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Paleoshoreline geomorphology of Böön Tsagaan Nuur, Tsagaan Nuur and Orog Nuur: the Valley of Lakes, Mongolia

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Abstract

We conducted a preliminary study of paleoshoreline features associated with Böön Tsagaan Nuur, Tsagaan Nuur, and Orog Nuur, lakes located in the Gobi–Altai transition zone of the Valley of Lakes (Dolina Ozor) which stretches from central to western Mongolia. The paleoshoreline features were first identified on RADARSAT satellite SAR imagery. We investigated the features during the 1998 field season of the Joint Mongolian–Russian–American Archaeological Expedition to the Gobi–Altai region. We identified paleoshorelines of multiple elevations in the field, which are considered to be relict beach ridges and wave-cut terraces. Other paleolake landforms include spits and Gilbert-type deltas. These landforms are complex, large and well established, implying that the paleolakes were stable for extended periods. The reconstructed paleolakes cover extensive areas of the valley floor, implying that hydrological and climatic conditions were very different in the past. Paleolake expansions may have occurred under a variety of circumstances. One hypothesis is that the high lake stands occurred during the wetter period corresponding to the Oxygen Isotope Stage 3 prior to the Last Glacial Maximum (LGM), during the warmest early Holocene and the late Holocene, or during all these periods. If low evaporation rates due to lower temperatures, glacier meltwater and possibly increased precipitation are important factors, then the expansions may have occurred during the terminal Late Glacial period after the Last Glacial Maximum. The greatly expanded lakes in the Gobi–Altai could have significantly affected the Quaternary human demography and migration in the region.

Keywords: Mongolia; Gobi Desert; Altai Mountains; Lakes; Shoreline features; Quaternary

1. Introduction

The paleohydrology of Mongolia has been, due to the country's recent geopolitical history, studied primarily by researchers from the former Soviet bloc. Some research results have been published (e.g., Devyatkin et al., 1978; Murzayeva et al., 1982; Dorofeyuk, 1988, 1992; Sevastyanov et al., 1989; Atlas of the Mongolian People's Republic, 1990; Sevastyanov and Dorofeyuk, 1992), however little has appeared in major international journals. In addition, because of the size of the country and logistical problems, large areas remain for more detailed study. Some new studies were conducted in western Mon-

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golia, focusing on both geomorphological and paleoclimatic elements (e.g., Grunert et al., 2000). Our study intends to provide a basis for more detailed researches that should be compared with a regional trend summarized by Lehmkuhl and Haselein (2000) and other paleohydrological elements such as rivers and glaciers in Eurasia.

We had an opportunity to study the paleoshorelines of two lakes in south-central Mongolia, in the transition zone between the Gobi Desert and Altai Mountain Range. This opportunity came as part of the 1998 Joint Mongolian–Russian–American Archaeological Expedition, which has undertaken a long-term study of Paleolithic human occupation in the region (Derevianko et al., 1996, 1998, 2000; Blackwell et al., in press). One of our goals on the expedition was to study the paleolakes and reconstruct the environment in which early humans migrated and settled. Böön Tsagaan Nuur and Orog Nuur are lakes located in the so-called 'Valley of Lakes' (Fig. 1). The Valley of Lakes is a region currently occupied by a chain of lakes in central and western Mongolia. This valley is bounded by the Hangai Plateau to the north and the Altai Mountain Range to the south. Böön Tsagaan Nuur is located south of the Hangai Plateau that is one of main sources of water for the lake via the Baidrag Gol. Orog Nuur is located in a valley north of Ikh Bogd, a mountain range up to about 4000 m high (Lehmkuhl, 1998). This lake is fed by the Tüin Gol from the Hangai Plateau, in addition to smaller drainages from the Ikh Bogd range. These two lakes were chosen for study because of their proximity to our ongoing cave excavations at Tsagaan Agui where a large number of Paleolithic stone tools dating back as far as 100,000 years ago has been discovered (Derevianko et al., 2000).

Our analyses were conducted using RADARSAT SAR imagery (Fig. 2) in conjunction with field observations. The RADARSAT SAR operates at a wavelength of 5.66 cm and HH (horizontal–horizontal) polarization. The RADARSAT products that we used are Standard Beam Full Resolution images with 12.5-m pixel spacing. At Böön Tsagaan Nuur, we

