Incised-valley Sedimentary Succession and Evolution of the Nanjing Section of the Yangtze River since the LGM

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ABSTRACT


The incised valley at the Nanjing section of the Yangtze River contains a detailed sedimentary succession since the last glacial maximum (LGM). As stratigraphic and chronologic frameworks are not available for the Yangtze at the Nanjing section, five cross sections were constructed from 230 boreholes. Twenty-five radiocarbon and five ESR ages provided a detailed chronological framework. Based on analysis of lithology and sedimentary architecture, six deposition units were divided. The two main stages included the deep cutting stage from 23,000 to 15,000 cal yr BP and the lateral developing stage from 15,000 cal yr BP to the present. During the deep cutting stage, relative sea level change was the primary factor determining incised valley evolution. The great gradient provided a powerful hydrodynamic condition for paleo-channel cutting into the bedrock and large pebble gravel deposition. The faults and injection of the tributaries resulted in an incised depth deeper than the upstream and downstream. During the lateral developing stage, with the rapid rise of sea level and the moister and warmer climate, the incision power decreased and the channel broadened, resulting in a gradual reduction of sediment size.

ADDITIONAL INDEX WORDS: Yangtze River, Nanjing section, Last Glacial Maximum, incised valley, sedimentary sequence.

INTRODUCTION

The sedimentary characteristics of incised valley fillings contain the knowledge of climate change, sea level change, land sea interaction and sedimentary environment evolution in geological history (Li et al., 2002; Nian et al., 2018) which have been research hotspots for a number of years. Numerous studies have been conducted on changes in the sedimentary sequence of the incised valley in recent decades (e.g., Blum and Aslan, 2006; Eriksson et al., 2006; Lin, Zhuo, and Gao, 2003; Mattheus et al., 2007; Olszak, 2011; Sakai, Fujiwara, and Kamataki, 2006; Salcher and Wagreich, 2010; Schulte et al., 2008; Simon and Rinaldi, 2006; Talling, 1998; Vis, Kasse, and Vandenberghe, 2008; Xu, Lai, and Li, 2019). The Yangtze River is the largest river in the Asian monsoon region and the third longest river in the world (Liu et al., 2007; Wang et al., 2009). Some studies have examined the estuary to Zhenjiang section of the Yangtze delta region since the last glacial maximum (LGM) (Hori et al., 2001a, b; Hori et al., 2002a, b; Li et al., 2000; Li et al., 2002; Nian et al., 2018; Xu et al., 2016). However, few studies have been carried out on the upper segment of the lower Yangtze.

The Nanjing section of the lower Yangtze is presently located near the estuary. It has been assumed that the glacial palaeo-valley of the Yangtze at the Nanjing section was generally buried under loose sediments about tens of meters deep (Fang, 1991; Institute of Geography, CAS, and Yangtze River Institute of Water Resources and Hydro-Power Research, 1985; Yang, Xu, and Yang, 1995). However, the sedimentary sequence and evolutionary characteristics are not very clear, and direct chronological data are scarce. There are two main reasons for this: in the past few decades, not enough boreholes have been drilled in this region, and it is difficult to find materials suitable for dating from the gravel layer. With the demand for rapid economic development in recent years, the Nanjing section of the Yangtze has experienced a boom in bridge construction. In the building of the No. 1 Yangtze Bridge, the No. 2 Yangtze Bridge, the No. 3 Yangtze Bridge, the Yangtze Bridge for the Beijing-Shanghai high-speed railway, and the No. 4 Yangtze Bridge, a lot of boreholes were drilled, which presents a good opportunity for rebuilding the sedimentary sequences and evolution of the Nanjing section.

