Paleoclimatic implications from late Quaternary terrestrial archives in the Gobi Desert: Examples from the Ejina Basin and Orog Nuur Basin

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Kaifeng Yu

aus Jiangsu, China

Berichter: Univ.-Prof. Dr. rer. nat. Frank Lehmkuhl

apl. Prof. Dr. rer. nat. Bernhard Diekmann

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Dedicated to my parents and Cathrin, without whose support, assistance and patience, this endeavor would not have been possible.

谨将此博士学位论文献给我的父亲俞忠祥，母亲张兰英，以及凯特琳，是他们无微不至的支持和帮助使我能够继续追求地学梦想并完成三年的博士工作。

Gewidmet meinen Eltern und Cathrin, ohne deren Unterstützung, Hilfe und Geduld diese Arbeit nicht möglich gewesen wäre.
Preface

It was in 2006, during the journey to the campus of Lanzhou University, the author got the first impression of topographic and geomorphological characteristics of the arid / semi-arid central Asia. In 2010, after four years training in the major of physical geography, he wrote the Bachelor thesis entitled: “Environmental changes in Sangshuyuan region of the Chinese Loess Plateau over the last ~150 ka” supervised by Prof. Xiuming Liu, employing paleomagnetism studies comprising anhysteretic remnant magnetization (ARM), isothermal remnant magnetization (IRM) and coercive force (B_cr) on sediments from a ~9 m loess sequence on the western flank of the Chinese Loess Plateau (CLP). During the Master study from 2010 to 2013, at Nanjing University, the author reviewed semi-quantified paleoclimate signals of the Last Glacial Maximum (LGM) and Holocene Optimum (HO) in the arid northern China under the supervision of Prof. Huayu Lu. The Master thesis is entitled: “A preliminary quantitative paleoclimate reconstruction of the dune fields of northern China during the Last Glacial Maximum and Holocene Optimum”.

Aforementioned field, lab, and publication experiences have prompted and enabled the author to continue with works regarding paleoclimate changes in the arid realm. Since September 12th, 2013, the author start with the PhD study supervised by Prof. Frank Lehmkuhl, at RWTH Aachen, in the framework of German Federal Ministry of Education and Research project (BMBF-CAME: 03G0814A): “Supra-regional signal pathways and long-time archives: Quaternary monsoon dynamics at the northern margin of the Tibetan Plateau”, German Research Foundation project (DFG: LE 730/16-1): “Late Pleistocene, Holocene and ongoing geomorpho-dynamics in the Gobi Desert, South Mongolia” and the financial support from the China Scholarship Council (CSC: 201306190112). The research focus is using sedimentological and geochemical signatures incorporated in diversified sediment archives to disentangle Quaternary paleoclimate change and sedimentary processes in the Ejina Basin and Gobi Desert of Mongolia. To briefly outline the structure of this dissertation, the chapters are outlined and described as follows: 1, introduction to the status of the paleoclimate research in the research area and motivations to carry out this study; 2, geologic, climate, vegetation and paleoglacial settings of the study area; 3, field investigations, sampling, lab and mathematic methodologies employed in this study; 4, geochemical characteristics of different terrestrial archives (first paper); 5, multidisciplinary study to infer the paleoenvironmental change in the Orog Nuur catchment in the Gobi Desert (second manuscript); 6, bulk-geochemistry of the lacustrine sediments and potential elements and ratios to decipher integrated paleoenvironmental and provenance signals (third manuscript); 7, a synthesis concerning the paleoenvironmental reconstruction and proxy studies; brief abstract of the dissertation in English and in German language; references, and appendix are added at the end of this dissertation.

俞凱峰
(Kaifeng Yu)

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Aachen
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List of Units, Symbols and Abbreviations

Units of the International System (SI) have been guidelines in this dissertation. Unless otherwise specified, the abundances of trace element are based on the total content by weight of those in oven-dried material.

Units:
- **A.D.** anno Domini, used to label or number years in Julian and Gregorian calendars
- **a.s.l.** above sea level
- **cal ka BP** calculated thousand years before present (1950 A.D.)
- **ppm** parts per million; 1 ppm = 1 µg/g

Symbols:
- **AMS** Accelerator mass spectrometry
- **ELA** Equilibrium Line Altitude
- **pH** Minus logarithm, base 10, of H⁺ concentration

Abbreviations:
- **AMOC** Atlantic Meridional Overturning Circulation
- **CNS** Analysis of total carbon, nitrogen and sulfur
- **ECORD** European Consortium for Ocean research Drilling
- **EGU** European Geosciences Union
- **ESR** Electron spin resonance
- **gLGM** global Late Glacial Maximum
- **GSD** Grain size distribution
- **INQUA** International Union for Quaternary Research
- **IODP** Integrated Ocean Drilling Program
- **ITCZ** Intertropical Convergence Zone
- **MIS** Marine Isotope Stage
- **OSL** Optically stimulated luminescence
- **REE** Rare earth element
- **XRD** X-ray Diffraction
- **XRF** X-ray fluorescence
- **YD** Younger Dryas
Arid regions are areas of concern, because of population growth, the impacts of desertification and of natural phenomena, particularly droughts” (David S.G. Thomas, 1996)

1. Introduction

Being a fragile ecological system, environmental change in arid central Asia exerts tremendous influence on a significant percentage of population concerning nomadic migration and alternation of political regimes (Pederson et al., 2014). The arid central Asia (Fig. 1-1) is sensitive to paleoclimate changes. The comprehensive framework of alluvial fans, terraces, periglacial mass movement, aeolian and lacustrine sediments has documented the manner of the paleoclimate changes as well as the markedly anthropological influences since the late Holocene (Lehmkuhl and Haselein, 2000). Lehmkuhl et al. (2003) reported a successive geomorphological section in the arid central Asia from higher Khangai Mountain to the Gobi Desert, Badain Jaran Desert, Qilian Mountain, Qaidam Basin and eventually to the NE Tibet (Fig. 1-1). According to climatic and topographic settings, this section covers a holistic array of geomorphic units including glacial and periglacial landforms, pediments/bajadas, steppe and desert gorges, aeolian landforms and floodplain valleys with meandering rivers. In conjunction with high resolution sampling, well constrained chronological framework and robust interpretations of physical, geochemical and geobiological proxies, all this set of archives has the potential to serve as pivotal repository for paleoclimate (thermal and moisture) signals, which in turn will benefit the climate modelling and archaeological studies.

The Gobi Desert in arid northern China and southern Mongolia was recognized as one of the main dust sources for Chinese Loess Plateau and pelagic sediments in the western Pacific (Pye and Zhou, 1989; Xiao et al., 1997; Lu and Sun, 2000; Vandenberghe et al., 2006). Previously, broad pattern of late Quaternary (in particular Holocene) paleoclimate signatures of arid central Asia were defined and reviewed by Pachur and Wünneeman (1995), Yang et al. (2004, 2011), Feng et al. (2005), Herzschuh (2006), Chen et al. (2008), An et al. (2008), Wang et al. (2010) and Wang and Feng (2013). Ample compilations have suggested a distinct moisture regime of middle and southern Mongolia in comparison to that of higher latitude Baikal catchments and East Asian Summer Monsoon (EASM) domain of northern and eastern China (Yang et al., 2004; An et al., 2008; Wang et al., 2010; Wang and Feng, 2013). However, it remains elusive with respect to how and to what extent have EASM and
Westerlies affected the thermal and moisture signals in this spectacularly arid region. In addition, substantially temporal and spatial heterogeneity exist in this arid realm, namely, most of the records have poured attention into temporally the Holocene period and spatially, the arid northern China and northwestern Mongolia.

Fig. 1-1: Atmospheric circulations over the central and eastern Asia, with panel A denoting the summer pattern and panel B representing winter pattern. Solid lines indicate ca. 3,000 m a.s.l. airflow while dashed lines indicate earth surface flow at ca. 600 m (adapted from Benn and Owen, 1998; Lehmkuhl and Haselein, 2000; Barry and Chorley, 2009; An et al., 2014; Loibl, 2015). Study areas of the Ejina Basin and Orog Nuur Basin are marked as white rectangle in the panels. More detailed analyzed sections in this dissertation refer to following Figs. 2-2 and 2-3.

In this dissertation, terrestrial archives including aeolian, fluvial/alluvial and lacustrine sediments are selected and retrieved from the Ejina Basin and Orog Nuur (nuur = lake) catchment, respectively (Fig. 1-1), in trying to decipher the late Quaternary paleoenvironmental signals based on a robust multidisciplinary study. In addition, this dissertation is assembled primarily from three manuscripts (i.e., Chapters 4, 5 and 6). Several fractions in Chapter 1 may therefore overlap with paragraphs in those chapters.

1.1. Research framework and outline

This dissertation work is carried out in the framework of (i) German Federal Ministry of Education and Research project (BMBF-CAME: 03G0814A): “Supra-regional signal pathways and long-time archives: Quaternary monsoon dynamics at the northern margin of the Tibetan Plateau”, (ii) German Research Foundation project (DFG: LE 730/16-1): “Late Pleistocene, Holocene and ongoing geomorpho-dynamics in the Gobi Desert, South
Mongolia” and (iii) the financial support from the China Scholarship Council (CSC: 201306190112). The focus of this dissertation is using sedimentological and geochemical signatures incorporated in diversified terrestrial archives to decipher late Quaternary paleoclimate change and sedimentary processes in the Ejina Basin and Gobi Desert of Mongolia. On the other hand, additional studies including geobiological proxy analysis (i.e., palynology and ostracod) and geomorphological investigations were also conducted (Lehmkuhl and Lang, 2001; Hempelmann, 2010; Felauer, 2011; Hülle, 2011; Murad, 2011) with the intention to gain a sound and compelling paleoenvironmental implications. To briefly outline the structure of this dissertation, the main chapters are outlined as follows: 1, introduction to the status of the paleoclimate research in the research area and motivations to carry out this study; 2, geologic, geomorphological, climate, vegetation, paleoglacial and anthropo-zoogenic settings of the study area; 3, field investigations, sampling, lab and mathematic methodologies employed in the study; 4, geochemical characteristics of different terrestrial archives (the Ejina Basin; first manuscript); 5, multidisciplinary study to infer the paleoenvironmental change in the Orog Nuur catchment in the Gobi Desert (the Orog Nuur catchment; second manuscript); 6, bulk-geochemistry of the lacustrine sediments and potential elements and ratios to decipher integrated paleoenvironmental and provenance signals (the Orog Nuur core; third manuscript); 7, a synthesis concerning the paleoenvironmental reconstruction and proxy studies; brief abstract of the dissertation in English and German language; references, and appendix are added at the end of this dissertation.

1.2. Terrestrial archives in the Gobi Desert

To address those issues rose at the very beginning of the chapter, careful selection and full understanding of the geological repository is a prerequisite and pivotal step.

1.2.1. Lacustrine sediments

In the context of the Gobi Desert, lacustrine sequence is a critical archive for climate and provenance signatures. In particular in the arid central Asia, due to scarcity of abundant continuous loess-paleosol or oceanic archives, lacustrine records were more often employed as the Quaternary paleoenvironmental repository (Boyle, 2001; Mischke et al., 2005; Jin et al., 2015). Southern Mongolia is located on the margin of the Westerlies dominated arid central Asia and East Asian Summer Monsoon dominated costal eastern Asia (Chen et al., 2008). Acquiring of a continuous and chronological reliable past environment record in this
region is of exceedingly importance concerning the refinement of the understanding of the comprehensive climate pattern and possible corresponding driving mechanisms. However, there exist hitherto numerous spatial and temporal heterogeneities concerning the archives. In the Gobi Desert of Mongolia, only two continuous records were previously reported i.e., Bayan Tohomin Nuur (Felauer et al., 2012) and Ulaan Nuur (Lee et al., 2011; 2013). Nonetheless, none of these two cores provide paleoenvironment records that trace back to ages before ~15 ka. A record spanning longer time period is therefore indispensable to address aforementioned issues.

1.2.2. Aeolian, fluvial and alluvial sediments

Apart from the lacustrine sequence, it is also indispensable to gain a better understanding concerning other terrestrial archives embracing aeolian, fluvial and alluvial sediments to figure out the robust paleoenvironmental implications. Previously, the main factors controlling geochemical compositions of sediments are the nature of parent rocks, chemical weathering, diagenesis, mechanical disaggregation and abrasion, authigenic / allothigenous input, and metamorphism in case of relatively old e.g., early Cenozoic and Mesozoic sediments (Bhatia, 1983; Johnsson, 1993; Fralick and Kronberg, 1997; Young et al., 1998; McLennan, 2001; S. Yang et al., 2004; Xu et al., 2011). Analyzing geochemical characteristics along with other characteristics of sediments is therefore a powerful tool to decipher the nature of aforementioned processes. Previously, elemental (isotopic) and mineral fingerprints have been employed to evaluate the provenance of the American loess / mudstones / sandstones (Gallet et al., 1998; Zhang et al., 2014b), European loess (Amorosi et al., 2002; Buggle et al., 2008; Újvári et al., 2014), Eastern / Central Asian loess / desert sands (Liu et al., 1993; Honda and Shimizu, 1998; Jahn et al., 2001; Honda et al., 2004; Yang et al., 2007; Maher et al., 2009; Stevens et al., 2010; Chen and Li, 2011; Xu et al., 2011; Xiao et al., 2012; Wang et al., 2012) and Greenland dust (Újvári et al., 2015). Nesbitt and Young (1982) reported the major element content to represent a quantitative chemical weathering proxy, whereas in absence of strong chemical weathering (e.g., in arid and semi-arid environments, Zhu et al., 2014), the bulk-composition and mineralogy can be explained by physical abrasion, comminution and sorting (Nesbitt and Young, 1996; von Eynatten et al., 2012). Elemental characteristics of lacustrine or aeolian deposits have been employed to reconstruct the paleoenvironmental change in the northern Tibetan Plateau and the Mongolian Plateau during the late Quaternary (e.g., Hartmann and Wünnewann, 2009; Schwanghart et al., 2009; Lu et al., 2010; IJmker et al., 2012a; Felauer et al., 2012; Guo et al., 2013). Apart from
provenance and paleoenvironmental studies, the nature of bulk-compositions of different sediment archives is hitherto incompletely understood. On the other hand, whether and how geochemical composition can be assigned to sedimentary processes in arid region is seldom studied. To further decipher the past processes and controlling factors, a better understanding of the geochemical fingerprints recorded in these archives is needed.

