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Reconstructing the Paleoenvironmental Record of the Wuqi Paleolake in the Northern Chinese Loess Plateau

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Abstract. Lacustrine sediments can allow useful reconstructions of paleoenvironmental conditions. We collected a 22.39 m sediment core from within the Wuqi Paleolake in the northern Chinese Loess Plateau in order to reconstruct the region's climatic fluctuations within the Neogene-Quaternary transition. Paleomagnetic, magnetic susceptibility, grain size, and loss on ignition data were used constrain the lake's temporal formation and extinction and to reconstruct its paleoenvironment. The Wuqi Paleolake existed from 2.58–0.78 Ma BP, experiencing four distinct stages: a formation stage during which the climate warmed from slightly cold and dry conditions (2.58–2.33 Ma BP), a high-water stage which was sharply interrupted (2.33–1.80 Ma BP), a low-water stage during which the climate moderated but aeolian sediments began to increase (1.80–0.95 Ma BP), and a final stage during which the lake level fluctuated substantially (possibly reflecting an unstable climate) before finally drying up (0.95–0.78 Ma BP).

Keywords: Paleoenvironment, Regional Setting, Grain Size.

1. Introduction

Changes in climate since the late Cenozoic have been a focus of research activity in East Asia and adjacent regions over the past 30 years [1-3]. Aeolian red clay and loess deposited on China's Loess Plateau since the Neogene-Quaternary period contains abundant information on the region's paleoclimate and paleoenvironment[4]. Such aeolian deposits are widely developed in several paleolakes of different sizes distributed throughout the Loess Plateau and the surrounding region[5], forming lacustrine deposits of varying thicknesses.

Several methods are used to study and characterize lacustrine deposits. First, paleomagnetic dating allows the determination of a clear chronology for lake formation and development. Second, changes in grain size distribution over time have been widely applied to study the evolution of ancient climates and environments[6-9] as the physical energy of lake water represents the strength of hydrodynamic forces and the relative quantity precipitation in the region [10-14]. Smaller grains indicate drier climates and lower water levels whereas coarser grains indicate more humid climates and higher lake levels [15,16]. Third, the magnetic susceptibility of lacustrine sediment is sensitive to changes in the sedimentary environment and can serve as an index for climate change, but as its formation mechanism varies in different types of lakes, it should be used in combination with other indicators such as grain size [17]. Fourth, loss on ignition (LOI) measures the organic content of lake sediments and can indicate the productivity of lakes and the preservation of organic material, thus indirectly reflecting past climatic environments[18-22].

According to Zhang et al. [23], a paleolake with an area of approximately 200 km2 developed in the Wuqi area of Shaanxi Province, between the Loess Plateau to the south and the Mu Us Desert to the north, during the late Neogene to early Quaternary periods (hereafter referred to as the Wuqi Paleolake). That study developed a composite profile at Tufosi in Wuqi County and performed preliminary research on the paleolake's magnetic stratigraphy and grain size, defining the upper section of the profile is loess sediments, the middle section as lacustrine deposits, and the bottom section as red clay. However, paleomagnetic samples were collected only at 100 cm intervals and failed to define a specific period for the Wuqi Paleolake, restricting further research [23,24].

Additionally, this previous work only analyzed the paleolake's changing characteristics of the grain size and mineral components, not its paleoenvironment or developmental history.

The Wuqi Paleolake's geographic setting provides a rare opportunity to study environmental changes in a climatically sensitive desert-loess transitional zone. In this study, we sought to further define and understand the paleoenvironmental history of the Wuqi Paleolake and the surrounding region as well as provide a temporal basis for comparison with other sections in the Neogene-Quaternary transitional.

2. Regional Setting

Wuqi County is located in the northern Loess Plateau, just south of the Baiyu Mountains that divide the region from the Mu Us Desert to the north (Fig. 1). These mountains are oriented roughly east-west at an elevation of approximately 1200–1800 m and hold the headwaters of the North Luo River and several tributaries to the Yellow River.

