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ARTICLES

Preliminary research on Megalake Jilantai-Hetao in the arid areas of China during the Late Quaternary

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We identified geomorphological, sedimentary and biological evidence of high lake levels around the current Jilantai Salt Lake through field investigations and through analyses of regional remote sensing images. There are four groups of shorelines at elevations of around 1060, 1050, 1044 and 1035 m a.s.l., being 37, 27, 21 and 12 m above the current salt lake surface, respectively. Littoral deposits of sand and gravels are found at elevations between 1070 and 1080 m a.s.l., 47 to 57 m higher than the current salt lake surface, although palaeoshoreline landforms are only preserved at several sites. At Herimuxini, on the northern margin of the Ulan Buh Desert, typical lacustrine sediments and sand-gravel littoral deposits also occur at elevations of 1080 m a.s.l. and below. A 11-km-long typical spit extends eastward from this shoreline gradually reducing in elevation from 1050 to 1035 m a.s.l. In some sand-gravel quarries along the southern bank of the Yellow River on its Great Bend, such as those located near the Hydrological Gauge Station and Shilazhao Town, shoreline features were identified. Littoral deposits overlying the alluvial-diluvial layers occur in a sand quarry near Balagong in Hangjin County. There are also beachrock and littoral deposits preserved on the cut-and-built terraces at several sites along the southern piedmont of Langshan-Yinshan Mountains. In addition, a profile revealing subaqueous delta sediments was identified near Wuhai, where the Yellow River enters the basin. Typical lake sediments also exist at the Togtoh Platform on the eastern end of the Hetao Plain. Aquatic Mollusk shells are common in the littoral deposits, including several species of *Corbicula*, *Radix lagotis*, *R. xauricularia* and *Gyraulus convexiusculus*. Ostracode shells can also be identified in finer sediments. Typical vertical prograding sequences are evident in outcrops where lacustrine sediments were well preserved. Wave-rolled cobbles and beachrock are very commonly preserved on the top of profiles in the embankments at higher elevations. All this evidence suggests that there was once a huge palaeo-lake covering the Jilantai region and most part of the Hetao Plain with the highest lake level reaching ~1080 m a.s.l. We refer to the huge paleolake, which was larger than modern Lake Baikal, as "Megalake Jilantai-Hetao." OSL dating results indicate that the megalake formed before ~60－50 ka , and the four shorelines at elevations between 1060 and 1035 m a.s.l. likely represent the lake level variations from ~60－~50 ka to the early Holocene. The discovery of the Megalake Jilantai-Hetao likely will impact understanding of the development of the Yellow River during the late Quaternary, the evolution of the Ulan Buh and Kubq deserts, neotectonism in the region, and possibly regional climatic changes.

Megalake Jilantai-Hetao, shorelines, lacustrine sediments, late Quaternary, high lake levels

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GEOGRAPHY

Jilantai Salt Lake lies in the northeastern margin of the Alashan Plateau. Tectonically, it is part of the Hetao basin, a Cenozoic fault basin surrounded by the Ordos Plateau, the Helan Mountain and the Yinshan Mountains. Extensive Quaternary lacustrine sediments are deposited in the center of the basin[1]. Normal faults along the south piedmont of the Yinshan Mountains are associated with rapid uplift of the massif, and buried faults occur along the southern margin of the Hetao Plain[2]. The modern Yellow River flows northward into the Hetao Plain through the Lanzhou and Yinchuan basins, bends eastward around the Ordos Plateau, then turns to the south, forming the famous Great Bend of the Yellow River (Figure 1). The Hetao Plain is now at the margin of the modern Summer Monsoon, where the annual precipitation varies between 300 and 100 mm. The dry climate results in two deserts, Ulan Buh Desert to the southeast and Kubq (or Qukuqi) Desert to the south (Figure 1).

Slightly elevated Holocene shorelines on the eastern bank of Jilantai Salt Lake have been previously identified[3] and interpretation of remote sensing images has suggested even higher shorelines on the southwest margin of the salt lake[4]. Zhang et al.[5] also reported high lake shoreline features around Jilantai Salt Lake and suggested a paleolake in Jilantai may have possibly extended to the Hetao Plain. Regional geological investigations have revealed that Late Quaternary lacustrine sediments, indicative of a Late Quaternary Hetao Paleolake[6], are widely distributed in this area, including those reported in the eastern Hetao Plain[7] on the second platform along the piedmont of the Daqing Mountain[8] and on the Togtoh Platform in the southeast[6,9]. The possibility that a huge unified paleolake once existed in the Jilantai basin and the Hetao Plain is an important regional environmental issue that deserves extensive research. We conducted field investigations around Jilantai Salt Lake and on both sides of the Yellow River in the Great Bend to study past shoreline features, lacustrine sediments and assemblages of biological remains. In combination with Optical Stimulated Luminescence (OSL) and ^{14}C dating results, we here report aspects of the range and age of a paleolake that once covered Jilantai and most of the Hetao Plain.

1 Methods

Field investigation of shoreline features, lacustrine sediments and littoral deposits were based on the examination of exposed outcrops and exploratory profiles excavated into shoreline sediment. The spatial distribution of the shoreline features was extracted in the laboratory from remote sensing images of the Jilantai-Hetao area. The shoreline elevations were measured by differential GPS in the field. The ages of the shorelines were dated by OSL and/or radiocarbon dating methods on sediments collected in the field.

In measuring the shoreline elevations, we selected the second-level national survey control point (1103 m a.s.l.), 15 km north of Jilantai Town as the basis for the elevation control. Following the method described by Zhang et al.[10], we measured the main shorelines around Salt Lake Jilantai with two ProMARK X GPS receivers. The measurement errors were obtained through two other second-level national survey control points within the area. The final elevation of each point is the average values of three measurements. The mean error is 0.3 m, and maximized at 0.5 m.

At sites where there was not enough organic material for ^{14}C dating, we used OSL dating to obtain a chronology of the shorelines. In the early 1990s, Murray et al., after comparing the OSL signals from several water-lain samples, concluded that lakeshore sediments formed well-bleached sample suitable for OSL dating[11]. OSL dating was subsequently applied successfully to lakeshore sediments from Eyre Lake in Australia[12], and in recent years OSL dating method has been widely applied to date lakeshore sediments[13−15]. Because of the anomalous fading of the luminescence signal in potassium rich feldspars (K-feldspar), OSL dating using K-feldspars may induce a problem of age underestimation[16−19]. For OSL dating in this study the 125−300 μm grain size quartz was separated by using a routine method[16]. OSL dating was completed in the Luminescence Dating Laboratory in the Cold and Arid Regions Environment and Engineering Research Institute, CAS. OSL measurements of all samples were carried out using the automated Risø TL/OSL-DA-15 reader. The environmental dose-rate in a sample is created by radioactive elements in the grains of the sample and in surrounding sediment, with a contribution from cosmic rays. The U, Th concentrations and K contents in raw samples were determined by means of Neutron Activation Analysis (NAA). All measurements were converted to alpha, beta and gamma dose rates according to standard conversion