This paper aims to investigate the lithology, sedimentary architecture, and chronology of the incised valley of the Yangtze at the Nanjing section, and construct a stratigraphic-chronologic framework since the last glacial maximum (LGM). To achieve the objective, five incised valley cross sections were constructed from 230 drillings. Twenty-five 14C ages and five ESR ages provided the exact chronology for the incised valley.
STUDY SITES

The Yangtze originates from the Qinghai-Tibetan Plateau with a drainage area of $1.8 \times 10^6 \text{ km}^2$ and flows 6,300 km into the East China Sea. Because the Yangtze belongs to the monsoonal climate zone, the flood season from May to October has about 70% of the annual discharge and 87% of the annual sediment load (Shen, Zhang, and Mao, 2000). According to Datong Station, representing the lower reach of the Yangtze River, the average annual discharge is about $28,700 \text{ m}^3\text{s}^{-1}$, and the average annual flood and low discharge are respectively about $56,800 \text{ m}^3\text{s}^{-1}$ and $16,500 \text{ m}^3\text{s}^{-1}$. The Nanjing section of the Yangtze River is part of the near-mouth section, about 95 km long and about 350 km away from the Yangtze River estuary (Figure 1). It is mainly influenced by the upper fluvial runoff and a small irregular semidiurnal tide, which averages about 0.539 m, and in the dry season about 1.56 m (Zheng, Zhang, and Lei, 2007).

The strata system of the study area is developed relatively completely, and the geological formations are primarily Quaternary deposits (Table 1 and Figure 2). The incised valley of the Yangtze below the Zhenyang section during the LGM was 10-60 km wide and 60-90 m deep, and developed upon Quaternary sediments with a thickness of 100-450 m (Li et al., 2008), so the incised valley swings greatly, making it difficult to recover the shape and location of the palaeo-valley. In contrast, the Yangtze at the Nanjing section is located in the lower Nanjing-Wuhu fault zone of the Yangtze paraplatform. The river developed along the tectonic fault zone so that the swing of the channel was relatively small over the last 100,000 years (Yang, Han, and Yang, 1983). The regional geomorphology belongs to the alluvial plain of the Yangtze. On the north bank, there is an open alluvial flat composed of Holocene clay at an elevation of about 4 m. However, on the south bank dominated by mountains and terraces, the alluvial flat is not well developed (Figure 2).

MATERIAL AND METHODS

Geological boreholes were collected from the Yangtze at the Nanjing section and sorted out in a line of every cross section; 230 holes were selected for the restoration of the cross sections (Table 2).

For the 230 geological drillings, the distances and depths between cores were sorted, and the vertical and horizontal scales were determined. The elevation of every cross section was corrected to the national vertical datum from 1985, the Yellow Sea Datum. Then, the five stratigraphical cross sections of the Yangtze at the Nanjing section were constructed using CorelDRAW 12 software. From the upper to the lower, the cross sections were

Table 1. Simplified strata system of the study area (Yang, Han, and Yang, 1983).

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td></td>
</tr>
<tr>
<td>Quaternary (Q)</td>
<td>clay, mild clay, sand, gravelly sand and gravel.</td>
</tr>
<tr>
<td>Tertiary (N)</td>
<td>silty sand, fine sand, sand gravel; olivine basalt, tufaceous glutenite, fine sandstone, coarse sandstone, and tuff.</td>
</tr>
<tr>
<td>Cretaceous (K)</td>
<td>Silty sandstone and fine sandstone, mudstone; volcanic breccia, limestone-breccia, rock-fragment sandstone.</td>
</tr>
<tr>
<td>Jurassic (J)</td>
<td>volcanic rock system: sandstone, conglomerate, shale; quartzose conglomerate, silty sandstone, shale with coal.</td>
</tr>
<tr>
<td>Triassic (T)</td>
<td>Mudstone, marlstone, powder crystal limestone, pelsparite, calcilithite, gypsum karst breccia, silty sandstone, fine sandstone, thin coal seam.</td>
</tr>
<tr>
<td>Permian (P)</td>
<td>Limestone, siliceous shale, calcareous shale, silicalcite, sandstone, mudstone, coal seam.</td>
</tr>
<tr>
<td>Carboniferous (C)</td>
<td>Limestone, claystone, sand, sandstone, dolostone, coal seam.</td>
</tr>
<tr>
<td>Devonian (D)</td>
<td>Sandstone, conglomerate, mudstone, shale, claystone, thin coal seam.</td>
</tr>
<tr>
<td>Silurian (S)</td>
<td>Silty sandstone, fine sandstone, mudstone, argillaceous siltstone, siliceous shale.</td>
</tr>
<tr>
<td>Ordovician (O)</td>
<td>Gray dolomite, limestone, mudstone, claystone.</td>
</tr>
<tr>
<td>Cambrian (e)</td>
<td>Shale, silty sandstone, limestone, dolomite, marble.</td>
</tr>
<tr>
<td>Proterozoic</td>
<td></td>
</tr>
<tr>
<td>Sinian (Z)</td>
<td>dolomite</td>
</tr>
</tbody>
</table>
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A total of 30 samples from 10 drillings were used for dating. Among them, 25 samples were measured for 14C ages; 21 samples were tested at the Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences; two were tested at the Accelerator Mass Spectrometry Laboratory, Peking University, China; and two were measured at the State Key Laboratory of Western China’s Environmental Systems, Lanzhou University, China. The other five ESR ages were measured in the Institute of Geology, China Earthquake Administration. When the measured 14C ages were less than 15,000 years, CALIB 5.0.1 software (Stuiver, Reimer, and Reimer, 2005) was used for calendar age calibration. Ages greater than 15,000 years were not calibrated in this study. Calibrated ages in this paper are reported as calendar 14C ages before AD 1950 (cal yr BP), and uncalibrated ages are given as 14C years BP (14C yr BP). Because 14C and ESR ages put in a table are not easy to arrange, in Table 3 the ESR ages are given as cal yr BP, in fact they should be given as a.