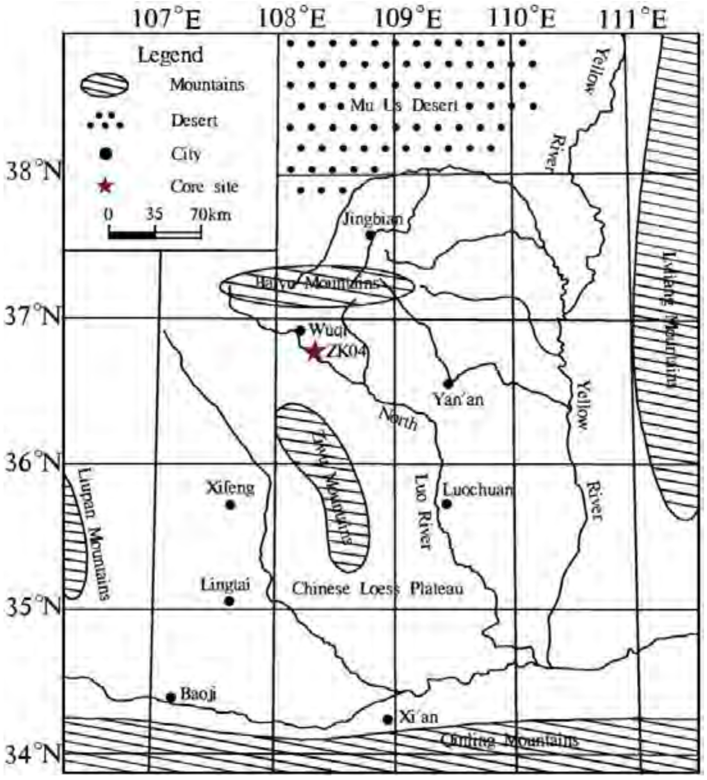

Fig. 1 Location of the ZK04 core on the Loess Plateau in northern China

3. Material and Methods

3.1 Sampling Location.

We collected a core sample (ZK04, 36°47′35.36″N，108°19′05.24″E) in the northern Luo River Basin (Fig. 1), approximately 20 km southeast of the town of Wuqi [25]. This core had a depth of 92.20 m and a coring rate above 95%. The core can be divided into three lithologic units from top to bottom: 1) a cultivation layer above a typical loess series (0–38.17 m), 2) lacustrine strata from the Wuqi Paleolake (38.17–60.56 m), and 3) thick red clay (60.56–92.20 m).

3.2 Sampling Methods.

Sediment samples for magnetic susceptibility and grain size analysis were collected at 2 cm intervals within the core's lacustrine strata, while those for loss on ignition (LOI) analysis were collected at 4 cm intervals, for a total of 1000 and 500 samples, respectively. A total of 22.39 m-long U-channel samples (U-shaped, 2×2 cm square cross-sections, 1.5 m in length, non-magnetic plastic tubing, with an arrow marking "up") were taken from one half of the split core for continuous long-core magnetic measurements.

3.3 Paleomagnetic Dating.

We measured the core's paleomagnetism at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences (CAS). The remanence was measured using a 2G-cryogenic superconducting magnetometer (model 755R) housed in a magnetic shielded space. All U-channel cores were subjected to stepwise alternating-field (AF) demagnetization at fields of up to 80 mT with 5 or 10 mT increments (the measuring space is 2 cm). Demagnetization results were evaluated by orthogonal diagrams and the principal component directions were computed using a "least-squares fitting" technique [26].

3.4 Magnetic Susceptibility.

The high-frequency (4700 HZ) and low-frequency (470 HZ) magnetic susceptibility was measured with a Bartington MS2 meter. Low-frequency magnetic susceptibility (χ_{lf}) is the most common measurement, reflecting the total content of magnetic minerals in the samples. We used the low (χ_{lf}) and high (χ_{hf}) frequency susceptibility measurements to calculate the frequency dependent susceptibility χ_{fd}% (defined as (χ_{lf}-χ_{hf})/ χ_{lf}×100%), which represents the relative behavior of the frequency-dependent susceptibility [27].

