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Sedimentary Sequence and Age of Core NTCJ1 in the Sheyang Estuary, Western South Yellow Sea: A Re-Interpretation

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Abstract: The Sheyang estuary is located on the northern Jiangsu muddy coast, in the western South Yellow Sea, and in the transition area between the eroded coast of the abandoned Yellow River delta and the silted coast of the central Jiangsu. This area is also one of the key areas of interactions between the paleo-Yellow River and paleo-Changjiang River during the late Quaternary. In order to investigate deeply the late Quaternary sedimentary sequence models of coasts and continental shelves under the interactions of the above two large rivers, the sedimentary sequence and age of the core NTCJ1 drilled at the Sheyang estuary were re-examined and re-interpreted recently, based on the existing data on lithology, grain size, ostracods, foraminifera, clay minerals, geochemical elements, and Electron Spin Resonance (ESR) dating, together with other adjacent key cores and shallow seismic profiles. The three new perspectives were summarized as follows: Firstly, the 22.00 m-long core NTCJ1 recorded the evolution of the sedimentary environments since Marine Isotope Stage 5 (MIS 5), and the first continental facies layer formed in MIS 4-2 is supposed to be missing; therefore, the MIS 1 marine facies layer directly overlays on the MIS 5 marine facies layer. Furthermore, the second continental facies layer formed in MIS 6 and/or the stage of the relatively low sea-level of MIS 5 has not been drilled yet. Secondarily, the middle-upper part of the NTCJ1 core sediments (0.00–17.95 m) are characterized by a finer grain, with a predominantly silty texture and dark yellow tone, and from bottom to top it shows a change from fine to coarse and then to fine in grain size, which could be substantially interpreted as the abandoned Yellow River deltaic deposits mainly formed in 1128–1855 CE, and may contain a small amount of Holocene coastal-shallow marine deposits at the bottom; however, it is difficult to identify them currently. Thirdly, the lower part of the NTCJ1 core sediments (17.95–22.00 m) have not yet been drilled through and are characterized by a coarser grain, with a predominantly fine sandy texture and dark grey tone, which could be interpreted as a delta front deposit in the MIS 5 tidal estuary and were obviously influenced by the paleo-Yellow River.

Keywords: South Yellow Sea; middle Jiangsu coast; Sheyang estuary; paleo-Yellow River; late Quaternary; sedimentary sequence

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1. Introduction

The Earth's coasts and continental shelves are highly susceptible and sensitive to global changes and human activities, meanwhile, both are a repository of information and an important contributor with regard to past and present global changes [1]. In the context of the global changes during the Quaternary period, coastal and continental shelf environments have undergone different system responses and state transitions during their evolutionary history [1]. Moreover, the sedimentary record analysis that could provide fundamental data for comparing the sedimentary systems formed during different periods is an important method and tool for studying the above system responses and state transitions. It could facilitate the analysis of the processes and mechanisms of system evolution and to clarify the complex relationships between global changes and coastal-continental shelf sedimentary systems [1,2].

Since the late Quaternary, the evolution of the landforms and sedimentary environments of China's coasts and continental shelves has been controlled by complex land–sea interactions under the glacial-eustatic cycles [3]. Meanwhile, the interactions between rivers and coastal-continental shelves are extensive and strong, especially for large rivers such as the Yellow River and Changjiang River. The products, processes, and mechanisms of interactions between large rivers and coastal-continental shelves should be an important part of the study of the land–sea interactions in China [4]. The sedimentary systems formed by the interactions of large rivers with coasts and continental shelves contain a wealth of information on global changes; therefore, they are important research carriers for reconstructing sea-level changes and the evolutions of coastal landforms in the estuaries of large rivers, and estimating the fluxes and fates of sediments from large rivers into the sea [4]. Both the Yellow River and Changjiang River have flowed into the South Yellow Sea through the central Jiangsu coast since the late Quaternary, and the river–sea interactions have resulted in a series of deposits, including the Radial Sand Ridge Field (RSRF) off the middle Jiangsu coast formed after the Holocene transgression [4] (Figure 1). Therefore, the central Jiangsu coast and RSRF are ideal areas for studying the sedimentary sequence models of coasts and continental shelves under the interactions of different large rivers in the late Quaternary. Furthermore, they are also important carriers for studying the late Quaternary sea-level changes in the Yellow Sea, the coastal geomorphic evolutions of the paleo-Changjiang and paleo-Yellow River estuaries, and the fluxes and fates of sediments from these two paleo-rivers into the sea.

