6 Holocene climate and landscape evolution of the Ugii Nuur basin

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Abstract

In this study we investigate the Holocene environmental evolution of the Ugii Nuur basin in the Orkhon Valley, central Mongolia, in order to gain a better understanding of the climate and landscape dynamics of the steppe region in Central Asia. We assess terrestrial and lake sediments using mineralogical, geochemical and statistical techniques and provide absolute chronologies by radiocarbon datings and infra-red stimulated luminescence datings including fading correction. Our findings and their discussion in a broader regional context show that there is a Mid Holocene climate optimum. The shift towards warmer and wetter conditions involved changes from aeolian dynamics of sand mobilization to loess-like sediment accumulation owing to the establishment of dust-trapping vegetation. Between 4 and 2.8 ka BP we track a decline in moisture supply which is then followed by relatively humid conditions until today. We infer that the region is sensitive to changes of the westerlies dynamics. In addition, we conclude that the Late Holocene was characterized by favorable climatic conditions that probably were an important prerequisite for the repetitive colonization of the Orkhon Valley throughout the last 3000 years.

Keywords: principal component analysis, Central Asia, loess, lake sediments, geoarchaeology

6.1 Introduction

Information on Holocene environmental evolution are scarce in Mongolia. At its southern border, numerous investigations on lake sediments (Wünnemann and Hartmann, 2002; Xiao *et al.*, 2004; Wünnemann *et al.*, 2005; Hartmann and Wünnemann, 2007), speleothems (Dykoski *et al.*, 2005; Wang *et al.*, 2008b) and loess profiles (Porter, 2001; Roberts *et al.*, 2001; Rost, 2001; Xiao *et al.*, 2002; An *et al.*, 2005; Maher, 2008) provide spatially distributed information on landscape and climate evolution in the northern part of the People's Republic of China. Along the northern border various lake basins have been studied, most prominently Lake Baikal and Lake Hovsgol (e.g. Demske *et al.*, 2002; Fedotov *et al.*, 2004; Poberezhnaya *et al.*, 2006; Hövsgöl Drilling Project Group, 2007; Prokopenko *et al.*, 2007), Uvs Nuur (Grunert *et al.*, 2000) and various smaller basins (e.g. Gunin *et al.*, 1999; Tarasov *et al.*, 2000; Peck *et al.*, 2002; Fowell *et al.*, 2003) providing insight into the evolution of the continental, boreal region. The vast steppe area in between these two regions, however, is only poorly explored (see overview in Harrison *et al.* (1996) and Herzschuh (2006)).

Knowledge on the environmental history of this extremely continental area is required to understand its sensitivity to current global climate change. Northern Mongolia has been warming twice as fast as the global average during the last 40 years and experiences a decline in permafrost (Nandintsetseg *et al.*, 2007; Bohannon, 2008), and projections indicate a more arid climate in the future (Sato *et al.*, 2007). The manner of how ecosystems react to these changes affects vital functions of the Mongolian society. Hence, investigating the Holocene climatic and environmental evolution contributes to an understanding of ecosystem sensitivity not only because the past few millennia are the natural baseline from which to differentiate current climate change, but also because Holocene evolution is linked to human cultural evolution (Cronin, 1999).

In this study we investigate the Holocene evolution of the Ugii Nuur basin located in the steppe region of Mongolia using lacustrine and terrestrial sedimentary archives. The study site gains relevance not only due to its situation in a poorly investigated region of Mongolia. It is located in the sphere of influence of the westerlies whose role in the climatic evolution of Central Asia is highly disputed (Chen *et al.*, 2008). Moreover, it is part of the Orkhon Valley that hosts various archaeological sites that document an human influence for the last ∼ 3000 years with a climax in the 13-14th century (c.) AD when Dschingis Khan chose the Orkhon Valley as location for his capital Karakorum (Qara Qorum) (Bemmann *et al.*, 2008).

A pollen profile of one of the sediment cores presented in this study has been investigated by Rösch *et al.* (2005). Yet, climate and environmental reconstructions based on pollen samples only are less reliable for arid and semi-arid regions owing to the influence of long-distant transport and the often unknown degree of human influence on vegetation densities and assemblages (Tarasov *et al.*, 2007c,b). Hence we complemented this work by an extensive geochemical and mineralogical approach of lake and terrestrial sediments. In this paper we resume the findings that were partly published in more detail in Schwanghart and Schütt (2008) and Schwanghart *et al.* (2008). Moreover, we provide new records and dates obtained from the infra-red stimulated luminescence (IRSL) technique including fading correction. We place emphasis on an interpretation and synthesis of the results and discuss their significance in a spatially broader context.

6.2 Study site

The Ugii Nuur basin is located in central Mongolia (47°44'N and 102°46'E, Fig. 6.1) and comprises elevations between 1328 and 1600 m. Ugii Nuur is a lake with a surface area of approx. 26 km^2 and a maximum depth of 16 m. It is fed by the Old Orkhon River (Chögschin Orkhon Gol) and is ephemerally drained by a ca. 8 km long water course connected to the Orkhon River (Orkhon Gol) (Fig. 6.2). During two field trips in 2005 and 2006 surface runoff along this outlet was absent.

Climate is characterized by extreme continentality. Ugii Nuur Sum, located about 10 km southwest to Lake Ugii Nuur, shows an annual mean temperature around zero and an annual precipitation of around 250 mm. The continentality causes a strong seasonality. Mean January air temperatures of −21.5°C contrast July air temperatures of 17.0°C. Precipitation in winter (November to March) mostly occurs in solid form and rarely exceeds 10 mm per month, while rainfall in summer is predominantly linked to convective cells associated

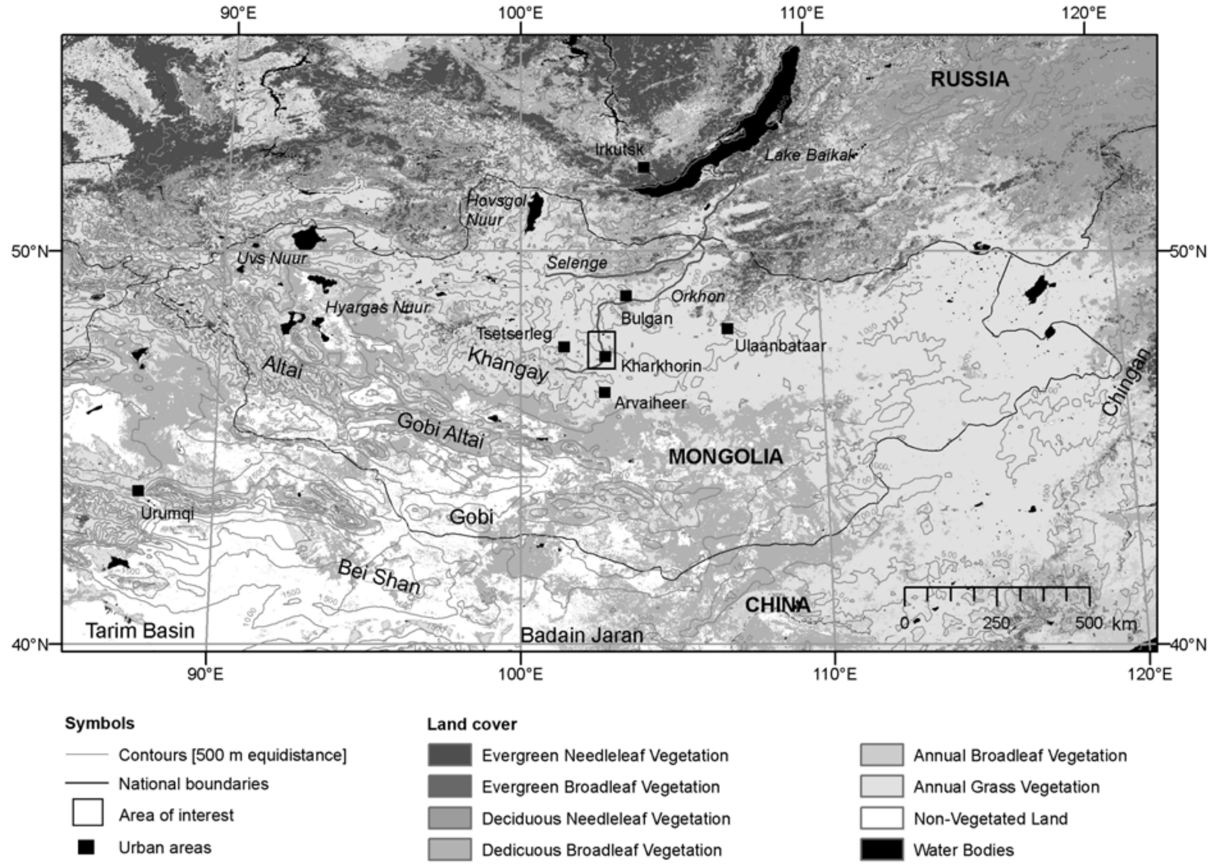

Figure 6.1: Map of central Asia and location of the study site. Vegetation data is derived from the Global Land Cover Characteristics data base (Running *et al.*, 1995). Elevation data (isolines with equidistance of 500 m) is based on GTOPO30 data.