1.3. State of art of the paleoclimate research in the Gobi Desert and adjacent regions

1.3.1. The Ejina Basin and arid northern China

In the arid northern China, i.e., where Ejina Basin locates, from west to east, either deserts or dunefields embracing Badain Jaran Desert, Tengger Desert, Mu Us Desert, Horquin, Songnen and Hunlunbuir Sandfield have dominated the region (Lu et al., 2013; Yu et al., 2013). In this arid realm, as compiled from peat bog, loess-paleosol sequences, lacustrine sediments, a sensitive alteration of the documented moisture and thermal signals in response to the paleoclimate changes are concluded (Yu et al., 2013). In particular, compared with modern times, the temperature has decreased by 5-11 °C and the precipitation decreased by 180-350 mm during the Last Glacial Maximum (LGM, ~26~16 ka in global scale), whilst the temperature has increased by 1-3 °C and the precipitation increased by 30-400 mm in the Mid-Holocene Optimum (~9~5 ka in global scale) (Yu et al., 2013). In the arid and semi-arid regions of northern China, particularly, in basin systems, lacustrine / playa, aeolian and alluvial / fluvial sediments are common. Spatial and temporal characteristics of these sediments are correlated to littoral and pelagic deposition systems of paleolake expansion and desiccation (Wünnemann, 1999), which can be ascribed to climatic variations. The endorheic Ejina Basin is regarded as a fundamental dust provenance of the Chinese Loess Plateau and adjacent regions (Pye and Zhou, 1989; Lu and Sun, 2000; Vandenberghe et al., 2006; Sun et al., 2008). For the Ejina Basin and adjacent areas, the land relief, geomorphological backgrounds, late Pleistocene deposition characteristics, neotectonic constrains and hydrological changes were conducted by Wünneumann et al. (1999, 2007), Mischke et al. (2003), Hartmann et al. (2009, 2011), Wang et al. (2011) and Zhu et al. (2014). Deciphering the geochemical characteristics of archives in this basin system would have been one crucial step towards a better understanding of the paleoenvironmental changes and sedimentary processes that are related to dust activities (see Chapter 4).
1.3.2. The Orog Nuur catchment and Mongolian Plateau

Further to the north, more attentions have been dedicated to the northern and western Mongolia as well as the Baikal catchments in Russia, albeit most of the lacustrine sequence listed here spans no longer than the Holocene period: Baikal Lake (Horiuchi et al., 2000; Karabanov et al., 2000; Prokopenko et al., 2001; Murakami et al., 2012; Kostrova et al., 2014), Kotokel Lake (Shichi et al., 2009), Karakul Lake (Komatsu et al., 2015), Hovsgol Nuur (Tarasov et al., 1999; Fedotov et al., 2004; Karabanov et al., 2004; Prokopenko et al., 2002, 2007; Hovsgol Drilling Project Members, 2009; Murakami et al., 2010; Fumiko Watanabe et al., 2014), Khuvsgul Nuur (Orkhonselange et al., 2013); Bayan Nuur (Dorofeyuk and Tarasov, 1998; Nauman, 1999), Telmen Nuur (Peck et al., 2002; Fowell et al., 2003), Khuisiin Nuur (Tian et al., 2013; 2014), Gun Nuur (Feng et al., 2005; Zhai, 2008; Zhang et al., 2012), Ugii Nuur (Schwanghart et al., 2008, 2009; Wang et al., 2009), Uvs Nuur (Walther, 1999; Grunert et al., 2000), Hoton Nuur (Tarasov et al., 2000; Rudaya et al., 2009), Lake Tuolekule (An et al., 2011); Tsetseg Nuur (Klinge and Lehmkuhl, 2013); Dada Nuur (Gunin, 1999), Yamant Nuur (Gunin, 1999), Dood Nuur (Dorofeyuk and Tarasov, 1998), Achit Nuur (Gunin, 1999), Ulaan Nuur (Lee et al., 2011; 2013) and Bayan Tohomin Nuur (Felauer et al., 2012). In addition, concerning other terrestrial archives, several loess paleosol sequences e.g. Karakorum (Lehmkuhl et al., 2011), Shaamar (Feng et al., 2005) and Khyaranny (Feng et al., 2001) were reported. The well dated interstadial Marine Isotope Stage 3 (MIS 3) paleoglacial advance in Altai Mountain, Kanas River valley, Western Khangai, and Darhad Basin were previously published by Reuther et al. (2006), Gillespie et al. (2008), Xu et al. (2009), Lehmkuhl et al. (2011; 2015), Zhao et al. (2013), and Rother et al. (2014), providing promising marks of the paleoclimate signals in this arid/semi-arid region. In general, the high pedogenesis i.e., soil layers and large scale glacial expansions are intimately correlated to the higher moisture supplies. However, especially in the central to southern Mongolia, all this suite of studies has presented an urgent requirement to retrieve and reverse a reliable paleoclimate sequence spanning longer time periods than the Holocene.

As aforementioned, on the Mongolian Plateau and adjacent arid central Asia, continuous lacustrine sequences are widely regarded as fundamental repository for paleoenvironmental signatures. A wealth of works has been reported concerning the late Quaternary moisture and thermal history. However, an array of paramount aspects still needs to be tackled. They are summarized as follows: (i) biased or even contradictory conclusions may occur due to the interpretations of different proxies. For instance, Schwanghart et al. (2009) advocated a
warmer and wetter mid-Holocene in Ugii Nuur (in central-northern Mongolia) as inferred from the mineral composition and bulk-geochemistry, while an arid mid-Holocene was reconstructed from palynology studies (Wang and Feng, 2013). (ii) Most of the works poured attention into the Holocene period, while only few records addressed the climate history during the Pleistocene (Pachur and Wunnemann, 1995; Feng et al., 1998; Grunert et al., 2000; Lehmkuhl and Haselein, 2000). (iii) Substantial spatial heterogeneity is also noteworthy. Amount of studies on lacustrine deposits were carried out in the Baikal catchments in Russia, northern and western Mongolia and northern China. Only two lacustrine sequences were hitherto conducted in southern Mongolia, namely, Bayan Tohomin Nuur (Felauer et al., 2012) and Ulaan Nuur (Lee et al., 2013) (cf., Fig. 5-1A). Furthermore, above problems might have been reinforced by uncertainties in different radiocarbon age models due to a varying hard water effect (Mischke et al., 2013).

On the other hand, among the suite of the multidisciplinary studies on argillaceous sediments, geochemistry appears most likely the promising tool to decipher the interplay between the environmental change, source lithotype and sediment bulk-composition (Boyle, 2001). Considering the late Quaternary lacustrine sediments, the bulk-geochemistry may be controlled by source terranes, authigenic or allothigenic input, which may be modulated by the past environmental conditions, while pedogenesis and diagenesis might exert only limited overprints (Yu et al., 2016). Knowledge of the major and minor element abundance downcore variance along with the field investigation and carefully examined geologic mapping will thereby enable us to gain a better understanding of the climate-induced environment and provenance changes throughout the deposition process. Furthermore, surveys considering the major and minor element abundance and corresponding environmental interpretations in the pelagic realm have been systematically conducted and reviewed (Calvert and Pedersen, 2007), while their counterpart elucidations in the lacustrine sediments still await more investigations (cf., Roser and Korsch, 1988; Norman and De Deckker, 1990; Roy et al., 2012; Doberschütz et al., 2013; Davies et al., 2015; Liang and Jiang, 2015).

1.4. Research Motivations

As reviewed above, an array of paramount aspects has inhibited our complete understanding of the broad pattern of Quaternary moisture and thermal history of the arid central Asia and their underlying mechanisms. Main knowledge gaps are summarized as follows:
(1) It remains elusive regarding how and to what extent have EASM and Westerlies affected the thermal and moisture signals in this spectacularly arid region;
(2) Most of the geologic records have poured attention into the Holocene period, whereas only few records can extend back to earlier marine isotope stages;
(3) Substantially spatial heterogeneity is noteworthy in the area. Exceeding amounts of studies were carried out in the Lake Baikal catchment, northern and western Mongolia, while only two continuous lacustrine sequences (spanning ~ 15 ka) were hitherto conducted in southern Mongolia (Lehmkuhl and Lang, 2001; Felauer et al., 2012; Lee et al., 2013);
(4) Concerning identical archive sequences, biased or even contradictory conclusions may occur due to the interpretations of palynological and bulk-geochemical signals (e.g., Schwanghart et al., 2009; Wang and Feng, 2013), multidisciplinary study is therefore indispensable to reconstruct sound paleoenvironmental signals;
(5) Apart from provenance and paleoenvironmental studies, the nature of bulk-compositions of different sediment archives and different granulometric proportions is hitherto incompletely understood. On the other hand, whether and how geochemical composition can be assigned to sedimentary processes in arid region is seldom studied. To further decipher the past processes and controlling factors, a better understanding of the geochemical fingerprints incorporated in this set of terrestrial archives is needed;
(6) Surveys considering the bulk-geochemistry and corresponding environmental interpretations in the marine realm have been systematically conducted and reviewed, while their counterpart explanations in the lacustrine sediments still await more investigations (cf., Boyle, 2001; Calvert and Pedersen, 2007).

Based on those knowledge gaps, the core fraction of the dissertation is outlined and demarcated into three chapters, from which Chapter 4 is dedicated to the Ejina Basin while Chapters 5 and 6 represent the multidisciplinary study on two lacustrine drilling cores ONW I and ONW II recovered in the Orog Nuur catchment:

Manuscript 1: Discriminating sediment archives and sedimentary processes in the arid endorheic Ejina Basin, NW China using a robust geochemical approach (Chapter 4):

In this study, a geochemical approach in conjunction with a broad field of granulometric, mineralogical and generally constrained chronological data is presented in order to:

- Identify the broad pattern of lithologic units at the northern margin of the Ejina Basin;
Differentiate the distinct nature of bulk-compositions in different granulometric compositions and the array of archives obtained from these units;

Employ a multivariate statistic approach to test which assemblages of elements are suitable, sensitive and robust to reconstruct sedimentary processes and thereby to evaluate the controlling factors for the bulk-composition of sediments in (semi-)arid regions. Hence, ultimately, the aim is to improve our understanding of the intriguing sedimentary processes in this arid terrestrial endorheic context.

Manuscript 2: Lake sediments documented late Quaternary humid pulses in the Gobi Desert of Mongolia: Vegetation, hydrologic and geomorphic implications (Chapter 5):

A multidisciplinary study is performed on a critically selected lacustrine sequence in attempting to gain a robust and unambiguous knowledge of the past environmental changes. In this study, two carefully selected parallel cores were recovered from Orog Nuur, in southern Mongolia. Based on previous investigations, a multidisciplinary study involving sedimentology, bulk-geochemistry, palynology, and ostracod analyses were carried out on lacustrine cores ONW I and ONW II, intending to:

- Gain a reliable knowledge of moisture history in the Orog Nuur catchment over the last ~50 ka, and its governing atmospheric circulation pattern;
- Elucidate broad pattern of interrelated vegetation and hydrologic history of the Orog Nuur catchment;
- Generate and refine understandings on the spatial and temporal traits of moisture and thermal signals in Gobi Desert of Mongolia, with aid of comparison with adjacent aeolian, pelagic and mountainous glacial expansion records.

Manuscript 3: Geochemical imprints of coupled paleoenvironmental and provenance change in the lacustrine sequence of Orog Nuur, Gobi Desert of Mongolia (Chapter 6):

In this study, high resolution major and trace element contents accompanied by calcium carbonate concentration and C/Natomic ratios of the lacustrine sequence are examined in attempts to:

- Test the possible element ratios that can be employed to extract the broad pattern of the diversified source terranes throughout the depositional period;
- In terms of certain elements e.g., Co, Mn and Zr, examine the underlying driven mechanism and environmental interpretation in the lacustrine realm;
In conjunction with briefly constrained mineral abundance, an array of major and trace elements’ downcore variance were illustrated to indicate the interplay in the integrated paleoenvironmental and provenance change in the depositional system.
“Mongolia is situated where contrasting geological structures intersect, within the zone of interaction of different systems of global atmospheric circulation. Here, at the junction of the Siberian taiga forest, Dahurian steppes, and Gobi desert is a crossroad of plant and animal distribution” (P.D. Gunin et al, 1999)

2. Regional setting

The Gobi Desert covers a broad area including both northern China as well as the central to southern Mongolia (Fig. 2-1). In this dissertation, two representative study areas comprising the Ejina Basin in the south and the Orog Nuur catchment in the north are selected.