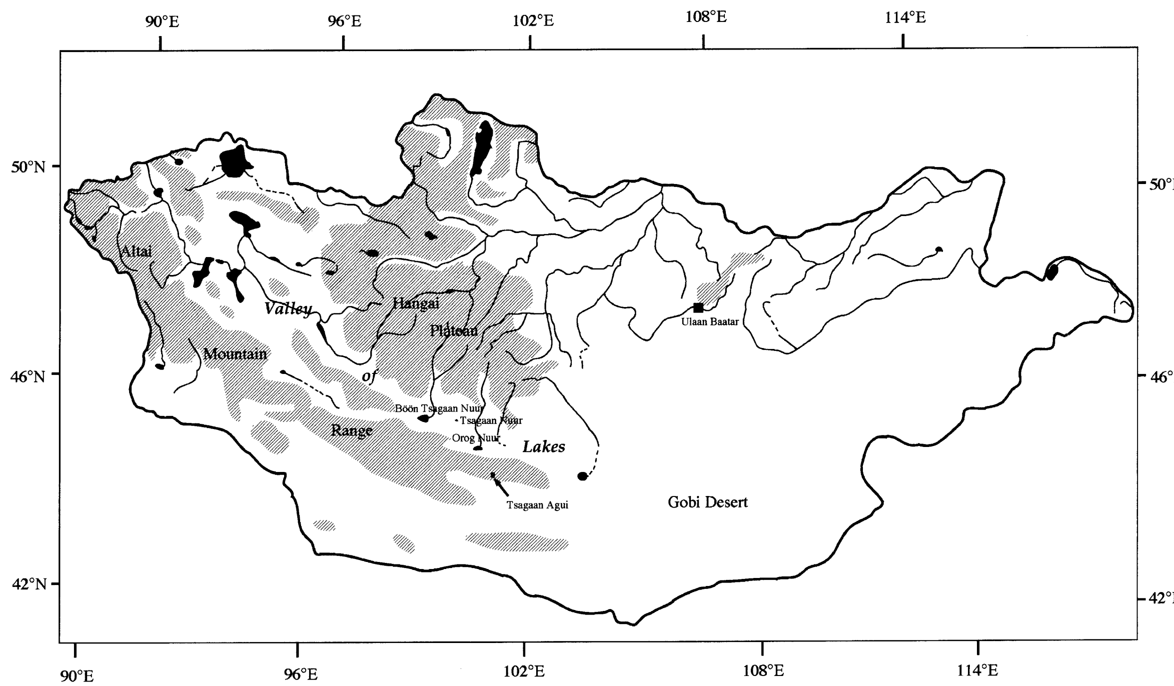


Fig. 1. Geographical map of Mongolia and locations of Böön Tsagaan Nuur, Tsagaan Nuur and Orog Nuur, lakes discussed in this paper. These lakes are located in the Valley of Lakes. The location of our archaeological excavation site Tsagaan Agui is also shown.

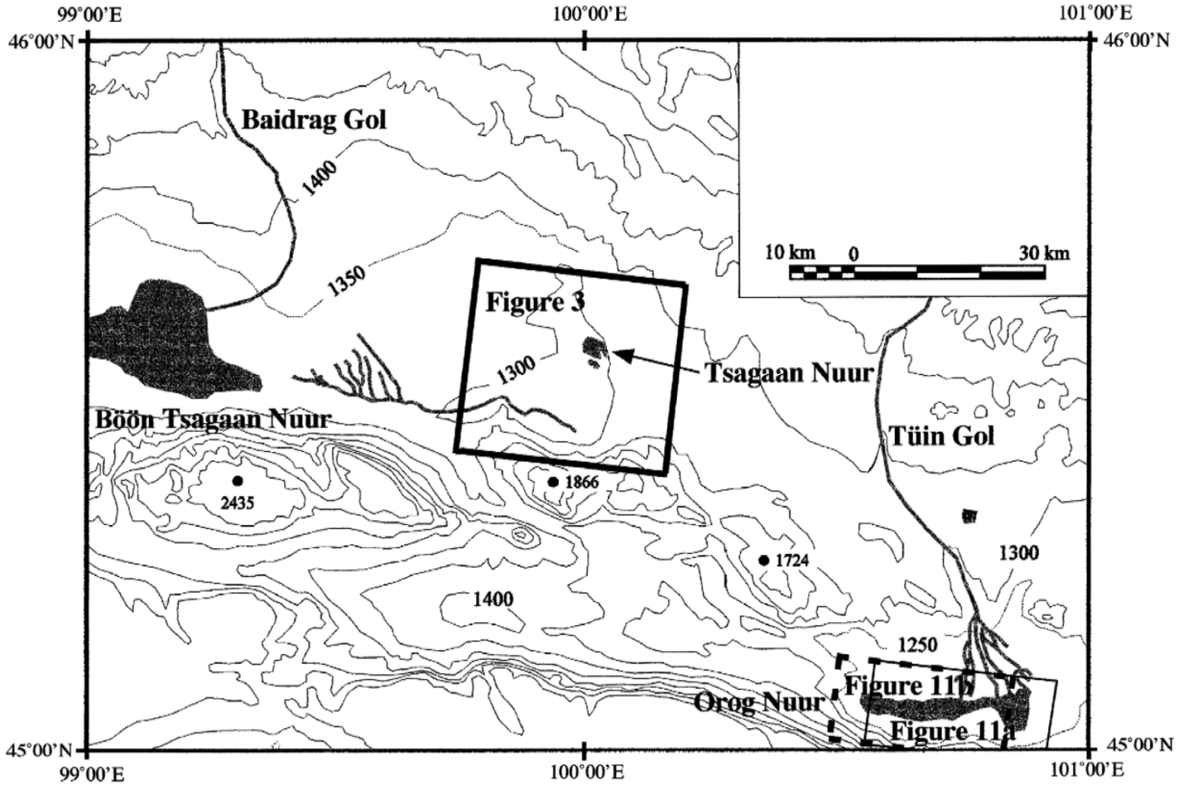


Fig. 2. Locations of RADARSAT images used in this study.

focused our study on an area about 60 km east of the modern-day lake. This area is a small closed depression in the valley and contains excellent exposures of paleoshorelines. Tsagaan Nuur is a small ephemeral lake in this depression. Paleoshorelines associated with Orog Nuur are preserved mostly along the shore of the modern-day lake, therefore research was conducted in close proximity to the lake.