3.5 Grain Size.

We conducted grain size analysis to determine the median diameter (d(0.5)) and the percentages of clay (%), silt (%) and sand (%) fractions of all 1000 samples using a Malvern Mastersizer 2000 laser grain-size analyzer, which has a measurement range of 0.02–2000 μm (diameter). Samples were pretreated with 10–20 mL of 30% H2O2 to remove organic matter, then washed with 10 ml of 10% HCl to remove carbonate. After adding approximately 2000 mL of deionized water, the sample solution was stored for 24 h to rinse acidic ions. The sample was then dispersed with 10 mL of 0.05 M (NaPO3)6 on an ultrasonic vibrator for 10 min before grain size analysis [28,29].

3.6 Loss on Ignition.

Loss on ignition (LOI) is a common, simple, and widely used method for estimating the organic and carbonate content of sediments. Samples were weighed when wet, after drying overnight at 105 °C, and after heating by a muffle furnace at 550 °C for 2 h[18,19,29] in order to calculate the water content and weight of organic matter as follows:

$$LOI550 / \% = \frac{M_{105} - M_{550}}{M_{105}} \times 100\% \tag{1}$$

where LOI550 represents LOI at 550 °C (as a percentage), M105 represents the initial dry weight of the sample before combustion, and M550 is the dry weight of the sample after at 550 °C (all values in g).

4. Results and Discussion

4.1 Chronology.

More than 80% of the total samples yielded a reliable remanence from AF demagnetization. The core recorded nine magnetozones (five normal and four reverse) within the lacustrine sediments (Fig. 2). By comparison with the latest Geomagnetic Polarity Time Scale (GPTS) [30,31] and existing data and literature, we determined that the Wuqi Paleolake formed at approximately 2.58 Ma BP and terminated at approximately 0.78 Ma BP.

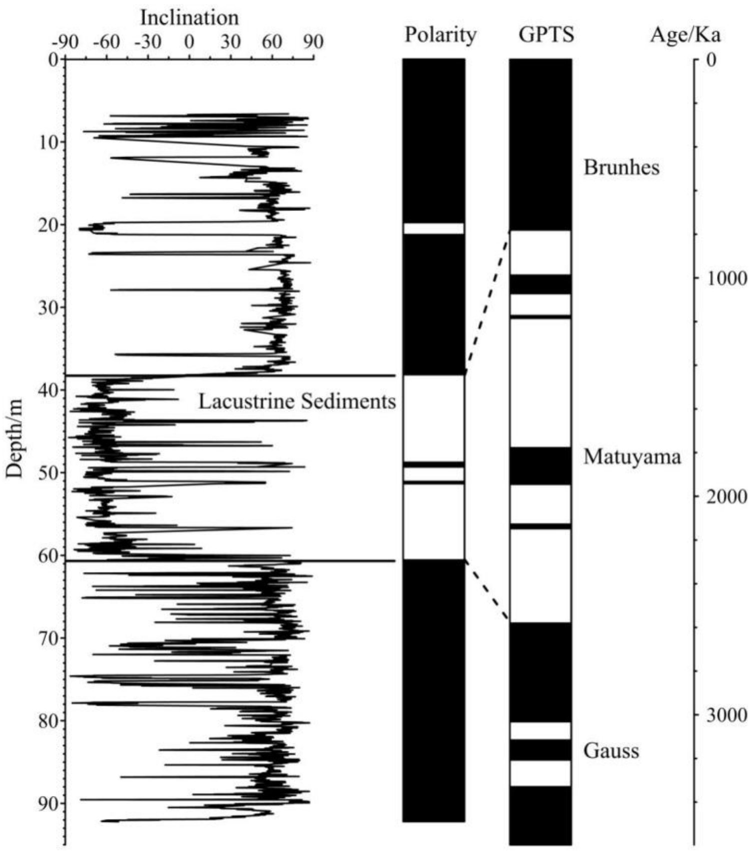

Fig. 2 Magnetic polarity data from the ZK04 core compared with the Geomagnetic Polarity Time Scale (GPTS)