2.1. Geologic and geomorphic setting

2.1.1. The Ejina Basin

The Ejina Basin (synonym: Gaxun Nur Basin) lies in the lower reaches of the endorheic Hei River catchment (with an area of ca. 130,000 km², Fig. 2-2), which contains one of the world’s largest continental alluvial fan systems (Hartmann et al., 2011). The basin covers an area of about 28,000 km² and is fed by the Hei River discharging from the Qilian Mountains. The elevation ranges from 880 to 1,300 m above sea level (a.s.l.) (Hartmann et al., 2011) and late Quaternary sediments are up to ~300 m thick (Zhang et al., 2006; Hartmann and Wünnemann, 2009). The infilling of the basin started probably at earliest 250 ka ago, as retrieved from the D100 drilling core (Fig. 2-2, 42.1°N 100.85°E, 940 m a.s.l., Wünnemann, 1999, Wünnemann et al., 2007a). Paleozoic to Mesozoic intrusive bedrock can be observed in the northern Juyanze and Wentugaole basins (Fig. 2-2, Becken et al., 2007; Rudersdorf et al., 2015). The basin is bound by the Heli Mountains in the south, the Bei Mountains to the west, the Badain Jaran Desert / Alashan Plateau to the east and the Gobi Altai Mountains to the north (Fig. 2-2). Temporal and spatial patterns of fluvial and lacustrine deposition are influenced by neotectonics (e.g., the western margin has a subsidence rate of ca. 0.8-1.1 m/ka, cf., Hartmann et al., 2011). Nowadays, only the Ejina oasis near Juyanze paleolake receives ephemeral water input (Hartmann et al., 2011). Typical geomorphological features are gravel plains, yardangs, playas, sand fields and sporadically distributed mobile linear and barchan dunes (Zhu et al., 2014; Fig. 2-1).
Fig. 2-1: Photographs of representative contexts in the study area: (A) Gobi surface and Precambrian intrusive bedrocks with background of Mountains in Mongolia. (B) Megadunes on the northern margin of Badain Jaran Desert. (C) Common observed Haloxylon ammodendron on the gobi surface. (D) Unparallelled sand ripples on the dune surface. (E) Playa surface of western Juyanze Basin with particularly high contend of evaporite minerals. (F) The ancient city Khara Khoto (synonyms: Black City, abandoned in 1,372 A.D.) and nearby accumulated dunes.
Fig. 2-2: Geologic map and section locations in the northern Ejina Basin: Section HC8 is an escarpment between the western and eastern Juyanze sub-basin. Sections KK1 and KK2 are located by the braided river channel near ancient of Khara Khoto. Sections WT1 and WT2 are yardangs located on the margin of Wentugaole Sub-basin and Badain Jaran Desert. Black (dash-) lines denote strike-slip neotectonics compiled from Wünnemann et al. (2007), Hölz et al. (2007), Hartmann et al. (2011), Cunningham (2013) and Rudersdorf et al. (2015). D100 correspond to the drilling core from Wünnemann (1999) and Wünnemann et al. (2007).

2.1.2. The Orog Nuur catchment

The Orog Nuur catchment lies in the Valley of Gobi Lakes in southern Mongolia (Fig. 2-3; Tab. 2-1). The Orog Nuur is a brackish habitat that is subjected to desiccation and it occasionally turns into a playa environment. Tuyn Gol (gol = river) is the main inflow that originates from the southern slopes of Khangai Mountains around 220 km north of the lake. The lake has no conspicuous outflow, resulting in a hydrologically closed basin system. The northwest-southeast orientated Valley of Gobi Lakes (ca. 1,400 to 1,800 m above sea level, a.s.l.) is an elongated intramontane depression between the Siberian Craton and the Tarim and Sino-Korean Cratons (Baljinnyam et al., 1993; Windley and Allen, 1993; Cunningham et al., 1996, 1997; Owen et al., 1999; Bardarch et al., 2000; Webb and Johnson, 2006; Cunningham,
2013; Guy et al., 2014). The Valley of Gobi Lakes is bounded by the Khangai Mountains in the north and Gobi Altai Mountains in the south (Fig. 2-3B). The maximum elevation of the Khangai Mountains is around 4,000 m a.s.l. at Otgon Tenger Uul in the west (4,008 m a.s.l., 47°36’30”N, 97°33’09”E) and ca. 3,000 m a.s.l. at Erhet Hayrhan Uul in the east (3,037 m a.s.l., 46°39’18”N, 101°13’56”E), whilst the Gobi Altai has a summit at 3,957 m a.s.l. (Ikh Bogd Uul: 44°59’42”N, 100°13’51”E; uul = mountain). A left lateral strike-slip fault is located at the southern side of the Khangai Mountains (Tapponnier et al., 1979; Walker et al., 2007; Cunningham, 2013), while the southern part of the Orog Nuur watershed exhibits the tectonic escarpment of the Gobi Altai and gently inclined alluvial fans (Baljinnyam et al., 1993; Johnson, 2004; Vassallo et al., 2007, 2011). The elongated forebergs of the Gobi Altai are markedly faulted, warped and partially uplifted by thrust faults (Owen et al., 1997; Bayasgalan et al., 1999). For instance, in the Gobi Altai, due to the 1957 earthquake with a magnitude of 8.3, left-lateral displacements reached 6 m and vertical displacements approached 1.5 m (Baljinnyam et al., 1993), which may lead to misinterpretations regarding the shoreline ridges or terraces. Paleozoic volcanic and plutonic rocks are exposed in the basin and some places are overlain by conglomerates. Previously, a much larger lake extent in the basin was reconstructed based on three sets of shorelines (Lehmkuhl and Lang, 2001; Komatsu et al., 2001; Grunert et al., 2009). This suite of recessional beaches are determined to be ~60 m, ~23 m and ~16 m, respectively, higher than the modern lake-level. East-west oriented mobile dunes and cuspate bars lie in the vicinity of the Orog Nuur (Stolz et al., 2012).

2.2. Climate regime

2.2.1. Climate of the Ejina Basin

The Ejina basin as part of the Gobi Desert is located beyond the limits of the East Asian Summer Monsoon (cf., Chen et al., 2008). The winter Siberian Anticyclone dominates the climate regime (Chen et al., 2008; Mölg et al., 2013). The mean January and July air temperatures are ca. -11°C and 26 °C, respectively. More than 90% of the ca. 38 mm annual precipitation occur between July and early September, albeit the annual precipitation in the upper reaches of the Hei River catchment in the Qilian Mountains can reach 300-500 mm (Wang and Cheng, 1999; Wünremann et al., 2007a). The theoretical potential evaporation is around 3,700 mm.
Fig. 2-3: Present-day distribution of geologic terranes in the Orog Nuur catchment (marked with dashed line). Northern region of Orog Nuur Basin is dominated with Devonian-Triassic felsic quartz syenite, granite and plagiogranite, accompanied by intermediate mafic fractions. Southern region of Orog Nuur exhibit increasing fraction of mafic and ultramafic basalt and andesite-basalt rocks. Alkaline syenite occurs sporadically in the lower Orog Nuur catchments. The depositional basin is bounded by eastern Khangai in the north and the Gobi Altai Mountains in the south. More details concerning representative minerals see Tab. 2-1. Concerning the geomorphological and topographic settings refer to Fig. 5-2 of the same region.

2.2.2. Climate of the Orog Nuur catchment

Further to the north, Mongolia is dominated by a continental climate characterized by dry and cold winter and a precipitation maximum in summer (An et al., 2008). The mean annual precipitation along a north-south transect ranges from ~500 mm to <100 mm. 65-75 % of the precipitation occurs in summer due to the enhanced south-eastern cyclonic activity along the polar front (Kostrova et al., 2014). Only ~100 mm precipitation is delivered in the lower Gobi Desert of southern Mongolia, while the higher elevated Khangai Mountains can reach ~400 mm. According to records at Bayankhongor weather station near the Orog Nuur, the mean
July and January temperature in the Gobi Desert are ~16 °C and ~20 °C, respectively, while the mean annual temperature is about -2 °C to 5 °C (Felauer, 2012). In spring, dust- or sandstorms frequently occur with maximum wind speeds exceeding 20 m/s (Hempelmann, 2010; Felauer, 2012). There is generally no snow cover because of the immense winter dryness related to the predominant Siberian Anticyclone (Kostrova et al., 2014).

Tab. 2-1: Inventory of the plutonic rocks, volcanic / subvolcanic rocks and Quaternary deposits in the Orog Nuur catchments. For geologic mapping refer to Fig. 1-3. This set of sources rocks is of vital importance concerning the bulk-geochemistry discussed in Chapter 6.

<table>
<thead>
<tr>
<th>Plutonic rocks and complexes</th>
<th>Volcanic and subvolcanic rocks</th>
<th>Genetic types of Quaternary deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultramafic</td>
<td></td>
<td>a alluvial</td>
</tr>
<tr>
<td>σ dunite, peridotite, serpentinite melange</td>
<td>β basalt</td>
<td>l lake</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>µβ diabase, dolerite</td>
</tr>
<tr>
<td>σδ ultrabasite-basalt layered series</td>
<td>τβ trachbybasalt</td>
<td>al alluvial-lake</td>
</tr>
<tr>
<td>Anorthosite</td>
<td></td>
<td>p proluvial</td>
</tr>
<tr>
<td>ση gabbro-troctolite-anorthositic complex</td>
<td>αβ andesitebasalt</td>
<td>d talus</td>
</tr>
<tr>
<td>v gabbro, gabbronorite</td>
<td></td>
<td>tα trachyandesitebasalt</td>
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<tr>
<td>Ud gabbrodiomite</td>
<td></td>
<td>v proluvial-talus</td>
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<tr>
<td>Intermediate</td>
<td></td>
<td></td>
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<tr>
<td>δ diorite</td>
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<td>qδ quartz diorite</td>
<td></td>
<td></td>
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<tr>
<td>Felsic</td>
<td></td>
<td>λ dacite, rhyolite, quartz porphyry</td>
</tr>
<tr>
<td>δ-γ diorite-granitic complex</td>
<td></td>
<td>μλ rhyodacite, trachrhyodacite</td>
</tr>
<tr>
<td>γδ granodiorite, tonalite, plagiogranite</td>
<td>tλ trachydacite, trachyrhyolite</td>
<td></td>
</tr>
<tr>
<td>γ granite, leucogranite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γζ granosyenite, quartz syenite, subalkaline granite</td>
<td>βδ spilite-keratophytic and</td>
<td></td>
</tr>
<tr>
<td>γ-γζ granite-granosyenitic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γξ granite-porphory</td>
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<tr>
<td>Alkaline</td>
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<tr>
<td>εδ alkaline gabbro, ijolite, urite</td>
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<tr>
<td>εξ nepheline syenite, alkaline syenite</td>
<td></td>
<td></td>
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<tr>
<td>εγ alkaline granite</td>
<td></td>
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</tr>
</tbody>
</table>

2.3. Soils and vegetation cover

Primary soil type in central to southern Mongolia is dry-steppe Kastanozems. Other common soil types are Chernozems/dark Kastanozem in the forest-steppe zone as well as brown semidesert soils (Tamura et al., 2012). In modern context, arable soil is relatively scarce in both the Ejina Basin and Orog Nuur catchment. The modern vegetation follows a north-south transect from alpine tundra, mountain taiga, mountain/forest steppe, grass steppe, desert steppe (Orog Nuur catchment) and finally to desert communities such as the Ejina Basin (Fig. 1-1; Hilbig, 1995; Gunin et al., 1999). In Khangai and Altai Mountains, the dominant tree species is Larix sibirica (accompanied by patches of Betula and Populus) on the northern and eastern slopes, while steppe prevail the sun-exposed southern and western slopes (Miehe et al., 2007). The uppermost boundary of the alpine meadows is ~ 2,900 m a.s.l. (Lehmkühl and Lang, 2001). Most of the lowland regions in the basin system are characterized by open desert...
steppes and bare gobi surface. Dwarf bushes and reed-halophytes are the dominant communities in lower reaches of the Orog Nuur catchment (Murad, 2011), while, as outlined in Fig. 5-1A, the higher elevated catchment of the Orog Nuur is covered by forest steppe and / or alpine steppe.

2.4. Paleo- and modern glacial setting

As illustrated in Fig. 2-4, there is no modern glacier or periglacial activity in the Ejina Basin, albeit glaciers exist in the further southern higher elevated Qilian Mountains. On the other hand, as the depositional basin of Orog Nuur is linked to the higher Khangai Mountains via Tuyn Gol, Quaternary glacial variance may play a pivotal role in terms of water supply and the clastic delivery. In modern times, only the western Khangai has small ice caps and the average equilibrium line altitude (ELA) was estimated in a range from 3,900 to 4,000 m a.s.l. (Fig. 2-4; Rother et al., 2014). The modern periglacial zone reaches down to 2,700 m a.s.l. (Lehmkuhl and Lang, 2001; Klinge et al., 2003). A set of Last Glacial Maximum (LGM) moraines at an altitude of ~2900 m. a.s.l. in the southern Khangai Mountains was dated thereafter to >21 ka (Lehmkuhl and Lang, 2001). In addition, Ritz et al. (2006) determined ages of alluvial sediments of the forelands of Gurvan Bogd (bogd = massif) by $^{10}$Be cosmogenic nuclides exposure dating and supposed an aggradation of sediments in the context of the global glacial terminations. In the Gobi Altai, permafrost developed at ca. 22-15 ka and degraded since ~13 ka, and was thereafter diminished since the early Holocene (Owen et al., 1998).