2. Paleoshoreline geomorphology

2.1. Tsagaan Nuur topographic depression 60 km east of Böön Tsagaan Nuur

This topographic depression exhibits a wide range of shoreline geomorphology commonly observed with well-studied paleolakes such as Glacial Lake Bonneville in the USA (e.g., Gilbert, 1890; Currey, 1980, 1990). From radar imagery analysis, we identified a clearly defined group of paleostrandlines on the valley floor (Group A in Fig. 3). Also on the flank of the granitic massif south of the valley there are other strandline features, not visible in the radar image, but identified in the field (Group B; location shown in Fig. 3).

2.1.1. Group A strandlines

The entire strandline zone is about 5–10 km wide east–west, and about 20 km long north–south (Fig. 3). The zone can be divided into three sub-groups, designated as 1, 2, and 3 from west to east. There is a total of 15–20 prominent strandlines recognizable in the radar image but not all of them are continuous. Fig. 4 shows sub-group 1 enhanced by low-angle sunset light. On the ground, the strandlines appear as alternating ridges and troughs (Fig. 5a and b). Their amplitudes typically range from less than 1 m to a

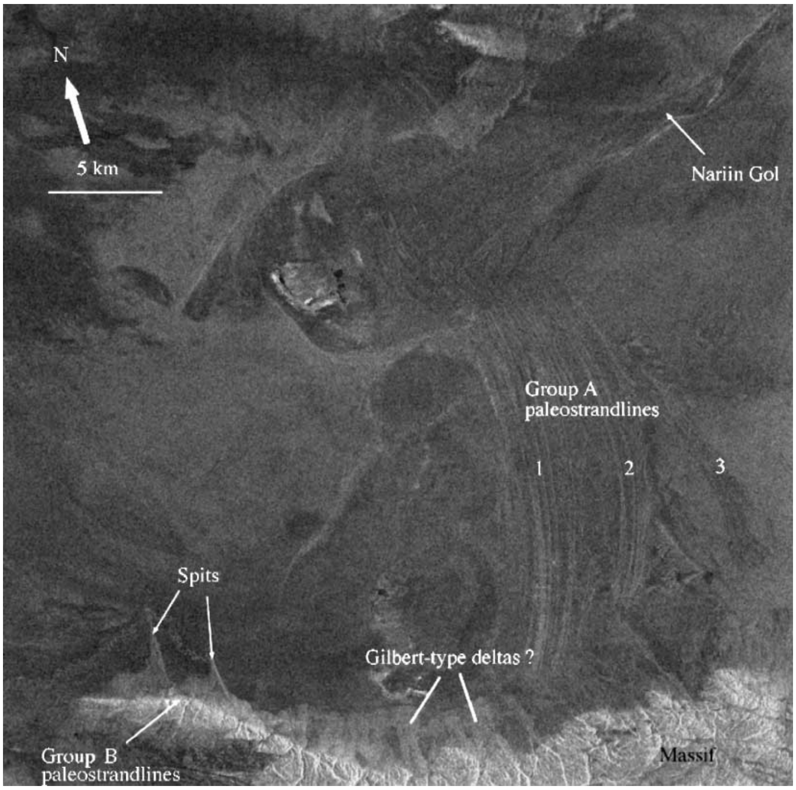


Fig. 3. Paleoshoreline features in the Tsagaan Nuur topographic depression 60 km east of Böön Tsagaan Nuur. Tsagaan Nuur was not present when this image was acquired. Group A paleostrandline zone can be divided in three sub-groups, designated as 1, 2, and 3. RADARSAT Standard Beam Full Resolution image R107266336. ©Canadian Space Agency/Agence Spatiale Canadienne (1997).

few meters. The ridge surfaces are covered with coarse-grained gravel a few centimeters in diameter and the intervening troughs are mantled by fine-grained gravel less than 1 cm in diameter. We interpret these features as relict beach ridges. Their preservation is partly the result of subsurface calcite cementation (caliche). The elevation of a prominent broad ridge (in the sub-group 1) from the closest lowest valley floor is about 20 m (Fig. 6a).

2.1.2. Group B strandlines

There are also paleostrandlines preserved on the flank of the southern massif (Fig. 7). The highest of these is at least 30 m above the valley floor (Fig. 6b). These strandlines are not visible on radar imagery, but their location is shown in Fig. 3. In the field, they appear to be wave-cut terraces carved on unconsolidated slope materials or on bedrock in some locations. Note the valleys in Fig. 7. These valleys are significantly wider above the strandlines and narrower below. This may indicate that the valley incision was limited below the strandlines during a period when the local water surface was much higher. Near shoreline lacustrine deposits perhaps mantled the lower valleys during this period. Upon desiccation, the lacustrine deposits were incised.

2.1.3. Other shoreline morphologies

Many mounds, about 1–2 m high and 5–20 m long, are distributed inside the innermost strandline. These mounds are made of fine-to-coarse grained sands and were probably beach ridges, later reworked by eolian processes (Fig. 8). In any case, these light-colored mounds were perhaps associated with the last semi-permanent paleolake. The lower section of one of these mounds also contains organic

Fig. 4. Sub-group 1 of the group A paleostrandlines. These strandlines are enhanced by low-angle sunset light. These features are probably relict beach ridges.

materials of unknown origin. These organic materials were dated to be 405 ± 40 ^{14}C years B.P. Two prominent spits (1–3 km long) extend north from the massif at the southern end of the paleolake (Figs. 3 and 9). These gravel-rich spits were presumably formed by the movement and deposition of materials by longshore currents in the paleolake. The fans emanating from the massif (Fig. 3) morphologically show flat tops marking former lake levels (about the same levels as Group B strandlines), and they are steep-sided toward the center of the basin (Fig. 10). This geometry is characteristics of Gilbert-type deltas, a type of fan delta (Ori and Roveri, 1987; Oviatt et al., 1994; Milligan and Chan, 1998; Lemons and Chan, 1999; Enzel et al., 2000). Gilbert-type deltas are also characterized by a well-defined near horizontal stratification pattern at their tops (topsets) and oblique beds (foresets) in their main bodies underlying the topset facies. In the field, we observed the near horizontal fine to coarse-grained stratification but not the oblique ones. The lower parts of the bodies (where we expect the foresets) are covered by detritus. However, the Gilbert-type delta interpretation is strongly supported due to the facts that the bodies are placed at the mouths of mountain streams, and their external geometry, the flat surfaces and steep sides.