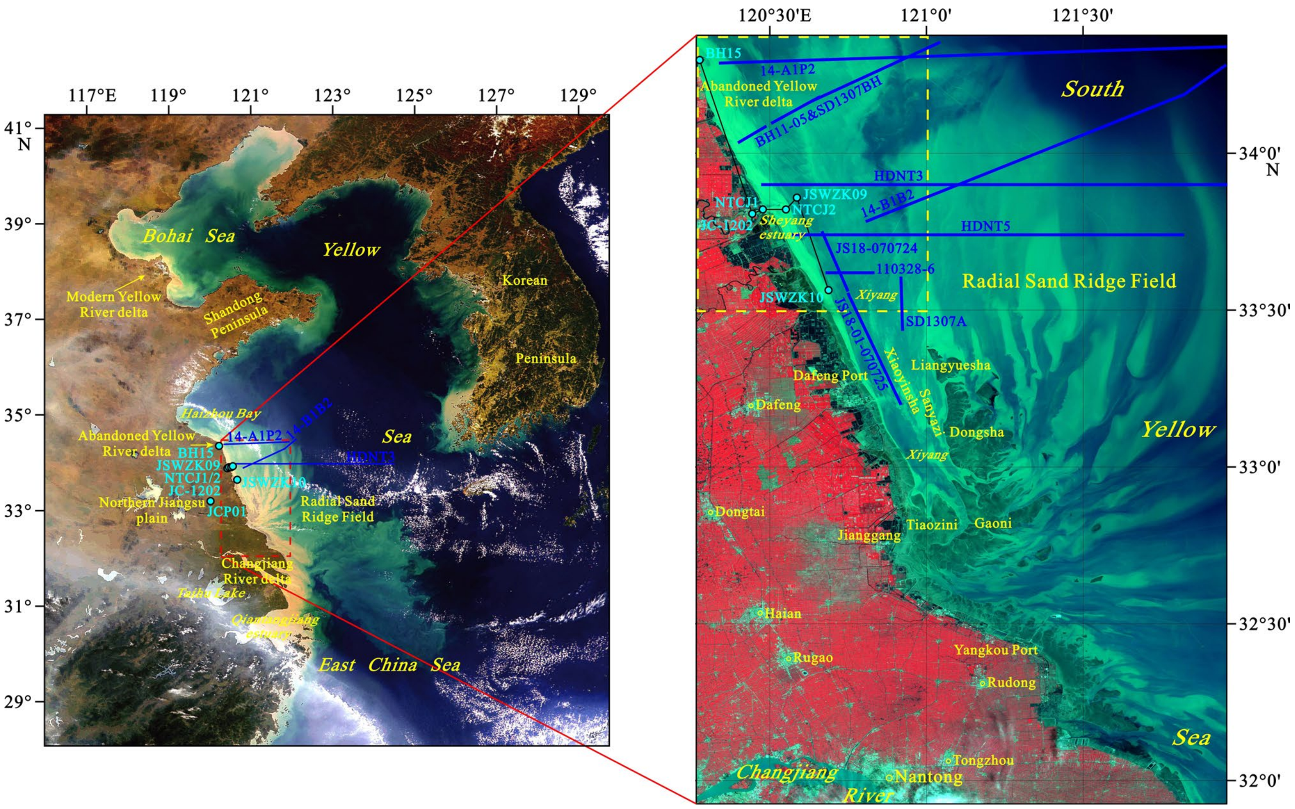

Figure 1. Remote sensing imageries of the Sheyang estuary in northern Jiangsu, western South Yellow Sea and its adjacent regions and locations of sedimentary cores and track lines of shallow seismic profiles mainly studied in this paper; the blue line segments show the track lines of shallow seismic profiles; the cyan round dots show the locations of sedimentary cores.

The Sheyang estuary is located in the northern end of the transition zone between the northern abandoned Yellow River delta and southern modern Changjiang River delta (Figure 1). Therefore, it becomes an important window area to reveal the sedimentary sequence model formed in the coasts and continental shelves under the active interactions between the Yellow River and Changjiang River during the late Quaternary. Hence, the comprehensive and in-depth research on the sedimentary sequence and geochronological framework during the late Quaternary in the Sheyang estuary area will be an important basis for the establishment of the above-mentioned model. In addition, according to the coastal development plan of Jiangsu Province, the Sheyang Port with a 35,000-ton channel and wharf is now constructing a 50,000-ton channel and wharf, and is meanwhile carrying out the preliminary demonstration for a 100,000-ton port (according to the official website's information, [5]). Therefore, the in-depth investigation of the late Quaternary sedimentary sequence of the Sheyang estuary and its evolution can provide an important scientific basis for the expansion and sustainable high-quality development of Sheyang Port in the future.

Judging from the published literature on the Sheyang estuary area, the research on the sedimentary sequence and geochronological framework during the late Quaternary are primarily based on sedimentary cores and shallow seismic profiles. In addition, the integrated studies on sedimentology and various dating research were often combined. The representative research works are as follows: between 1980 and 1984, the investigators of "the Comprehensive Investigation on Coastal Zones and Resources of Tidal Flats in Jiangsu Province" plotted the profile maps and synthesized columnar sections of Quaternary geology in the middle Jiangsu coast based on the available hydrogeological cores. However, these plots only show sketchy information of the sedimentary sequence and age in the Sheyang estuary area, meanwhile, they indicate that the thickness of Holocene strata is more than 30 m [6–8]. In the late 1980s and early 1990s, in order to support the expansion and normal operations of the Sheyang Port, the investigators drilled and analyzed a series of engineering geological cores in the Sheyang estuary. Additionally, these new data revealed more detailed information on the shallow sedimentary sequence and age in the Sheyang estuary area except for the absolute dates. These results show that the thickness of Holocene strata in the Sheyang estuarine delta is ca. 15–19 m, and the terrigenous stiff mud layer formed in the late Pleistocene could be found in the elevation of ca. -29 m [9]. Between 2000 and 2007, the investigators of "the Marine Areal Geological Survey of Nantong Sheet in the Scale of One-Millionth" collected and analyzed two cores (NTCJ1 and NTCJ2) and two sections of shallow seismic profiles (HDNT3 and HDNT5) in the Sheyang estuary area (see Figure 1 for the locations of cores and track lines) [10–13]. The original researchers provided a large amount of basic geological data for the study of the sedimentary characteristics and environmental evolution of the Sheyang estuary during the late Quaternary, via geological logging and laboratory analyses of grain size, geochemical elements, and minerals, micropaleontology, and Electron Spin Resonance (ESR) dating of the two cores. Meanwhile, the original researchers differentiated the main sedimentary sections based primarily on the analysis results of lithology, grain size, ostracods, and foraminifera of these two cores [13]. Based on the correlations of sporopollen assemblages of these two cores with the results of previous studies, they also concluded that the strata revealed by core NTCJ1 and NTCJ2 (with a thickness of 22.00 m and 20.60 m, respectively) are both Holocene deposits [13]. It was further concluded that due to the erosion, transportation, and redeposition of some local and adjacent older seafloor sediments by waves and tides, the Holocene strata of the Sheyang estuary were mixed with these older sediments, resulting in the presence of many fossils that were not consistent with the prevailing environments [13]. Consequently, the ESR dates from three quartz sand samples at the base of these two cores are inevitably and significantly older than the real ages, thus cannot be used as evidence for age determination [13]. Between 2004 and 2011, the investigators of "Chinese Offshore Investigation and Assessment" acquired and interpreted a series of high-resolution shallow seismic profiles in the western South Yellow Sea and some track lines that were located in the Sheyang estuary area. The interpretation results of these shallow seismic profiles suggests that two main seismic bounding surfaces (S1 and TS) could be identified, and S1 indicates the bottom boundary of the modern delta while TS indicates the post glacial transgressive surface. Therefore, the bottom boundary elevation of the Holocene strata is ca. −30 m (Two Way Travel Time: ca. 40 ms) [14,15]. Between 2006 and 2010, the investigators of "the Investigation and Assessment of Environmental Geology in the Sandy and Muddy Coastal Area, North of the Changjiang Estuary" also collected and analyzed a large amount of high-resolution shallow seismic profiles in the western South Yellow Sea including the Sheyang estuary area. Based on these seismic data and four key cores, they mapped the Marine Isotope Stage 3 (MIS 3) delta distribution and shallowly buried dendritic drainage systems in the western South Yellow Sea. Meanwhile, these maps show that the elevation of the top surface of the MIS 3 delta in the Sheyang estuary area is ca. −20 m [16]. Between 2012 and 2015, the investigators of "the Investigation and Monitor of Integrated Coastal Geology in the Changjiang River Delta" drilled and analyzed a sedimentary core (JC-1202) with a length of 79.75 m in the Sheyang estuary (see Figure 1 for the core location). They finished the differentiation of sedimentary units and chronostratigraphic sequence, and the results show that the thickness of the Holocene strata is 17 m, moreover, the Holocene deposits are almost derived from the abandoned Yellow River (1128–1855 CE). Additionally, beneath the Holocene strata, the MIS 3 deltaic deposits could be identified with a burial depth of 17.00–31.60 m [17]. Between 2018 and 2019, He et al. drilled and analyzed a series of sedimentary cores in the middle Jiangsu coast including the Sheyang estuary area, aiming to reconstruct the detailed stratigraphic architecture from the coastal plain to the sand ridge region and examine its evolution since the late Pleistocene [18]. The analysis results of the relevant cores (JSWZK 09 and JSWZK 10, see Figure 1 for the locations of cores) could provide more detailed information on the sedimentary sequence and age in the Sheyang estuary. Meanwhile, the results show that the bottom boundary elevation of the Holocene strata is ca. −18 m and the sediments derived from the abandoned Yellow River (1128–1855 CE) dominate the Holocene deposits. Additionally, beneath the Holocene strata, the MIS 2 flood plain and MIS 3 deltaic deposits could also be identified [18].