2.5. Anthropo-zoogenic setting

In Neolithic period, first signs of nomadic presence on the NE Tibetan Plateau were reported to be as early as 7,200 cal a BP, when temperature was up to 2 °C warmer than today (Schlütz and Lehmkuhl, 2009). The descendant nomadic migration routes were established at least at ~2,200 years BP (Schlütz and Lehmkuhl, 2009). The “Nomadic Anthropocene” was postulated by Schlütz and Lehmkuhl (2009) and Miehe et al. (2014) for the last 6,000 years when nomads transformed the natural steppe-like vegetation into K. pygmaea pasture. Landforms become more heterogeneous due to fragmentation of the rangelands (Yu et al., 2017). Furthermore, in this region, agriculture facilitated permanent settlements were suggested since 3,600 a BP (Chen et al., 2015). In modern times, human activities play an important role in regulating the desert-steppe biomes in northern China and central to southern Mongolia (Lehmkuhl, 1997). However, in our context, the time spanning of ~50 ka
to the early Holocene has ruled out intensively anthropo-zoogenic impacts, the reversed thermal and moisture data indicate therefore exclusively paleoenvironmental signals.

Fig. 2-4: Schematic north-south oriented topographic transect and corresponding vegetation patterns. The eastern parts of Khangai Mountains (higher reach of the Orog Nuur catchment) with altitudes between 3,500 m and 3,700 m a.s.l. have no modern glaciers, while small ice-fields may reach down to 3,200 m a.s.l. in the western Khangai Mountains (Lehmkuhl and Lang, 2001).
“Paleoclimatic research provides the essential understanding of climate system variability, and its relationship to both forcing mechanisms and feedbacks, which may amplify or reduce the direct consequences of particular forcings...the proxy material has acted as a filter, transforming climatic conditions at a point in time, or over a period, into a more or less permanent record, but the record is complex and incorporates other signals that may be irrelevant to the paleoclimatologist” (Raymond S. Bradley, 1999)

3. Materials and methods

3.1. Field work and sampling strategy

In the Ejina Basin, three field investigations were carried out in 2011, 2012 and 2014. Selected profile locations are distributed along three geomorphological systems (Figs. 2-2), i.e., following inverted channels (sections KK1 and KK2) to the lower Juyanze playa (section HC8) and then toward the higher Wentugaole / Badain Jaran Desert margin (sections WT1 and WT2, see cross-section Fig. 4-1B). Ninety-three samples from five sections with different geomorphological contexts were collected for further sedimentological and geochemical analysis. Samples were acquired at 10-50 cm intervals based on stratum thickness and properties. Fewer samples were acquired within the generally homogeneous lithological units.

Concerning the Orog Nuur, two parallel cores (ONW I: 6.00 m, 45°03’48”N, 100°34’39”E; ONW II: 13.35 m, 45°04’28”N, 100°35’08”E, 1,219 m a.s.l.) are retrieved from the western part of Orog Nuur during the playa phase in 2007 (Fig. 2-3). The core was opened, described and documented in the field. Samples were separated and transported to University of Göttingen, Free University of Berlin and the Alfred Wegener Institute in Bremerhaven for palynological, ostracod, X-ray fluorescence and X-ray powder diffraction analyses. The remaining material of the cores is preserved at RWTH Aachen University for grain size and TOC analysis. The paleoenvironmental reconstruction is carried out primarily based on the longer core ONW II.
3.2. Laboratory methods

3.2.1. Chronological methods

For the Ejina sequences, in order to acquire and assess a generally constrained chronological framework which can be compared with previously established lacustrine or beach bar records, AMS radiocarbon dating was applied to six samples in the Poznan Radiocarbon Laboratory, Queen’s University Belfast and the Beta Analytic Radiocarbon Dating Laboratory. Dated materials were bulk organic matter and carbonates. Radiocarbon ages were calibrated to calendar years using the CALIB rev.7.1 (Stuiver et al., 1998) with the latest calibration dataset (Intcal13.14c, Reimer et al., 2013). Radiocarbon ages are presented as calibrated years (cal BP) unless otherwise noted. Optically Stimulated Luminescence (OSL) dating was applied to six samples at Nanjing University. The samples were treated with 30 % hydrogen peroxide and 10 % hydrochloric acid. The fine sand-sized (63-90 µm) quartz grains were extracted by wet sieving. 2.58 g/cm³ sodium polytungstate was used to separate the quartz and K-feldspar. Treatments with 40 % hydrogen fluoride for 40 min and 10 % hydrochloric acid for 20 min were applied to purify the quartz. After washing and drying, the grains were mounted as monolayer on the 9.8 mm diameter stainless steel discs using silicon spray. All luminescence measurements were carried out using a Risø TL/OSL-DA-20 C/D reader equipped with blue LEDs (470±30 nm) and an IR laser diode emitting at 830 nm (Bøtter-Jensen et al., 2010). Irradiations were carried out with ⁹⁰Sr/⁹⁰Y beta sources mounted on the readers and calibrated for discs. The quartz OSL signals were collected through 7.5 mm of Schott U-340 (UV) glass filter. Equivalent dose (Dₑ) was determined by single-aliquot regenerative does (SAR) protocol following Murray and Wintle (2003). For samples with feldspar contamination after a maximum of three etching treatments with hydrofluoric acid, infrared IR-stimulation is inferred prior to the optical (blue-light) stimulation to both measure and deplete the feldspar signal prior to the OSL measurement. A preheat of 260 °C for 10 s and cut heat of 220 °C combination was used for routine equivalent dose measurements. The ²³⁸U, ²³²Th and ⁴⁰K concentrations were detected using Neutron Activation Analysis (NAA) at the China Institute of Atomic Energy. As the in-situ water content is extremely low, 25 % of saturation water content was used in dose rate calculation and the absolute uncertainty on the water content was assumed to be ±5%. Using the revised dose rate conversion factors of Guérin et al. (2011) and water content attenuation factors (Aitken, 1998), the elemental concentrations were converted into effective dose rate. The cosmic ray dose rate was calculated following Prescott and Hutton (1994).
Concerning Orog Nuur drilling cores (ONW I; ONW II), ten radiocarbon ages were
determined from bulk materials (Tab. 5-1) using accelerator mass spectrometry (AMS) at the
University of Erlangen-Nürnberg and subsequently calibrated to calendar years using CALIB
rev. 7.1 (Stuiver et al., 1998) with the latest IntCal 13.14c calibration curve (Reimer et al.,
2013). All radiocarbon ages are presented as calibrated years (cal a BP). Apart from the
unrecovered uppermost sediments, a polylinearly regressed age-depth model of core ONW II
(25-1,335 cm) was computed. Reservoir effects at different depth are assessed by (i)
calculating the surface age from the age model, (ii) identifying Termination I in bulk-
geochemical and palynological sequences, and (iii) comparing the Younger Dryas (YD,
Dansgaard et al., 1989)-related sand layer in Orog Nuur and Ulaan Nuur (Fig. 5-1A, ~200 km
northeast of Orog Nuur, Lee et al., 2011, 2013). Two radiocarbon ages from core ONW I (at
386 cm and 588 cm, respectively) are employed to compare timing of the stratigraphic units
relative to ages of counterpart depths in core ONW II (Tab. 5-1 and Fig. 5-4).

3.2.2. Grain size analysis

The grain size distributions (GSDs) of all samples from the Ejina Basin and Orog Nuur Basin
were measured using a Beckman Coulter LS13320 Laser Diffraction Particle Size Analyzer
with a detection range of 0.04-2,000 µm. Portions larger than 2,000 µm were previously
removed by sieving. As previously proposed, the GSD, in particular the finer proportions (i.e.,
< 2 µm) in sand and loess sediments, may be potentially altered by different pretreatment
methods (e.g., Lu et al., 2001; Kovács, 2008; Mason et al., 2011). Therefore, before
measuring, a parallel test (HCl/H2O2- and H2O2-only-treatment) was done to test the impact of
possible incorporated calcium carbonate on the resulting GSD, revealing however no
pronounced differences (cf. Schulte et al., 2016). Thus, all measurements were performed
uniformly without hydrochloric acid treatment. 700 µl of 35 % H2O2 was added to remove the
organic components. Afterwards samples were dried at 70 °C for two days. Sodium
pyrophosphate was added to avoid coagulation. Optical properties (fluid RI = 1.33, sample RI
= 1.55, imaginary RI = 0.1) were used as described in Özer et al. (2010) for quartz dominated
samples. The final GSD represents the average of two subsamples. Each of them was
measured twice to ensure the reliability of the results. In case of conspicuous offset existing
between subsamples, the aforementioned procedure was repeated for the sample.
3.2.3. X-ray fluorescence analysis and X-ray diffraction

For those samples from the Ejina Basin, X-ray fluorescence (XRF) analysis was conducted at RWTH Aachen University on all ninety-three samples using an Ametek X-ray Fluorescence Spectrometer (Spectro Xepos, 2007). The whole sample material was dried, sieved through a 2,000 µm mesh sieve and then ground to < 63 µm using a Pulverisette 7 before mixing 8 g sample with 2 g wax. The mixed powder is pressed into steel rings for measuring with a pressure of 15 tons for 20 s. Following calculation procedure, root mean square errors of calibration and lower limit of detection can be inferred from Spectro Xepos (2007). Certified reference materials involving No. 5358-90, Nos 2504-2506-83, Nos 2498-2500-83, NCS DC 73375, JF-1, UG-QLO-1 and UG-SDC-1 were referred to during the analyzing. Thirty elements are selected for further analysis. However, several values of the samples were below detection limit (BDL). X-ray diffraction (XRD) was applied on fifty-three samples from section HC8 to determine mineral abundances (Hartmann and Wünnemann, 2009). The XRD was measured at Freie Universität Berlin using a Philips PW1710 and graphite monochromator with a Cu-K-alpha at 36 kv, 24 mA. The powdered samples were scanned from 3° to 40° at °2θ, angle spectrums are conducted by Xpert Highscore software, the classification of impulses rates following Hartmann and Wünnemann (2009). Examples of dispersive spectrums of XRD are illustrated in Fig. 4-4.

Concerning the Orog Nuur core sequences, the X-ray fluorescence (XRF) analysis was carried out in Alfred Wegner Institute (AWI) for Polar and Marine Research in Bremerhaven, Germany, using an Avaatech XRF Core Scanner configured with Canberra X-Pips 1500-1.5 detector (slit 10 mm, 10, 30 keV, 300 and 700 µA). The scanning interval is 1 cm, resulting in 1,335 measurements for the core ONW II. Processes comprising subtracting a background curve, applying statistical corrections for physical processes in the detector and deconvolution of overlapping peaks were performed using scanner equipped WinAxil package (NIOZ and Avaatech, 2007). To gain a direct knowledge about the depositional environment of former sediment-water interface, two factors were computed based on the element dataset using factor analysis given in Yu et al. (2016). Thereby, high loading elements for each factor in conjunction with the factor scores provide intriguing information about the sedimentary processes (Yu et al., 2016). In addition, X-ray diffraction (XRD) for 14 samples at different depths was performed to assess the general mineral composition and provide additional information for the interpretation of bulk elemental compositions. The sediment color (RGB model) was scanned using a CCD line scan camera.
3.2.4. Electrical conductivity and magnetic susceptibility measurements

For the core ONW I from the Orog Nuur, electrical conductivity (EC, here equals specific conductivity) and magnetic susceptibility (MS) were carried out as an environmental and salinity proxies. 50 ml water and 0.01 g KCl were added for each sample, the EC with 10 cm interval was measured after 30 min using a WTW LF 196 probe. MS at 1 cm interval was measured using a Barrington MS2 with a MS2 E sensor.

3.2.5. Carbon, nitrogen, sulfur, TOC and CaCO₃ analyses

For the core ONW II from the Orog Nuur, Carbon (TC), nitrogen (TN), sulfur (TS) concentrations, and the Total Organic Carbon (TOC) content were determined, in order to gain a better understanding of the geochemical habitats of the former water sediment interface. Samples were dried at 36 °C for 24 hours. The samples in zinc capsules were subsequently analyzed in CHNS Analyzer EA3000. The Scheibler gas method (DIN 19684) was employed to calculate the CaCO₃ content, and 1-5 g samples were utilized respectively. Calculation equation is as follows:

\[ CaCO_3 (\%) = \frac{V \times p \times 0.1602}{(t + 273)} \times E \times K \]

Where \( V \) is the volume of CO₂ (cm³), \( p \) represents the atmospheric pressure (mm Hg), \( t \) denotes room temperature (°C), \( E \) is the loss of weight (g) and \( K \) exhibits the correction factor (here 2 is used). TOC was subsequently computed following Scheffer and Schachtschabel (2002):

\[ TOC = (C - (CaCO_3 \times 0.12)) \times 1.72 \]

The \( C/N_{\text{atomic}} \) ratios throughout the ONW II core were computed and examined for further interpretations (Meyers and Teranes, 2001).