2.2. Orog Nuur

The radar imagery shows paleoshorelines close to modern-day Orog Nuur (Fig. 11a and b). Groups of paleostrandlines are observed east and west of the lake. The paleostrandlines east of Orog Nuur have a surface ridge and trough geomorphology similar to the valley floor strandlines near Tsagaan Nuur. These are probably relict beach ridges. We were not able to conduct detailed topographic surveys due to swampy

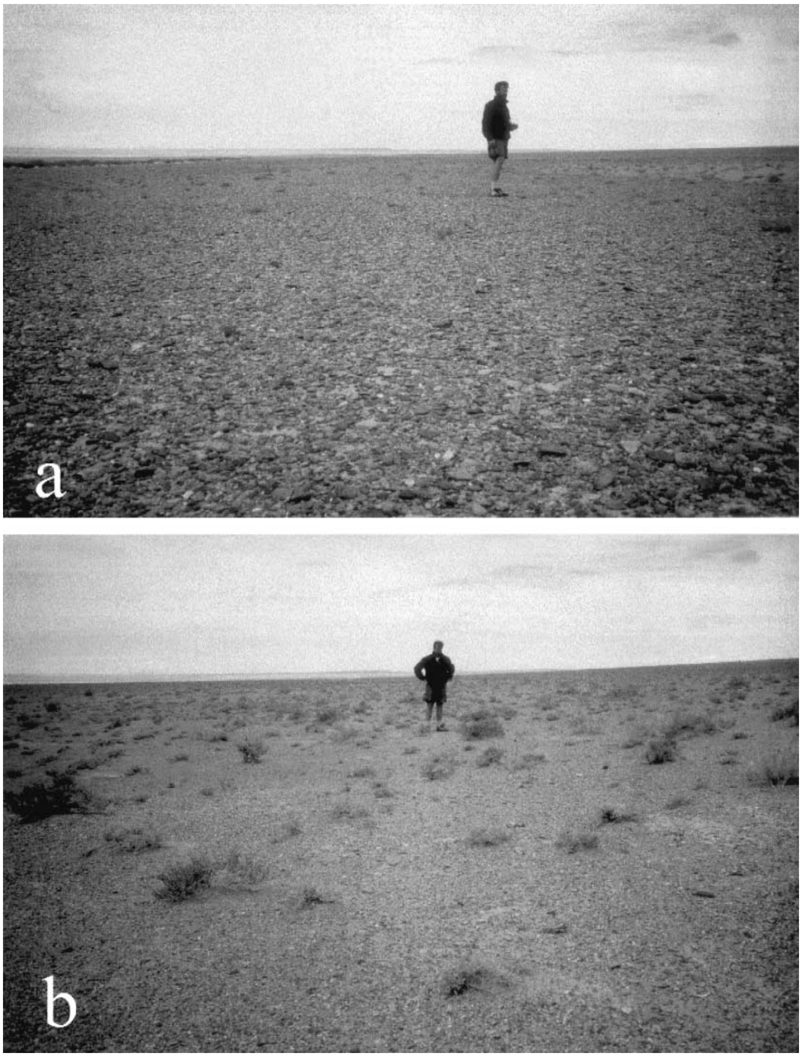


Fig. 5. (a) Ridges of strandlines are covered with coarse-grained gravel a few centimeters in diameter. (b) Intervening troughs are mantled by fine-grained gravel less than 1 cm in diameter.

conditions near the lake. It is also possible that higher level shorelines exist on the alluvial fans to the south of Orog Nuur, but we found no clear evidence on our expedition.

The paleoshoreline landforms associated with the Tsagaan Nuur topographic depression and Orog Nuur are complex, large and well established features. This implies that the paleolakes were stable for extended periods. For example, the formation of multiple level beach ridges and wave-cut terraces requires a prolonged history of transgressions and regressions. Depositional features such as spits and Gilbert-type deltas are relatively large (maximum, a few km long), and this means that the paleolakes responsible for these features were not ephemeral in nature.