with warming of the continental interior (Harrison *et al.*, 1996), cyclonic disturbances of the westerlies (Weischet and Endlicher, 2000) and intense diurnal mountain wind systems (Böhner, 2006). In general, rainfall events in summer are short, intense and accompanied by high wind velocities.

Bedrock in the study area consists of strongly tilted Carboniferous shists and shales that outcrop on ridges and steep slopes. Along the lake shore of Ugii Nuur reddish conglomerates are exposed that can be attributed to the late Cretacious and Tertiary and testify fluvial dynamics with high bedload transport generating pebble beds and channel bar sandstones (Traynor and Sladen, 1995). The origin of the topographic depression is unclear but may be linked to Miocene volcanism nearby Ugii Nuur (Kovalenko *et al.*, 1997) or to an east-west left-lateral strike-slip fault (Walker *et al.*, 2008).

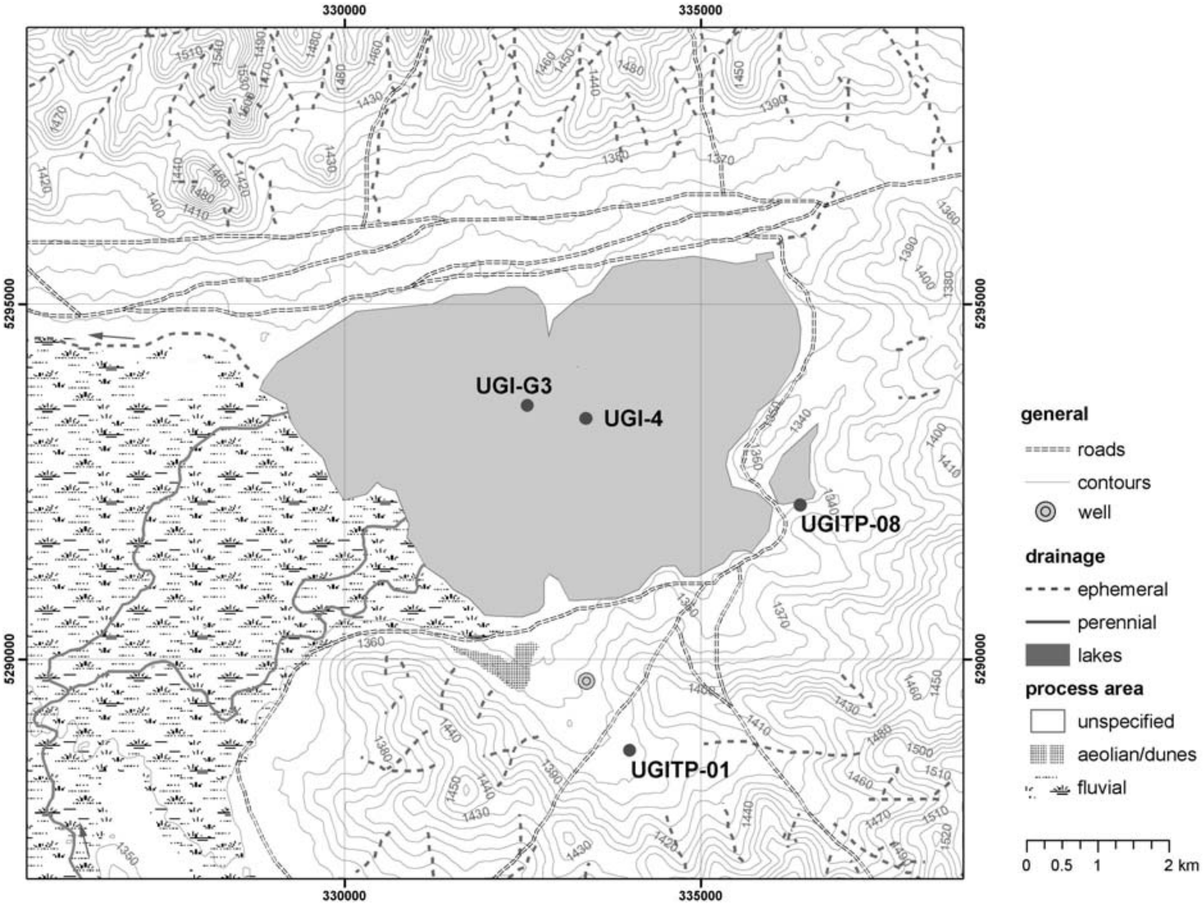

Figure 6.2: Map of the study site indicating locations of profiles described in the text.

The shallow subsurface is dominated by vast fanglomerates accumulated during the Pleistocene (Richter *et al.*, 1963; Grunert *et al.*, 2000; Schwanghart and Schütt, 2008). The debris layers are poorly sorted and comprise grain sizes ranging from silt to blocky debris. Where alluvial sedimentation prevailed, bands with pebble clusters occur, separated by soil sediments or fines. In flat or slightly inclined areas layering may also be attributed to frost heaving processes. Soils developed on periglacial debris are dominated by Kastanozems. On steep slopes these steppe soils are poorly developed, frequently only a few decimeters thick and classified as Regosols or Leptosols. The study site is situated within the area of dry, grass steppes (Hilbig, 1995; Opp and Hilbig, 2003) and is dominated by grasses (*Cleistogenes*, *Stipa*), forbs (*Allium*), and shrubs (*Artemisia*, *Caragana*) while trees are generally lacking. Present day human activities are largely restricted to herding. The large quantities of lifestock that have been established since the fall of the soviet regime result in large-scale land degradation.

6.3 Methods

Our study aims at deriving local and regional paleoclimatic and paleoenvironmental information from lacustrine and terrestrial sedimentary archives of the Ugii Nuur basin. Since the acquired data reflects *insitu* conditions and/or source area characteristics of material fluxes, a regional synthesis of our results is gained by a comparison with existing paleoenvironmental datasets of the region.

6.3.1 Sediment analysis

We report the findings from two lake sediment cores: UGI-4 and UGI-G3. UGI-4 was excavated at the deepest location of Ugii Nuur in 2003 (Fig. 6.2) with a Usinger piston corer (Walther, 2005). The core has a length of 630 cm and was sampled with an interval of 10 cm and a resolution of 2 cm. A gravitational corer was used to retrieve UGI-G3, a 2 m long core with a sample interval of 5 cm and a 2 cm resolution. In addition, we document two terrestrial profiles (UGITP-01, UGITP-08) located in relatively flat terrain to exclude a strong influence of lateral water and material fluxes (Fig. 6.2).

Prior to chemical and mineralogical analysis the samples were dried, screened on components larger 2 mm and homogenized in an agate disk swing mill (Lieb-Technik). We used a conductrometric carbon analyzer (Wöesthoff, detection limit = 0.02 mass-% C) to determine the total (TC) and inorganic carbon (TIC) content. Total organic carbon (TOC) content was calculated as the difference of both values. Mineralogical compounds were analyzed by X-ray powder diffraction (XRD) using a copper k_α-tube (PW1729/40, Phillips) from $2\theta = 2 - 52°$ and a step width of $\Delta 2\theta = 0.01°$ with each step measured for one minute. Contents of mineral components were analyzed semi-quantitatively (vol-%) using the software package Phillips X'Pert Highscore v. 1.0b (PW3209). After preparing samples using aqua regia and microwave digestion, we analyzed the element composition (Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, PO_4, S, Sr) by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Optima 3000, Perkin Elmer). TC, H and N were analyzed using a LECO CHN 1000 (detection limit = 0.01 mass-%). Grain size distributions analyzed for one terrestrial profile were derived from pipette and sieve analysis.