By means of the above review of the representative research, we could find that the sedimentary sequence and geochronological framework during the late Quaternary in the Sheyang estuary area are not well-established and there are obvious divergences on the geochronological framework. In the meantime, the insufficient correlations of the sedimentary cores in the land and sea, together with the absence of correlations between the sedimentary cores and shallow seismic profiles have constrained the comprehensive and in-depth understanding of the shallow sedimentary sequence model. For this reason, when we tried to carry out the above-mentioned correlations, some contradictions between core NTCJ1/NTCJ2 and other adjacent cores or shallow seismic profiles were observed. Additionally, in the absence of more dates and based on the correlations of sporopollen assemblages alone, it is clearly insufficient and unconvincing to conclude the ages of sedimentation. At the same time, the sedimentary sections differentiated for the two cores are relatively sketchy, just involve the facies of coastal, neritic, estuarine, continental etc, and need to be further investigated to meet the needs of other related studies. Consequently, it is necessary to re-examine and re-interpret these two cores for further study on the shallow sedimentary sequence model of the Sheyang estuary. Considering the similar stratigraphic sequences of these two cores and the higher recovery ratio of core NTCJ1, the re-examination and re-interpretation as follows will be carried out only for the sedimentary sequence and age of core NTCJ1, based on the existing analysis data of lithology, grain size, ostracods, foraminifera, clay minerals, geochemical elements, and ESR dating, together with other adjacent key cores and shallow seismic profiles (Figure 1).

2. General Settings

In the regional tectonics, the Sheyang estuary area belongs to the Sheyang Bulge in the Yanfu Depression of the southern Basin of the northern Jiangsu-South Yellow Sea on the northern Yangtze Paraplatform, with loose Quaternary sediments up to 200–240 m thick on the Sheyang Bulge [6]. In the regional landforms, the Sheyang estuary is located on the northern Jiangsu muddy coast, as well as in the transition zone between the northern eroded coast of the abandoned Yellow River delta and the southern silted muddy coast. This area is both a node of the modern coastal geomorphic evolution and one of the key areas of interactions between the paleo-Yellow River and paleo-Changjiang River during the late Quaternary [19]. The Yellow River migrated southward and flowed into the South Yellow Sea, north of the Sheyang estuary in 1128–1855 CE, which has profoundly influenced the historical geomorphic evolution of this area [6,19]. Additionally, the Sheyang River is currently an important seagoing river in northern Jiangsu, and historically it used to be a good channel to the sea. Before 1938, 5000-ton sea vessels used to reach Sheyang directly from Shanghai and travel up the river to the Funing area, but the construction of the tide barrier gate of the Sheyang River in 1956 was followed by the severe siltation under the gate and in the outer channel, resulting in the interruption of navigation on the Sheyang River and the paralysis of Sheyang Port [6,9,20]. In order to promote the comprehensive and rapid economic development of northern Jiangsu Province, the Chinese government approved the reconstruction of Sheyang Port in 1978, and the Sheyang Port was approved as a second-class and first-class national port open to the outside world in 1994 and 2017, respectively, becoming one of the closest ports to Korea and Japan in China [9,19,20]. Up the Sheyang Port, it is first connected to the Sheyang River and Huangsha River, and then to the Tongyu Canal and Beijing-Hangzhou Grand Canal, forming a river–sea intermodal transport system that reaches the Changjiang River in the south, Beijing and Tianjin in the north, and radiates to Jianghuai Region.