Before the ESR measurements, each sample was separated into two portions in a red lamp room: one for extracting the quartz grains, and the other for measurement of water content. Particles 200-105 μm in size were separated by sieving. The size samples were soaked in 30% H2O2 for 24 hours to remove organic matter, in 40% HCl for 24 hours to remove carbonate material, and in 40% HF for 40 minutes to remove feldspar, then cleaned to neutral with distilled water and dried at a low temperature (Liu and Liu, 2010). Magnetism separation was used for the pure quartz. Each pure quartz sample was divided into 10 parts weighing 0.2 g, and then received a regeneration dose of 0-10000 Gy at Peking University.

A total of 4,000 sediment size analyses were collected from the Yangtze incised valley at the Nanjing section. Based on the collected data, two additional cores, NJ01-1 and NJ05-1, were drilled on November 2009 to further reveal the sedimentary characteristics of the Yangtze incised valley (Figure 3 and Figure 7). Samples 2-4 cm thick were taken, generally at 10 cm to 1 m intervals, for grain size analysis. The sediment size of the whole drilling profile changed greatly. The lower part was gravel and coarse sand, and the upper part was silty clay, silt, and fine sand. A total of 180 samples were measured by both sieve and laser particle size analyzer (Mastersizer2000, Malvern Instruments, Ltd., UK) methods. Grain size parameters were calculated following Folk and Ward (1957).

RESULTS

Based on lithology, sedimentary architecture, grain size parameters (Figure 9a-b), and radiocarbon and ESR ages, the stratigraphic cross section of the incised valley can be divided from the bottom up into the following units.

Deposition Unit 1 (DU1)

Deposition unit 1 was deeply incised into the bedrock; the channel shapes were kept almost intact and were quite narrow compared with the present. The deep incised valley was all located on the left of the present riverbed. The channel near the NJ01 cross section was braided from right to left at about -79.5 m, -75 m, and -73 m, cutting into the bedrock (Figure 3). Seen from the NJ02 cross section, the deep incised valley cut into bedrock at about -80.5 m. The top width was around 515.3 m; the depth was around 28 m (Figure 4). Near the NJ03 cross section, the deep incision valley cut into bedrock at about -93.5 m. The top width was around 325 m; the depth was around 30 m (Figure 5). Because the drilling in the NJ04 cross section was not deep enough to reach the bedrock, the shape of the palaeo-valley was not completely recovered. However, it could be inferred that the incision was at least -95 m cutting into bedrock. The top width was around 325 m; the depth was around 30 m (Figure 6). The NJ05 cross section, the deep incised valley cut into bedrock at about -93.5 m. The top width was around 325 m; the depth was around 30 m (Figure 7). Because the drilling in the NJ04 cross section was not deep enough to reach the bedrock, the shape of the palaeo-valley was not completely recovered. However, it could be inferred that the incision was at least -95 m cutting into bedrock. The top width was around 325 m; the depth was around 30 m (Figure 6). Near the NJ05 cross section that reached the bedrock, the top width and depth were -100 m, 925 m, and 30 m respectively (Figure 7).