6.3.2 Statistical analysis

The sequence of element compositions of UGI-4 was statistically analyzed with a principal component (PC) analysis (PCA) based on the correlation matrix. Prior to the analysis the data was transformed using centered log-ratios to account for the constant sum constraint (Aitchison, 1986; Kucera and Malmgren, 1998). Subsequently all variables were z-transformed. Since standardization tends to inflate the influence variables whose variance is small, we excluded H, Na and PO_4 from the PCA owing to their low concentrations and thus low signal-to-noise ratio (Davis, 1986). A VARIMAX rotation of the principal components (PC) was chosen to enhance the interpretability of the PCs.

6.3.3 Radiocarbon and luminescence datings

Absolute chronologies were obtained from radiocarbon (^{14}C) and fading corrected IRSL datings (table 6.1, 6.2). ^{14}C ages were determined from bulk organic matter in lacustrine sediments and conjointly on humins and humic acids for terrestrial samples in the Poznan Radiocarbon Laboratory. Despite the relatively few dates on the lacustrine core we assume that the chronology is valid due to absence of e.g. event layers that may indicate strong ruptures of sedimentation rates. ^{14}C ages were calibrated with CalPal Online (Danzeglocke *et al.*, 2008) using the calibration curve CalPal2007_HULU (Weninger and Jöris, 2007). Ages between dated samples were obtained by linear interpolation. In the following text, radiocarbon ages are provided as calibrated years unless otherwise noted.

Aeolian sediments like loess and dune sands are particularly suitable for the application of luminescence dating techniques to determine the "deposition age" of the sediments (Frechen, 1999; Frechen and Dodonov, 1998). Luminescence is the light emitted from crystals such as quartz, feldspar or zircon when they are stimulated with heat or light after receiving a natural or artificial radiation dose. The equivalent dose is a measure of the past radiation energy absorbed and, in combination with the dose rate, yields the time elapsed since the last exposure to sunlight. An important assumption of luminescence

Table 6.1: List of radiocarbon ^{14}C dates reported in this study.

Sample number	Milieu	Core/profile name	Depth [cm]	Uncal. ^{14}C age $\pm 1\sigma$ [y]	Cal. age $\pm 1\sigma$ [y BP]
POZ-16767	lacustrine	UGI-4	210	3535 ± 30	3809 ± 57
POZ-16847	lacustrine	UGI-4	510	7770 ± 50	8538 ± 55
POZ-16768	lacustrine	UGI-4	580	9210 ± 50	10382 ± 84
POZ-15083	terrestrial	UGITP-01	50	4010 ± 35	4482 ± 37
POZ-15084	terrestrial	UGITP-01	148	8500 ± 50	9506 ± 24
POZ-15085	terrestrial	UGITP-01	198	9670 ± 50	11031 ± 136

Table 6.2: List of fading corrected IRSL ages of the section UGITP-08.

Sample number	Depth [cm]	Doserate [Gy/ka]	D_E [Gy]	Uncorrected age [ka]	$g_{2\ days}$-value [% /decade]	Fading corrected age [ka]
1575	10-15	3.74 ± 1.19	0.55 ± 0.12	0.15 ± 0.03	2.90 ± 0.29	0.17 ± 0.07
1576	36-40	3.60 ± 0.31	4.67 ± 0.07	1.30 ± 0.11	2.90 ± 0.29	1.59 ± 0.21
1577	60-64	3.77 ± 0.30	7.66 ± 0.22	2.03 ± 0.15	2.90 ± 0.29	2.51 ± 0.33
1578	130-135	3.37 ± 0.42	31.85 ± 2.37	9.44 ± 0.95	2.90 ± 0.29	11.95 ± 2.11
1579	145-150	3.53 ± 0.32	31.10 ± 1.34	8.81 ± 0.72	2.90 ± 0.29	11.12 ± 1.59
1580	160-165	3.59 ± 0.52	48.80 ± 4.36	13.60 ± 1.54	2.90 ± 0.29	17.27 ± 3.40

dating techniques is that the mineral grains were exposed to sunlight sufficiently long enough prior to deposition. Eight loess samples were taken in light-tight tubes about 250 g each in the field. Furthermore, about 1 kg of sediment was sampled for gammaspectrometry to determine the amount of radioactivity in the sediment.

Polymineral fine-grained material (4-11 μm) was prepared for the measurements, as described by Frechen *et al.* (1996). The Single Aliquot regenerative Protocol (SAR) was applied to determine equivalent dose values (Wallinga *et al.*, 2000). The IRSL ages were fading-corrected following Huntley and Lamothe (2001). A Schott BG39/Corning 7-59 filter combination was placed between photomultiplier and aliquots for the measurements. Alpha efficiency was estimated to 0.08 ± 0.02 for all samples. Dose rates for all samples were calculated from potassium, uranium and thorium contents, as measured by gamma spectrometry in the laboratory, assuming radioactive equilibrium for the decay chains.

Cosmic dose rate was corrected for the altitude and sediment thickness, as described by Aitken (1998) and Prescott and Hutton (1994). The natural water content of the sediment was estimated to 7.5 ± 2.5 %.

6.4 Results and interpretation

6.4.1 Lacustrine archives

Geochemical and mineralogical analysis

^{14}C datings of UGI-4 date the onset of lake sedimentation to the Pleistocene/Holocene boundary (see table 6.1). Above a sandy base the sediments are dominated by silt and clay indicating continuous lacustrine sedimentation with alternating phases of carbonate precipitation and organic carbon accumulation in the sediment. Based on the lithology and geochemical parameters UGI-G3 can be correlated with section 1 of UGI-4 (Fig. 6.3).

The mineral composition of UGI-4 is dominated by quartz and feldspars (Fig. 6.3). Along with clay minerals, mica and hornblende the allogenic mineral fraction outweighs the authigenic fraction which mainly consists of calcite, monohydrocalcite (MHC), pyrite and gypsum. Authigenic minerals frequently occur in the lower part of the profile (section 2–13) while gypsum was found in the upper part (section 1) only with very low concentrations ($\sim$ 1 vol.-%). Calcite varies between 0 and 30 vol.-%, pyrite and gypsum range between 0 and 4 vol.-%, respectively. MHC was detected with high concentrations in 160 cm depth (21 vol.-%) and in 310 cm depth (3 vol.-%). The hydrous form of calcium carbonate has often been interpreted to reflect very cold lake water conditions (Lippmann, 1973). Yet, as discussed in Schwanghart *et al.* (2008) this mineral may also be biogenic in origin.

Corresponding to the presence of calcite, TIC varies from 1–3 mass-% (8-24% $CaCO_3$) (section 2, 9, 11). TOC concentrations are relatively high throughout the core (median = 2.6 mass-%). Variations of TOC and related variables may be affected by diagenetic processes that alter the organic matter composition (Talbot and Johannessen, 1992). Yet, we argue that at least significant diagenesis of the organic matter can be excluded since evidences for a downcore selective loss of TOC or N are missing (Salzmann and Hoelzmann, 2005).

Minor fluctuations of C_{TOC}:N_{TN} (C:N) atomic weight ratios are recorded in the core.