3. Materials and Methods

The core NTCJ1 (Location: 33°49′15.36″ N, 120°28′39.48″ E) and core NTCJ2 (Location: 33°49′14.76″ N, 120°33′4.98″ E) were drilled and firstly analyzed by Qingdao Institute of Marine Geology, China Geological Survey in August 2002 supported by "the Marine Areal Geological Survey of Nantong Sheet in the Scale of One-Millionth" [13]. The 22.00 m-long core NTCJ1 is located near the high tide line in the supratidal zone, 260 m onshore from the shoreline, with 91.50% mean recovery ratio, and its top elevation is ca. 2.0 m. The 20.60 m-long core NTCJ2 is located at a water depth of 6.0 m in the subtidal zone, with 76.00% mean recovery ratio, 6520 m away from the shoreline and 6810 m away from core NTCJ1 (see Figure 1 for the location details) [13]. For core NTCJ1, subsamples were taken at ca. 1 m intervals and 24 samples were analyzed for each proxy except the ESR dating. The laboratory analysis methods and procedures of lithology, grain size, ostracods, foraminifera, clay minerals, and geochemical elements are in accordance with "Specification for Oceanographic Survey—Marine Geology and Geophysics Investigation (GB/T 13909-1992)" [21]. Additionally, the testing parameters of ESR dating are described in Table 1.

Table 1. ESR dates of quartz sands from core NTCJ1 and NTCJ2 sediments [13].

Sample No.	Depth (m)	U (10^{-6})	Th (10^{-6})	K_2O (%)	AD (Gy)	Age (ka)	Comment
1E-2	18.38–18.41	1.44	9.09	1.92	316.9	134.3	Referencable
1E-3	21.98–22.00	1.41	7.75	1.94	343.9	150.8	Referencable
2E-4	20.57–20.60	1.74	10.9	2.14	240.3	87.4	Referencable

Note: "1E" and "2E" denote the ESR dating samples of core NTCJ1 and NTCJ2, respectively; test method: Ge core method; test conditions: room temperature, X-band, central magnetic field of 348 mT, sweep width of 5 mT, modulation amplitude of 0.1 mT, microwave power of 2 mW, conversion time of 5.12 ms, time constant of 40.96 ms; dating error of ca. 10–15%; AD: Accumulated Dose; comments were added by the authors of this paper.

4. Results

4.1. Lithology, Grain Size and ESR Dating

Based on the analysis data of the lithology and grain size [13] (Figure 2a,b), from top to bottom, core NTCJ1 can be divided into four sections as follows: (1) 0.00–3.75 m: Dark yellow and grayish yellow clayey silt, of which the top (i.e., 0.00–0.50 m) is dark yellow planting soil containing a large number of plant roots. (2) 3.75–12.86 m: Dark yellow and grayish yellow sandy silt; the lithology of Sections 1 and 2 is relatively stable, with an average grain size ranging from 4.2 to 5.8 Φ and a tendency to become finer upwards, reflecting the characteristics of the tidal flat sequence. (3) 12.86–17.95 m: Dark yellow clayey silt with uniform lithology and an average grain size ranging from 6.3 to 7.0 Φ. (4) 17.95–22.00 m: Dark grey silty sand with an average grain size ranging from 3.8 to 4.6 Φ, and the layer with a burial depth of 21.26–21.76 m is rich in shell fragments.

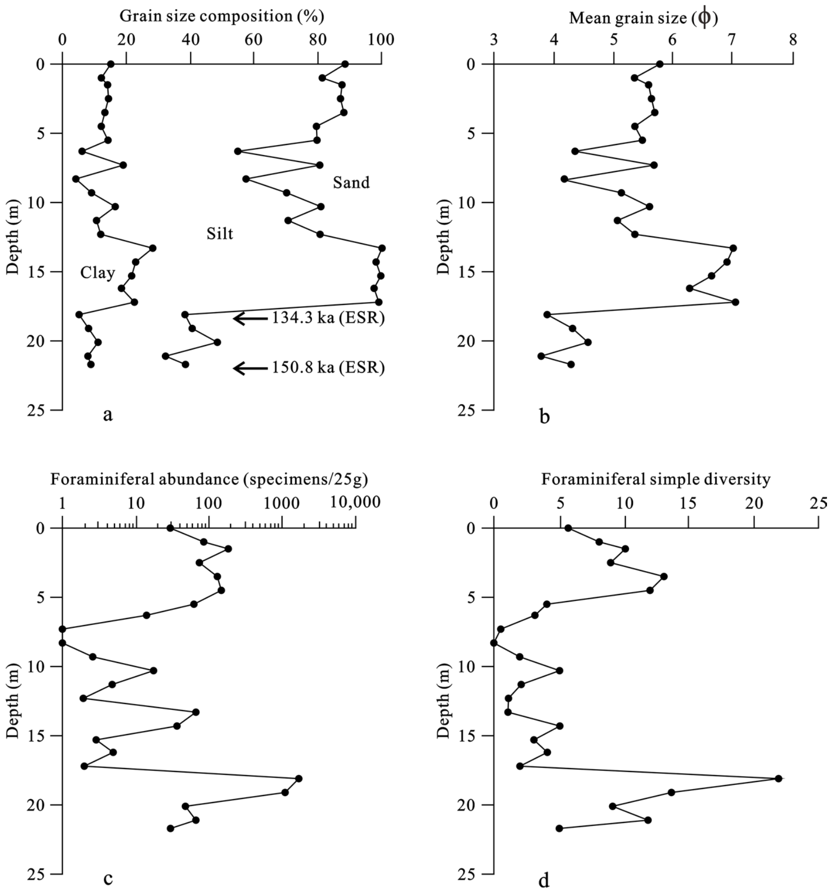

Figure 2. Vertical distributions of several parameters of grain size and foraminifera from core NTCJ1 sediments (modified after reference [13]); (**a**) vertical distribution of grain size composition of core NTCJ1; (**b**) vertical distribution of average grain diameter of core NTCJ1; (**c**) vertical distribution of foraminifera abundance of core NTCJ1; (**d**) vertical distribution of foraminifera simple diversity of core NTCJ1; two ESR dates from the lower part of core NTCJ1 were plotted in Figure 2a.