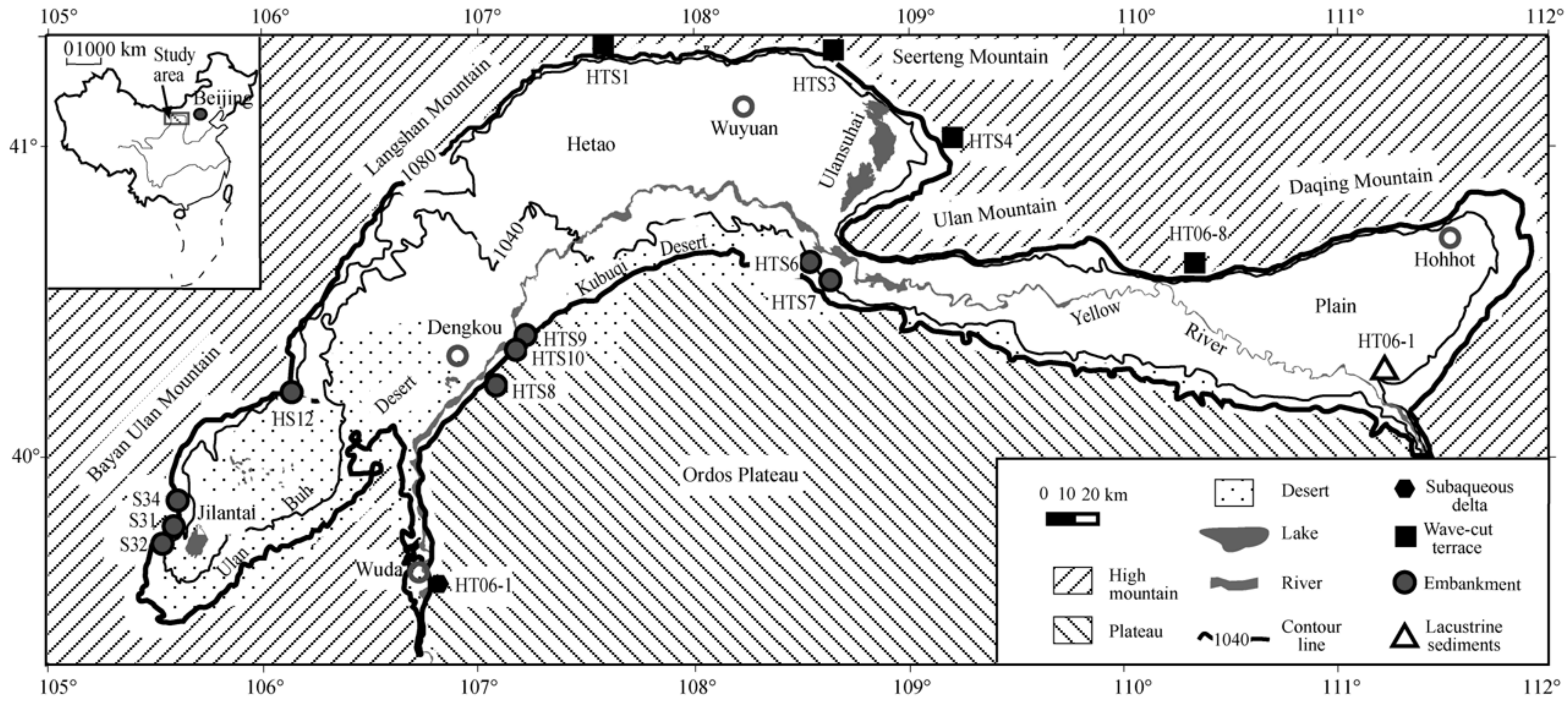

Figure 1 Map of geographical settings in the Jilantai-Hetao area and the investigated sites where the highest lake levels once reached. The heavy dark line is the contour of 1080 m a.s.l. The 1040 m a.s.l. contour line shows that the modern Jilantai and Hetao basins become separate below the elevation. The shaded elevations of the mountains and plateau are those areas higher than 1100 m a.s.l. The illustration on the top left corner indicates the location of our study area in northern China.

factors[20]. The dose rate from cosmic rays was calculated using sample burial depths and altitudes of the sections[21]. Radiocarbon dating was applied to some lacustrine sediments with relatively high organic matter content after standard pretreatments. Radioactivity was detected by a Wallac Quantulus 1220 Liquid Scintillation Counter with ultra-low background in the Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University. The ^{14}C ages were calibrated to Cal a BP with CALIB 5.01 for those younger than 26 ka[22] and CalPal for those older than 26 ka[23].

2 Evidence of Megalake Jilantai-Hetao

2.1 Lakeshore accumulative landforms

Lakeshore accumulative landforms are formed by the transversal movements of sediments accompanied with shore drift, including longshore levees, subaqueous bars, barrier bars (usually 2—3 m higher than the normal lake level) and subaqueous accumulative terraces. These shoreline features are unified as embankment as they are all parallel to the lakeshore[24]. To the west and southwest of Salt Lake Jilantai, there are several shorelines around the lake consisting of parallel bands of shoreline features evident in different types of remote sensing images[1)] (Figure 2). During field investigations we found shorelines are well preserved along the west and northwest parts of the salt lake that can also be identified in remote sensing images (Figure 2(b) and (c)).

Based on differential GPS measurements, two major groups of shorelines are at elevations of around 1050 and 1060 m a.s.l. and can be clearly identified in ETM+

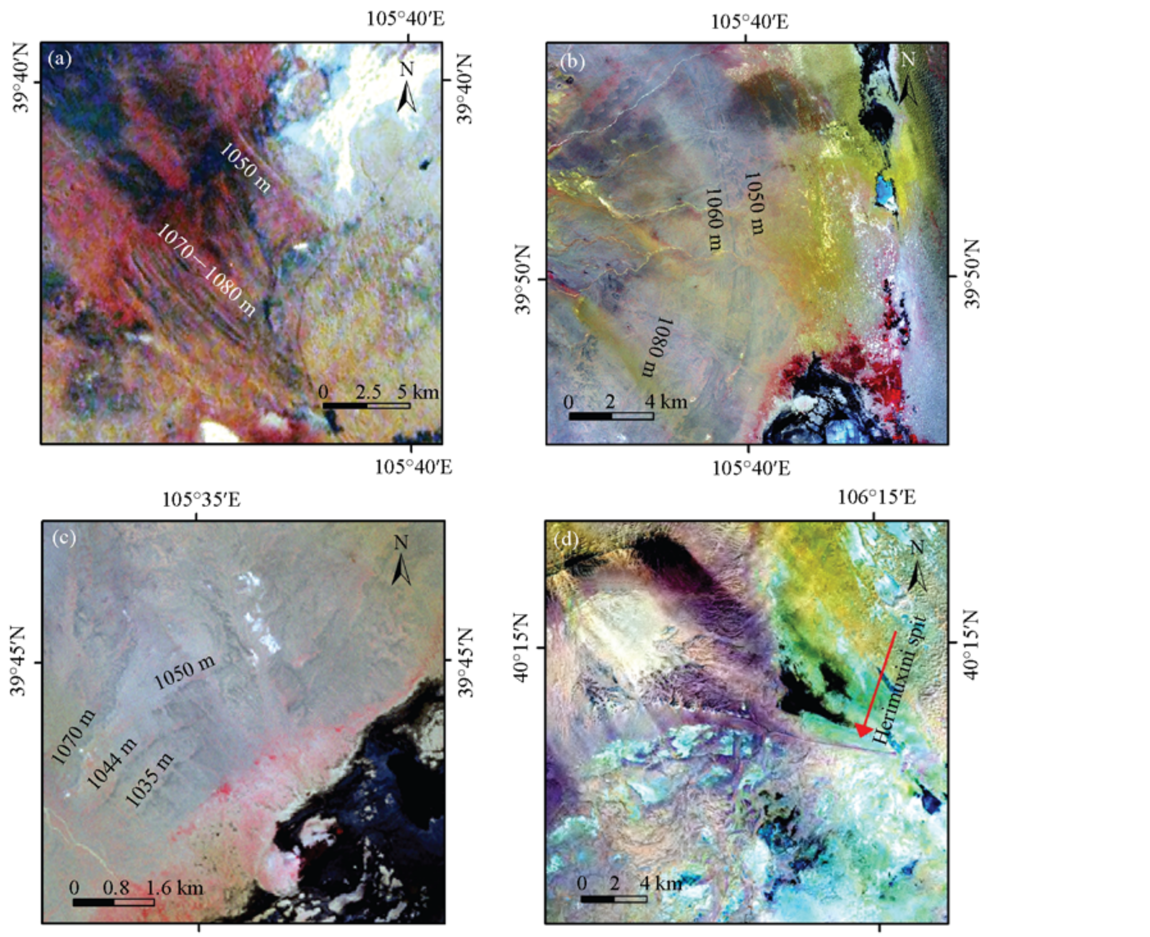

Figure 2 Remote sensing images of palaeoshorelines around Jilantai Salt Lake. (a) NASA image of palaeoshorelines at 1050 and 1070—1080 m a.s.l. to the southwest of the salt lake; (b) ETM+ image of major palaeoshorelines at 1050 and 1060 m a.s.l. to the north of the salt lake; (c) ETM+ image of palaeoshorelines at lower elevations of 1050, 1044 and 1035 m a.s.l. on the west margin of the salt lake; (d) TM image of a typical spit at Herimuxini.