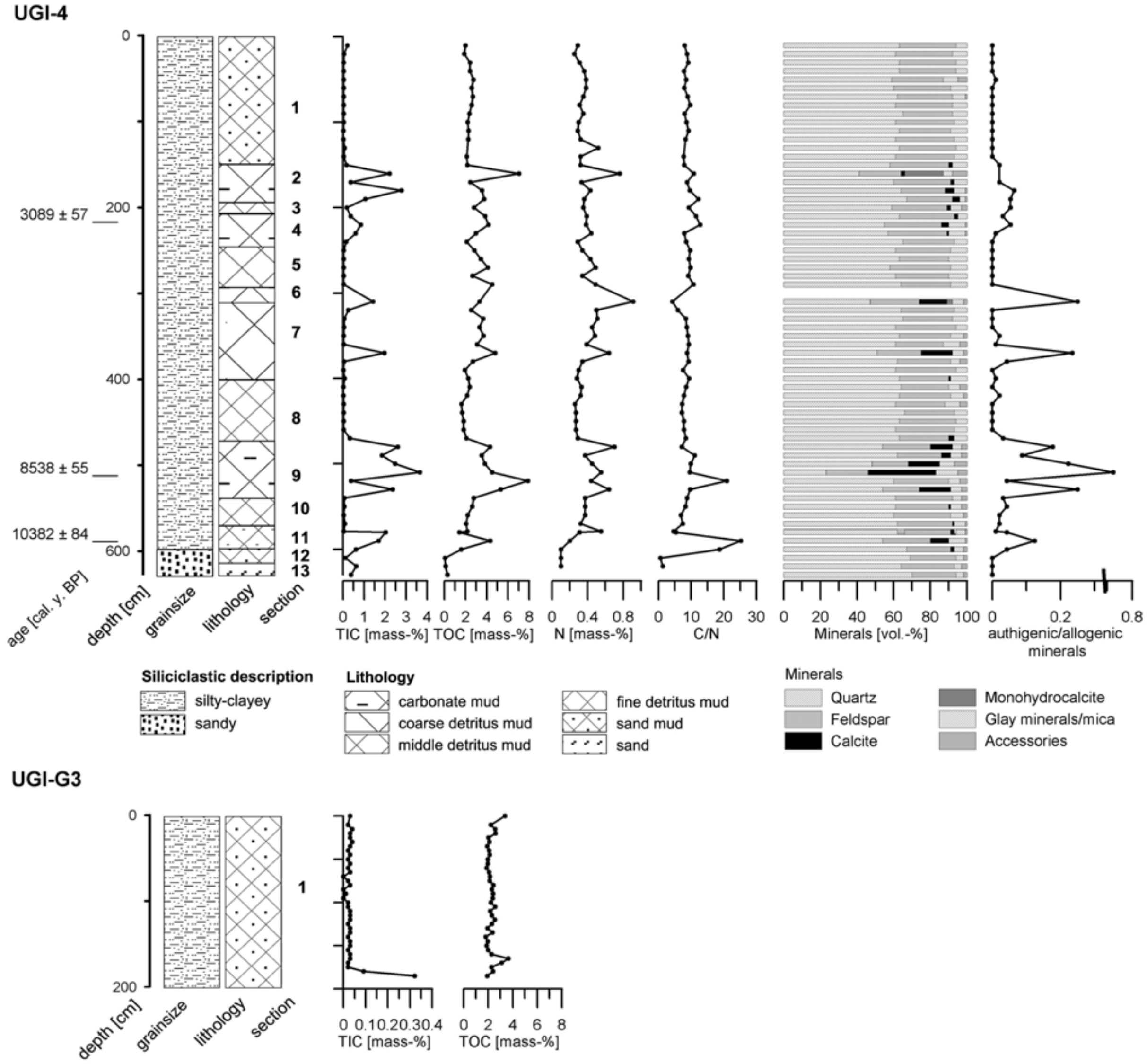

Figure 6.3: Lithology and geochemical and mineralogical sediment composition of UGI-4 and UGI-G3.

The dominance of values below 12 suggest that sediment organic matter is predominantly algal in origin (Meyers and Lallier-Verges, 1999). Two major peaks with ratios up to 25 during the early Holocene indicate a contribution of terrestrial, vascular plant material to the lake bottom. Yet, these maxima likely reflect singular events but do not provide evidence for prolonged phases of terrestrial plant accumulation in the sediment.

The upper part of the core (section 1) is characterized by minor fluctuations for all parameters. The uniformity of this section is confirmed by the higher sampling frequency of

Table 6.3: Factor loadings and communalities of centered logratio transformed variables after Varimax rotation. Loadings > 0.7 and < 0.7 are highlighted bold

element	factor loading			communality
	PC 1	PC 2	PC 2	
Mg	**0.980**	0.019	-0.075	0.97
Cr	**0.979**	0.179	0.005	0.99
Fe	**0.972**	0.190	0.019	0.98
Pb	**0.964**	0.214	0.036	0.98
Ni	**0.945**	0.258	0.063	0.96
K	**0.943**	0.177	-0.135	0.94
Cu	**0.833**	0.474	0.120	0.93
TIC	**-0.885**	-0.246	-0.229	0.90
Ca	**-0.868**	-0.420	-0.151	0.95
Sr	**-0.791**	-0.520	-0.155	0.92
S	**-0.767**	0.469	-0.045	0.81
Mn	-0.291	**-0.841**	-0.054	0.79
TOC	-0.060	-0.146	**0.842**	0.73
N	0.124	0.334	**0.711**	0.63

UGI-G3. The top of the profile UGI-G3 captures an increase in TOC at the sediment/water interface.

Statistical analysis

The PCA extracts three PCs with eigenvalues greater than 1 (Kaiser-Criterion). The communalities of each variable retained in the PCs are higher than 90 % for most variables, but totals only 63 – 81 % for S, TOC, TIC and N (table 6.3). Ten out of 14 variables are basically explained by PC1. Mg, K and all metals except Mn are positively related to PC1 while TIC, Ca, S and Sr have negative loadings (Fig. 6.4, table 6.3). While former elements reflect the allogenic mineral fraction, latter form the authigenic mineral assemblage in the sediment. It is important to note, that the concurrent mapping of these two material fractions on one PC reflects an archive entailed concurrence and not a concurrence of processes. It may partly be explained by a rather coarse sampling resolution that is unable to resolve rapid changes in the hydrological regime responses of the relatively small lake.

The environmental meaning of the PCs is discussed in detail in Schwanghart *et al.*

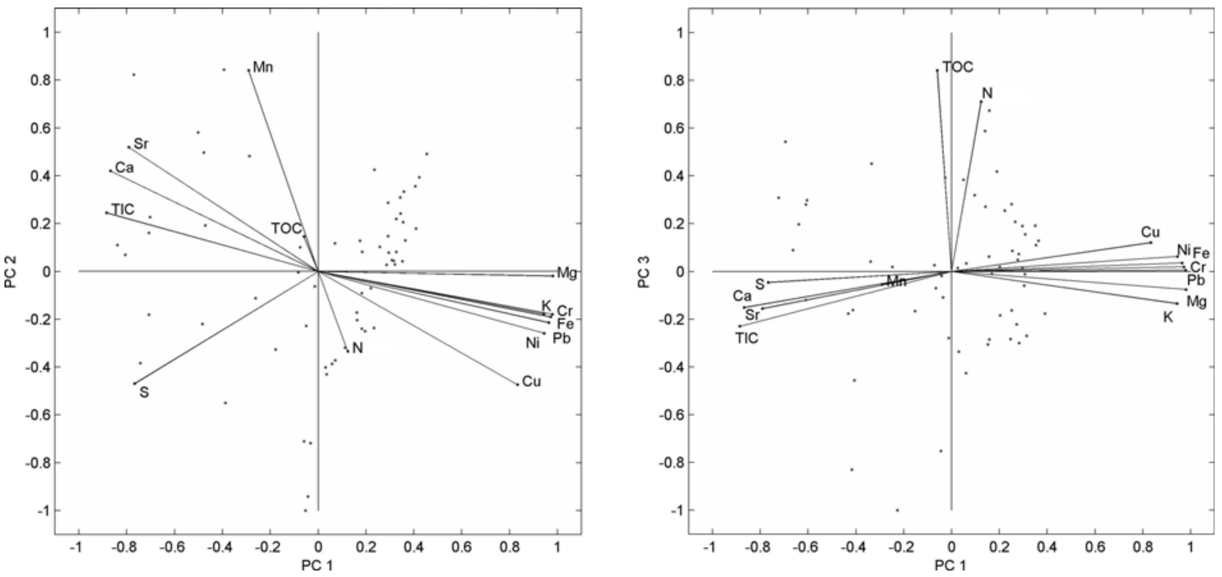

Figure 6.4: Biplots of the PC loadings (vectors) and PC scores (dots). Note that the biplots follow the convention, forcing the element with largest magnitude in each column of the loadings matrix to be positive.