In DU1, at the bottom, the sediments were mainly saturated, dense, light gray pebble gravel mixed with middle and coarse sand. The pebble material was mainly subrounded, accounting
Figure 3. The NJ01 stratigraphical cross-section of the incised valley at Nanjing section of the Yangtze.

Figure 4. The NJ02 stratigraphical cross-section of the incised valley at Nanjing section of the Yangtze.

Figure 5. The NJ03 stratigraphical cross-section of the incised valley at Nanjing section of the Yangtze.
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for about 20-60% of the bulk sediment; the pebble diameters were usually 20-60 mm, with a maximum of 100 mm. The main components of these pebbles were quartzite and quartz sandstone. In the upper part, poor-sorting, saturated, dense, steel-gray middle and coarse sand with gravel were prevalent, which were floodplain-deposited in this period. The average sizes were 2.24-3.97 φ, with poor sorting performance and positive skewness (Figure 9). The cumulative grain size distribution curves were mainly four-section type (Figure 10). Because not enough boreholes and dating materials were obtained in the gravel layer, chronological data were scarce in the past research. Based on the sampling of several boreholes, the \(^{14}\)C dating samples obtained in this paper were mainly concentrated at -60 m and above, and the formation age of sedimentary sequences above -60 m could be clearly determined (Schneider and Takeshi, 2018). However, only one \(^{14}\)C chronological data (23520 ± 150 cal a BP) was obtained at -72 m. In order to establish a more accurate stratigraphic age, five samples were collected at the paleo Valley -71 ~ -88 m for ESR dating. The results are 16,000 ± 1000 a (NJSQR02), 21,000 ± 2000 a (NJSQR05), 23,000 ± 2000 a (NJSQR04) and 26,000 ± 2000 a (NJSQR06) (Table 3 and Figure 8). According to the results, it can be concluded that the lowest part of the paleo valley formed in the LGM.

**Deposition Unit 2 (DU2)**

In DU2, sediment sizes changed from gravel sand to fine sand, that is, from riverbed facies to floodplain facies. The bottom part was mainly grey gravel sand that average size value was -1.09 φ, with poor sorting performance and with positive skewness (Figure 9). The middle part was mainly grey medium sand. The average size value was 1.82 φ in the middle part, with poor sorting performance and with negative skewness (Figure 9). The average size value was 3.36 φ with poor sorting performance in the upper part (Figure 9).

Two radiocarbon ages of 15,893 ± 150 cal yr BP (NJSQ39) and 15,960 ± 160 cal yr BP (NJSQ40) in the NJ05 cross section were obtained (Table 3 and Figure 8). According to Yang (1995) and Zhu (1984), the formation time of the terrace near the Nanjing Yangtze River Bridge was about 14,227 ± 978 cal yr BP or 14,438±2044 cal yr BP at about -60 m. According to the Yang and

Figure 6. The NJ04 stratigraphical cross-section of the incised valley at Nanjing section of the Yangtze.