In terms of the entire core, the middle-upper part of core sediments (0.00–17.95 m) are characterized by a finer grain, with a predominantly silty texture, and from bottom to top it shows a change from fine to coarse and then to fine in grain size. The lower part of the core sediments (17.95–22.00 m) are characterized by a coarser grain, with a predominantly fine sandy texture. Moreover, there is also a clear distinction in the sediment color between the middle-upper part and the lower part, with a dark yellow tone and dark grey tone, respectively. Combined with the re-analysis results of micropaleontology, clay minerals, geochemical elements and shallow seismic profiles (see below for details), it can be inferred that these differences were probably caused by a significant shift in the sedimentary environments, from a tidal estuary with a lower deposition rate and a larger water depth to the abandoned Yellow River delta (1128–1855 CE) with a very high deposition rate and a smaller water depth. Additionally, two ESR dates were obtained in this core (Figure 2a and Table 1).

4.2. Ostracods and Foraminifera

Based on the analysis data of micropaleontology (i.e., ostracods and foraminifera; the foraminifera results as the representative showed in Figure 2c,d) [13], from top to bottom, core NTCJ1 can be divided into four sections as follows: (1) 0.00–6.45 m: The ostracod abundance is 10–134 valves with a mean of 65 valves, and the simple diversity of ostracod is 2–5 with a mean of 4, meanwhile, the dominant species is *Sinocytheridea impressa*. The foraminiferal abundance is 16–181 specimens with a mean of 99 specimens, and the simple diversity of foraminifera is 3–13 with a mean of 8, meanwhile, the dominant species is *Ammonia beccarii* vars. The foraminiferal and ostracod assemblages of this section are characterized by monotonous genus-species and a higher dominance that could indicate that the coastal environments have a water depth less than 5 m. (2) 6.45–17.95 m: The ostracod abundance is very low, ranging from 0 to 14 valves, with no ostracods seen in some samples and the simple diversity of ostracod is 0–3. The abundance and simple diversity of foraminifera are both lower, with no foraminifera seen in individual samples, and the mean abundance and simple diversity are 13 specimens and 2, respectively, meanwhile, no dominant species was found. Both the ostracods and foraminifera found in this section are common in shallow coastal waters; however, their abundances and simple diversities are quite low, indicating an environment with a high deposition rate [22]. Moreover, considering the history of the regional coastal evolution, lithology (coarse at the top and fine at the bottom, dark yellow tone), and the ratio of the ostracod and foraminiferal abundance (ca. 5, indicating estuarine deltaic environments) [23], we can judge that this section belongs to the Yellow River subaqueous deltaic deposits. (3) 17.95–19.60 m: The ostracod abundance is 18–96 valves with a mean of 57 valves, and the simple diversity of ostracod is 6–13 with a mean of 10, meanwhile, the dominant species are *Bicornucythere bisanensis* and *Neomonoceratina chenae*. The foraminifera are extremely abundant, and the mean abundance and simple diversity are 1414 specimens and 18, respectively, meanwhile, the dominant species is *A. beccarii* vars., moreover, *Spiroloculina lucida* and *A. annectens* make up a large proportion and are only just less than the dominant species. The foraminifera *S. lucida* and *A. annectens* found in this section are often the dominant species in shallow waters less than 20 m deep and are highly abundant, meanwhile, the dominant species of ostracods are also the dominant species in shallow waters less than 20 m deep, so this section should be littoral deposits in a water depth less than 20 m. (4) 19.60–22.00 m: Only the layer with a burial depth of 20.32–20.35 m is very rich in ostracods, with an abundance of 226 valves and a simple diversity of 26, and the dominant species are *B. bisanensis* and *N. chenae*, while the rest of this section has very few ostracods, with an abundance of 0–2 valves and a simple diversity of 0–1, with only *Neosinochere elongate* being seen. The mean foraminiferal abundance and simple diversity are 49 specimens and 12, respectively, and the dominant species is *A. beccarii* vars. All the numbers of species and of individual ostracods and foraminifera in this section is lower than in the previous section, with the absence of *A. annectens* and *S. lucida* in the assemblage, indicating that this section is still littoral deposits; however, with slightly weaker marine characteristics.

4.3. Clay Minerals

The analysis data of clay minerals [13] show that illite dominates in core NTCJ1, accounting for 44.4% to 72.0% (mean: 59.1%), followed by montmorillonite, accounting for 10.2% to 40.0% (mean: 21.2%). However, the kaolinite and chlorite contents are relatively lower, accounting for 7.9% to 14.0% (mean: 10.9%) and 5.7% to 14.4% (mean: 8.8%), respectively. In contrast to the Changjiang River sediments, the Yellow River sediments are characterized by a lower content of illite (ca. 60%), higher content of smectite (ca. 15%), and an illite/smectite ratio of less than 6 [24,25]. The composition of the clay minerals in the core NTCJ1 sediments is basically consistent with the above-mentioned fact, indicating that the Yellow River-derived sediments are definitely the dominant source. In addition, montmorillonite is clearly responsive to climate changes, and the higher content of montmorillonite may indicate a warm and wet environment. Therefore, with regard to the vertical distribution of montmorillonite content with the burial depth of 0.00–17.95 m (Figure 3a), if we ignore the two sample points with unusually large values at burial depths of ca. 5.5 m and 10.3 m, sedimentary records of a warm and wet climate may exist in the burial depths of ca. 0.0–5.5 m and 11.3–17.2 m, while sedimentary records of a cold and dry climate may exist in the burial depth of ca. 5.5–11.3 m.