1) Yang L P, Chen F H, Chun X, et al. The Jartai Salt Lake shorelines in northwestern dryland China revealed by remote sensing images. J Arid Environ, 2007, doi:10.1016/j. jaridenv.2007.10.006 (in press).

images (Figure 2(b) and (c)). They are well preserved in many sites, such as sand quarries in the west, both sides of a new road to the northwest of the lake, and Daokouliang site to the southeast of the lake (Figure 3). In some sites, continuous shorelines extend longer than 20 km, with a width of 20 to 30 m. The major shorelines usually consist of two to three parallel sub-shorelines, such as those found in the Kuluntaolegai at an elevation of 1060 m a.s.l. close to the Bayinwula Mountain (Figure 3). For example, two parallel sub-shorelines 100 to 150 m wide lie on the flat slop of a major shoreline at around 1060 m a.s.l. near section S42. The cross-section of the shorelines is asymmetrical, with a flat lakeward face and steep landward slope. Some negative landforms developed on the landward side as lagoon systems, with fine sediments in some sites. These shorelines have characteristic of a typical barrier bar. At elevations below 1050 m a.s.l., two barrier bars were measured at 1044 m a.s.l. (S16, Figure 3) and 1035 m a.s.l. (Figure 2(c)), but are smaller in size, about 5 km long. Above 1060 m a.s.l., between 1070 and 1080 m a.s.l. several shorelines are preserved west of Jinsanjiao to southwest of the lake. These shoreline features are weakly preserved for the most part, but at several sites to the west of the lake, such as at sites S32 and S34, preservation of calcium cemented sand and gravels (beachrock) and aquatic mollusk shells within the sediments indicate that it was a littoral environment.

In summary, based on our field observations there are four shorelines at around 1060, 1050, 1044, and 1035 m

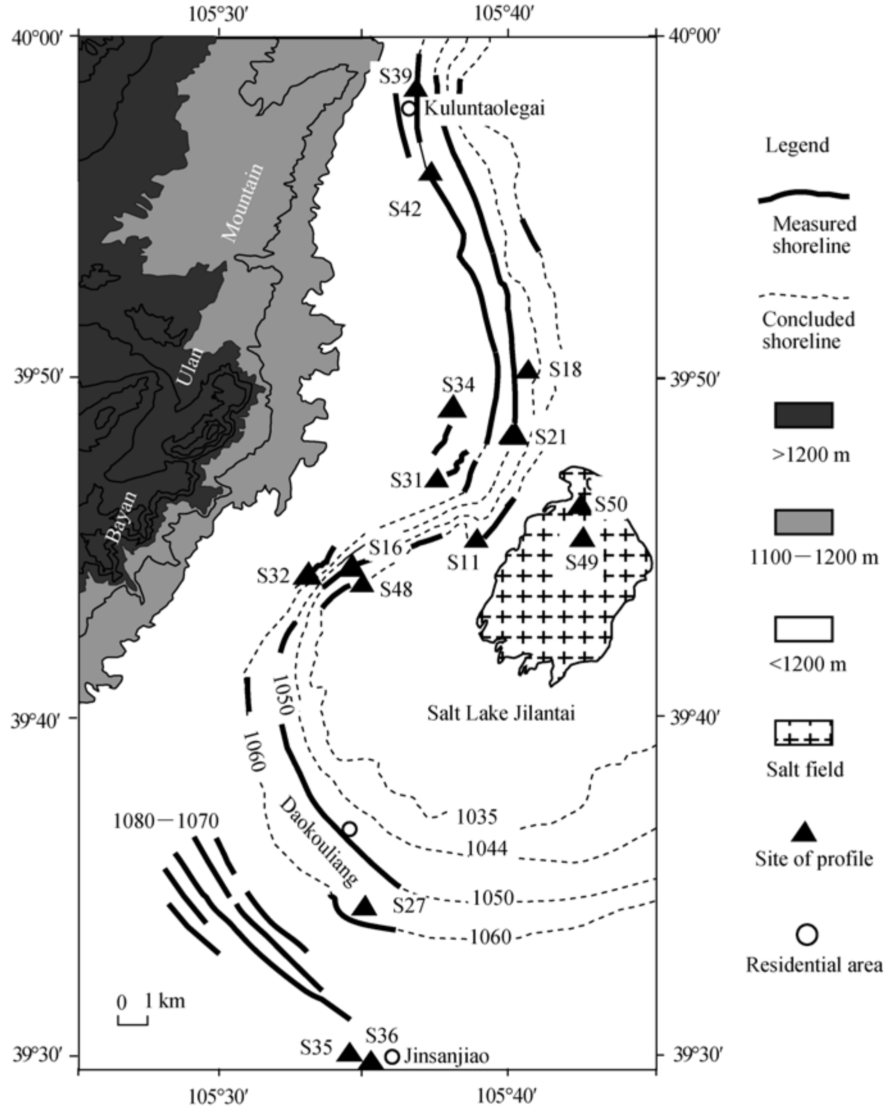

Figure 3 Distribution of palaeoshorelines to the west and southwest of Jilantai Salt Lake confirmed by both field investigations and from remote sensing images. The filled triangles indicate the locations of sections examined in detail.

a.s.l., or about 40, 30, 22, and 12 m higher than the current playa surface in the Salt Lake Jilantai catchment, respectively. Above the elevation of 1060 m a.s.l., there are remnants of littoral deposits and shorelines preserved at 1070 to 1080 m a.s.l., that are 47 to 57 m higher than the current playa and represent the highest lake level in this region.

Littoral deposits and shorelines between 1081 and 1050 m a.s.l. are also observed in Herimuxini (HS12 in Figure 1) , 70 km to the northeast of Jilantai Salt Lake. The shoreline features are weakly preserved due to the long-term erosion. Typical longshore accumulative landforms are also found at many sites along the southern bank of the Yellow River in the Hetao Plain. The embankments are 3 to 5 m high and have become sand quarries used for local construction, making the shoreline features fragmentary. However, their lithologic character clearly indicates their formation in littoral environments. For example, in a sand quarry near Yellow River Hydrological Gauge Station, 5 km to the east of Sanshenggong Bridge in Dengkou County, the shoreline extended longer than 10 km at an elevation of 1055 m a.s.l. (HTS9 and HTS10 in Figure 1). Similar landforms are also identified near a Shilazhao sand quarry on the southern bank of the Yellow River in Hangjin County. The shoreline there extends 13 km at an elevation of 1045 m a.s.l. (HTS6 and HTS7 in Figure 1).