3. Reconstruction of paleolakes

We investigated the areal and volumetric extent of the paleolakes associated with the depressions where

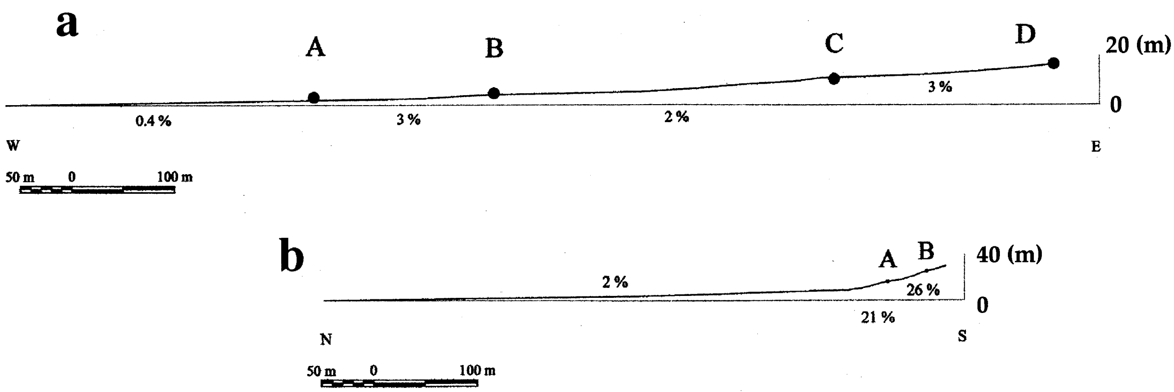


Fig. 6. (a) Longitudinal profile of valley floor strandlines. A, B, C and D correspond to each strandline. (b) Longitudinal profile of massif strandlines. A and B correspond to two levels of terraces. Also shown are the slopes of each segment of the profiles.

we studied the paleoshoreline features described above. We used field data obtained on our expedition combined with United States Geological Survey 1-km grid digital topographic models (DTMs) of the world

Fig. 7. Massif strandlines (group B strandlines). See two people and a truck for scales. Note the valleys that are significantly wider above the strandlines and narrower below. The valley incision was perhaps limited in the lower part during a period when the local water surface was much higher.

Fig. 8. Exposed cross-section of mounds made of fine-to-coarse grained sands distributed inside the innermost group A strandlines. Based on the convex-up stratification and the low angle cross lamination, we consider that these mounds were beach ridges. The near horizontal beds on top of this beach ridge are probably eolian deposits.

(Fig. 12). Mongolian topographic maps (1:500,000) were also used to assist this work. We employ Orog Nuur data for supplementary purposes only. Our field survey method for obtaining the cross-sectional

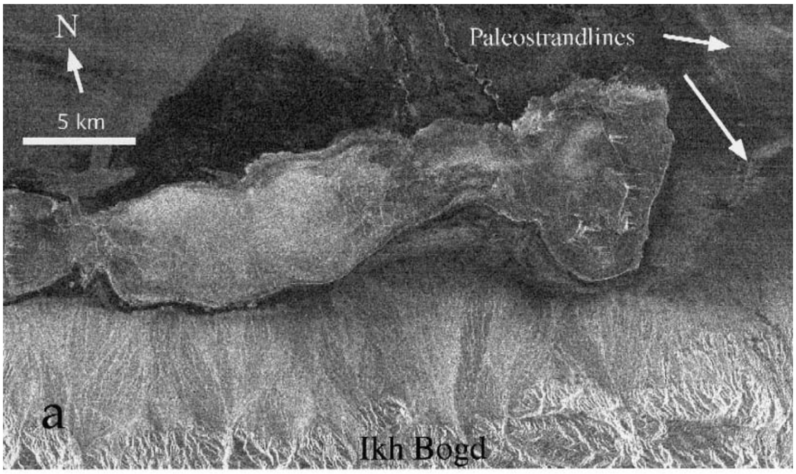
Fig. 9. This gravel-rich ridge is one of two spits extending from the massif south of the paleolake.

Fig. 10. A complex of possible Gilbert-type deltas. Note the flat top and steep-sided structure of the fan deltas in front of the mountains.

profiles (Fig. 6a and b) chose a datum in the flat valley floor close to the strandlines. The datum levels are not co-registered to the topographic maps accurately nor to each other. Instead, we carefully compared the radar image, field observations, GPS coordinates, and topographic maps to derive the altitude of the strandlines. We conclude that the valley floor strandlines (Group A) correspond to altitudes ranging from slightly less than 1300 to about 1350 m. The massif strandlines (Group B) are more difficult to constrain and the highest level of these may reach over 1350 m. We conservatively estimate that the massif strandlines also correspond to 1300–1350 m. Therefore, we have reconstructed paleolakes for three lake levels, 1250, 1300 and 1350 m (Fig. 13a, b, and c; Table 1). We do not know the exact altitude of the deepest part of the Tsagaan Nuur topographic depression. But based on the DTM, the maximum depth of the paleolake at the 1350-m level may have reached 100 m locally.

Because the region is relatively active with neotectonics (Cunningham et al., 1997; Owen et al., 1997), these reconstructions of the paleolakes should be assessed with caution. However, we consider the reconstructions reliable based on the fact that the paleoshoreline features follow the modern-day topography relatively closely.

The modern-day lake level of Böön Tsagaan Nuur is slightly higher than 1300 m and the divide between the two areas is about 1320 m. At the 1350-m level, the paleo-Tsagaan Nuur is completely connected with Böön Tsagaan Nuur 60 km to the west. It is unclear at this point whether or not Orog Nuur experienced expansions up to 1300 and 1350 m; we have not found clear shoreline evidence corresponding to these altitudes. The altitudes of the paleostrandlines east and west of modern-day Orog Nuur are probably less than 1250 m, and are more likely about 1220–1230 m based on available topographic maps. The level of the present-day lake lies at about 1210–