4.2 Grain Size.

The grain size changes in the lacustrine strata were complex, showing that the content of each size fraction changed frequently over a wide extent (Fig. 3), particularly with regard to medium and small grain sizes. The median diameter was approximately 19.0 μm and the content of < 4 μm and 4–32 μm grains was approximately 24% and 67%, respectively. The lithology of the lacustrine strata was mainly silty clay and clayey silt.

Previous studies have shown that the major grain size distribution curve of typical aeolian loess and red clay is unimodal, with silt particles (5–50 μm) dominant and sand larger than 63 μm diameter and clay less than 5 μm being relatively scarce[32,33]. However, the grain size distribution curve of the lacustrine strata in our core fell mainly between 1.0–35.7 μm (Fig. 3) and showed a bimodal pattern. This pattern is similar to the grain size distribution characteristics of lakeside sediments[34] and suggests that two or more sediment sources contributed to the depositional environment at this location.

The grain size distribution changed significantly at a depth of 40.26 m. Smaller grains (less than 16 μm) sharply decreased while coarser grains (greater than 16 μm) significantly increased. This suggests that the Wuqi Paleolake entered an extinction stage at this point during a transition to aeolian loess accumulation. This stage was completed by 38.17 m, after which aeolian loess accumulation dominated. Thus, we speculate that the Wuqi Paleolake finally disappeared at approximately 0.78 Ma BP.

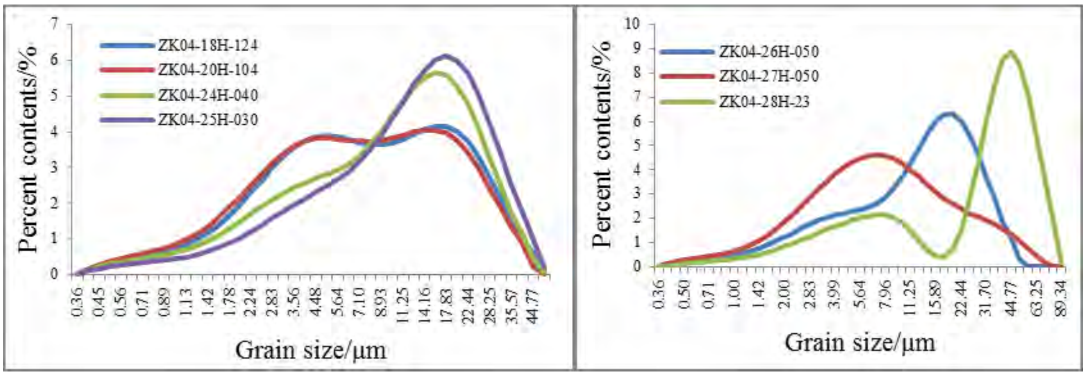

Fig. 3 The grain size distribution curve of typical lacustrine samples in the ZK04 core

4.3 Magnetic Susceptibility.

The low-frequency magnetic susceptibility values ranged from 17.05–120.78 10-8 m3/kg with an average of 43.70 10-8 m3/kg; changes in these values can be roughly divided into four stages (Fig .4). In the first stage (60.56–57.46 m), the magnetic increased with significant fluctuations. In the second stage (57.46–50.92 m), the magnetic susceptibility reached its lowest values and remained fairly stable. In the third stage (50.92–40.26 m), the magnetic susceptibility first increased and then decreased with more significant fluctuations and curves characteristic of aeolian sediments. In the fourth stage (40.26–38.17 m), the magnetic susceptibility again fell to a lower level.