2.2 Spits

A spit is a typical shoreline features formed by a littoral current[25]. A major spit is found in Herimuxini site, extending from a high paleoshore east to the near center of the modern Ulan Buh Desert (Figure 2(d)). The landforms of the spit are well preserved with a flat and straight crest currently being used as a road by local residents. It is 11 km in length and drops in elevation from 1050 to 1035 m a.s.l. The surface of the crest is about 5 m wide, with maximum width of 30 m and with relative height of 3 to 10 m. The spit has a typical "V" shape in the area connected to the past shoreline. Several sub-aqueous bars are connected to the spit at its proximal end, indicating that lake levels retreated progressively. The spit ends abruptly, with the surface elevation decreasing rapidly 6 m within a span of 20 m, at the end of the spit to playa surface indicating that the lake was drying up during the process of spit construction. We dug five exploratory shaft profiles at intervals of 2 km along the top of the spit and found that the sedimentary structure is generally the same. The top 20 cm of sediments are sandy desert soil with white crystalline carbonate or gypsum. At depths from 20 to 50 cm the sediments are dominated by sand and gravel with less silt. Below 50 cm, sediments are predominately gravels with lenticles of coarse sand. The gravels are well rounded, and aquatic mollusk shells of *Corbicula* and *Gyraulus convexiusculus* are well preserved within the sediments.

Another spit is found at site S11 on the southwest margin of Jilantai Salt Lake (Figure 3). It extends from the paleoshore at 1045 m a.s.l. towards the southwest. The South Sand Quarry is located at the end of the spit, with a surface elevation of 1038 m a.s.l. The quarry exposures consist of 10 m of gravels with lenticles of coarse sands overlying fine grained lacustrine sediments. Above the 10-m lacustrine gravel is a layer of clayey silt or fine sand capped with 30 cm of desert soil. Foreset beddings in the exposure are typical of spit development. Shells of *Corbicula* are also preserved.

A series of spits is found at the south end of Salt Lake Jilantai near what was the southwestern margin of the paleolake (Figure 2(a)). A highly eroded, but still extensive spit extends southeast from the pediment of the Bayan Ulan Mountains about 10 km from the highest paleoshoreline at about 1080 m a.s.l. to Jinsanjiao. The massive spit is more than 1 km wide near the paleoshoreline, but its features are indistinct due to erosion. As second, lower spit at about 1048 m a.s.l., parallels the first, but is located to the north on the extreme southern end of Jilantai Salt Lake. The spit extends about 7 km from the western paleoshoreline to the southeast. Numerous other small spits around the paleolake can be identified in remote sensing images.

2.3 Wave cut terraces

Wave-cut platforms and shoreline notches are widely distributed overlying metamorphic bedrocks along the southern piedmont of the Yinshan Mountains from Langshan Mountain to the Daqing Mountain. The platforms are several dozens of meters to 200 m in width with lacustrine sandy silt, fine sand or beachrock at the bottom and alluvial-proluvial gravel on the top along the outer margins. These make up the typical cut-and-built terraces in the area, such as those at site HTS3 in the southern margin of Langshan Mountain and at site HT06-8 to the east of Baotou City (Figure 1). Wave-cut platforms and beachrocks are also found near Wuda on the east bank of the Yellow River before it enters the Hetao Plain. Wave-cut notches, cliffs, terraces and platforms are the typical lakeshore erosive landforms in this region. Though the elevations of these landforms in each site are not exactly the same (between 1080 and 1100 m a.s.l.), the similar sedimentary structures indicate the same littoral cut-and-built[24] dynamics.

2.4 Lacustrine sediments and aquatic mollusk assemblage

River-mouth deltas usually occur in the transitional belt between land and lakes, and sub-aqueous deltas are excellent indicators of a paleolake[24]. A sub-aqueous delta sediment profile is found at site HT06-1 on the east bank of the Yellow River along the piedmont near Wuda, Inner Mongolia (Figure 1). A 13-m profile is located in a large quarry with a surface elevation of 1093 m a.s.l. Sediments in the profile are composed of subangular gravel alluvium and proluvium in the top 3 m and grayish yellow silty clay between 3—13 m. Within the stratum dominated by grayish yellow silty clay, there are 3 intervals of fine sands containing some terrestrial plant remnants and shells of *Radix*. The strata generally tilt northwest at a low angle toward the center of the megalake. This type of sediment and structure indicates a typical interdistributory bay environment between tributaries. A lenticula of plant fragments mixed with charcoals at the bottom of a silty-fine sand layer at the depth of 7 m was dated to 35690 ± 320 ^{14}C BP. This age was calibrated to 41450 ± 470 cal a BP. We think that the sample may give a limiting date indicating that the site was in a subaqueous delta environment sometime prior to about 41000 years.

Another complete sedimentary profile extending down from alluvial-proluvial, through lacustrine silty sand, to littoral gravel was found in a sand quarry 4 km to the southeast of Balagong town in Hangjin County (site HTS8 in Figure 1). The entire profile is 10 m think with a surface elevation of 1104 m a.s.l. The top 2 m is alluvial-proluvial gravel, 2—3.5 m is lacustrine silt to fine sand with ripple-laminated beddings, and 3.5—5.5 m is composed of well rounded cemented gravel. At the bottom of this layer there are obvious ripple markings indicative of littoral environment. Alluvial-proluvial sand gravel comprises the lower part of the section between 5.5—10 m, with lacustrine sandy lenticules on the top. The whole section unconformably overlies brown sandstone (Figure 4).

The exposed profiles of littoral deposits in this area have a general vertical prograding sequence, such as those at sites HS12, HTS3 and S32, where the lacustrine silty clay is overlain by the littoral sand-gravel. Calcareous Cemented gravels (beachrock) are also found below littoral gravel at some sites. Desert soil with a depth less than 30 cm is relatively well developed on top of the littoral deposits. Sediments below the desert soil are composed commonly of light-colored gravels with diameters of 2—5 cm.

Aquatic mollusk shells including *Corbicula*, *Radix lagotis*, *Radix xauricularia* and *Gyraulus convexiusculus* are commonly found in the littoral deposits at almost all sites. In the littoral deposits above 1050 m a.s.l., *Corbicula* is the only species found. In the littoral deposits

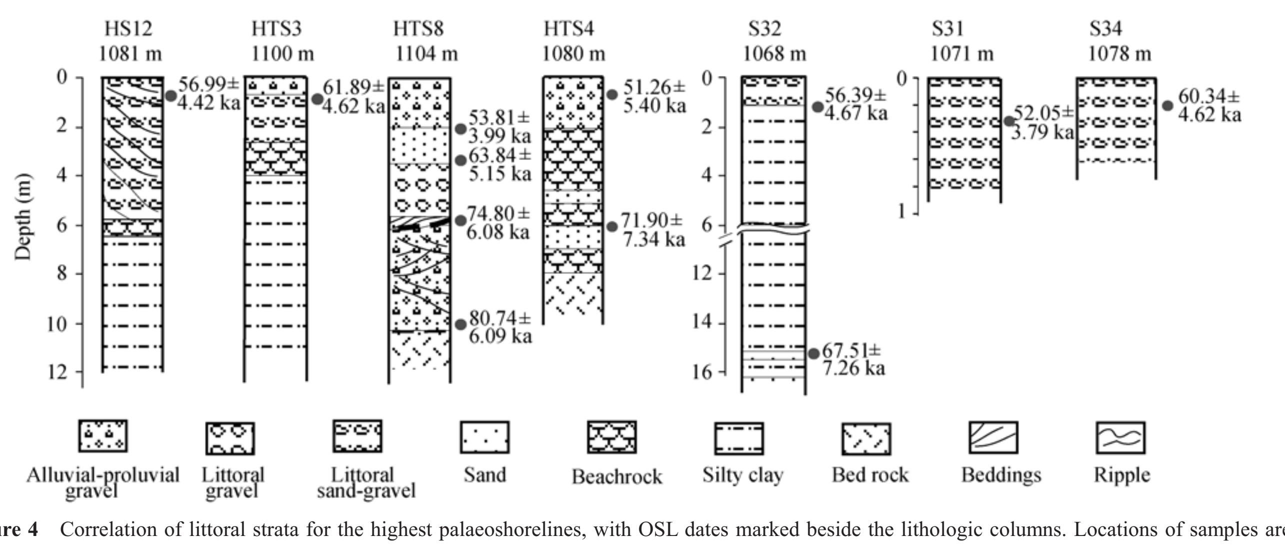

Figure 4 Correlation of littoral strata for the highest palaeoshorelines, with OSL dates marked beside the lithologic columns. Locations of samples are identical to those in Figure 1 and Table 1.

below 1050 m a.s.l., however, the mollusk assemblage is dominated by *Radix lagotis*+R*adix xauricularia*, and *Corbicula* is only found in a few sites. Ostracode shells are also found in fine grained lacustrine sediments such as silt or silty clay.

