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River-Sea Interaction During the Formation of the North Jiangsu Plain, China: A Multi-Analysis of Sedimentology, Geochemistry and Authigenic Minerals from the Baoying Borehole

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The Northern Jiangsu plain along the Yellow Sea is located on the northern side of the Yangtze River and south of Cape Lan-Shan Tou, between 32^{o}10' $\sim$ 35^o 05'N and 118^o 40' $\sim$ 120^o 30'E. The topography is mainly lowland, sloping gently from the Grand Canal in the west towards the Yellow Sea to the east. Lowest elevations occur around the Xinghua-Sheyang Lake area located in the middle part of the plain.

Since abandonment by the Yellow-Huai River system in the north, a network of rivers, canals and lakes comprise the major hydrologic features between the Yellow and the Yangtze River systems and numerous lakes in the south. Historical records and previous studies have indicated that the outer part of the Northern Jiangsu plain was formed from the sea during a Holocene high sea level period at 5000 aBP, as defined by a series of abandoned shell beach ridges extending some 200 km long from north to south, and located some 60 km landward of the modern coastline. The present study is focused on the inner part of the plain which is located landward of the shell beach ridges and to the west of the Grand Canal.

Geomorphologic interpretation indicates the evolution of the inner plain west to the Fan-Gong dike by following features: (i) The limits of the North Jiangsu Plain are defined by a series of rocky hills surrounding an arc-shaped embayment; (ii) A series of lakes including the Hongze Lake, the Gaoyou Lake, and the Shaobo Lake, located on the west side of Grand Canal, are almost connected to each other either by lowland or by wetlands. There are several rivers entering the lakes with deltaic forms on the west side or inland side of lakes. Indeed, the Grand Canal was originally constructed partly by utilising the water channels to connect these lowland swamps and the lakes; (iii) A series of artificial islands based on the natural bars or barriers, are located within the lakes or swamps (locally known as Dun, Duo, Gang or Wei, which means artificial bars or crossways in Chinese). These are the preferred areas for settlement by local people living in the water country area. All of the islands or barriers are aligned in a North-South direction. That is, they are still parallel to the present coastline, and marine shells and fragments have been found in the sediments of these islands indicating that they originated as beach ridges. Humans added the artificial bars on the top of them.

A sediment core of BY1 penetrated 145 m deep at Wangzhigang Town of Baoying County, in the central lowland area between the lakes and the outer coastal ridges; 97 m of clay and silty sediment samples were obtained, which have been used to interpret the plain history since 2.58Ma ago by a multidisciplinary study of sedimentary facies, microfossil, geochemistry and authigenic minerals. The core analysis shows (1) The basement of the plain (between the M/G boundary of 95.22 m and 97 m) was a denudated surface with volcanic effects of 2.58 Ma ago. (2) Above the basement (from 95.22 - 64.45 m), it was terrigenous facies of alluvial and lacustrine deposits, but flooded over occasionaly by seawater. The top part of the layer had been exposed and compacted to a hard clay layer. (3) From 64.45 m up to 58.0 m of the core are sandy and silty strata with marine facies of shallow sea and nearshore deposits. (4) From 58.0 m up to 45.63 m, layers were terrigeous facies of flood plain deposits, most of which were formed during the time period of 1.07∼0.99 Ma (Jaramillo reversal). (5) The layer between 45.63 m and 39.16 m is characterized by flood plain and lake deposits with occasional seawater incursions. The Brunhes/Matuyama reversal of 0.78 Ma is on the top of the strata. (6) The major marine facies of shallow sea and tidal flat deposits are located between 39.16 m and 14.96 m. Abundant marine foraminifera fossils represented by 10-18 species, are found mainly in the layer at 15-24 m depth indicating euryhaline conditions under water depth of less than 20 m, and partly between 30-50 m with salinity of 31-32 ‰ and a temperate climate. This represents the major marine transgression period of 30,000 aBP during the late Pleistocene. (7) The top of the core sediments from 14.96 m up comprise lake and depression deposits of terrigenous formation, but still with occasional tidal water influence. The Holocene base appears to occur between the layers of 13.1 m and 10.3 m of the core.

The results from major, trace and rare earth element analyses of the core sediments and authigenic minerals also indicate that the plain formed through river-sea interaction. Higher P and S contents in sediments of the 15-24 m interval are suggestive of a marine origin and consistent with the existence of authigenic apatite and pyrite. The mineral pyrite (FeS_2) is a common and widespread authigenic constituent of marine sediments associated with organic matter and is an indicator of anaerobic, sulfuric digenesis. Within this interval, large numbers of foraminifera and marine ostracods were found, which strongly supports a marine origin. Between 24 m and 39 m the evidence is for a mainly freshwater marl-depositing lake environment, but possibly close to the shoreline and suffering occasional saltwater overwash during storms. The faunal and floral evidences for freshwater $CaCO_3$-rich lakes extend from 23.80 to 31.80 m. Most are concentrated around 24 m. This is also the depth at which cemented sediment occurs and it coincides with calcium and phosphorus concentration peaks. Below 39 m, deposits are dominantly continental and represent alluvial plains or shallow lakes, but with several important transgressions. For example, in the interval of 39-45 m, abundant Ferromanganesian nodules occur within the sediments. These Fe-Mn nodules show a typical seawater-like REE distribution pattern of light-REE depletion and heavy-REE enrichment in a NASC-normalized diagram, but unlike the negative Ce anomaly in seawater, most of these Fe-Mn nodules show positive Ce anomaly, which is suggestive of an oxidizing environment. However, there are two Fe-Mn nodules having a flat pattern in the NASC-normalized REE distribution diagram and positive Ce anomalies (similar to REE patterns for buried manganese nodules from the Central Indian Basin), which may suggest their formation during the burial process in a less oxygenated environment within the sediments. From 45 m to the bottom of the core, the combination of high contents of Ca, Mg, Fe, Mn, P and S in the sediments indicate there were at least three minor trangressions or occasional saltwater incursions (floods, storms, etc.).

It is clear from the multiple lines of evidence that the evolution of the inner part of North Jiangsu Plain formation was characterized by fluvial-marine interactive dynamic courses during Pleistocene time.

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