(2008). They conclude that PC1 can serve as a proxy for lake level variability since carbonate precipitation is heavily influenced by activation or deactivation of the lake outlet. During closed basin conditions evaporation from the water surface is the main driver to maintain the water balance of the lake, leading to an enrichment of dissolved carbonate concentrations in the lake water. In combination with a decline of thermal stratification and generally higher water temperatures during summer, carbonate precipitation rates are increased during these periods. Open basin conditions involve a constant renewal and exchange of the lake water. During such periods intense carbonate precipitation can be excluded and deposition of the allogenic mineral fraction prevails. Despite the metric scale of PC1 the derived lake level curve (Fig. 6.5) cannot be translated to precise water surface elevations but remain a qualitative estimate.

We are aware, that this simplified interpretation of the complex dynamics of lake sediment formation disregards sediment fluxes that may be triggered by the exposition of the riparian lake zone or the sheer fact that sediment characteristics change as the litoral zone approaches the borehole location during low lake levels. Moreover, the meandering nature of the Old Orkhon and the Orkhon River and associated sediment dynamics in

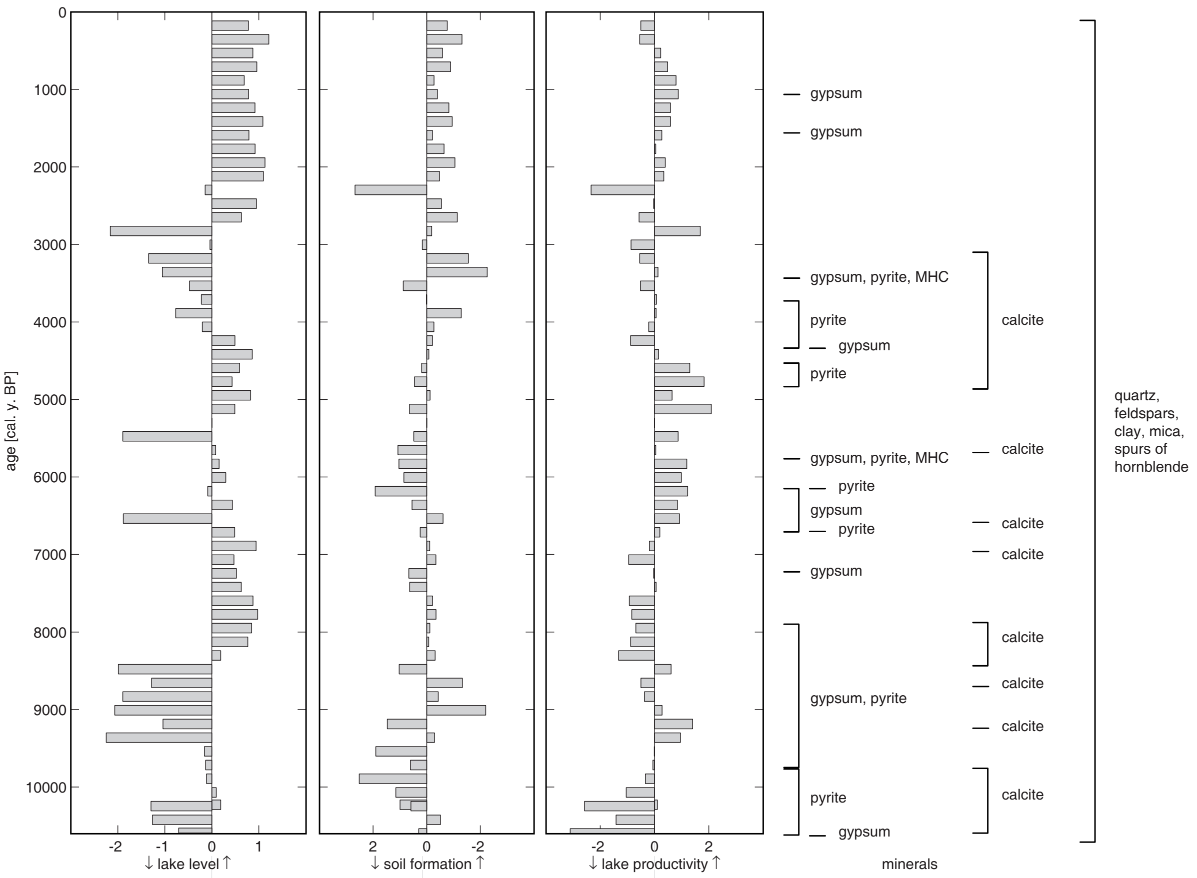

Figure 6.5: Factor scores and mineral occurrences of UGI-4.

the delta area may have caused a bypass of the inlet to the lake. At the current state of our knowledge we cannot exclude fluviodynamic effects of the inlet on the lake level and, hence, paleoclimatic interpretations are limited. Since the lake level proxy agrees well with other findings in the area, it is assumed that these dynamics either did not effect the lake level, or had a short duration not resolved in our record.

The behavior of Mn and its relation to Fe is reflected by PC2. Schwanghart *et al.* (2008) conclude that Mn is both related to the lithogenic sediment fraction and soil derived, dissolved Mn by groundwater supply. During low lake level phases surface runoff contribution and delivery of eroded material was largely replaced by groundwater discharge enriched in dissolved Mn due to its higher mobility in soils (Schlichting and Schweikle, 1980; Scheffer, 2002). Due to the large uncertainty associated with the reification of PC2 we omit its use in the paleoenvironmental interpretation.

TOC and N are associated with PC3. TOC as proxy for paleoclimatic interpretations can be misleading owing to the variety of sources and processes generating organic matter in lakes (Hartmann and Wünnemann, 2007). Since we can infer from C:N ratios that variability of organic matter is predominantly linked to aquatic organisms we interpret PC3 to reflect biologic lake productivity.

6.4.2 Terrestrial archives

Landforms in steep terrain in the study area are ridges and convex to straight slopes characterized by outcrops and relatively thin covers of blocky debris. A often sharp, concave knick in the lower slope section passes into a moderately inclined accumulation section of interfingering fans and colluvial material. Texture is spatially highly variable, characterized by partly layered debris that is embedded in a texture of sands and silts (Schwanghart and Schütt, 2008). These archives are generated by a combination of geomorphological processes of rock fall, concentrated runoff or sheet wash that produce cut-fill sedimentary patterns associated with single rainfall events. Indications of cryoturbation show that denudational processes such as soil creep and upheaval play a major role in the genesis of these profiles.

Terrestrial profiles in the flat to gently undulating terrain of the southern part of the study area are spatially less variable. In general, these terrestrial archives show a predominance of the silt fraction in the upper part of the profiles overlying fine to coarse sands (Fig. 6.8. A horizon with secondary carbonate formation in variable depth is common, visible by concretion and carbonate coatings on lower sides of gravel and pebbles (Klinge, 2001; Lal, 2004), characterized by elevated TIC concentrations (Fig. 6.6 and 6.7) and detected by mineralogical analysis (Schwanghart and Schütt, 2008).

The terrestrial profiles in UGITP-01 and UGITP-08 (Fig. 6.2, 6.6 and 6.7) are located on profile straight and planform straight to convex slopes with inclinations of ∼2°. UGITP-01 is situated in the lower, southwest exposed slope section of a broad, saucer-shaped valley. UGITP-08 is a section partly exposed on a cliff-like scarp surrounding the backwater of Ugii Nuur (Fig. 6.2). A thicker silty section in UGITP-01 than in UGITP-08 is probably owing to enhanced material contribution by sheetwash that is more intense due to the

