an otherwise predominantly mixed forest consisting of both temperate and subtropical floristic elements. The climate from 12,000 to 11,000 yr B.P. was probably only slightly cooler than that of today.

By 11,000 to 10,800 yr B.P. rapidly rising sea level had submerged much of the once-exposed continental shelf. The Qidong area was changed to a coastal or estuarine wetland subject to tidal influence. For the next 2500 yr the transgressing sea encroached upon Qidong and the sediments were removed due to coastal erosion. After 8500 yr B.P. the coastline retreated west of Qidong, and marine sedimentation resumed at the coring site. The climate during the mid-Holocene was slightly warmer and more humid than at present, allowing more subtropical broadleaved evergreen trees to flourish on the upland forests on both sides of the wide Yangtze River estuary. Deltaic sedimentation began during the mid-Holocene, and the Yangtze River delta prograded southeastward by building successive estuarine sand bars during the last 6000 yr. The delta front did not reach Qidong until the late Holocene. The climate became cooler about after 3800 yr B.P., causing the subtropical broadleaved evergreen trees to decrease in abundance relative to *Quercus* and *Pinus*. The present deltaic plain was formed in Qidong during the last two centuries.

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