3.2.6. Pollen, non-pollen palynomorphs and palynofacies analyses

Concerning the core ONW II, palynological studies were processed at University of Göttingen. Sediment subsamples of 1 or 2 cm³ were acquired at 5-10 cm intervals through the core ONW II. In total 123 samples were extracted and treated with standard laboratory procedures including KOH, HCl, HF treatments and subsequent acetolysis (Erdtman, 1960; Moore et al., 1991). Lycopodium spores were added as marker before calculation of the
pollen, spores and charcoal particle concentration (grains/cm$^3$). Except for few samples, at least 400 grains were counted for statistics. A total of 50 pollen and 40 spore taxa were identified through the core ONW II. Clump of pollen that denotes immature grains sticking together was calculated as paleoecological signals (Schlütz and Lehmkuhl, 2007). Available references (Moore et al., 1991; Vanky, 1994; Van Geel et al., 2003) were employed to identify the taxonomic nomenclature of pollen and spores. All taxa were subsequently aggregated into several groups, namely, arboreal plants, humidity indicators, aquatic algae, aridity indicators and grazing indicators. Two ratios were employed to compute the annual temperature ($T$) and moisture ($M$) following Ma et al. (2008) (flora groups and equations see Tab. 5-2). The moisture and thermal signals are further compared with the A/C ratios as well as the pollen concentration, respectively.

3.2.7. Ostracod analysis

A total of 131 sub-samples from core ONW II were collected at 10 cm intervals for ostracod analysis in order to examine and verify the paleohydrological conditions. The sediment was treated with 3 % H$_2$O$_2$ for 48 hours and washed through 0.25 and 0.1 mm meshes. All ostracod valves were picked from the dried sieve residues and identified according to Meisch (2000) and Mischke and Zhang (2011). The species-specific ecological inferences are mainly based on Hiller (1972), Hammer (1986), Anadon et al. (1994), Meisch (2000) and Mischke et al. (2005).

3.3. Mathematical methods: Correlations and multivariate statistics

Data mining is an indispensable and vital step in trying to better understand intriguing information in the bulk-geochemistry of the different sediment archives. Here, correlation analysis and multivariate statistics (factor analysis) are computed. Multivariate statistics are employed in both Chapters 4 and 5, while correlations analysis was only performed in Chapter 4.

To provide an aid to illustrate the elemental characteristics of each archive type (see conceptual model in Fig. 4-5), Spearman’s rank correlation was performed between GSD proportions and XRF dataset (as a data set is not normally distributed, Spearman’s rank is preferred to be conducted, see Spearman, 1904). In order to simplify interpretation of the geochemical data (Fig. 4-5), a robust Factor Analysis (RFA) (Filzmoser et al., 2009; Zhang et al., 2014a) was conducted on the whole multivariate dataset of ninety-three samples with
sixteen elements. Elements showing virtually all concentrations below the respective detection limit or depicting low loadings in the conventional factor analysis were excluded. Rarely occurred values lying below the detection limit are regarded as missing values (or N/A) and will hinder the FA analysis (no zero value is allowed). They are therefore substituted with ½ the lower detection limit (cf., IJmker et al., 2012b). Since the geochemical dataset is sum-constrained and however not normally distributed, isometric log-ratio transformation (Egozcue et al., 2003, and literature therein; Filzmoser et al., 2009) has been applied, and the axis is rotated to the maximum direction of variance (i.e., varimax rotated axis; Kaiser, 1958). Subsequently, the number of factors for interpretations needs to be determined. Parallel analysis (Franklin et al., 1995) was performed and shows the first four factors are higher than the parallel confidence. Thus, they are regarded as confident factors. To further evaluate the overall quality of the analysis, communalities are computed by summing up the squared loadings for each element (> 0.9 represent good representation for an element).

Hereby, most of the original data characteristics are summarized in fewer decorrelated factors. Cosine of the angle between the elements and the attribute- and factor-axis denote the loading of this element on the factor (e.g., 45° represent the loading of 0.7), thus, the factor-loading-matrix (eigenvector matrix) can be regarded as a correlation matrix for partial correlation of input variables to factor ensemble (eigenspace bases). Sedimentary interpretations for each factor can be inferred from corresponding higher loadings of specific elements. Factor scores of each sample were obtained for detailed discussions of sedimentary processes (Fig. 4-5).
“The stratigraphic record of sedimentary rocks is the fundamental database for understanding the evolution of life, plate tectonics through time and global climate change” (Gary Nichols, 2009)


Kaifeng Yu 1*, Kai Hartmann 2, Veit Nottebaum 1, Georg Stauch 1, Huayu Lu 3, Christian Zeeden 1, Shuangwen Yi 3, Bernd Wünneumann 2,3, Frank Lehmkuhl 1

1 Department of Geography, RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany

2 Department of Earth Sciences, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany

3 School of Geographic and Oceanographic Sciences, Nanjing University, Xianlin Avenue 163, 210023 Nanjing, China

Geochemical characteristics have been intensively used to assign sediment properties to paleoclimate and provenance. Nonetheless, in particular concerning the arid context, bulk geochemistry of different sediment archives and corresponding process interpretations are hitherto elusive. The Ejina Basin, with its suite of different sediment archives, is known as one of the main sources for the loess accumulation on the Chinese Loess Plateau. In order to understand mechanisms along this supra-regional sediment cascade, it is crucial to decipher the archive characteristics and formation processes. To address these issues, five profiles in different geomorphological contexts were selected. Analyses of X-ray fluorescence and diffraction, grain size, optically stimulated luminescence and radiocarbon dating were performed. Robust factor analysis was applied to reduce the attribute space to the process space of sedimentation history. Five sediment archives from three lithologic units exhibit geochemical characteristics as follows: (i) aeolian sands have high contents of Zr and Hf, whereas only Hf can be regarded as a valuable indicator to discriminate the coarse sand proportion; (ii) sandy loess has high Ca and Sr contents which both exhibit broad correlations with the medium to coarse silt proportions; (iii) lacustrine clays have high contents of felsic, ferromagnesian and mica source elements e.g., K, Fe, Ti, V, and Ni; (iv) fluvial sands have
high contents of Mg, Cl and Na which may be enriched in evaporite minerals; (v) alluvial gravels have high contents of Cr which may originate from nearby Cr-rich bedrock. Temporal variations can be illustrated by four robust factors: weathering intensity, silicate-bearing mineral abundance, saline / alkaline magnitude and quasi-constant aeolian input. In summary, the bulk-composition of the late Quaternary sediments in this arid context is governed by the nature of the source terrain, weak chemical weathering, authigenic minerals, aeolian sand input, whereas pedogenesis and diagenesis exert only limited influences. Hence, this study demonstrates a practical geochemical strategy supplemented by grain size and mineralogical data, to discriminate sediment archives and thereafter enhance our ability to offer more intriguing information about the sedimentary processes in the arid central Asia.

4.1. Introduction

The main factors controlling geochemical compositions of sediments are the nature of parent rocks, chemical weathering, diagenesis, mechanical disaggregation and abrasion, authigenic / allothigenic input, and metamorphism in case of relatively old e.g., early Cenozoic and Mesozoic sediments (Bhatia, 1983; Johnsson, 1993; Fralick and Kronberg, 1997; Young et al., 1998; McLennan, 2001; S. Yang et al., 2004; Xu et al., 2011). Analyzing geochemical characteristics along with other characteristics of sediments is therefore a powerful tool to better decipher the nature of aforementioned processes. Previously, elemental (isotopic) and mineral fingerprints have been employed to evaluate the provenance of the American loess / mudstones / sandstones (Gallet et al., 1998; Zhang et al., 2014b), European loess (Amorosi et al., 2002; Buggle et al., 2008; Újvári et al., 2014), Eastern / Central Asian loess / desert sands (Liu et al., 1993; Honda and Shimizu, 1998; Jahn et al., 2001; Honda et al., 2004; Yang et al., 2007; Maher et al., 2009; Stevens et al., 2010; Chen and Li, 2011; Xu et al., 2011; Xiao et al., 2012; Wang et al., 2012) and Greenland dust (Újvári et al., 2015). Nesbitt and Young (1982) reported the major element content to represent a quantitative chemical weathering proxy, whereas in absence of strong chemical weathering (e.g., in arid and semi-arid environments, Zhu et al., 2014), the bulk-composition and mineralogy can be explained by physical abrasion, comminution and sorting (Nesbitt and Young, 1996; von Eynatten et al., 2012). Elemental characteristics of lacustrine or aeolian deposits have been employed to reconstruct the paleoenvironmental change in the northern Tibetan Plateau and the Mongolian Plateau during the late Quaternary (e.g., Hartmann and Wünnemann, 2009; Schwanghart et al., 2009; Lu et al., 2010; IJmker et al., 2012a; Felauer et al., 2012; Guo et al., 2013). Apart from provenance and paleoenvironmental studies, the nature of bulk-compositions of different
sediment archives is hitherto incompletely understood. On the other hand, whether and how geochemical composition can be assigned to sedimentary processes in arid region is seldom studied. To further disentangle the past processes and controlling factors, a better understanding of the geochemical fingerprints recorded in these archives is needed.

In arid and semi-arid areas, particularly, in basin systems, lacustrine, aeolian and alluvial / fluvial sediments are common. Spatial and temporal characteristics of these sediments are correlated to littoral and pelagic deposition systems of paleolake expansion and desiccation (e.g., Wünnemann, 1999; Shanahan et al., 2013), which can be ascribed to climatic variations. The endorheic Ejina Basin is regarded as a fundamental dust provenance of the Chinese Loess Plateau and adjacent regions (Pye and Zhou, 1989; Lu and Sun, 2000; Vandenberghe et al., 2006; Sun et al., 2008). Deciphering the geochemical characteristics of archives in the basin system is one crucial step towards a better understanding of the sedimentary processes related to dust activity.

In this study, a geochemical approach in conjunction with a broad field of granulometric, mineralogical and generally constrained chronological data is presented in order to:

1. Identify the broad pattern of lithologic units at the northern margin of the Ejina Basin.
2. Differentiate the distinct nature of bulk-compositions in different granulometric compositions and the array of archives obtained from these units.
3. Employ a multivariate statistic approach to test which assemblages of elements are suitable, sensitive and robust to reconstruct sedimentary processes and thereby to evaluate the controlling factors for the bulk-composition of sediments in (semi-)arid regions. Hence, ultimately, the aim is to improve our understanding of the intriguing sedimentary processes in this arid terrestrial endorheic context.
Fig. 4-1: Simplified geologic map and section locations in the northern Ejina Basin: (A) Section HC8 is an escarpment between the western and eastern Juyanze sub-basin. Sections KK1 and KK2 are located by the braided river channel near ancient of Khara Khotu. Sections WT1 and WT2 are yardangs located on the margin of Wentugaole Sub-basin and Badain Jaran Desert. Black (dash-) lines denote strike-slip neotectonics compiled from Wünneemann et al. (2007), Hölz et al. (2007), Hartmann et al. (2011), Cunningham (2013) and Rudersdorf et al. (2015). Black bold lines denote schematic elevation cross-section in panel B. D100 correspond to the drilling core from Wünneemann, 1999 and Wünneemann et al., 2007. (B) Cross-section from Khara Khotu to Juyanze (playa) and Wentugaole (sub-basin).
4.2. Regional Setting

The Ejina Basin (synonym: Gaxun Nur Basin) is located in the lower reaches of the endorheic Hei River catchment (with an area of ca. 130,000 km², Fig. 4-1), which contains one of the world’s largest continental alluvial fan systems (Hartmann et al., 2011). The basin covers an area of about 28,000 km² and is fed by the Hei River discharging from the Qilian Mountains. The elevation ranges from 880 to 1,300 m above sea level (a.s.l.) (Hartmann et al., 2011) and late Quaternary sediments are up to ~300 m thick (Zhang et al., 2006; Hartmann and Wünnemann, 2009). The infilling of the basin started probably at earliest 250 ka ago, as retrieved from the D100 drilling core (Fig. 4-1, 42.1°N 100.85°E, 940 m a.s.l., Wünnemann, 1999, Wünnemann et al., 2007a). Paleozoic to Mesozoic intrusive bedrock can be observed in the northern Juyanze and Wentugaole basins (Fig. 4-1, Becken et al., 2007; Rudersdorf et al., 2015).

The basin as part of the Gobi Desert is located beyond the limits of the East Asian Summer Monsoon (cf., Chen et al., 2008). The winter Siberian Anticyclone dominates the climate regime (Chen et al., 2008; Mölg et al., 2013). The mean January and July air temperatures are ca. -11°C and 26 °C, respectively. More than 90% of the ca. 38 mm annual precipitation occur between July and early September, albeit the annual precipitation in the upper reaches of the Hei River catchment in the Qilian Mountains can reach 300-500 mm (Wang and Cheng, 1999; Wünnemann et al., 2007a). The theoretical potential evaporation is around 3,700 mm.

The basin is bound by the Heli Mountains in the south, the Bei Mountains to the west, the Badain Jaran Desert / Alashan Plateau to the east and the Gobi Altai Mountains to the north (Fig. 4-1). Temporal and spatial patterns of fluvial and lacustrine deposition are influenced by neotectonics (e.g., the western margin has a subsidence rate of ca. 0.8-1.1 m/ka, cf., Hartmann et al., 2011). Nowadays, only the Ejina oasis near Juyanze paleolake receives ephemeral water input (Hartmann et al., 2011). Typical geomorphological features are gravel plains, yardangs, playas, sand fields and sporadically distributed mobile linear and barchan dunes (Zhu et al., 2014, Fig. 4-2).
Fig. 4-2: Photographs of representative geomorphological contexts from the northern Ejina Basin: (A) Inverted channels near Khara Khoto. (B) Gobi surface and Precambrian intrusive bedrocks in Wentugaole sub-basin. (C) Khara Khoto and nearby accumulated dunes. (D) Yardangs in southern Wentugaole sub-basin. (E) Playa surface of western Juyanze Basin. (F) Megadunes on the northern margin of Badain Jaran Desert.