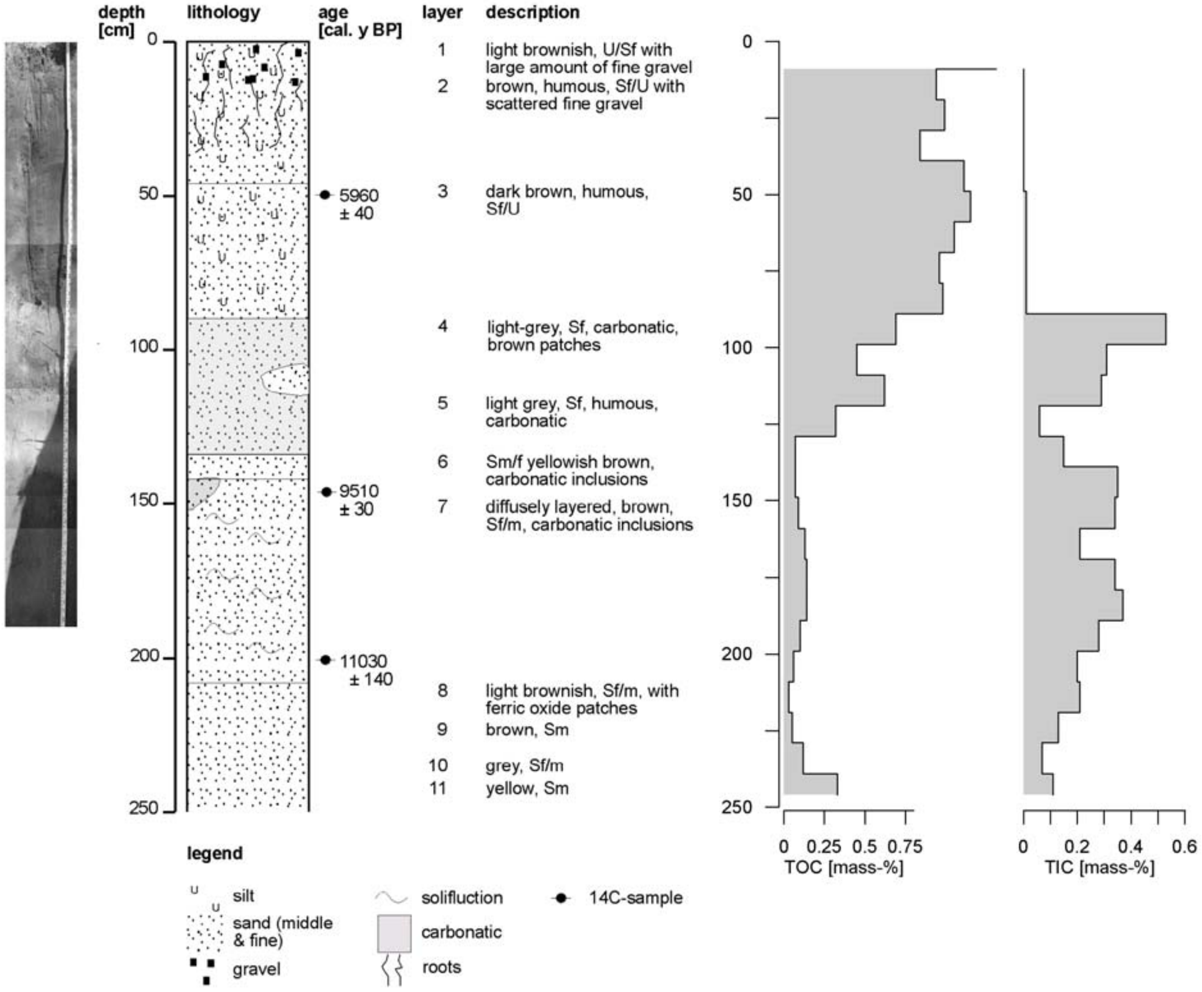

Figure 6.6: Lithology, total inorganic (TIC) and organic carbon (TOC) of UGITP-01.

profile's topographic situation and a larger upslope contributing area (see. Fig. 6.2). Non-declining, but generally low TOC concentrations in the upper part of UGITP-01 support the interpretation that soil formation was accompanied by more efficient burial by lateral material fluxes than in UGITP-08. The presence of partly rounded gravel in UGITP-08 (layer 6) suggests the accumulation of coarse material subject to fluvial erosion or ground by relocation in the litoral zone of lake Ugii Nuur. Insufficient slope and upslope area for efficient fluvial transport, low lateral variation and a lack of evidence for paleodrainage at this location suggest that litoral processes probably formed the gravel layer.

Both fading corrected IRSL ages and calibrated ^{14}C ages provide Holocene chronologies of the terrestrial sediment sequences under study. The sand dominated sections can be

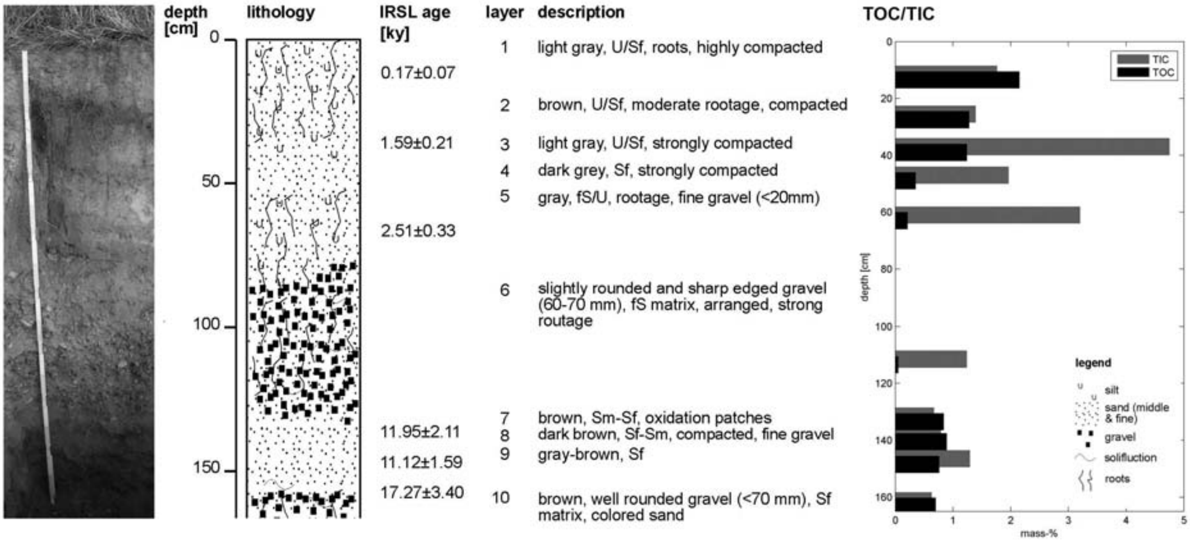

Figure 6.7: Lithology, total inorganic (TIC) and organic carbon (TOC) of UGITP-08.

attributed to the Late Pleistocene and Early Holocene while the silt dominated sections can be placed in the Mid to Early Holocene. The pebble-rich section in UGITP-08 suggests a high lake level stand between these two phases, leading to the accumulation and grinding of coarser clastics. The origin of the clastics are Tertiary fanglomerates outcropping along cliffs at the lake shore. The location of UGITP-08 along a cliff-like scarp at the backwater of Ugii Nuur suggests a backward retreat due to litoral erosion simultaneously to or following the silt accumulation phase.

6.5 Discussion and paleoclimatic and paleoenvironmental interpretation

6.5.1 Pre-Holocene evolution ($>$ 10 ka)

Lake reservoir filling by the end of the Pleistocene epoch is in good agreement with other lake systems in Central Asia (Herzschuh, 2006). Most lakes in NW China and Mongolia had low lake levels or were dried out during the last glacial maximum (LGM) (Grunert and Dasch, 2004; Hartmann and Wünnemann, 2007; Karabanov *et al.*, 2004; Tarasov *et al.*, 1999b; Walther, 1999; Walther *et al.*, 2003; Wünnemann *et al.*, 1998; Wünnemann and Hartmann, 2002; Yang *et al.*, 2004) owing to a largely weakened summer monsoon and