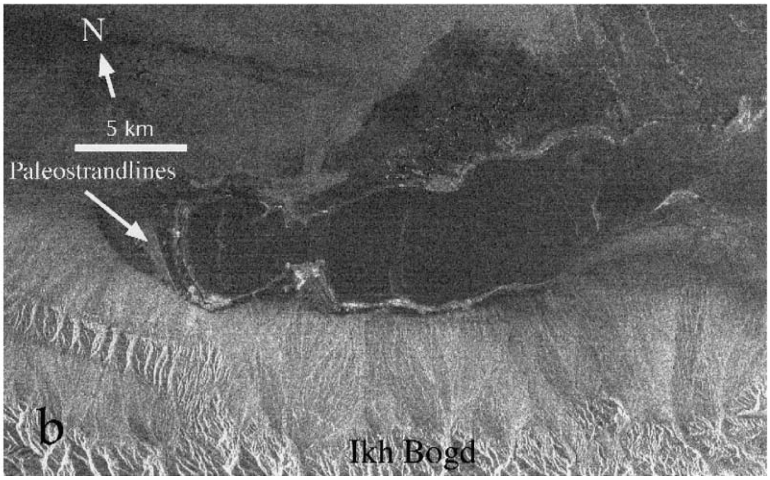


Fig. 11. (a) Paleostrandlines east of Orog Nuur. The lake is ice-covered. RADARSAT Standard Beam Full Resolution image R107023338. ©Canadian Space Agency/Agence Spatiale Canadienne (1997). (b) Paleoshorelines west of Orog Nuur. The lake is ice-free. RADARSAT Standard Beam Full Resolution image R107266336. ©Canadian Space Agency/Agence Spatiale Canadienne (1997).

1220 m. The paleolake expansion of Orog Nuur to 1220–1230 m is almost negligible. At the 1400 m level (Fig. 12), the lake basins of the Böön Tsagaan Nuur–Tsagaan Nuur system and Orog Nuur join to form a large lake. However, this lake would also spill into the central Gobi. In the case of Orog Nuur, a paleolake of 1350 m would spill to the central Gobi. As these reconstructions suggest, relatively small increases in lake levels (0–50 m) result in drastic changes in lake size due to the flatness of the surrounding valley floor.

4. Paleoclimatic implications

The increased volumes of the paleo-Böön Tsagaan Nuur–Tsagaan Nuur system and the possible ex-

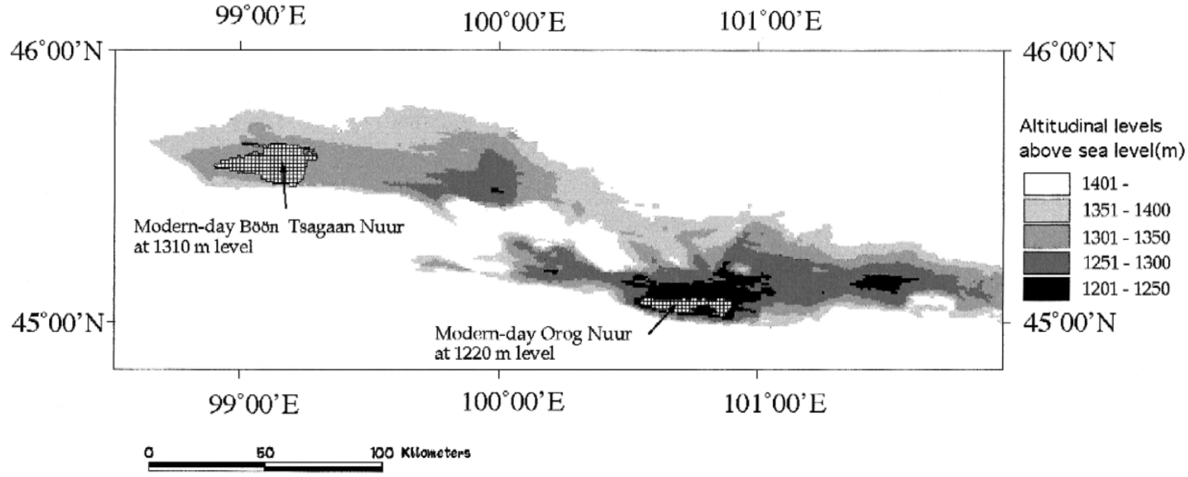


Fig. 12. Topography of the study area at selected elevations. Modern-day Böön Tsagaan Nuur and Orog Nuur are also shown.

panded paleo-Orog Nuur suggested by the paleoshoreline levels require major changes in the hydrological balance in the region. The modern-day Gobi–Altai region receives slightly more than 100 mm of rainfall annually (NOAA, 1999). This is not enough precipitation to support even the 1300-m level paleolake. Unfortunately, the formation ages of the major strandline features have not been determined in our project, and resolution of this point must await future studies. According to the Atlas of the Mongolian People's Republic (1990), three lake shorelines of different ages, all Pleistocene, are evident. However, no details are discussed nor cited in this reference. At this point, paleoclimatological data from the Gobi–Altai region are very limited. However, it is useful to hypothesize the formation of these paleolakes in the context of paleoclimatological studies in other parts of Mongolia and neighboring central China and eastern Siberia.