Figure 7. The NJ05 stratigraphical cross-section of the incised valley at Nanjing section of the Yangtze.
Table 3. Radiocarbon and ESR ages from incised valley sediments.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Lab No</th>
<th>Altitude (m)</th>
<th>Material</th>
<th>Lithology</th>
<th>$^{14}$C age/yr BP</th>
<th>Calibrated Age / Cal yr BP</th>
<th>Probability</th>
<th>Dating Way</th>
</tr>
</thead>
<tbody>
<tr>
<td>NJ05-1</td>
<td>NJ07</td>
<td>-58.33</td>
<td>peat</td>
<td>gravelly sand</td>
<td>14682±110</td>
<td>17628±518</td>
<td>0.98</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ20</td>
<td>-23.71</td>
<td>plant fragment</td>
<td>silty fine sand</td>
<td>2700±65</td>
<td>2843±109</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ21</td>
<td>-30.55</td>
<td>plant fragment</td>
<td>silty fine sand</td>
<td>3810±50</td>
<td>4246±163</td>
<td>0.99</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ23</td>
<td>-45.72</td>
<td>plant fragment</td>
<td>silty fine sand</td>
<td>8150±90</td>
<td>9094±273</td>
<td>0.92</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQK02</td>
<td>-83.47</td>
<td>quartz</td>
<td>coarse fine sand</td>
<td>16000±1000</td>
<td></td>
<td></td>
<td>ESR</td>
</tr>
<tr>
<td></td>
<td>NJSQ29</td>
<td>-37.07</td>
<td>plant fragment</td>
<td>silty fine sand</td>
<td>5253±50</td>
<td>6024±105</td>
<td>0.86</td>
<td>$^{14}$C</td>
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<td>NJ05-6</td>
<td>NJSQ03</td>
<td>-86.77</td>
<td>quartz</td>
<td>medium sand</td>
<td>23000±2000</td>
<td></td>
<td></td>
<td>ESR</td>
</tr>
<tr>
<td></td>
<td>NJSQ04</td>
<td>-87.71</td>
<td>quartz</td>
<td>medium sand</td>
<td>24000±2000</td>
<td></td>
<td></td>
<td>ESR</td>
</tr>
<tr>
<td></td>
<td>NJSQ31</td>
<td>-21.96</td>
<td>organic clay</td>
<td>silty fine sand</td>
<td>6010±80</td>
<td>6845±182</td>
<td>0.96</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ33</td>
<td>-71.95</td>
<td>organic clay</td>
<td>fine sand</td>
<td>23520±150</td>
<td></td>
<td></td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ05</td>
<td>-74.76</td>
<td>quartz</td>
<td>coarse sand</td>
<td>21000±2000</td>
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<td></td>
<td>ESR</td>
</tr>
<tr>
<td></td>
<td>NJSQ06</td>
<td>-77.26</td>
<td>quartz</td>
<td>medium sand</td>
<td>26000±2000</td>
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<td>NJSQ34</td>
<td>-35.58</td>
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<td>7011±60</td>
<td>7828±123</td>
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<tr>
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<td>NJSQ37</td>
<td>-53.95</td>
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<td>12058±347</td>
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<tr>
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<td>NJSQ40</td>
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<td>gravelly sand</td>
<td>15960±160</td>
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<td>$^{14}$C</td>
</tr>
<tr>
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<td>NJ03</td>
<td>-28.46</td>
<td>organic clay</td>
<td>clay</td>
<td>8748±114</td>
<td>9755±215</td>
<td>0.80</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJ04</td>
<td>-38.50</td>
<td>organic clay</td>
<td>silty fine sand</td>
<td>9616±107</td>
<td>10947±276</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJ05</td>
<td>-40.46</td>
<td>organic clay</td>
<td>clay</td>
<td>13287±161</td>
<td>15769±544</td>
<td>1</td>
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<tr>
<td></td>
<td>NJSQ08</td>
<td>-24.75</td>
<td>organic clay</td>
<td>clay</td>
<td>4750±35</td>
<td>5518±68</td>
<td>0.83</td>
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<tr>
<td></td>
<td>NJSQ14</td>
<td>-53.90</td>
<td>organic clay</td>
<td>clay</td>
<td>11515±45</td>
<td>13352±94</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ03</td>
<td>-40.20</td>
<td>organic clay</td>
<td>silty fine sand</td>
<td>10822±240</td>
<td>12653±561</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ04</td>
<td>-51.40</td>
<td>organic clay</td>
<td>clay</td>
<td>11305±130</td>
<td>13169±230</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ05</td>
<td>-39.10</td>
<td>organic clay</td>
<td>silty fine sand</td>
<td>8984±65</td>
<td>10078±166</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td></td>
<td>NJSQ06</td>
<td>-37.50</td>
<td>organic clay</td>
<td>clay</td>
<td>10845±250</td>
<td>12667±578</td>
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<tr>
<td></td>
<td>SQ1-12</td>
<td>-17.2</td>
<td>plant fragment</td>
<td>fine sand</td>
<td>3470±179</td>
<td>3792±450</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
<tr>
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<td>SQ1-25</td>
<td>-44</td>
<td>plant fragment</td>
<td>medium sand</td>
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<td>12085±810</td>
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<td>plant fragment</td>
<td>medium sand</td>
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<td>11222±855</td>
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<td>medium sand</td>
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<td>6915±422</td>
<td>0.97</td>
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</tr>
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<td></td>
<td>SQ2-28</td>
<td>-47.7</td>
<td>plant fragment</td>
<td>silty fine sand</td>
<td>11147±453</td>
<td>12891±1123</td>
<td>1</td>
<td>$^{14}$C</td>
</tr>
</tbody>
</table>