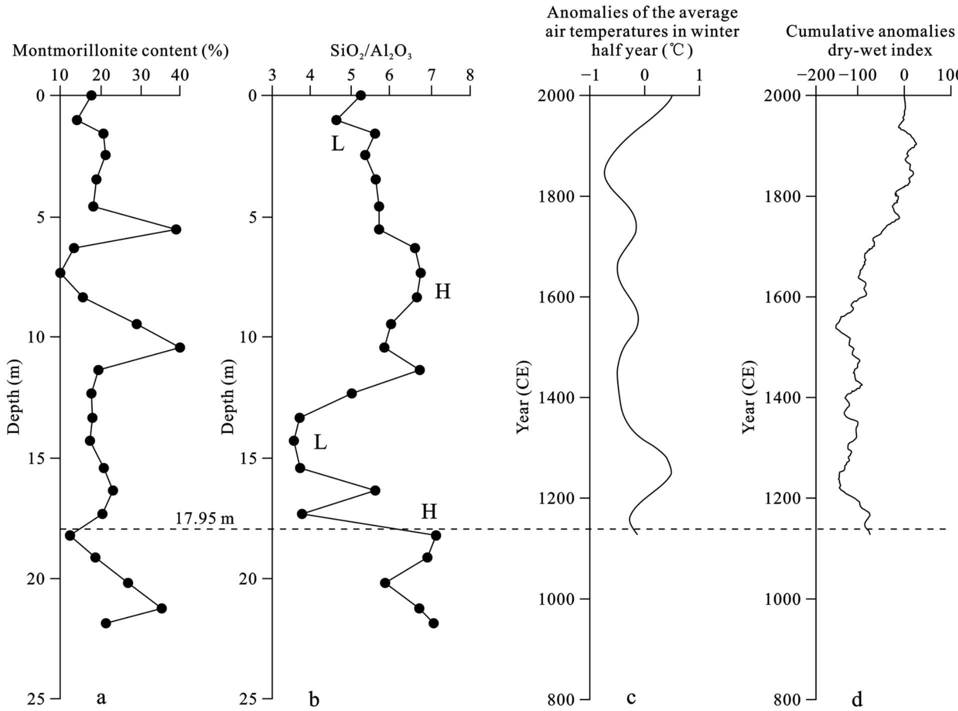

Figure 3. Vertical distribution of montmorillonite content and SiO_2/Al_2O_3 ratios of core NTCJ1 sediments and correlation between these indicators and historical climate changes; (**a**) vertical distribution of montmorillonite content of core NTCJ1 (modified after reference [13]); (**b**) vertical distribution of SiO_2/Al_2O_3 ratios of core NTCJ1 (modified after reference [13]); (**c**) anomalies of the average air temperatures in winter half year for East and Central Regions of China since the Southern Song Dynasty (modified after reference [26]); (**d**) cumulative anomalies of dry-wet index for Jianghuai Region of East China since the Southern Song Dynasty (modified after reference [26]); the capital letters H show the high ratios and the capital letters L show the low ratios.

4.4. *SiO_2/Al_2O_3 Ratio*

In supergene geochemistry, the SiO_2/Al_2O_3 ratio is an important indicator of the hydrothermal structure of sedimentary environments, characterizing the relationships between the contents of certain minerals, and is related to the climatic conditions and weathering degrees. A small SiO_2/Al_2O_3 ratio reflects a relatively warm and humid climate with a stronger chemical weathering, meanwhile, a large SiO_2/Al_2O_3 ratio reflects a relatively cool and dry climate with a weaker chemical weathering [27,28]. The SiO_2/Al_2O_3 ratios of core NTCJ1 sediments with the burial depth between 17.95 and 0.00 m generally show the four stages with variations from high to low, then to high and to low again (Figure 3b), which can be correlated well with the temperature and humidity variations of the Chinese historical climate since the Southern Song Dynasty (Figure 3c,d) [26]. Consequently, this ratio could be used as a secondary determination indicator of the sedimentary age scale of the middle-upper part of core NTCJ1. Moreover, the paleoclimatic indications of the SiO_2/Al_2O_3 ratio and montmorillonite content of these core sediments are also in general agreement (Figure 3a,b), which can cross-check the reliability of these paleoclimatic indicators.

5. Discussion

By means of combining the foregoing re-analysis results of the lithology, grain size, ostracods, foraminifera, clay minerals, and SiO_2/Al_2O_3 ratios of core NTCJ1, and then correlating them with the study results of the same sedimentary layer in the adjacent cores BH15, JC-1202, NTCJ2, JSWZK09, and JSWZK10 (i.e., the burial depth of 0.00–18.16 m in core BH15, 0.00–16.26 m in core JC-1202, 0.00–10.4 m in core NTCJ2, 0.00–2.35 m in core JSWZK09, and 0.00–6.75 m in core JSWZK10) [13,17,18,29] (Figure 4, see Figure 1 for the locations of cores), and with the seismic unit SU1 (low-angle clinoform) in the shallow seismic profiles to the north and south of the Sheyang estuary (Figures 5 and 6, see Figure 1 for the locations of track lines), we can judge that the section with the burial depth of 0.00–17.95 m of core NTCJ1 is essentially the abandoned Yellow River deltaic deposits mainly formed in 1128–1855 CE, and may contain a small amount of Holocene coastal-shallow marine deposits at the bottom; however, it is difficult to identify them currently.