Though the shoreline landforms are not well preserved above 1060 m a.s.l. in the Jilantai area, the lacustrine deposits have a relative clear stratigraphic structure. For example, at site S36 (1082 m a.s.l., Figure 3) in Jinsanjiao to the southwest of Jilantai Salt Lake, the eolian sand at the bottom is overlain by silty clay and medium to fine sand (1—2 m thick) and then by littoral gravel. The similar sedimentary sequence exists at the profile S32 to the west of Jilantai Salt Lake (1068 m a.s.l., Figure 3). The top 1 m of cemented gravel layer overlying silty sand and silty clay dominated lacustrine sediments (Figure 4), indicates that the lake level reached this site and possibly exceeded this elevation. Relatively complete lacustrine sedimentary sections are also found at site HS12 in Herimuxini (1081 m a.s.l., Figure 4). Sediments of this profile are dominated by a suit of fine grained sediments such as silty clay, silt and fine sand that were likely deposited in deep to shallow lake environments. These fine-grained sediments are capped by littoral sand and gravels with foreset beddings and contain *Corbicula* shells. One thin layer of cemented sand and gravel is found at the bottom of the littoral deposits.

In the Yellow River valley to the south of Togtoh County in the eastern Hetao Plain (site HT06-11 in Figure 1), typical grayish-green lacustrine silty clay (about 20 m thick) is covered by a ~1 m paleosol and then by ~8 to ~10 m eolian loess. This was previously reported as the evidence of the Hetao Paleolake[9]. The assemblage of aqueous mollusk shells, the prograding sequence of the littoral deposits and cemented beachrocks are critical in identifying littoral deposits[26] and are helpful to recognizing shorelines.

The widely distributed geomorphological evidence of cut-and-built terraces, barrier bars and spits, the sedimentary evidence of typical lacustrine deposits, the presence of a subaqueous delta with prograding sequences, and the biological evidence of mollusk shells (*Corbicula*, *Radix lagotis*, R*adix xauricularia* and *Gyraulus convexiusculu*) and ostracod shells, all indicate that a huge paleolake once existed in the current arid Jilantai-Hetao area.

3 Result and discussion

3.1 Spatial distribution of Megalake Jilantai-Hetao

The geomorphological, sedimentary and biological evidence indicates there are several palaeoshorelines at different elevations around Jilantai Salt Lake. The shoreline features at 1035, 1044, 1050 and 1060 m a.s.l. are particularly well preserved. However, the palaeoshorelines and littoral deposits at elevations of 1070—1080 m a.s.l. and above are weakly preserved except those in the area to the south of Daokouliang in the southwest of Jilantai Salt Lake (Figure 2(a)) and at sections S32, S33 and S34 to the west of the salt lake (Figure 3). Most of the shoreline evidence we found in our field investigations generally does not exceed 1080 m a.s.l. For example, at sites S31, S32 and S34 to the west of the salt lake, the elevations of the shorelines are at 1071, 1068 and 1078 m a.s.l., respectively (Figure 3). The elevations of several relatively well preserved shorelines to the south of Daokouliang in the southwest of the salt lake are at elevations between 1070 and 1080 m (Figure 3). In the hinterland of the current Ulan Buh Desert, the highest lacustrine sedimentary section at site HS12 in Herimuxini (Figure 1) is at an elevation of 1081 m a.s.l. Therefore, we consider that the highest shoreline of the paleolake in the Jilantai region has been at an elevation of around 1080 m a.s.l.

There are exceptions for this general pattern, however, particularly in the Hetao Plain on the east arm of the paleolake, where differences between elevations of the lakeshore deposits are larger. For example, the elevation of the land surface for site HTS8 (Figure 1) in the sand quarry near Balagong Town in the southeastern bank of the Yellow River is at 1104 m a.s.l. with littoral deposits at 1102 m a.s.l. if the overlaid 2 m of alluvial-proluvial gravels are deducted. The top of the subaqueous delta at site HT06-1 near Wuda is at an elevation of 1090 m a.s.l. after the top 3 m of the capping alluvial-proluvial gravels is deducted. Difference elevations of the cut-and-built terraces along the piedmont of Yinshan Mountains are also large due to the different thicknesses of capping alluvium-proluvium and to regional tectonic movements. For example, at site HTS3 near a cement factory in Wuyuan County, the land surface is 1100 m a.s.l. (Figure 1). At site HTS1 to the north of Wugai Town in Wuyuan County, the littoral gravel lies at 1083 m a.s.l. At site HTS4 it is at 1090 m a.s.l. while at site HT06-8 along the piedmont of the Daqing Mountain the littoral deposits are at 1089 m a.s.l. Previous research has indicated that the elevations of lacustrine sediments on the Togtoh Platform are between 1000 and 1080 m a.s.l.[6,8,9]. Besides these highest shorelines, lower shorelines are also found in the Hetao Plain. For example, at sites HTS9 and HTS10 in sand quarries near the Hydrological Gauge Station in Hangjin County on the southern bank of the Yellow River, the surface elevation of these embankments are about 1055 m, those in HTS6 and HTS7 in the Shilazhao sand quarry are about 1045 m (Figure 1). Due to the strong tectonic movements in the Hetao area, shoreline features and lacustrine sediments of the same age were apparently uplifted or subsided to different elevations. However, the preserved remnants of the highest shorelines found in the Hetao area generally do not exceed 1100 m a.s.l.

While the highest shorelines and littoral deposits found at different elevations in the Hetao Plain may belong to different lake intervals, it is more likely that they have been altered to different elevations by regional tectonic movements. For example, the littoral cut-and-built terraces along the piedmont of the Langshan-Daqing Mountains, the littoral deposits near Balagong Town in Hangjin County and those in the Jilantai region are generally higher than the shorelines found on the bank of the Yellow River. The Hetao Plain was formed within a Cenozoic fault basin[27] and the basin has been strongly influenced by active tectonic movements through the Quaternary. The Jilantai region, on the other hand, has been relatively stable[28]. The uplift rate on the margin of the Ordos Plateau is 0.3 mm/a[29] and that along the piedmont of the Yinshan Mountain can reach several millimeters per year[27], indicating that the uplift of the mountains surrounding the Hetao Plain is quite rapid. We therefore think the different elevations of the lakeshore terraces along the southern piedmont of the Yinshan Mountain to the northern bank of the Yellow River, varying from 1080 to 1100 m a.s.l., are related to regional tectonics. As a result, we conclude that the highest shoreline in the stable region around Jilantai likely represents the highest lake levels of the megalake in the Jilantai-Hetao area. That is, the highest lake level was at about 1080 m a.s.l. The highest clay-dominant deep-water sediments located at 1060 m a.s.l. on the Togtoh Platform are also thought to reflect the highest lake level of 1080 m in this region[9].