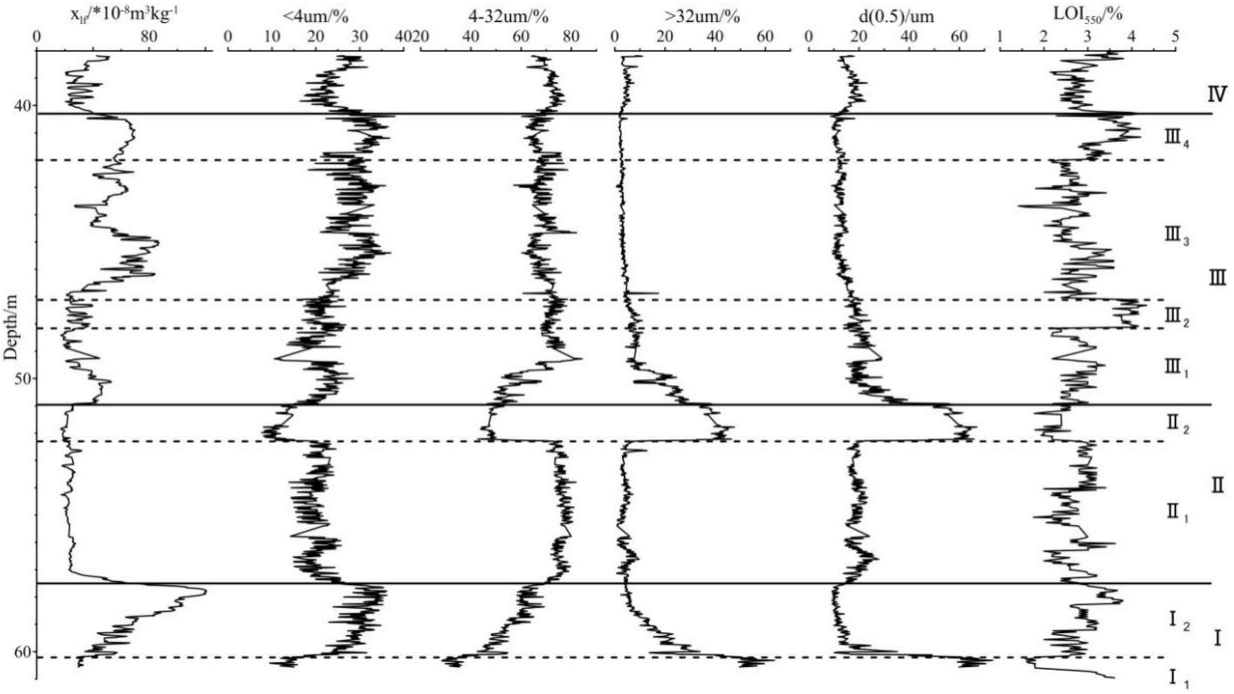

Fig. 4 Comparison of variations in magnetic susceptibility, < 4 μm grain percentage, 4–32 μm grain percentage, > 32 μm grain percentage, d(0.5), and LOI550 data from the ZK04 core. Numbered stages mark different climatic periods within the history of the Wuqi Paleolake as defined from these data

4.4 LOI550.

Environmental conditions control the temperature, evaporation and precipitation in the lake region, the water level of lakes, lake area, water chemical property of lakes, the biological productivity and preserved ability of organic material. These conditions then affect the process of sedimentation of organic material in lakes and the LOI variations [35]. Therefore, the LOI in lake sediments reflects many processes and can indirectly indicate the regional climate and environmental conditions for the duration of formation and deposition of organic material. Analyzing the LOI variation in combination with other indexes can recover the organic content of the sediments and the environmental conditions in its formation and reconstruct the climatic environment evolution process in the lake region.

The climate is the main factor affecting the organic productivity and preserved ability of organic material. Under different climatic conditions, the accumulation of organic material shows differences. During high temperature conditions, the vegetation grows readily, and the residual body accumulation increases. This growth results in increasing the organic content; Low temperature conditions are not conducive to plant growth, resulting in decreased organic material. In general, high LOI550 values indicate warm and humid conditions, whereas low LOI550 values represent a cold and dry climate.