From a simple lake water-balance model, we can infer the condition that a lake can maintain an expanded area and volume. A change in lake volume

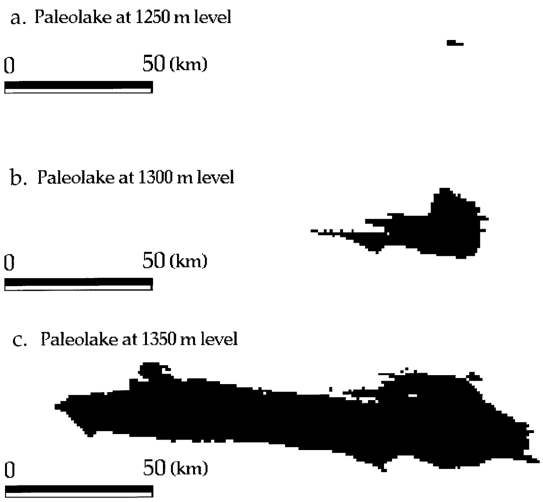


Fig. 13. Paleolakes at elevations of (a) 1250 m, (b) 1300 m, and (c) 1350 m. These paleolakes were reconstructed from data acquired in the Tsagaan Nuur topographic depression 60 km east of modern-day Böön Tsagaan Nuur. Note that the paleolake completely encompasses modern-day Boon Tsagaan Nuur at the elevation of 1350 m.

Table 1
Areas of paleolakes inferred from paleoshorelines in the Tsagaan Nuur depression 60 km east of Böön Tsagaan Nuur. The 1350-m level lake encompasses modern-day Böön Tsagaan Nuur

(m)	Area (km^2)
< 1250	8
< 1300	615
< 1350	3256

(V) can be approximated by the balance equation (Brown, 1995):

$$V = A_L(P_L - E_L) + (R - D) + (G_L - G_O) \quad (1)$$

where V = change in lake volume, A_L = lake area, P_L = precipitation over the lake, E_L = evaporation over the lake, R = runoff from the catchment, D = surface discharge from the lake, G_L = groundwater inflow to the lake, and G_O = groundwater outflow from the lake. R can be expressed as:

$$R = A_B(P_B - E_B) + M \quad (2)$$

where A_B = drainage basin area, P_B = precipitation over the drainage basin, E_B = evaporation over the drainage basin, and M = glacier meltwater. Here, we assume that the groundwater component is negligible so that G_L and G_O equal zero. Also, because these are closed lake basins, $D = 0$. In an equilibrium state ($V = 0$), the Eq. (1) reduces to:

$$A_L = \frac{A_B(P_B - E_B) + M}{E_L - P_L} \quad (3)$$

Based on Eq. (3), we can consider three climatic conditions in which the paleolakes in the Gobi–Altai were larger. Assuming no glacier meltwater ($M = 0$), the lake area A_L is larger when precipitation is higher and evaporation is lower (condition a in Fig. 14). The lake is also larger when the increase in precipitation exceeds the increase in evaporation (b in Fig. 14) or the decrease in evaporation exceeds the decrease in precipitation (c in Fig. 14).

The shoreline features are well preserved, indicating that the expansions of the lakes were relatively recent events, as late as the late Pleistocene and Holocene. But note that a possibility of high lake stands as old as the early to middle Pleistocene certainly exists. Analyses conducted on lacustrine samples taken from Lake Manas, in the Zhunggar Basin of northwestern China, indicate that a late Pleistocene humid episode (condition a, or, in some cases, b in Fig. 14) between 37,000 and 32,000 ^{14}C years B.P. was followed by a period of extreme aridity, which ended at about 12–10 ka (Rhodes et al., 1996). Based on paleolake studies in the Tengger Desert of north-central China, Pachur et al. (1995) inferred humid and cool conditions from about 39,000 to about 23,000 ^{14}C years B.P., then becoming drier. Owen et al. (1997) tentatively correlated the drying trend in central China to changes of sedimentological

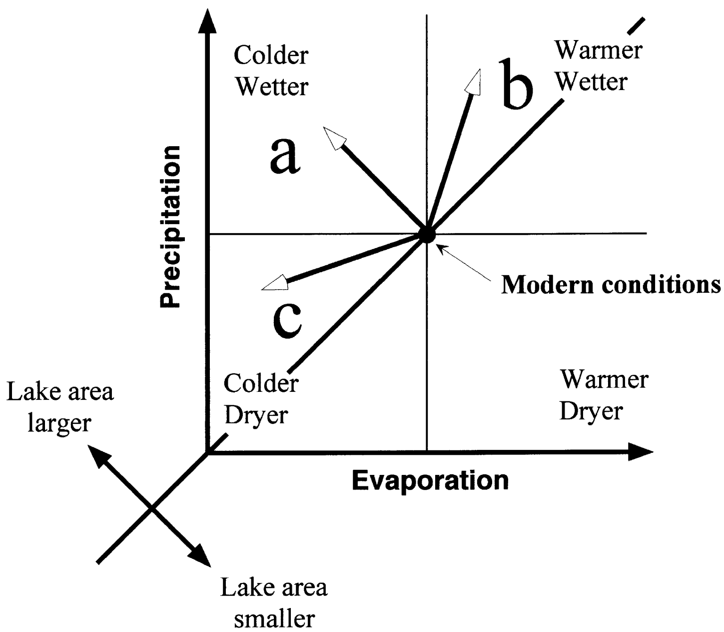


Fig. 14. Schematic diagram showing climatic conditions when a lake is larger.

structures in alluvial fans located in the Gobi–Altai. According to Hopkins (1982), based on correlations in Alaska and eastern Siberia (collectively called Beringia), there are two major ice ages recorded (Happy period, 75–60 ka and Duvanny Yar period, 25–9.2 ka) since the last interglacial period. In Beringia, a drying trend was evident in unglaciated areas during the Duvanny Yar period glaciation. If this drying trend applies to the Gobi–Altai region, the regression of the Böön Tsagaan Nuur–Tsagaan Nuur system and Orog Nuur may be explained in the same climatic-change framework. And these lakes were larger during a period before the full glacial period including the Last Glacial Maximum (LGM), corresponding to the Oxygen Isotope Stage 3.