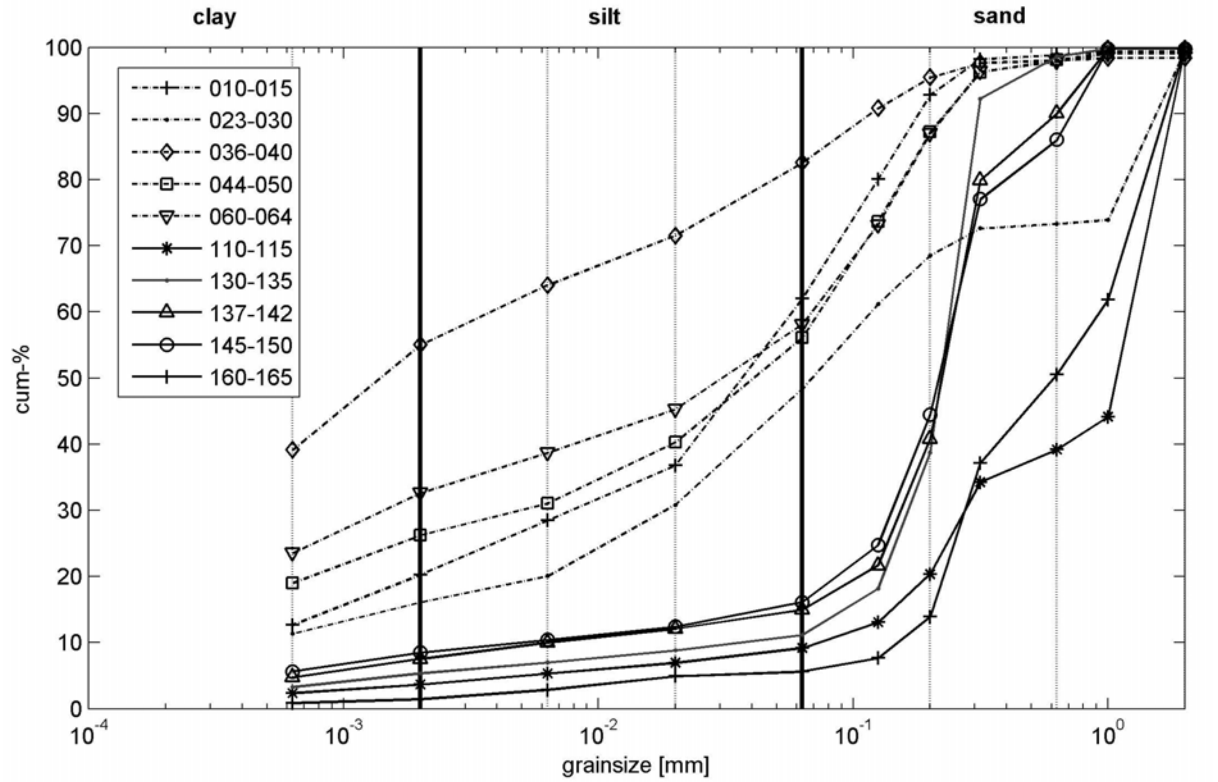

Figure 6.8: Grain size distribution in various depths of UGITP-08.

moisture depleted westerlies (Kutzbach and Guetter, 1986; Foley *et al.*, 1994; Bush, 2004; Tarasov *et al.*, 2007c).

Despite the rather general notion of a dry LGM, the re-establishment of moisture supply and associated lake phase beginnings were asynchronous in Central Asia. This may be due to the gradual establishment of the EA monsoon associated with the summer insolation maximum in the Late Glacial and Early Holocene (Sirocko *et al.*, 1993; Harrison *et al.*, 1996; Wang *et al.*, 1999; Blyakharchuk *et al.*, 2004; Herzschuh, 2006) and discharge connectivity to glaciated regions (Walther, 1999). Different geological settings result in different rates of aquifer filling and provide an explanation for time lags between climate amelioration and lake evolution (Hartmann and Wünnemann, 2007).

Since the Ugii Nuur catchment comprises parts of the Khangay mountains, glacier retreat in this area (Lehmkuhl and Lang, 2001; Lehmkuhl *et al.*, 2004) probably contributed to discharge to the Ugii Nuur basin. Thick periglacial debris covers (Richter *et al.*, 1963;

Lehmkuhl and Lang, 2001; Schwanghart and Schütt, 2008) of the Orkhon Valley suggest that initial discharge served as recharge of riparian groundwater aquifers and may have delayed lake evolution.

According to Lehmkuhl and Haselein (2000) and Lehmkuhl and Lang (2001) a phase of sand accumulation is followed by a loess phase at the end of the Pleistocene (ca. 15 ka). The terrestrial profiles investigated here suggest that sand sheets and/or dunes were active until at least the Early Holocene, but also Mid Holocene. The sand originated from floodplains and was transported only over short distances while silt-sized particles were transported over long distances due to the lack of a vegetation cover acting as dust trap (Grunert and Lehmkuhl, 2004).

6.5.2 Early Holocene (ca. 10–8 ka)

While the EA Monsoon dominated region of North Eastern China faced a moisture optimum during the Early Holocene (An *et al.*, 2000), various records suggest a dryer climate in the westerlies-dominated region of Central Asia (Wünnemann *et al.*, 2003; Xiao *et al.*, 2004; Herzschuh, 2006; Chen *et al.*, 2008; Hartmann and Wünnemann, 2007). A strong seasonal contrast induced by the positive summer insolation anomaly during this time resulted in convective heating on the Tibetan Plateau and lead to subsidence of air masses and a dryer climate northwest of the plateau (Broccoli and Manabe, 1992; Duan and Wu, 2005). In contrast, moisture availability in the Baikal watershed was higher during the Early Holocene and declined by 7.5-8 ka (Prokopenko *et al.*, 2007). The warmer and more humid climate during this time resulted in afforestation of steppe landscapes (Naumann, 1999; Westover *et al.*, 2006) and permafrost degradation (Tarasov *et al.*, 2007a). A wetter Early Holocene in the boreal region of Central Asia is explained by the weakening of the Siberian winter anticyclone that gave way to Atlantic cyclone activity (Blyakharchuk *et al.*, 2004). Moreover, subsidence of air masses in the Gobi region may also have contributed to a northward displacement and narrowing of the westerlies zone during summer.

Since Ugii Nuur's lake phase started at 10 ka we can infer that moisture supply to the lake at least exceeded precedent supply. Allothigenic material input to the lake as indicated by PC1 reflects mobility of surface material during the initial lake phase and ongoing sand mobility inferred from the terrestrial archives in the Ugii Nuur basin points to arid conditions. Similar conditions are found in other regions of Mongolia during the Early Holocene. Grunert *et al.* (2000) report dune dynamics from the Uvs Nuur basin and Kowalkowski (2001) identifies a dry-warm phase with an increase of meadow steppe and steppe vegetation from 11 to 8.5 ka in the Altai Mountains. According to Gunin *et al.* (1999) steppe vegetation dominated at most sites in Mongolia and deserts occupied large depressions in western Mongolia from 11.5 to 8.9 ka.

6.5.3 Mid Holocene (ca. 8–4 ka)

The Mid Holocene atmospheric conditions in Central Asia are characterized by a southeast retreat of the maximum EA Monsoon limit due to the weakening of the summer insolation. Particularly in east China, but also in north China there is evidence for a decline in moisture supply (An *et al.*, 2000; Hartmann and Wünnemann, 2007). A trend towards dryer conditions is also found in the Hovsgol and Baikal region around 7 ka (Prokopenko *et al.*, 2007). Peck *et al.* (2002) and Fowell *et al.* (2003) infer a trend towards dryer conditions during the Mid Holocene for Lake Telmen. Westover *et al.* (2006) detect a decline of temperature and humidity by 6 ka in the Altai Mountains, and significant afforestation cannot be recognized in most pollen profiles (Gunin *et al.*, 1999).

Many lake systems in westerlies dominated north China and Mongolia show favorable moisture conditions during the Mid Holocene (Shi *et al.*, 1993; Dorofeyuk and Tarasov, 1998; Tarasov *et al.*, 2000; Grunert and Dasch, 2004; Herzschuh *et al.*, 2004; Yang *et al.*, 2004; Xiao *et al.*, 2006; Chen *et al.*, 2008). Contradictory to the interpretations of An *et al.* (2000) some authors relate the wetter conditions to further Monsoon penetration.

Our lake level proxy suggests that Ugii Nuur experienced higher lake levels during the Mid Holocene. This is supported by the presence of litoral material in UGITP-08 whose accumulation likely dates to the same period and Rösch *et al.* (2005) infer a trend towards more woodland. The proxy for biological lake productivity (PC3) also features the highest values during this time. In addition, we detect a change from sand dynamics towards loess deposition which has been shown to be an indicator for the transition from arid to semi-arid conditions (Yair and Bryan, 2000; Küster *et al.*, 2006). Hence, we infer that the climate governing the evolution of the Ugii Nuur basin during the Mid Holocene was characterized by increased precipitation and temperature providing better conditions for the establishment of dust-trapping vegetation and supporting algal growth in the lake during the Mid Holocene.