4.5 Climate Reconstruction.

A side-by-side comparison of the above variables allowed us to divide the environmental/climatic evolution of the Wuqi Paleolake into four main stages (Fig. 4) as discussed below.

4.5.1 Stage I (60.56–57.46 m, 2.58–2.33 Ma BP). This is a transition stage covering the formation of the paleolake, during which the magnetic susceptibility fluctuations and increasing <4 μm grains suggest that a small-scale water body may have formed, but the large-scale lake basin had not yet developed because of terrain and climate factors. In sub-stage I1 (60.56–60.17 m, 2.58–2.55 Ma BP), the low LOI550, high d(0.5), and coarser particles indicated mildly cold and dry conditions. In sub-stage I2 (60.17–57.46 m, 2.55–2.33 Ma BP), the percentage of fine and median particles increased, resulting in a low d(0.5) value, and the LOI550 content increased. High LOI550 values, a low percentage of coarser particles, and low d(0.5) values indicated a warm and humid climate.

4.5.2 Stage II (57.46–50.92 m, 2.33–1.80 Ma BP). Stage II represents the high lake surface stage. During this period, magnetic susceptibility was quite low, suggesting a reducing environment in which discouraged the formation and preservation of magnetic minerals. In sub-stage II1 (57.46–52.26 m, 2.33–1.91 Ma BP), high LOI550 values, a high percent of fine and median particles, and low d(0.5) values represented a warm and humid climate with relatively deep water. In sub-stage II2 (52.26–50.92 m, 1.91–1.80 Ma BP), the content of <4 μm and 4–32 μm components and LOI550 content decreased, while that of >32 μm components increased, implying that the climate was interrupted by a cold and dry period that reduced the lake level as the overall climate changed from semi-arid to drought.

4.5.3 Stage III (50.92–40.26 m, 1.80–0.95 Ma BP). Stage III represents the low lake-level stage, during which the magnetic susceptibility increased and both this and the grain size curves showed characteristics of aeolian sediments. This indicated an increase in airborne dust components and a shallower water body. In sub-stage III1 (50.92–48.12 m, 1.80–1.58 Ma BP), the percentage of >32 μm particles and the median diameter decreased and the LOI550 content increased, indicating the climate began to moderate. In sub-stage III2 (48.12–47.08 m, 1.58–1.49 Ma BP), the percentage of <4 μm particles increased, the d(0.5) value decreased, and the LOI550 content peaked, suggesting a rapid and transient period of more warm and humid climate conditions. In sub-stage III3 (47.08–41.96 m, 1.49–1.08 Ma BP), although the d(0.5) value remained stable, the low-frequency magnetic susceptibility and percentage of LOI550 closely tracked the <4 μm components, suggesting climate conditions similar to sub-stage III1. In sub-stage III4 (41.96–40.26 m, 1.08–0.95 Ma BP), the increasing content of <4 μm particles and the higher LOI550 values indicated that the climate returned to warm and humid conditions.

4.5.4 Stage IV (40.26–38.17 m, 0.95–0.78 Ma BP). Stage IV reflects a period of lake-surface fluctuations during which the magnetic susceptibility, the percentage of <4 μm particles, and the LOI550 content first fell and then increased, suggesting that the climate was quite unstable. The Wuqi Paleolake was mainly a shallow lake in this period, with fluctuations in the water level associated with the strong climatic fluctuations. At the end of this stage, the lake vanished from the sedimentary record.

5. Conclusion

We collected lacustrine sediment samples from a core obtained within the Wuqi Paleolake in northern China and performed a detailed analysis of the core's paleomagnetic, grain size, magnetic susceptibility, and LOI550 components, allowing a reconstruction of the paleoenvironmental record.

The Wuqi Paleolake existed from 2.58–0.78 Ma BP period and experienced four main stages in the early Pleistocene: (I) transitional formation, (II) high lake surface, (III) low lake surface, and (IV) fluctuation and eventually disappearance around 0.78 Ma BP.

Acknowledgments

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