The early Holocene is another possibility for the lake expansion. Paleoclimatic data complied by Harrison et al. (1996) from lakes in northern Mongolia (Dorofeyuk, 1988, 1992; Sevastyanov et al., 1989; Sevastyanov and Dorofeyuk, 1992) indicate that high lake stands occurred about 7 ka. According to a paleobotanical study of northeast Eurasia (Igarashi, 1998), during the early Holocene (about 8 ka), northeastern Siberia experienced high humidity and temperatures comparable to the present (condition b in Fig. 14). Melting of ice sheets in the Northern Hemisphere was rapid. Analyses of lacustrine sediments in Lake Manas indicate humid and warm conditions after 10 ka until about 6 ka (Rhodes et al., 1996). It is possible that the Gobi–Altai region also had a more humid, warmer climate than present in the early Holocene. This environment could have provided another opportunity for the lakes in the Gobi–Altai to expand. Indeed, a recently conducted dating analysis of the group A strandlines in the Tsagaan Nuur topographic depression obtained an oldest age of about 8.5 ka (Lehmkuhl and Lang, in press). This does not exclude even older lake expansion events but it nonetheless confirms the major lake expansion during the early Holocene. By about 6 ka, the climate in northeast Eurasia became milder and drier than about 8 ka or almost the same as the present day. Therefore, by the middle Holocene, it is likely that the lakes in the Gobi–Altai regressed and reached essentially their modern size. Low lake levels seem to have occurred in northern Mongolia about 3 ka (Harrison et al., 1996) but it is not clear if the paleolakes in the Gobi–Altai region also experienced this dry phase. The late high stands seem to have occurred at about 1.4–1.5 ka (Lehmkuhl and Lang, in press) and the last semi-permanent lake probably existed about several hundred years ago based on the dating of the organic materials in the youngest beach ridges (Fig. 8). It is possible that the paleolakes had expanded phases in all the late Pleistocene, the early Holocene and late Holocene.

The periods discussed above were relatively wet episodes in the late Quaternary of northeast Asia. In contrast, it is generally accepted that the full glacial period (the Oxygen Isotope Stage 2) that includes the LGM was a dry and cold environment in unglaciated areas of Siberia and central China. However, it is known that lower temperatures suppress evaporation, and this effect may have been significant during glacial periods (condition c in Fig. 14). It is known that pluvial lakes, such as Lake Bonneville and Lake Lahontan in the Great Basin of the USA, experienced high stands during and after the abovementioned full glacial period (Benson, 1978; Scott et al., 1983; McCoy, 1987; Oviatt et al., 1987, 1992; Oviatt and Nash, 1989; Street-Perrott et al., 1989; Oviatt, 1997; Adams and Wesnousky, 1998). Low evaporation rates due to low temperatures may have been important in the Great Basin during this period, but also other factors such as diversion of storm tracks southward by the presence of North American ice sheets (e.g., Oviatt, 1997) probably contributed to the existence of these great lakes. Whether or not the lakes in the Gobi–Altai during the full glacial period (the Oxygen Isotope Stage 2) sustained their presence because of the low evaporation effect alone remains to be investigated. The low evaporation effect combined with increased meltwater from hypothesized glaciers in the Altai Range and the Hangai Plateau (Lehmkuhl, 1998) may have sustained the paleolakes in the Gobi–Altai region effectively during the terminal Late Glacial period after the full glacial period (condition c in Fig. 14). Also, it is possible that during the terminal Late Glacial period, precipitation was actually high in some areas (condition a in Fig. 14). For example, a detailed stratigraphic study from Chikhen Agui, an Upper Paleolithic rockshelter site about 90 km south of Böön Tsagaan Nuur, revealed that depositional processes continued and water percolating through the deposits may have indeed increased during the LGM (D.C.

Hyland, personal communication). This suggests that the area around the site was at least locally wet. Some paleolake data from northern Mongolia record high stands about 12,000 B.P. (Harrison et al., 1996; Grunert et al., 2000) and the above factors were probably the reasons.

5. Archaeological significance

While we have not yet identified archaeological materials in direct association with the strandline features, there is abundant archaeological evidence in adjacent regions that may complement our interpretation of the timing and paleoecological significance of the observed lacustrine features. For example, evidence accumulated from both buried and surficial geological contexts strongly suggests an initial human entry into the area prior to 40,000 years ago and possibly as early as the last interglacial (ca. 125,000 B.P.) (Derevianko et al., 1996, 1998, 2000). The significance of greatly expanded lakes in Mongolia during long periods of the Pleistocene and Holocene for human demography and migration in the region cannot be overestimated. Increased access to water and the broad spectrum of resources associated with stable lakes (migratory fowl, fish, a greater diversity of plant communities, etc.) would have had a profound impact on the scale and dynamics of human mobility in a region which is now severely constrained in its ability to support even small-scale mobile human populations.

6. Conclusions

In order to answer questions about the timing of these lake expansion events, further field investigations are needed. In addition to dating the expansions, it is essential to study other aspects of the lake evolution such as sedimentary processes, drainage influx, and precipitation/evaporation rates. The study of the paleohydrology in Mongolia is important for understanding Quaternary climatic change and human demography in northern Eurasia, and revealing the history of paleolakes in south-central Mongolia will provide key elements to this study.

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