Figure 8. The stratigraphic chronology of the incised valley at Nanjing section of the Yangtze.
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Zhu results of the chronological data and the chronological data in the NJ05 cross section, the formation time of this layer was from 18,000 to 15,000 cal yr BP that was equivalent to the later LGM.

Deposition Unit 3 (DU3)

In DU3, the sedimentation were gravel sand - coarse sand (or medium sand) - fine sand from the bottom to the top which reflected the sedimentary evolution from riverbed facies to floodplain facies. The lower part was composed of saturated, dense, gray gravel sand with poor sorting, mixing with a small amount of pebble gravel at grain sizes of 30-50 mm (Figure 9). Compared with the previous sedimentation, the sediment size became smaller and the power of sedimentation was weakened (Figures 3-7).

Eight $^{14}$C ages of 12,058 ± 347 cal yr BP (NJSQ37), 13,352 ± 94 cal yr BP (NJSQ14), 10,947 ± 276 cal yr BP (NJ04), 12,653 ± 561 cal yr BP (NJSQ03), 12,667 ± 561 cal yr BP (NJ03), 12,058 ± 981 cal yr BP (SQ1-25), 11,222 ± 855 cal yr BP (SQ1-28), and 13,135 ± 489 cal yr BP (SQ2-28) were obtained from plant fragments (Table 3 and Figure 8). According to the eight chronological data in the NJ05 cross section, the formation time of this layer was from 15,000 to 12,000 cal yr BP that was equivalent to the late glaciation.

Deposition Unit 4 (DU4)

At about -40 ~ -32 m in the lower layer of DU4, saturated, medium dense, gray medium sand predominated. The main composition was quartz, feldspar with a small amount of mica, and even gravel. Saturated, slightly dense, well sorting, gray fine sand was prevalent at the top, which also contained mica and shell debris. The average particle size of the lower part was 1.48 φ (Dai, Yin, and Bai, 2018). The sorting property was poor and the skewness was normal deviation. The upper part was gray fine sand and the average particle size was 3.51 φ (Figure 9). At the NJ01 cross section, a pottery fragment was obtained at about -35 m (Figure 3).

Four $^{14}$C ages of 6,845 ± 182 cal yr BP (NJSQ31), 7,828 ± 123 cal yr BP (NJSQ34), 9,094 ± 273 cal yr BP (NJSQ23), and 9,755 ± 215 cal yr BP (NJ03) were obtained (Table 3 and Figure 7). According to the four chronological data, the formation time of this layer was from 12,000 to 7,000 cal yr BP that was equivalent to the period from the early Holocene to the middle Holocene.

Deposition Unit 5 (DU5)

DU5 was characterized by saturated, medium dense, gray fine sand composed of quartz, feldspar, and a little mica at the bottom. The average size value was 3.62 φ in the lower part of -22.66 ~ -10.93 m, with poor sorting performance and positive skewness. The average size value was 5.04 φ in the middle and lower part of -10.93 ~ -3.3 m, with poor sorting performance. Its skewness was negative and its lithology was silty sand (Figure 9).

Three $^{14}$C ages of 3,792 ± 450 cal yr BP (SQ1-12), 4,246 ± 163 cal yr BP (NJSQ21), and 5,518 ± 61 cal yr BP (NJSQ08) were obtained (Table 3 and Figure 8). According to the three chronological data, the formation time of this layer was from 7,000 to 4,000 that was equivalent to the middle Holocene.