Assuming the highest lake level in the area was at 1080 m a.s.l., and given the current regional geomorphological distribution of remnants of littoral deposits and landforms, we deduce that the paleolake extended southwestward to the south of Jinsanjiao south of Jilantai Salt Lake, northward to the southern piedmonts of the Bayanwula-Langshan-Serteng-Daqing Mountains, southward to the northern margin of Ordos Plateau including much of the current Kubq and Ulan Buh Deserts, and eastward to Hohhot City, including the Hohhot-Baotou Basin on the far east end of the Hetao Plain (Figure 1). The area of the paleolake was possibly even larger than that of the current Lake Baikal, with a surface area of 34000 km^2, and during the late Quaternary was the largest confirmed inland lake in China. Based on previous nomenclature[9], we suggest the megalake be named "Megalake Jilantai-Hetao".

3.2 Chronology of Megalake Jilantai-Hetao

The ages of the Megalake Jilantai-Hetao lake levels are controlled primarily by OSL dating of samples collected in the field from lakeshore sands, eolian sands and lacustrine fine sands, and by ^{14}C ages of organic material (Table 1). In this study, bleaching of these samples before burial can be grouped into two situations based both on the character of D_e values distributed on a radial plot[30], and those of the relationship between D_e value and the corrected first regenerated OSL[17,31]. In the first situation, the samples were homogeneously bleached before burial (for example, sample HT050716-4) with concentrated D_e values in the radial plot (Figure 5(a)) and corrected-first-regenerated-OSL-independent D_e values (Figure 5(c)). In the second situation, the samples were heterogeneously bleached (for example, sample JLT040920-30(4)) with scattered D_e values or 2 dominant D_e values in the radial plot (Figure 5(b)) and corrected-first-regenerated-OSL-dependent D_e values (Figure 5(d)). In this study, most of the samples were completely bleached with a similar OSL character to those in the first situation, and individual samples were partly bleached with a similar OSL character to those in the second situation. For these partly bleached samples, the aliquots with smaller D_e values should present the adjacent age of the sediments[32]. We selected the aliquots with small D_e values in calculating the ages of these partly bleached samples.

Below about 1035—1040 m a.s.l., the area around Jilantai Salt Lake becomes a closed basin and is hydrologically separated from the Hetao Plain. Our Preliminary analyses of strontium ratios from mollusks in

Table 1 OSL and ^{14}C dating results of the remnants of Jilantai-Hetao shorelines

Sample No.	Sampling site	Location	Elevation /depth (m)	Strata	Material/method	Age
JSJ050702-2	S36/Jinsanjiao	39°29'55" 105°35'21"	1083/0.8	lacustrine silt	Quartz/OSL	79.61±6.05 ka
JLT040920-20(3)	S34/NW of JLT	39°47′44″ 105°37′19″	1078/0.2	littoral gravels	Quartz/OSL	60.34±4.62 ka
JLT20060707-6	S32/West of JLT	39°44′01″ 105°33′22″	1068/1.1	same as above	Quartz/OSL	56.39±4.67 ka
JLT20060707-7	Same as above	same as above	1068/15.2	eolian sand	Quartz/OSL	67.51±7.26 ka
JLT040920-30(4)	S31/ NW of JLT	39°46′59″ 105°37′31″	1071/0.3	littoral gravels	Quartz/OSL	52.05±3.79 ka
HRM040928-50	HS12/Herimuxini	40°12′41″ 106°08′16″	1081/0.5	littoral gravels	quartz/OSL	56.99±4.42 ka
HRM050712-1	same as above	same as above	1081/12.0	lacustrine sand	quartz/OSL	94.91±8.45 ka
HT20050716-1	HTS8/ Balagong sand quarry	40°15′55″ 107°03′06″	1104/2.0	littoral sands	quartz/OSL	53.81±3.99 ka
HT050716-2	same as above	same as above	1104/3.5	littoral gravels	quartz/OSL	63.84±5.15 ka
HT050716-3	same as above	same as above	1104/5.5	littoral sandy	quartz/OSL	74.80±6.08 ka
HT050716-4	same as above	same as above	1104/10.0	alluvial sand-gravel	quartz/OSL	80.74±6.09 ka
HT050714-1	HTS3/ Wuyuan County	41°18′57″ 108°29′00″	1100/0.6	lacustrine silty sand	quartz/OSL	61.89±4.62 ka
HT050714-2	HTS4/ Wuyuan County	41°07′28″ 108°56′21″	1090/0.5	littoral gravels	quartz/OSL	51.26±5.40 ka
HT20050714-4	same as above	same as above	1090/6.0	littoral gravels	quartz/OSL	71.90±7.34 ka
HT20060715-2	HT06-11/Tokq	40°13'30" 111°13′00″	1014/14.0	lacustrine silt	quartz/OSL	75.99±6.41 ka
HT050713-3	HTS1/Wugai Town	41°17′43″ 107°29′54″	1083/2.6	lacustrine clayey silt	quartz/OSL	52.19±4.15 ka
JLT20060709-2	S42/ 1060 m shoreline of JLT	39°57′00″ 105°37′01″	1061/1.0	littoral gravels	quartz/OSL	32.92±3.31 ka
JLT040920-30(8)	S18/1050m shoreline of JLT	39°47′53″ 105°39′58″	1048/0.3	littoral gravels	quartz/OSL	25.44±1.78 ka
JLT040923-35(4)	S16/ 1044 m shoreline of JLT	39°44′11″ 105°34′25″	1044/0.35	littoral gravels	quartz/OSL	7.05±0.66 ka
JLT040916-50	S11/south sand quarry of JLT	39°44′57″ 105°38′40″	1038/0.5	gravels on the top of sand spit	quartz/OSL	8.59±0.68 ka
JLT050703-1	same as above	same as above	1038/13.0	gravels at the bottom of the sand spit	quartz/OSL	10.39±0.88 ka
HRM040921-4	HS4/Herimuxini spit	40°11′49″ 106°11′26″	1042/0.6	gravels of sand spit	quartz/OSL	8.61±0.82 ka
OSL-15#	S7/West of JLT	39°39′53″ 105°36′17″	1032/0.4	eolian sand	quartz/OSL	5.82±0.47 ka
WP339-09-17	same as above	same as above	1032/0.5	on the top of wetland peat	charcoal/C-14	5.13±0.12 cal ka BP
HT060711-1	HT06-1/Wuda	39°32′52″ 106°46′28″	1093/7.0	lenticula in delta profile	charcoal and plant remains/C-14	41.45±0.47 cal ka BP
JLT050928-1	S49/Salt Lake Jilantai	39°43'37" 105°43'37"	1023/3.0	bottom of halite layer	bulk organic /C-14	5.45±0.13 cal ka BP
JLT050928-2	same as above	same as above	1023/3.0	same as above	bulk organic /C-14	5.47±0.24 cal ka BP
JLT050928-3	S50/Salt Lake Jilantai	39°47′17″ 105°42′41″	1023/2.7	bottom of halite layer	bulk organic /C-14	4.55±0.16 cal ka BP