Considering that the seismic unit SU2 in the shallow seismic profiles to the north and south of the Sheyang estuary, corresponding to the section with the burial depth of 17.95–22.00 m of core NTCJ1, exhibits a complex alternation of clinoforms and chaotic to hummocky reflections with cut-and-fill geometries and is widely distributed along the central Jiangsu coast (Figures 5 and 6), meanwhile, combining this with the various re-analysis results of core NTCJ1 mentioned above, and taking into account that the cores in the Sheyang estuary and its adjacent areas have revealed that this unit contains abundant tidal beddings [17,18,29,31,32] and the sedimentary indication of this unit's seismic facies [33], we can judge that the section with the burial depth of 17.95–22.00 m of core NTCJ1 could be interpreted as a delta front deposit in a tidal estuary under the influences of the paleo-Yellow River, and inferred to have developed during the period of high sea-level in MIS 5 via correlating its stratigraphic age with adjacent cores (Figure 4). The age inference was based on four aspects as follows: (1) Three quartz ESR dates were derived from this layer of core NTCJ1 and NTCJ2 (Table 1), ranging from ca. 87 to 150 ka. (2) Core JC-1202 yielded seven dates (four quartz OSL dates and three AMS ^{14}C dates) at this layer, with the OSL dates ranging from ca. 60 to 95 ka and all the AMS ^{14}C dates greater than 43.5 ka BP, exceeding the upper dating limit [17]. (3) Core BH15, JSWZK09, and JSWZK10 obtained three ^{14}C dates ranging from ca. 30 to 40 ka BP, one ^{14}C date greater than 43.5 ka BP and one quartz OSL date at ca. 30 ka in this layer. Additionally, there is a chronological inversion [18,29]; therefore, it is most possible that these ^{14}C dates are not advisable to adopt, and are underestimated due to the young carbon contamination of the samples exceeding the upper dating limit. (4) In the coastal plain of central Jiangsu, two sedimentary horizons with significant features of continental facies regularly appear within 60 m depth below the Earth's surface, which could be correlated with the first and second stiff mud layer in the northern Jiangsu and Changjiang River delta plain. The top plate elevation of the first continental facies layer is typically ca. -16 to -18 m, formed in MIS 2 or MIS 4-2, and the top plate elevation of the second continental facies layer is typically ca. -36 to -38 m, probably formed in MIS 4 or earlier (MIS 6-5), moreover, the first continental facies layer often reveals only the lower section with obvious ferromanganese contamination or is absent and directly overlain by tidal deposits interbedded with shell debris sometimes [4]. On the basis of the above four aspects, it can be further inferred that in core NTCJ1, the first continental facies layer formed in MIS 4-2 is supposed to be missing, so the MIS 1 marine facies layer directly overlays on the MIS 5 marine facies layer, moreover, the second continental facies layer formed in MIS 6 and/or the stage of relatively low sea-level of MIS 5 has not been drilled yet. This layer of core JCP01 (with a burial depth of 12–24 m, see Figure 1 for the core location) in the central Northern Jiangsu plain also recently yielded eight high-precision feldspar OSL dates, ranging from ca. 86 to 150 ka, and was interpreted as a MIS 5 tidal flat deposit [34], which could further support the age inference of this layer in this paper.

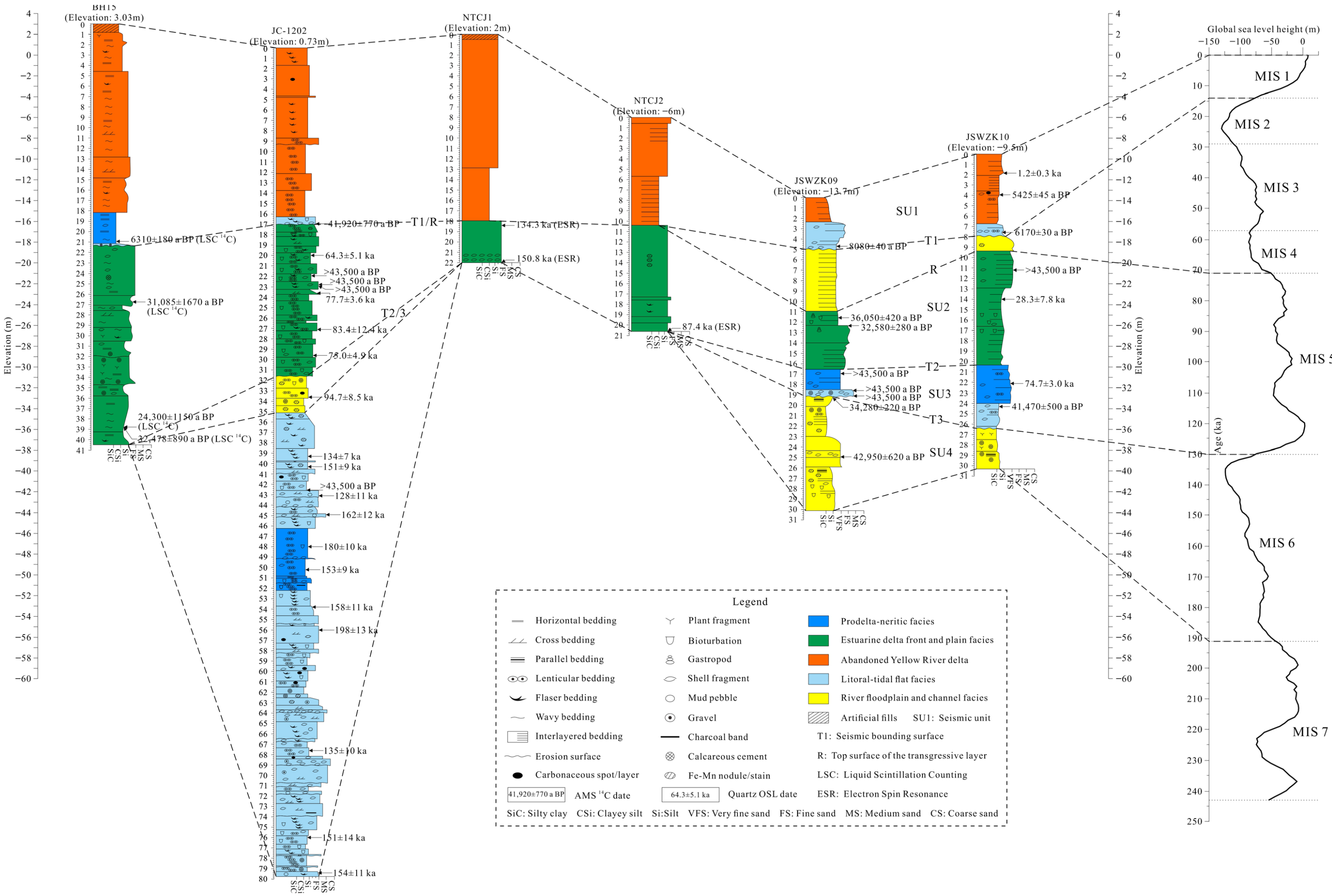

Figure 4. Correlation of the late Quaternary sedimentary sequences of mainly studied cores in the Sheyang estuary and its adjacent area; core BH15 was modified after reference [29]; core JC-1202 was modified after reference [17]; core NTCJ1 and NTCJ2 were modified after reference [13]; core JSWZK09 and JSWZK10 were modified after reference [18]; curve of global sea-level changes was modified after reference [30].