Deposition Unit 6 (DU6)

Saturated, loose, well sorting, gray silt dominated the lower part of DU6, with mica pieces and a thin layer of silty clay. At the bottom (-3.3 ~ 2.2 m), it mainly contained flowing, plastic
silty clay and the average size value was 5.36 φ, with good sorting performance. Soft, plastic, grayish yellow silty clay or clay appeared in the upper part of DU6, which contained iron and manganese spots. The uppermost part of DU6 had plant roots (Figures 2-6). The average size value was 6.39 φ in the upper part of 2.2 ~ 4 m, with good sorting performance (Figure 9). Based on the chorological data, DU6 has formed since 4,000 cal yr BP (Table 3 and Figure 8) that was equivalent to the late Holocene.

DISCUSSION

Deep Cutting Stage

At about 23,000 ~ 18,000 cal yr BP, the period of lowest sea level in the LGM, the sea level was about 130 m lower than today (Hori et al., 2001a; Kurt, 1990; Yang, 1987), and the coastline of the East China Sea was located 550 km seaward from the present shoreline (Zhu et al., 1979). Based on pollen analysis of the East China Sea continental shelf, research has demonstrated that Artemisia-dominated grassland must have covered the continental shelf and the above areas during the LGM, reflecting the colder and drier climate (Chen et al., 2006; Xu et al., 2009; Xu et al., 2010). The distance between NJ01 and NJ05 was about 45 km, and difference of elevation was about 20 m so the longitudinal gradient at the Nanjing section was about 4.5 × 10⁻⁴ in the LGM, however, at present it’s about 0.097 × 10⁻⁴ (Yu and Lu, 2005). Thus, although the climate was colder and drier in the LGM, the larger gradient provided a strong hydrodynamic condition, resulting in the channel deeply cutting into the bedrock and transporting large amounts of pebble gravel for a long distance to be deposited in the channel.

In the LGM, the bottom of the palaeo-valley in the Caoguzhou-Wuhu section of the Yangtze was at about -55 m (Yang, Xu, and Yang, 1995), and in the Zhenjiang section it was at about -84.8 m (Cao, Wang, and Qu, 2007; Li and Wang, 1998; Li and Zhang, 1995). However, it was at -80 ~ -100 m at the Nanjing section, which cut into the bedrock deeper than the upstream and downstream. The situation is similar in the present Yangtze (Institute of Geography, CAS, Yangtze River Institute of Water Resources and Hydro-Power Research, 1985; Yu and Lu, 2005). The results may be due to the effects of faults and tributaries (Lin et al., 2020). The Nanjing section is located in the lower Nanjing-Wuhu fault zone of the Yangtze paraplatform and develops along the fault zone. The channel was predominantly controlled by the bedrock, so that lateral development and deep incision were difficult. In the LGM, the ancient Qinhuai River in the south of the NJ03 cross section dismembered into the Yangtze, and the valley incised at a depth of -20 ~ -30 m (Jiang et al., 1986). Figure 7 shows that the NJ05 cross section sediments at the bottom of the palaeochannel were mainly composed of coarse and medium sand, but at the left they were gravel-mixed clay with poor sorting. Based on detailed analysis of the drilling profile, lithology, and sedimentary structure and the location of the modern Chu River, this part of the sediment seems to have come from the Chu River, a tributary of the Yangtze (Figure 2), with a fall of 40 ~ 50 m. The larger pebble gravel carried by tributaries indicates that strong erosion might be the main channel for the tributary to inject solids into the Yangtze.