4.3. Methods

4.3.1. Sampling strategy

Three field investigations were carried out in 2011, 2012 and 2014. Selected profile locations are distributed along three geomorphological systems (Figs. 4-1B and 4-3), i.e., following inverted channels (sections KK1 and KK2) to the lower Juyanze playa (section HC8) and then toward the higher Wentugaole / Badain Jaran Desert margin (sections WT1 and WT2, see
cross-section Fig. 4-1B). Ninety-three samples from five sections with different geomorphological contexts were collected for further sedimentological and geochemical analysis. Samples were acquired at 10-50 cm intervals based on stratum thickness and properties. Fewer samples were acquired within the generally homogeneous lithological units.

**Fig. 4-3: Lithostratigraphy and generally constrained chronology framework.** Chronology framework is labeled, and 2-sigma ranges for calculated radiocarbon ages are reported in Table 1. U1 is the lowermost aeolian sands (except for WT1), U2 is lacustrine stratum, and U3 is fluvial sands (mixed with gravels) unit (e.g., Fig. 2A). U3 of HC8 is especially thick mixture of poorly-sorted coarse alluvial sands and gravels.

**4.3.2. Chronological methods**

In order to acquire and assess a generally constrained chronological framework which can be compared with previously established lacustrine or beach bar records, AMS radiocarbon dating was applied to six samples in the Poznan Radiocarbon Laboratory, Queen’s University Belfast and the Beta Analytic Radiocarbon Dating Laboratory. Dated materials were bulk
organic matter and carbonates. Radiocarbon ages were calibrated to calendar years using the CALIB rev.7.1 (Stuiver et al., 1998) with the latest calibration dataset (Intcal13.14c, Reimer et al., 2013). Radiocarbon ages are presented as calibrated years (cal BP) unless otherwise noted.

Optically Stimulated Luminescence (OSL) dating was applied to six samples at Nanjing University. The samples were treated with 30 % hydrogen peroxide and 10 % hydrochloric acid. The fine sand-sized (63-90 µm) quartz grains were extracted by wet sieving. 2.58 g/cm³ sodium polytungstate was used to separate the quartz and K-feldspar. Treatments with 40 % hydrogen fluoride for 40 min and 10 % hydrochloric acid for 20 min were applied to purify the quartz. After washing and drying, the grains were mounted as monolayer on the 9.8 mm diameter stainless steel discs using silicon spray. All luminescence measurements were carried out using a Risø TL/OSL-DA-20 C/D reader equipped with blue LEDs (470±30 nm) and an IR laser diode emitting at 830 nm (Bøtter-Jensen et al., 2010). Irradiations were carried out with 90Sr/90Y beta sources mounted on the readers and calibrated for discs. The quartz OSL signals were collected through 7.5 mm of Schott U-340 (UV) glass filter. Equivalent dose (Dₑ) was determined by single-aliquot regenerative doses (SAR) protocol following Murray and Wintle (2003). For samples with feldspar contamination after a maximum of three etching treatments with hydrofluoric acid, infrared IR-stimulation is inferred prior to the optical (blue-light) stimulation to both measure and deplete the feldspar signal prior to the OSL measurement. A preheat of 260 °C for 10 s and cut heat of 220 °C combination was used for routine equivalent dose measurements. The 238U, 232Th and 40K concentrations were detected using Neutron Activation Analysis (NAA) at the China Institute of Atomic Energy. As the in-situ water content is extremely low, 25 % of saturation water content was used in dose rate calculation and the absolute uncertainty on the water content was assumed to be ±5%. Using the revised dose rate conversion factors of Guérin et al. (2011) and water content attenuation factors (Aitken, 1998), the elemental concentrations were converted into effective dose rate. The cosmic ray dose rate was calculated following Prescott and Hutton (1994).

4.3.3. Grain size analysis

The grain size distributions (GSDs) of all samples were measured using a Beckman Coulter LS13320 Laser Diffraction Particle Size Analyzer with a detection range of 0.04-2,000 µm. Portions larger than 2,000 µm were previously removed by sieving. As previously proposed, the GSD, in particular the finer proportions (i.e., < 2 µm) in sand and loess sediments, may be
potentially altered by different pretreatment methods (e.g., Lu et al., 2001; Kovács, 2008; Mason et al., 2011). Therefore, before measuring, a parallel test (HCl/H\textsubscript{2}O\textsubscript{2} and H\textsubscript{2}O\textsubscript{2}-only-treatment) was done to test the impact of possible incorporated calcium carbonate on the resulting GSD, revealing however no pronounced differences (cf. Schulte et al., 2016). Thus, all measurements were performed uniformly without hydrochloric acid treatment. 700 µl of 35 % H\textsubscript{2}O\textsubscript{2} was added to remove the organic components. Afterwards samples were dried at 70 °C for two days. Sodium pyrophosphate was added to avoid coagulation. The Mie Theory, instead of previously used Fraunhofer approximation (cf., Özer et al., 2010), is applied for GSD calculations. Optical properties (fluid RI = 1.33, sample RI = 1.55, imaginary RI = 0.1) were used as described in Özer et al. (2010) for quartz dominated samples. The final GSD represents the average of two subsamples. Each of them was measured twice to ensure the reliability of the results. In case of conspicuous offset existing between subsamples, the aforementioned procedure was repeated for the sample.
Fig. 4-4: Example of wavelength dispersive spectrums of X-ray diffraction (XRD). Panels A to E denote aeolian sands, lacustrine clay, fluvial sands, sandy loess, alluvial gravels, respectively from section HC8 (with depth). The powdered samples were scanned from 3° to 40° at °2θ, angle spectrums are conducted by Xpert Highscore software, the classification of

- 1 & 3, Chlorite
- 2, Muscovite/Illite
- 4 & 5, Quartz
- 6, Feldspar
- 7, Calcite
- 8, Dolomite/Mg calcite
- 9, Halite
impulses following Hartmann & Wünnemann (2009). The number of counts is illustrated as reference for e.g., aeolian sands.

4.3.4. X-ray fluorescence analysis and X-ray diffraction

X-ray fluorescence (XRF) analysis was conducted at RWTH Aachen University on all ninety-three samples using an Ametek X-ray Fluorescence Spectrometer (Spectro Xepos, 2007). The whole sample material was dried, sieved through a 2,000 µm mesh sieve and then ground to < 63 µm using a Pulverisette 7 before mixing 8 g sample with 2 g wax. The mixed powder is pressed into steel rings for measuring with a pressure of 15 tons for 20 s. Following calculation procedure, root mean square errors of calibration and lower limit of detection can be inferred from Spectro Xepos (2007). Certified reference materials involving No. 5358-90, Nos 2504-2506-83, Nos 2498-2500-83, NCS DC 73375, JF-1, UG-QLO-1 and UG-SDC-1 were referred to during the analyzing. Thirty elements are selected for further analysis. However, several values of the samples were below detection limit (BDL).

X-ray diffraction (XRD) was applied on fifty-three samples from section HC8 to determine mineral abundances (Hartmann and Wünnemann, 2009). The XRD was measured at Freie Universität Berlin using a Philips PW1710 and graphite monochromator with a Cu-K-alpha at 36 kv, 24 mA. The powdered samples were scanned from 3° to 40° at °20, angle spectrums are conducted by Xpert Highscore software, the classification of impulses rates following

Fig. 4-5: Conceptual modal of the robust geochemical approach to discriminate archives and sequence sedimentary processes.

X-ray diffraction (XRD) was applied on fifty-three samples from section HC8 to determine mineral abundances (Hartmann and Wünnemann, 2009). The XRD was measured at Freie Universität Berlin using a Philips PW1710 and graphite monochromator with a Cu-K-alpha at 36 kv, 24 mA. The powdered samples were scanned from 3° to 40° at °20, angle spectrums are conducted by Xpert Highscore software, the classification of impulses rates following
Hartmann and Wännemann (2009). Examples of dispersive spectrums of XRD are illustrated in Fig. 4-4.

4.3.5. Correlations and multivariate statistics

To provide an aid to illustrate the elemental characteristics of each archive type (see conceptual model in Fig. 4-5), Spearman’s rank correlation was performed between GSD proportions and XRF dataset (as a data set is not normally distributed, Spearman’s rank is preferred to be conducted, see Spearman, 1904).

In order to simplify interpretation of the geochemical data (Fig. 4-5), a robust Factor Analysis (RFA) (Filzmoser et al., 2009; Zhang et al., 2014a) was conducted on the whole multivariate dataset of ninety-three samples with sixteen elements. Elements showing virtually all concentrations below the respective detection limit or depicting low loadings in the conventional factor analysis were excluded. Rarely occurred values lying below the detection limit are regarded as missing values (or N/A) and will hinder the FA analysis (no zero value is allowed). They are therefore substituted with $\frac{1}{2}$ the lower detection limit (cf., IJmker et al., 2012b). Since the geochemical dataset is sum-constrained and however not normally distributed, isometric log-ratio transformation (Egozcue et al., 2003, and literature therein; Filzmoser et al., 2009) has been applied, and the axis is rotated to the maximum direction of variance (i.e., varimax rotated axis; Kaiser, 1958). Subsequently, the number of factors for interpretations needs to be determined. Parallel analysis (Franklin et al., 1995) was performed and shows the first four factors are higher than the parallel confidence. Thus, they are regarded as confident factors. To further evaluate the overall quality of the analysis, communalities are computed by summing up the squared loadings for each element (> 0.9 represent good representation for an element).

Hereby, most of the original data characteristics are summarized in fewer decorrelated factors. Cosine of the angle between the elements and the attribute- and factor-axis denote the loading of this element on the factor (e.g., 45° represent the loading of 0.7), thus, the factor-loading-matrix (eigenvector matrix) can be regarded as a correlation matrix for partial correlation of input variables to factor ensemble (eigenspace bases). Sedimentary interpretations for each factor can be inferred from corresponding higher loadings of specific elements. Factor scores of each sample were obtained for detailed discussions of sedimentary processes (Fig. 4-5).
4.4. Results

4.4.1. Lithology and chronology

Radiocarbon (Tab. 4-1) and OSL ages (Tab. 4-2) provide a chronological framework for the studied sections. In conjunction with field investigations and visual observations, three lithologic units were recognized (Figs. 4-3 and 4-5): (i) U1, the lowermost facies of the aeolian sands (except WT1) are dated to older than 200 ka BP according to OSL ages. (ii) U2, the clay to silty-clay stratum are dated to start at around the early global LGM ca. 26 and ca. 32 ka BP (for stratigraphy and error ranges see Fig. 4-3 and Tab. 4-1, respectively). (iii) U3, the uppermost poorly-sorted mixture of coarse sands and angular gravel strata are dated to start at around ca. 14 to 25 ka BP. The purported age difference resulting from the chronological methods falls out of the scope of this study (Zhang et al., 2006; Long and Shen, 2015). In addition, two sand samples from yardangs (corresponding to U1) in Wentugaole were obtained to test the feldspar dating performance. They yielded saturated equivalent doses as well. The section with the probably most complete sediment stratum, HC8 (Figs. 4-1 and 4-3), will be discussed as the key profile to assess the capability to reconstruct the sedimentary processes. Brief section descriptions are provided subsequently.

Tab. 4-1: Results of the AMS $^{14}$C-dating. Radiocarbon ages were calibrated to calendar years with 2 σ standard deviation using the CALIB rev.7.1 (Stuiver et al., 1998) with the latest calibration dataset (Intcal13.14c, Reimer et al., 2013).

<table>
<thead>
<tr>
<th>Location</th>
<th>Section name</th>
<th>Lab.-No.</th>
<th>Depth/cm</th>
<th>Dating material</th>
<th>$^{14}$C</th>
<th>TOC/mg</th>
<th>Age /ka BP</th>
<th>2 σ/cal ka BP (95.4 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khara Khoto</td>
<td>KK2</td>
<td>Poz-53749</td>
<td>50</td>
<td>Bulk material</td>
<td>-</td>
<td>0.15</td>
<td>11.82±0.13</td>
<td>13.73±0.29</td>
</tr>
<tr>
<td>Khara Khoto</td>
<td>KK2</td>
<td>Poz-53750</td>
<td>120</td>
<td>Bulk material</td>
<td>-</td>
<td>0.19</td>
<td>20.36±0.22</td>
<td>24.56±0.59</td>
</tr>
<tr>
<td>Khara Khoto</td>
<td>KK1</td>
<td>UBA-19486</td>
<td>U. surface</td>
<td>Bulk material</td>
<td>-23.6</td>
<td>-</td>
<td>23.87±0.14</td>
<td>28.09±0.17</td>
</tr>
<tr>
<td>Wentugaole</td>
<td>WT1</td>
<td>Poz-53751</td>
<td>470</td>
<td>Bulk material</td>
<td>-0.70</td>
<td>0.20</td>
<td>28.4±0.20</td>
<td>32.30±0.67</td>
</tr>
<tr>
<td>Wentugaole</td>
<td>WT1</td>
<td>Poz-53752</td>
<td>550</td>
<td>Bulk material</td>
<td>-0.20</td>
<td>0.20</td>
<td>21.26±0.21</td>
<td>25.42±0.27</td>
</tr>
<tr>
<td>Juyanze</td>
<td>HC8*</td>
<td>Beta-190785</td>
<td>502</td>
<td>Bulk organic carbon</td>
<td>-22.8</td>
<td>-</td>
<td>15.06±0.80</td>
<td>18.29±0.24</td>
</tr>
</tbody>
</table>

* HC8 radiocarbon age was published in Hartmann & Wünnemann, 2009.