Due to the inconsistent or asynchronous climatic signals in the region the atmospheric circulation patterns during the Mid Holocene cannot be derived straight forward (Herzschuh, 2006). A gradual southward spreading of the westerlies zone can be assumed to be a reaction to the cooling of the Tibetan Plateau (Herzschuh *et al.*, 2006). According to Chen *et al.* (2008) higher North Atlantic sea surface temperatures and high-altitude air temperatures intensified cyclonic activity and synoptic disturbances along the westerlies that result in higher convective precipitation rates in westerlies dominated Central Asia. If so, topographic barriers may have caused a tremendous effect on the spatial variability of moisture supply (Broccoli and Manabe, 1992) and be an explanation for the inconsistent climate changes in the region.

6.5.4 Late Holocene ($<$ 4 ka)

Since 3 ka EA monsoon dominated areas show lower effective moisture owing to gradual monsoon weakening since the mid-Holocene (Overpeck *et al.*, 1996; An *et al.*, 2000; Herzschuh, 2006). Westerlies-dominated areas, however, lack an uniform decline in effective moisture (Herzschuh, 2006; Chen *et al.*, 2008) and records from boreal Central Asia show moisture conditions similar to present since $\sim$ 4 ka (Gunin *et al.*, 1999; Prokopenko *et al.*, 2007). Various lake level records in Mongolia provide evidence for only small fluctuations (Tarasov *et al.*, 1996; Peck *et al.*, 2002; Fowell *et al.*, 2003; Walther *et al.*, 2003; Yang *et al.*, 2004).

Some records point at significant climatic oscillations from 4 to 2.5 ka that are not well dated and understood (Demske *et al.*, 2005; Prokopenko *et al.*, 2007). Vipper *et al.* (1989) report distinct gravely lamina in various Mongolian lakes with an average calendar age of $\sim$ 3.6 ka that they interpret to reflect a shift towards a regional precipitation regime with intenser storms. Moreover, modelling studies suggest increased aridity during the Late Holocene (Bush, 2005) and Prokopenko *et al.* (2007) report significant regional warming between ca. 4 and 2.5 ka in the Baikal watershed (Prokopenko *et al.*, 2007).

Lower lake levels during $4 - 2.8$ ka are also shown for Ugii Nuur and may be associated with increased aridity. Very high concentrations of MHC fall into this interval and a significant increase in TOC and N associated with this peak suggest a strong biological activity in the lake.

From 2.8 ka to present, the Ugii Nuur record indicates stable high lake levels that we interpret to reflect enhanced moisture supply during the Late Holocene. Allogenic material delivery to the lake is high and datings of loess-like sediments show ongoing mineral dust deposition (Fig. 7). On the one hand, this may be explained by changes in rainfall patterns intensifying runoff and bed load transport to the lake. Moreover, changing surface properties generated by accumulation of loess-like deposits and associated reduced infiltration capacities have shown to alter runoff characteristics (Yair and Bryan, 2000).

On the other hand, it is expected that humans have been significantly influencing the ecosystem in the region and associated lateral material fluxes since 2.8 ka. Rösch *et al.* (2005) infer from surface pollen records and a pollen record of UGI-4 an increased human influence on woodland clearance by the late Holocene. Tombs (Kurgans and Khirigsuurs), petroglyphs and wall remnants testify an anthropogenic influence since the Palaeolithic in the study site and the Orkhon valley (Bemmann *et al.*, 2008). A cemetery nearby the Tamir and Orkhon confluence with more than 250 burials is likely of Xiongnu origin (3rd-2nd c. BC) (Batsaikhan *et al.*, 2006), the memorial Khoshöö Tsaidam documents the influence of Turks ($6 - 8$th c. AD) and the Uighurs ($8 - 9$th c. AD) devised their capital Kharabalghasun and a rampart in the west to Lake Ugii Nuur (Minorsky, 1948; Drompp, 1999, 2005; Bemmann *et al.*, 2008).

In medieval times ($13 - 14$th c. AD) Chengis Khan decided to establish Karakorum as the capital of the the Mongolian empire in the Orkhon Valley ~ 70 km south of Ugii Nuur. Ugii Nuur was part of the peri-urban area of Karakorum, a domain where nomadic traditions mixed with various forms of agricultural activities to supply the political, economic and cultural center (Shiraishi, 2004; Erdenebat and Pohl, 2005). Travelogues report grain and vegetable cultivations on the bank of the Orkhon River, west of the lake (Shiraishi, 2004). Together with reports that the spring palace of the Mongolian emperor located on an elevation in the Orkhon floodplain was surrounded by numerous lakes (Shiraishi, 2004) that are presently only filled with water during wet spells (Bemmann *et al.*, 2008), these evidences support our inferred favorable moisture conditions during that time. The operation of furnaces with wood in the capital (Franken, 2005) may have strongly altered regional tree populations. Rearing and keeping animals within the surroundings of Karakorum was common in particular with regard for sheep (von den Driesch *et al.*, 2008) and can be regarded as an additional stress to the ecosystem by intensifying soil erosion processes especially in the vicinity of densely populated areas.

The construction of the monastery Erdenet Joo in Karakorum in 1585/86 and an abandoned settlement of seven stone buildings of Tungian Mandchurs origin (16 – 17th c. AD) in the northwest to Lake Ugii Nuur (Weiers, 2005; Bemmann *et al.*, 2008) provide evidence for ongoing human activities in this region.

6.6 Conclusion

In this study we present terrestrial and lake sediment records from Ugii Nuur in central Mongolia. The records allow for an insight into the environmental and climatic evolution of the steppe region in Mongolia, a region which is only loosely covered by paleoenvironmental studies so far. We conclude that the paleoenvironmental interpretations of our records provide similar results obtained elsewhere in the westerlies dominated region in Central Asia. A dry and cold pre-Holocene period is followed by slightly more humid conditions in the Early Holocene that were not sufficient to generate a dense vegetation cover to cease aeolian dynamics of sand mobilization. During the Mid Holocene our records point at favorable moisture conditions and warming associated with change from sand mobilization to loess accumulation. Between 4 and 2.8 ka we track a decline in moisture supply which is then followed by relatively humid conditions until today.

Our findings and their discussion in a regional paleoenvironmental context reveal, that the areas north of the predominantly EA monsoon governed region most likely reacted to changes of the westerlies extent. Yet, one has to keep in mind that especially for heavy rains in this area interactions between mid latitude frontal systems and lower latitude cyclone/anticyclone systems are essential (Bao, 1987). Hence, past changes in the magnitude and frequency distribution of such singular events may greatly influence the paleoenvironmental evolution in the westerlies dominated region. Assessing and interpreting sedimentary archives of such events remain a major challenge due to the complexity of the underlying climatic and surface processes.

In addition, our study provides insight into the Late Holocene evolution of the Orkhon Valley. At the current state of our knowledge, we exclude neither natural nor anthropogenic forcings on the environmental evolution during this time. The effects of humans and livestock on the steppe ecotone in this area are still highly disputed (Hilbig, 2000; Dulamsuren *et al.*, 2005a; Miehe *et al.*, 2007; Schlütz *et al.*, 2008) and population and cattle densities of former tribes and peoples indwelling the Orkhon Valley are largely unknown. Drivers of environmental change beyond natural forcing should be considered to understand the environmental evolution in this region. Various results support an interpretation that the environmental history of the Mongolian plateau is driven by natural forcings rather than by human activities (Tarasov *et al.*, 2007a; Schlütz *et al.*, 2008). Since most of these results are limited to specific areas, great difference can be expected among different regions. We suggest that the repeated colonization of the Orkhon Valley was a decisive driver of environmental evolution in this area throughout the last 3000 years.

The way, humans affected the environmental evolution of this area by husbandry and pasture farming, firewood use and other economical practices remains largely unknown. A more detailed survey of the human-environmental interrelations in this area will not only contribute to a better understanding of the historical evolution, but will provide us the means to assess the future environmental change in steppe region of Mongolia.

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