In the late period of the LGM, at 18,000 ~ 15,000 cal yr BP, the sea level rose rapidly from -130 m to about -80 m (Hori et al., 2001a; Hanebuth, Stattegger, and Grootes, 2000). As seen in DU2 from Figures 2-6, the palaeo-valley during this period was a little wider than it was at the peak of the LGM. The roundness and sorting of sediment in this period were poorer than at the peak of the LGM, suggesting that its transporting distance and separating time were not the same. The pollen found from this period was also mainly herb pollen, but in some areas, spruce and fir pollen accounted for 10-40% of the total. This reflects the cold and wet environment, in which there was probably more precipitation than there was from 23,000 ~ 18,000 cal yr BP (Xu et al., 1977). Although the sea level rose, the incision capacity was a little weaker than it was from 23,000 ~ 18,000 cal yr BP, indicating some extent of increased precipitation and lowered sea level. The river still had a strong capacity for incision and transportation.

When the sea level reached its lowest point, below the Zhenyang section the Yangtze channel formed a huge downcut valley with a thin layer of lag deposits mainly consisting of sand with gravel (Li et al., 2000). Gravel 0.3-0.5 cm in diameter accounted for less than 10% of the sediment (Li et al., 2002). No layered lag deposits with significant thickness were identified there (Li et al., 2000), so in the previous studies the sedimentary succession of the incised channel of the Yangtze in the LGM was neglected. In contrast, the sedimentary characteristics at the Nanjing section show the complete sedimentary succession.

Lateral Developing Stage

During the period from 15,000 ~ 12,000 cal yr BP, the sea level continued to rise rapidly, from -80 m to -50 m (Hori et al., 2001a; Lin, Zhuo, and Gao, 2005). According to the pollen study, Pinus pollen in this period increased and herbaceous pollen decreased, suggesting a growing trend in both temperature and precipitation (Xu et al., 2009; Xu et al., 2010), followed by discharge increase. The hydrodynamic must have been very strong due to the relative low sea level and large discharge. Subrounded and subangular gravel sand with poor sorting was deposited in DU3, which may suggest that the sediment was transported over a relatively short distance (Li, Cheng, and Gu, 2019). The Yangtze had shifted from the main deep incised erosion to lateral erosion.

The final rise in sea level occurred from 12,000 ~ 7,000 cal yr BP. Around 7,000 cal yr BP, sea level had reached its peak, and the Yangtze estuary moved to the Yangzhou-Zhenjiang area (Chen, Li, and Ye, 1995; Li and Wang, 1998). The fine silt couplets and shell debris found in DU4 indicate that the tides influenced the sediments (Hori et al., 2001a). Figures 3-7 show that the lateral erosion in this period was strong and the channel was very wide. From 7,000 ~ 4,000 cal yr BP, the sea level was relative stable. DU5 contains a large amount of fine sand and humus, and the channel is wider than in DU4 (Figures 3-7). From 5,000 ~ 4,000 a BP, flooding prevailed in eastern China, and the water level in the Yangtze gradually rose with widened and swinging channels (Yang, Xu, and Yang, 1995). For the period from 4,000 cal yr BP ~ present, DU6 is characterized by sediments such as silt and silty clay. The modern Yangtze has gradually shifted to the right and left a wide floodplain on its left bank.

CONCLUSIONS

A direct and well constrained chronology was built using 14C and five ESR ages. Based on the analysis of the stratigraphic sequence, six deposition units were identified: DU1: 23,000 ~ 18,000 a BP, DU2: 18,000 ~ 15,000 cal yr BP, DU3: 15,000 ~ 12,000 cal yr BP, DU4: 12,000 ~ 7,000 cal yr BP, DU5: 7,000 ~ 4,000 cal yr BP, and DU6: 4,000 cal yr BP ~ present.
From 23,000 ~ 15,000 cal yr BP, the evolution of the incised valley was closely linked to sea level change, local geological features, and tributaries. At low sea levels, the incised erosion dominated the shape of the channel. Under dry and cold climate conditions, the great gradient of $4.5 \times 10^4$ provided a powerful hydrodynamic condition so that the river cut deeply into the bedrock and large pebble gravels were deposited in the palaeo-valley. In addition, the Yangtze is developed along faults and controlled by bedrock, together with its tributaries, resulting in deeper incision in the palaeo-valley than upstream and downstream. After 15,000 cal yr BP, the sea level rose rapidly, and the Yangtze shifted from deep incised erosion to lateral erosion. With the moister and warmer climate, the palaeo-valley has been constantly broadened and the channel swing has been relatively large.

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