HC8 (41.9023°N, 101.7578°E, 934 m a.s.l.) represents a 13 m escarpment. Below 9 m, the section exhibits loose fine sand with increasing silt contents up to 8 m. 8-2.5 m (base of U2) show slightly indurated silty clay material. Sandy loess-like material was observed in depths of ca. 3.5-3.0 m. 3.0-0 m is represented by a poorly-sorted mixture of coarse sands and gravels.

KK1 (41.7494°N, 101.1582°E, 952 m a.s.l.) is located in an outcropping inverted channel near the ancient city of Khara Khoto / Black City (Fig. 4-1). Coarse sand prevails below 3.1
m, overlain by a cemented mixture of coarse sand and pebbles (3.1-2.5 m). Layers of fine to medium sand were preserved from 2.5 to 1.7 m, sand ripple structures and root channels were sporadically exhibited. Deposits from 1.7 to 0.1 m (U2) were weakly indurated clayey to silty-clayey sediments. The surface (0.1-0 m, U3) is covered by set of gravels with largest diameters of ca. 70 mm and mixed with coarse sand.

KK2 (41.7563°N, 101.1255°E, 953 m a.s.l.) is in the vicinity of section KK1 (see Fig. 4-1). U1 is represented by heterogeneous laminae of sand layers (3.2-1.25 m). U2 (1.25-0.2 m) is a slightly reddish clayey to silty-clayey stratum. The surface, representing U3 (0.3-0 m), consists of slightly indurated sand.

WT1 (41.3559°N 102.2468°E, 967 m a.s.l.) reflects a ca. 6 m yardang feature located on the northern margin of the Badain Jaran Desert (Wentugaole Basin). Indurated clayey to silty-clayey sediments were recovered below 5.4 m. 5.4-4.9 m is represented by diagonally cross-bedded silt to sand with interbedding gypsum crusts. It is comparably thin in regard of the other sections’ U1 unit. U2 (4.9-0.2 m) is clayey sediment while the surface (U3, 0.2-0 m) is composed of strongly cemented coarse sand.

WT2 (41.3593°N 102.2456°E, 960 m a.s.l.) is a yardang record adjacent to WT1. Between 7.75 and 7.70 m horizontally layered sand was recovered, which is interrupted by a 5 cm thick whitish-grayish laminated clay layer (7.75-7.70 m). The base of U2 is represented by a 5 cm thick laminated clay layer (7.05-7.00 m), while up to 0.10 m the deposit is homogeneous clay. The overlying U3 is an indurated white to greenish sandstone.

Tab. 4-2: Summary of water content, equivalent dose value (De), dose rate, number of used aliquots and luminescence ages of samples from study sections. $^{238}U$, $^{232}Th$ and $^{40}K$ concentrations were determined by Neutron Activation Analysis (NAA). Absolute uncertainty of the water content was assumed to be $\pm 5\%$. Due to saturation of the equivalent dose, brief constrained luminescence ages are presented here. More details concerning the method see Chapter 4.3.2.
4.4.2. Granulometric composition and pre-assessment of archives

Grains size distributions (GSDs) are divided into six fractions as described in Blott and Pye (2012): Clay (0.04-2 µm), fine silt (2-6.3 µm), medium silt (6.3-20 µm), coarse silt (20-63 µm), fine sand (63-200 µm), medium sand (200-630 µm) and coarse sand (630-2,000 µm). Granulometric composition is illustrated in a ternary diagram (Fig. 4-6A).

![Fig. 4-6: Ternary diagrams of granulometric properties and A-CN-K (molar proportions): (A) Granulometric ternary diagram. (B) A-CN-K ternary diagram. CaO is corrected to silicate carbonate following the procedure of McLennan (1993). The Chemical Index of Alteration (CIA, Nesbitt & Young, 1982) is related on the right side of the A-CN-K triangle. Abbreviations: A=Al₂O₃, C=CaO, N=Na₂O, K=K₂O, Ka=Kaolinite, Gi=Gibbsite, Ch=Chlorite, Il=illite, Mu=muscovite, Pl=plagioclase, Bi=Biotite, Ks=alkali feldspar, Ch=chlorite, Cp=clinopyroxene, Hb=hornblende.](image)

For section HC8 (cf., Fig. 4-10): (i) most samples in lower U1 are characterized by unimodal GSD curves and bimodal GSDs in the upper part. Clay proportion increases from 1.4 % to 18.9 % accompanied by an increasing silt proportion from 1.5 % to 24.5 %. Several coarse sand input intervals can be detected in these layers. Clay and silt fractions share quite similar depth patterns. Moreover, the medium sand proportion has the highest percentage (ca. 80 %) at the bottom (ca. 13 m), whereas the upper part shows broadly less than 30 % with low variance. (ii) U2 mostly consists of clay interbedded with coarse sand input. The clay proportion varies between 15-40 %, silt proportion varies between 30-70 % and sand proportion remains between 15-40 %. Generally, silt and sand proportions are increasing from basal U2 to the upper part. (iii) The surface samples from U3 are predominantly unsorted silt
to sands mixed with angular gravels. In contrast, the other sections exhibit thinner U3 strata. Regarding the other sections, broadly resembling GSD patterns throughout the profile can be observed (Fig. 4-3; detail GSDs not illustrated).

Fig. 4-7: Granulometric properties of archives: (A) aeolian sands (n=51), (B) lacustrine clay (n=19), (C) fluvial sands (n=18), (D) sandy loess (n=2), (E) alluvial gravels (n=2), different axis scales are used.
Fig. 4-8: Spearman’s rank correlation coefficients between geochemical properties and grain size parameters (all scales of red to blue units have passed 0.05 significant level). Not all elements exhibit grain-size dependence (e.g., As, Nd, S and Al). Red pixels denote positively correlated and blue ones depict negative correlations. These features can also shed light on elemental characteristics of archives. C, fSi, mSi, cSi, fS, mS and cS denote the particle size of clay, fine silt, medium silt, coarse silt, fine sand, medium sand and coarse sand, respectively.

According to the GSD patterns and the field investigation, all samples are differentiated into five archive categories: aeolian sands, lacustrine clays, fluvial sands, sandy loess and alluvial gravels (Fig. 4-5). The clusters of granulometric patterns are acquired as depicted in Fig. 4-7. Combined with the criterion reported by Lu et al. (2001), Blott and Pye (2012), Vandenberghe (2013) and Nottebaum et al. (2014), differentiation strategies are as follows: (i) aeolian sand usually has a unimodal or sometimes bimodal distribution with a mode at around 50-250 µm or even coarser (Fig. 4-7A); (ii) lacustrine clay usually shows bimodal or trimodal grain size distribution including well sorted suspension proportions (8-9 µm) as the main mode (Fig. 4-7B); (iii) fluvial sand’s GSDs are often polymodal, including a dominant well sorted saltation portion (usually 250-400 µm) as the main mode and poorly sorted suspension proportions (<63 µm) (Fig. 4-7C); (iv) sandy loess has a unimodal leptokurtic distribution and has a mode...
around 60 µm (cf., end member 1 in Vriend and Prins, 2005; Prins et al., 2007; Nottebaum et al., 2014, 2015b) and a minor population at around 2-15 µm (Fig. 4-7D); (v) alluvial gravels have a unimodal distribution and a mode much larger than 1,000 µm (Fig. 4-7E).

### 4.4.3. Elemental and mineralogical composition of archives

In total thirty major and trace elements in ninety-three samples were acquired (Tab. 4-3). The correlation coefficients between grain size proportions and element concentrations are illustrated in Fig. 4-8.

**Tab. 4-3:** Results of the oxides of ten major elements expressed as normalized wt % and other trace elements concentrations (ppm) of sediment archives as determined by X-ray fluorescence analysis. Decimal precision of the reported concentrations were revised according to the formats of their counterparts in the UCC data set (Rudnick and Gao, 2003). Root mean square errors (RMS) and lower limit of detection (LOD) of each element see Spectro Xepos (2007).

<table>
<thead>
<tr>
<th>Element</th>
<th>UCC*</th>
<th>Factors</th>
<th>Aeolian sands</th>
<th>Lacustrine clay</th>
<th>Fluvial sands</th>
<th>Sandy loess</th>
<th>Alluvial gravels</th>
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<td>13.18</td>
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<td>RF2(-)</td>
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<td>100</td>
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<td>140</td>
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<td>-</td>
<td>785</td>
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<tr>
<td>Nd</td>
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<td>52</td>
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<td>91</td>
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<td>-</td>
<td>2.8</td>
<td>2.8</td>
<td>3.1</td>
<td>2.0</td>
<td>3.7</td>
</tr>
</tbody>
</table>

* UCC=Upper Crust Composition (Rudnick and Gao, 2003). Total iron expressed as Fe₂O₃. Ten major elements are expressed as oxides (wt %), while other trace elements are expressed as ppm. The description of factors analysis refers to Tab. 4-4.
Fig. 4-9: Loading and score plot of geochemical data set: (A) Loading plot of conventional factor analysis, with thirty elements. (B) Score plot of conventional factor analysis, with thirty elements. (C) Loading plot of robust factor analysis, with sixteen elements. (D) Score plot of the robust factor analysis, with sixteen elements. Originally, the maximum direction of variance will be regarded as axes, however, rotation is performed to get varimax rotated axis (i.e., X-and Y-axis here) during the factor analysis to provide a higher loading for each elements (Tab. 4-4). Cosine of the angle between the elements arrow and the component (varimax rotated axes) are factor loadings, length of the arrows are corresponding to the element communalities. Compared with conventional factor analysis (Panels A and B), panels C and D exhibit higher cumulative proportions for RFs 1 and 2. Dashed line circles in panels A and C denote communality estimates (Tab. 4-4) and thereby assess the quality for each
element (> 0.9 can be regarded as good quality) in this factor modal. Panels B and D illustrate that multivariate statistic of elemental fingerprints appears to be a practical method to discriminate the archive types, of which mistakes may be yielded from field investigations and GSD observations alone.

For samples from section HC8, minerals comprising quartz, feldspar, amphibole, clay minerals, calcite, aragonite, dolomite, gypsum and halite abundances were determined. Generally, the U1 stratum has higher contents of quartz and feldspar, the U2 stratum has pronounced higher contents of clay minerals, gypsum and halite, and the U3 stratum has especially high content of calcite. They therefore shed light on the mineralogical compositions of archives, which will also aid the further interpretation of the XRF dataset.

4.4.4. Element assemblages and loadings as derived from conventional and robust factor analysis

To gain an overview of the distribution of all thirty elements, conventional factor analysis was done for all samples (Fig. 4-9A and 9B). Major and trace elements can be categorized into several assemblages as follows: (i) cluster of elements such as K, Rb, Ti, V, Nb, Fe, Ni, Cu, Zn, Al, Ga, As, Y, Nd, Pb and Th behave relatively similar with respect to convergence / variation against depth and the directions generally point to factor 1 positively. In section HC8, they have lower abundances in the basal U1 unit. Interestingly, there is one extremely high value for all these elements at a depth between 943 and 959 cm. All these elements show particularly low values in U3, accompanied by lower values in U1 and relatively higher values in U2. (ii) Concerning Na, Cl and S, the former two elements have resembled variation trends against depth. Three high value peaks within U2 can even reach 70,000 ppm for Na and 55,000 ppm for Cl. S has a similar convergence zone as Na and Cl. Na and Cl show slightly positive indications to both factor 1 and factor 2 (Fig. 4-9A). (iii) Si, Mg, Sr, Ca and Mn show a similar distribution in Fig. 4-9A. Ca and Sr have relatively high values within U3, whereas Mg exhibits extremely low contents in U3 (figures are omitted here). Mn is relatively rare and commonly originates from highly soluble minerals (e.g., mobile Mn^{2+}) and occurs in ultramafic rocks (e.g., dust transport of solid Mn^{3+} and Mn^{4+}, Ijmker et al., 2012a), it exhibits however higher concentrations in mixed fluvial sands (Tab. 4-3), the former process is thus more likely the origin of Mn. In contrast, no dominant trends can be extracted from the irregular variance of Si. All these elements show indications generally positive to factor 2 and may be connected to fluvial archives (Fig. 4-9A and 9B). (iv) For Cr, Hf, Zr and Ba, compared to U2, Hf and Zr values show remarkably higher contents in aeolian sands (U1). Cr
shows much more sensitive variations to the aeolian input, whenever aeolian sand input occurs. The Cr values are approximately three times higher than the neighboring sample values. Meanwhile, Ba values show irregular variances and no trend can be figured out. All Cr, Hf, Zr and Ba values show negatively correlations to factor 2 (Fig. 4-9A). (v) P and W show slightly positive loadings to both factors 1 and 2, no dominant trend can be extracted from their irregular variance. Thus, they were excluded from further discussions.