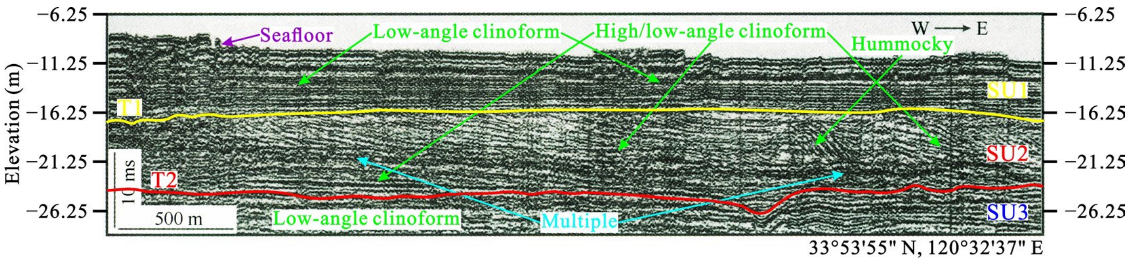

Figure 5. Shallow seismic profile of the west end of track line HDNT3 in the northern side of the Sheyang estuary and its interpretations; the original seismic data were quoted from reference [13] and interpreted by the authors of this paper; the capital letters SU show the seismic units and the capital letters T show the seismic bounding surfaces; Two Way Travel Times (TWTT) from the seismic profile were converted to sediment thicknesses using an acoustic velocity of 1500 m/s.

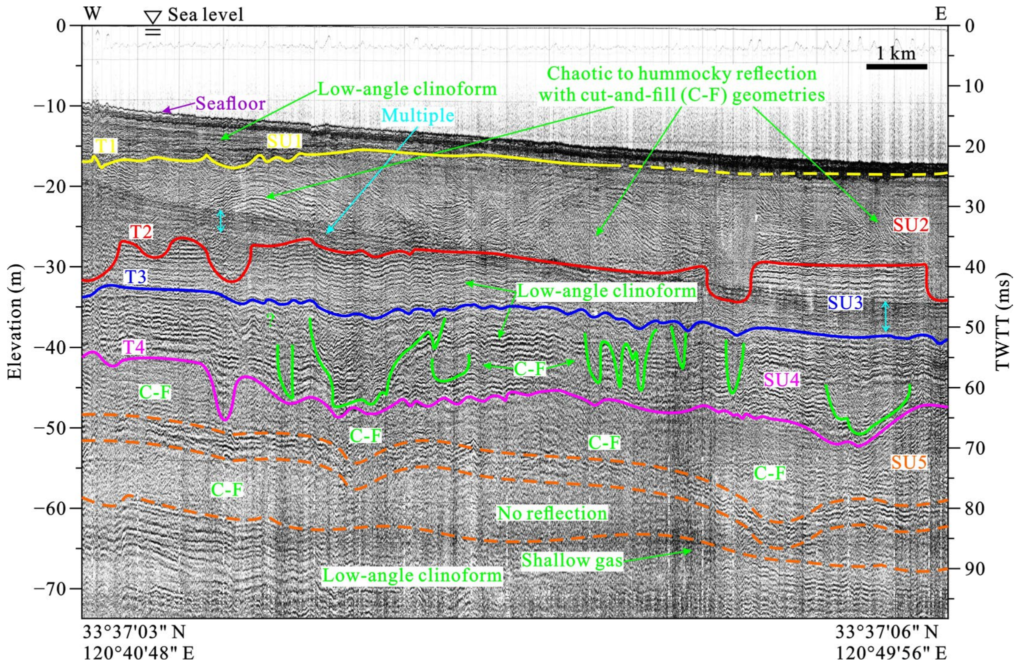

Figure 6. Shallow seismic profile of track line 110328-6 in the southern side of the Sheyang estuary and its interpretations; the original seismic data were acquired by the authors of this paper in March, 2011 using a GeoPulse Sub-bottom profiler (GeoAcoustics Ltd., Great Yarmouth, UK) and also interpreted by the authors of this paper; the capital letters SU show the seismic units and the capital letters T show the seismic bounding surfaces; Two Way Travel Times (TWTT) from the seismic profile were converted to sediment thicknesses using an acoustic velocity of 1500 m/s.

6. Conclusions

In this paper, the sedimentary sequence and age of core NTCJ1 drilled at the Sheyang estuary, western South Yellow Sea were re-examined and re-interpreted based on the existing data on the lithology, grain size, ostracods, foraminifera, clay minerals, geochemical elements, and ESR dating, together with other adjacent key cores and shallow seismic profiles. The three new perspectives were summarized as follows:

(1) The 22.00 m-long core NTCJ1 recorded the evolution of the sedimentary environments since MIS 5, and the first continental facies layer formed in MIS 4-2 is supposed to be missing, so the MIS 1 marine facies layer directly overlays on the MIS 5 marine facies layer, moreover, the second continental facies layer formed in MIS 6 and/or the stage of the relatively low sea-level of MIS 5 has not been drilled yet.

(2) The middle-upper part of the core NTCJ1 sediments (0.00–17.95 m) are characterized by a finer grain, with a predominantly silty texture and dark yellow tone, and from

bottom to top it shows a change from fine to coarse and then to fine in grain size, which could be substantially interpreted as the abandoned Yellow River deltaic deposits mainly formed in 1128–1855 CE, and may contain a small amount of Holocene coastal-shallow marine deposits at the bottom; however, it is difficult to identify them currently.

(3) The lower part of the core NTCJ1 sediments (17.95–22.00 m) have not yet been drilled through and are characterized by a coarser grain, with a predominantly fine sandy texture and dark grey tone, which could be interpreted as a delta front deposit in the MIS 5 tidal estuary and were evidently influenced by the paleo-Yellow River.

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