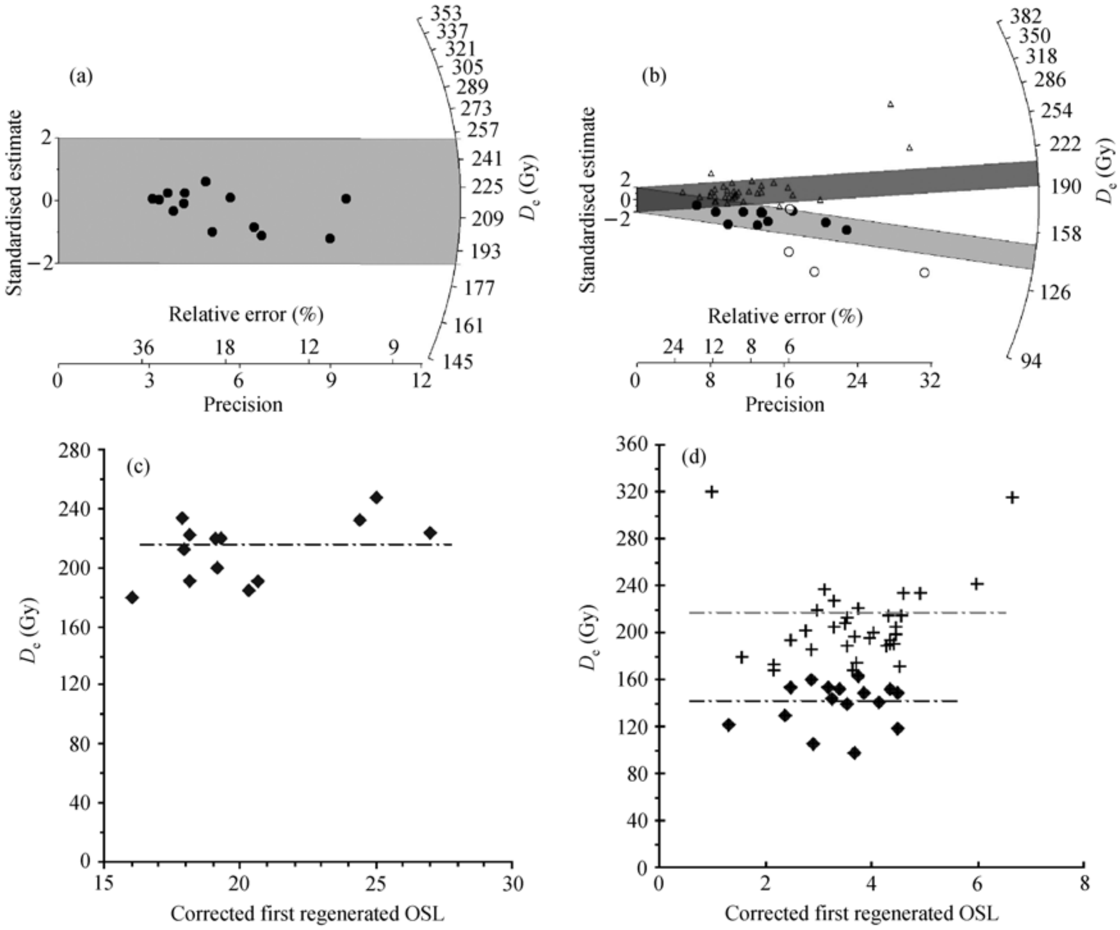

Figure 5 Radial plot of D_e values ((a) and (b)) and the relationship between D_e value and the corrected first regenerated OSL ((c) and (d)) for sample HT050716-4 ((a) and (c)) and sample JLT040920-30(4) ((b) and (d)). The filled circles in (a) and (b) are the D_e values used to calculate the average D_e. The filled diamonds in c and d represent the D_e values used to calculate the average D_e, and the crosses represent the D_e values rejected and not used to calculate the average D_e.

shoreline sediments suggest that water in the lake was derived primarily from the Yellow River when the megalake was at elevations above about 1050 m a.s.l., but that water in the lake below about 1050 m a.s.l. was derived from other sources (details are being prepared for publication in other journal). The preliminary dating results by both OSL and ^{14}C (Table 1) indicate that Holocene lake levels never exceed 1050 m a.s.l., and most possibly did not exceed 1040 m a.s.l., which is consistent with the previously reported dating results[3,44] and two ^{14}C ages from the samples from the bottom of the halite layer at 3 m depth in Jilantai Salt Lake (Table 1). These two ^{14}C ages indicate that the halite layer was formed only since 5500 cal a BP. Based on the strontium ratios from mollusks in shoreline sediments, together with the geomorphology of the basin floor, it is likely that a Holocene paleolake was closed within the Jilantan basin and did not cover the whole Hetao Plain. It maybe there are as yet unresolved issues with these Holocene age estimates, and more dates and field investigation are needed to solve the chronological, climatic, environmental and tectonic significance of the shorelines at lower elevations during the Holocene. For these reasons, understanding the ages of low elevation lake level fluctuations in the Jilantai basin constitutes a separate problem from understanding the chronology of Megalake Jilantai-Hetao. As we are still attempting to resolve issues with the ages of the lower elevation lakes, we here consider only the probable ages of the Megalake Jilantai-Hetao above about 1060 m a.s.l.

The OSL ages of the littoral sand-gravel on the highest shorelines in the west bank of Jilantai Salt Lake is 60.34±4.62 ka (S34, 1078 m a.s.l.) and 52.05±3.79 ka (site S32), similar to the age of the highest shoreline littoral deposits at site HS12 of Herimuxini (Figure 4). At site HS12, silt and silty clay lacustrine sediments more than 10 m thick underlies littoral sand-gravel (Figure 4). The littoral gravel was dated to be ~57 ka and a thin sand wedge between deeper water deposits to be ~94.9 ka at Herimuxini (HS12, Table 1), indicating that the area was covered by a paleolake before ~50 ka. Site HTS8 (1104 m a.s.l.) in the sand quarry near Balagong Town preserved the unique exposed section with complete sequences of alluvial-proluvial gravels, littoral gravels, lacustrine sand and silt from bottom to top. Four OSL dating results (Table 1, Figure 4) of this section indicate that the littoral gravels of the highest lake level were formed from ~70 to ~50 ka ago. The alluvial-proluvial gravels indicate that the paleolake did not reach that site before ~70 ka. As this site is located on the margin of the basin and tectonic movements may not be a concern, the highest lake level definitely did not reach an elevation higher than 1100 m a.s.l. before 70 ka. The OSL ages from 3 sites along the southern piedmont of the Langshan Mountain in Wuyuan County (HTS1, HTS3 and HTS4) are between ~60 and ~50 ka (Table 1). Shoreline deposits at altitudes of ~1070—1080 m a.s.l. (e.g., S32, S34, HS12, HTS1, HTS3, HTS4, and HTS8) consistently are between ~60—50 ka (as noted, we think shoreline features in the eastern arm of Megalake Jilantai-Hetao are tectonically elevated and use the features in the Jilantai area to estimate nominal lake levels). Based on these OSL dates of the highest shoreline deposits at different sites (Figure 4), we are confident that most of Jilantan-Hetao area was covered by a huge lake sometime before ~60—50 ka and the megalake began to decline in altitude afterward. Though the lake levels may have experienced several fluctuations during the period between 50 ka and the Holocene (Figure 3), both geomorphological evidence and available dating results indicate that lake levels generally regressed during this time and did not reach the higher elevations of Megalake Jilantai-Hetao.

Core data from the Hetao Plain suggest that lake environment were present in the basin throughout most of the Quaternary. For example, in cores Wu-9, Wu-12 in Wuyuan County and core Bai-1 in Urad QianQi, the thickness of continuous lacustrine sediments reaches 200 m[33,34]. Thick Quaternary lake sediments were also seen in cores ZKHB and CKB24 in the Baotou-Hohhot basin[35]. Long core documents in Salt Lake Jilantai also show alternating intervals of lacustrine sediments and sand-gravels during Quaternary[36]. In this study we found the oldest age estimate of ~94.9 ka was obtained from a thin sand wedge between deeper water deposits at a depth of 12 m at Herimuxini (HS12). While we cannot directly associate the lower deep water deposits with a known shoreline, it was likely significantly higher than the ~1069 m a.s.l. sample altitude. Deep water deposits at Jinsanjiao (S36) at an elevation of ~1082 m a.s.l. are dated as ~79.6 ka and those at Togtoh Platform (HT06-11) at an elevation of ~1014 m a.s.l. are dated as ~76.0 ka, but, again, although we are unsure of how much higher than these elevations the lake surface was during this interval it can be confirmed that even earlier lakes may exist in the study area. These data indicate that the Jilantai-Hetao area experienced several periods of paleolakes, among which the Megalake Jilantai-Hetao before and during ~60—50 ka reported in this paper was the largest one and most recent one.

Presently it is hard to identify the exact reason why the OSL dating results of littoral deposits at elevations between about 1070 and 1100 m a.s.l. are between ~60 and ~50 ka BP since there is a 30 m elevation difference among these sites. On the one hand, regional tectonic movements[37] are strong and the littoral deposits on the high shoreline along the piedmonts of Langshan Mountain and that near Balagong Town in Hangjin County may have been uplifted to different elevations. On the other hand, the climate during the period of 60—50 ka experienced large amplitude fluctuations as indicated by speleothems[38,39] and loess-paleosol sequences[39−41] that the Asian summer monsoon experienced large amplitude rapid changes at millennial scales. In the marginal regions of the Asian summer monsoon, however, the climate is relatively sensitive to these changes. For example, a core taken by the International Continental Drilling Project (ICDP) from the Qinghai Lake (current water depth is 27 m) indicated that the lake was nearly dried up during the last glacial period (Wang Sumin, personal communication). Under such climate situations, the lake level of Megalake Jilantai-Hetao was inevitably subject to large-amplitude variations. Unfortunately neither the resolution of littoral deposits nor the precision of OSL dating was able to reflect such rapid climatic events.

Another question needed to be solved is why the Megalake Jilantai-Hetao could exist in the Hetao Plain before ~60—50 ka. There are likely two possibilities.

First, we hypothesize that tectonic events created bedrock sills that dammed the Yellow River, resulting in the formation of the megalake in the Jilantai-Hetao basin. Downcutting across these sills and headward erosion up Jinshan Canyon likely gradually lowered lake level elevations to form the different low shorelines. We further hypothesize that the last major cycle of uplift and downcutting is associated with the development and recession of the Megalake Jilantai-Hetao interval reported here. Exactly when the Yellow River shifted northward around the Ordos Plateau is not yet fully known. Li et al.[43] suggest this occurred during the late Miocene or early Pliocene, which coincides with the regional geological report in the Hetao Plain[1]. Regardless of when the river first shifted to the north, for a megalake to have formed in the Jilantai-Hetao basin the Yellow River may have been dammed at some point. It is likely that this elevated sill was located somewhere near or northwest of the head of Jinshann Canyon where the Yellow River turns south around the Ordos Plateau, but the nature and exact location of this sill remains unknown. It is possible such a sill, and consequently lake formation in the Jilantai-Hetao basin, existed from the earliest entry of the Yellow River into the basin. This is just a propose and needs to be confirmed by further research.

Second, humid climate during the last glacial may also be partly responsible for formation of Megalake Jilantai-Hetao. In the arid regions of China, shoreline landforms and lacustrine sediments indicating high lake levels during the Late Quaternary have been widely discovered in the current Tenger Desert[5,45,46], Juyanze[47,48], Qaidam Baisin[49], and Chaiwobao Lake, Manas Lake[50] and Balikun Lake[51] in Xinjiang. In addition, high levels of paleolake during late Quaternary have also been reported on the Tibetan Plateau[52−54]. Radiocarbon dating on mollusk shells indicated that the megalake period in the Tengger Desert was between 40 and 20 ^{14}C ka BP[5,46]. The megalake period on the Tibetan Plateau was originally reported to be 40—30 ka BP[49,54] and later dating results suggest that it could be even earlier[55−57]. It is generally believed that a humid climate once existed in the arid area of China during MIS 3. We found multiple shorelines and lacustrine deposits in the Jilantai-Hetao region dated to after 50 ka, possibly as late as the Holocene, in addition to those of the megalake dated to ~60—50 ka ago. While it is obvious that these multiple shorelines must represent more than one interval of the paleolake, more extensive research is necessary to determine whether these shorelines and lacustrine sediments are the result of the regression of a single unified paleolake or of multiple lake level fluctuations. Further study must also resolve whether the evolution of Megalake Jilantai-Hetao was driven by regional tectonic movements or by multiple climatic fluctuations, and whether the formational mechanism of Megalake Jilantai-Hetao was similar to those of paleolakes reported in other regions in the arid area of China.

4 Conclusions

Based on geomorphological field investigations of well-preserved shoreline features around Jilantai Salt Lake, together with analyses of remote sensing images and analyses of sediments and biological remains, we confirmed that the presence of a paleo-megalake whose shorelines can be traced to the Hetao Plain. Remnant littoral deposits and shoreline landforms such as barrier bars and spits are well preserved to the west, north and southwest of Jilantai Salt Lake, and at sites such as the sand quarry near the Yellow River Hydrological Gauge Station and Shilazhao sand quarry farther east in the Hetao Plain. Four groups of shorelines at around 1060, 1050, 1044 and 1035 m a.s.l. are evident along the western margin of the salt lake, and are 37, 27, 21 and 12 m higher than the current Salt Lake Jilantai, respectively. On the southwestern margin of the salt lake the 1060 and 1050 m a.s.l. shorelines extended continuously ~20 km. The 1060 m a.s.l. shoreline is composed of two parallel sub-shorelines characterized by barrier bars, with combined width of 100 to 150 m. The 1050 m a.s.l. shoreline also contains several sub-shorelines. The 1044 and 1035 m a.s.l. shorelines are comparatively small and less developed.

Higher lakeshore landforms around elevations of 1070—1080 m a.s.l. are relatively well preserved in Jinsanjiao southwest of the salt lake and at individual sites west of the salt lake. Wave-cut platforms, shoreline notches and lacustrine sediments are found at elevations between 1080 and 1100 m a.s.l. along the southern piedmont of Yinshan Mountain, forming the cut-and-built terraces. In addition, a subaqueous delta was identified near Wuda where the Yellow River enters its Great Bend, and typical lacustrine sediments occur near

Togtoh where the Yellow River exits the Great Bend. Mollusk shells of *Corbicula*, *Radix lagoti*, *Radix xauricularia* and *Gyraulus convexiusculus* are common in these littoral deposits. Well-exposed profiles of littoral deposits in this area have a typical vertical prograding sequence. All this evidence indicates that there was once a megalake covering the Jilantai-Hetao area that we refer to as "Megalake Jilantai-Hetao." Shoreline elevations around much of the Hetao Plain have been altered by tectonic events, and we use the more stable elevations around Jilantai Salt Lake to estimate its size. When the lake level was at 1080 m a.s.l. or so, it covered the present Jilantai basin and most of the Hetao Plain, and, with an area of ~34000 km^2, was even larger than the modern Lake Baikal. Lakes may have begun to form in the Jilantai-Hetao basin as soon as the Yellow River was diverted to the north around the Ordos Plateau, but the nature and age of these earlier lakes is unknown. OSL dating of the littoral sand-gravels suggests that the most recent megalake cycle may begin to form sometime before ~100 ka, but the most well-preserved shoreline features of Megalake Jilantai-Hetao formed around ~60—50 ka ago, which is the last and recent largest lake in the area.

We stress that our current study of the Paleo-megalake Jilantai-Hetao is only in its initial stages and that many questions remain. For example, our hypotheses about how the lake was formed, the ages of the lower shorelines around the Jilantai basin, and the relation between lake level fluctuations and regional climatic change, all remain to be tested. The long-term development of the Yellow River, the formation and evolution of the Ulan Buh and Kubq deserts, and the nature and timing of tectonic movements are also still not clear. What is clear is that Megalake Jilantai-Hetao once occupied most of the Hetao Plain during the late Quaternary and likely had tremendous impact on the regional environment and climate. Further research on this amazing lake is needed.

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