Tab. 4-4: Standard deviations, variance / cumulative proportions, element loadings for each factor, and communalities for each element. High positive or negative (>0.75) loadings are shown in boldface, proportions in %.

<table>
<thead>
<tr>
<th>Elements</th>
<th>RF1, Weathering intensity</th>
<th>RF2, Silicate-bearing mineral abundance</th>
<th>RF3, Saline magnitude</th>
<th>RF4, Aeolian input</th>
<th>Communality estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>0.96</td>
<td>0.94</td>
</tr>
<tr>
<td>Mg</td>
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<td>-</td>
<td>-</td>
<td>0.95</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0.95</td>
<td>-</td>
<td>-</td>
<td>0.95</td>
</tr>
<tr>
<td>K</td>
<td>0.91</td>
<td>0.34</td>
<td>-</td>
<td>-</td>
<td>0.97</td>
</tr>
<tr>
<td>Ca</td>
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<td>-</td>
<td>-</td>
<td>0.44</td>
</tr>
<tr>
<td>Ti</td>
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<td>-</td>
<td>-</td>
<td>0.92</td>
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<tr>
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<td>0.26</td>
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<td>-</td>
<td>-</td>
<td>0.72</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>0.99</td>
</tr>
<tr>
<td>Cl</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.99</td>
<td>0.98</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>Th</td>
<td>0.98</td>
<td>-0.13</td>
<td>-</td>
<td>-</td>
<td>0.98</td>
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</tbody>
</table>

Blank represents those loadings which are under significant level in robust factor analysis. Communalities for each element are computed by taking sum of the squared loadings, it can be referred to the length of the element arrows in loadings plot.

As a comparison to the aforementioned conventional factor analysis, RFA was performed to reduce the systematic and random error of compositional data (according to Filzmoser, 2009; Fig. 4-9C and 9D). Subsequently, the suitable and sensitive elements for further assessment of sedimentological interpretations are compared. Element loadings (Tab. 4-4) and communalities (cf., Figs. 4-9A and 9C) are thereby significantly higher compared with the conventional method. Factors exhibiting eigenvalues >1 are extracted (e.g., five factors can be determined by applying the Kaiser-Guttman Criterion, Guttman, 1954). These factors have variance higher than an input variable. Finally, the first four factors which are above the parallel line are determined as confident factors (more details see Chapter 4.3.5; Franklin et al., 1995). They represent ca. 90.00 % of the total geochemical variance of the XRF data set.
Relatively high (> 0.75, Tab. 4-4) positive or negative loadings of elements for each factor are extracted. High loading elements for robust factor 1 (RF1) are Ti, Fe, K, Cu, Zn, Ga, Rb, Th. RF2 has high loadings of Si, Mg, Mn. RF3 is represented by Na and Cl. RF4 yields high loadings of Zr and Hf. All elements only display one relatively high loading, which implies that they have only specific interpretation for one specific factor.

4.5. Discussion

4.5.1. Late Quaternary lithostratigraphy at the northern margin of the Ejina Basin

Similar late Quaternary lithostratigraphic facies are shared by five sections. Considering HC8, aeolian phases dominated the sedimentary processes in U1 (beyond the upper limits of OSL ages), which was sporadically interrupted by ephemeral riverine sediments.

Accompanied by several high salinity periods, the lacustrine sedimentation (U2) started before 30 ka BP. The reported highest lake level of Sogo Nur occurred at around 41-33 ka BP (i.e., MIS 3a, Lehmkuhl and Haselein, 2000; B. Yang et al., 2004 and literatures therein). The highest shoreline of the Sogo Nur is radiocarbon dated to 33 ka BP (Wang et al., 2011). The highest remnant beach bars near the Juyanze Basin was also radiocarbon dated to 37-29 ka BP (Wünnemann et al., 2007; cf., Long and Shen, 2015). Molluscs from the highest shoreline of eastern Juyanze Lake to the northwestern Badain Jaran Desert were dated to 30.40±0.87 ka BP, indicating a huge expanded paleolake (Mischke et al., 2003). Additionally, δ18O reconstructions yielded high lake levels from 37-34, at 31 and 28-26 ka BP, respectively in the Ejina Basin (Wünnemann and Hartmann, 2002). However, a far more eastern “Jilantai-Hetao Megalake” existed between 50-60 ka BP (Chen et al., 2008a), the inception of the lacustrine period occurred earlier compared with the stratum U2 in HC8. Furthermore, calcite layers occur at depth of ca. 3.5 m within U2 (not captured in XRD data, Fig. 4-10). Cemented calcareous layers in present time can be referred to an annual precipitation of 100-300 mm (Hövermann, 1998), which indicates a much more humid period recoded by U2 compared to today. In addition, the Sogo Nur lake basin experienced dune accumulation between 19-14 ka BP (Lehmkuhl and Haselein, 2000), which is not observed here in section HC8. The uppermost lacustrine sediments of U2 (Tab. 4-1; Fig. 4-3) yield calibrated 14C ages of 13.661±0.227 and 28.757±0.500 ka BP, respectively.
Above U2, a mixture of fluvial / alluvial sand and gravels form a deflated gravel gobi surface. Local ephemeral runoff occurred in U1 and the mixed fluvial sands and gravels may be subsequently modulated by intensive deflation (cf., Nottebaum et al., 2015a).

4.5.2. Elemental characteristics of sediment archives

4.5.2.1. Elemental characteristics compared to granulometric composition

In order to properly interpret the geochemical behaviors of sediments, particular attention should be contributed to elemental characteristics in relation to grain size parameters (Honda and Shimizu, 1998), when assuming similar provenance. In case of absence of intensive pedogenesis (see low Chemical Index of Alteration (CIA) in Fig. 4-6B), this heterogeneity may originate in minerals’ re-distribution during transportation and deposition (Schettler et al., 2009) and their deviant resistances to weathering processes (von Eynatten et al., 2012). Most samples from U1 and U3 have higher proportions of coarse silt to sand. The clay proportion is relatively low, indicating that the transport mode is high energy fluvial or aeolian saltation, rather than a lacustrine or still water environment (Blott and Pye, 2012). The clay and fine silt proportions can be considered as detrital component. Medium silt contributes a considerable fraction to aeolian dust or loess deposits which are transported several hundred meters above the surface, being trapped and deposited subsequently (e.g., Prins et al., 2007; Nottebaum et al., 2014, 2015b). Winter monsoon here is a low altitude phenomenon (Vandenberghhe, 2013) which may be a possible transporting mechanism. In contrast, fine particles transported by Westerlies can reach up to 10,000 m (Sun et al., 2000; Sun, 2004). Silty sand (Fig. 4-3) and fine sand proportions may indicate near surface suspension and dust storm saltation occurring in winter and spring (Dietze et al., 2014). The medium to coarse sand proportions may represent high energy transporting processes (Derbyshire et al., 1998) exerted by the Hei River.

Previously, the grain size dependence of elemental (mineralogical) compositions of various archives were tested and evaluated by a set of studies e.g., Honda and Shimizu (1998), Yang et al. (2007), Schettler et al. (2009), Garzanti et al. (2009), Lupker et al., (2011) and von Eynatten et al. (2003, 2012). However, few studies have investigated bulk geochemical of granulometric proportions (cf., Fig. 4-5 and correlation matrix Fig. 4-8).

Median, mean, mode values are negatively correlated to alkali metals and ferromagnesian elements e.g., Al, K, Ti, V, Fe, Ni, etc. In contrast, the positively correlated K and Si may
originate from orthoclase in sands (e.g., K-feldspar; Divis and McKenzie, 1975). Hf may originate from weathering-resistant heavy minerals e.g., zircon, which are often enriched during long aeolian or fluvial sediment recycling (cf., Owen, 1987). Thus, silica-rich minerals (e.g., orthoclase) and allochthonous heavy minerals may be the main provenance for the coarser materials in this endorheic basin. Ferromagnesian, mafic and mica source elements encompassing Al, K, Ti, V, Fe, Ni, Cu, Zn, Ga Y, Nb, Nd, Pb and Th (cf., Nickel, 1954; von Eynatten et al., 2012) are broadly correlated (+0.5-0.6) to clay and fine to coarse silt (Fig. 4-8). S is only highly correlated to coarse silt (+0.5). Mg is only correlated to clay and fine silt (+0.6 and +0.5, respectively). Ca and Sr are generally correlated to medium to coarse silt proportions (cf., Fig. 4-8). Granitoid source elements e.g., K, As, Rb and V have negative correlation with coarse silt. Interestingly, the heavy mineral sourced element Zr shows slightly negative correlations with fine to medium sand (Fig. 4-8). von Eynatten et al. (2012) reported the hump-shaped pattern of Zr (i.e., relatively low abundance in both clay and coarse sand). In contrast, Zr has been suggested previously to be associated with coarse silt to sand in aeolian sediments (e.g., loess) (Yang et al., 2006). Thus, whether Zr can be attributed to the sand proportion needs to be tested in future studies. Furthermore, with similar geochemical behavior as Zr, Hf is positively correlated to medium to coarse sand (Fig. 4-8). Arsenic and Nd have no conspicuous correlations with any GSD fractions. This may be ascribed to their diversified sources or presence in different minerals with different weathering resistances. Silicon shows only intermediate correlation with medium sand (50 %). Being one of the typical elements in all aeolian sand, clay minerals and some heavy minerals (Millot, 1970; Pettijohn et al., 1973), Si cannot be easily applied as proxy for the coarse grain size proportions.

4.5.2.2. Elemental characteristics of sediment archives

After deflation and disaggregation in the weak chemical weathering environment (Fig. 4-6B), groups of minerals with similar physical and geochemical behaviors (e.g., durability) are more likely to be enriched / depleted in specific archives or grain size fractions (von Eynatten et al., 2012), in case no shifts of source rocks exist.

In the light of above statement, distinct enrichment / depletion of elements for certain archives can be observed in this study: (i) Aeolian sands have higher contents of Zr, Hf, Ba and Si. Aeolian sands transported in saltation mode during dust / sand storms have typical minerals of quartz, feldspar, pyroxene and some heavy minerals (e.g., zircon; Fitzsimmons et al., 2009). (ii) Lacustrine clay is composed of fine materials whose source minerals could be micas,
kaolinite, chlorite and some other ferromagnesian minerals (Hillier, 1993). They have a common enrichment in K, Rb, Y, Ti, V, Nb, Fe, Cu, Zn, Al, Ga, Pb, As Th and Nd. Titanium, Mg and Fe-bearing mafic minerals such as biotite are more often present in fine sediments (Nesbitt and Young, 1996; Young and Nesbitt, 1998). (iii) Fluvial sands show high contents in Mn, Mg, Cl and Na. This archive may contain more saline / evaporite minerals such as mirabilite and glauberite formed after paleolake desiccation / saline processes (Smith and Haines, 1964). (iv) Sandy loess has a distinctively high Sr content. Meanwhile, ferromagnesian provenance elements e.g., Fe, Ni and V show relatively low values, which may be ascribed to the lack of clay and fresh weathered materials in the archive. Generally, due to their similar hydro-geochemical characteristics in pelagic and lacustrine settings, Sr behaves quite analog as Ca (Calvert and Pedersen, 2007). Sr may engage together with Ca in carbonates in e.g., alkaline habitats. However, carbonates seems relatively rare in sandy loess (see low CaO and MgO content in sandy loess (Tab. 4-3), and low aragonite and dolomite in Fig. 4-10), leading to a distinctly different abundances between Sr and CaO (MgO). On the other hand, sandy loess samples are corresponding to layers with spikes of quartz and feldspar concentrations in the upper U2 (Figs. 4-4 and 4-10). And feldspar is more siliceous than most clay minerals (Millot, 1970; Pettijohn et al., 1973). These set of evidences imply that the higher concentration of quartz and feldspar may account for the higher Sr content (along with relative high Si concentration) in the sandy loess. (v) The unsorted alluvial gravels have high values of Ca, S, Cr, P and W. High content of P, S and W may result from the increasing anthropogenic activities in the last thousand years (cf., northern Tibetan Plateau in Chen et al., 2015). Naturally, Cr occurs in chromite together with Fe or Mg which is quite commonly observed in nearby ultramafic intrusive rocks and ophiolite deposits (i.e., upper reach of Hei River catchment in the western Qilian Mountains and the Bei Mountains, see Fig. 4-1 and Hu et al., 2014). The generally high correlation between Cr and Fe, as well as Cr and Mg (Fig. 4-8) demonstrate the chromite provenance transported not only as aeolian particles from the west (acidic intrusive rock in Bei Mountains, Fig. 4-1) but also as fluvial material transported by Hei River (greenschist-rich metamorphic rocks in mountain proximal reaches of the Hei River, see Schimpf et al., 2014).
Fig. 4-10: Principle component scores, main mineral compositions and granulometric properties of section HC8, RF1: weathering intensity, RF2: silicate-bearing mineral abundance (different within lacustrine and aeolian phase), RF3: saline magnitude of sediments, and RF4: quasi-constantly aeolian input. Lithologic patterns refer to Fig. 4-3. Clay mineral group includes smectite, illite, kaolinite and chlorite. $C$, $fSi$, $mSi$, $cSi$, $fS$, $mS$ and $cS$ denote the particle size of clay, fine silt, medium silt, coarse silt, fine sand, medium sand and coarse sand, respectively.

Specifically, throughout the section HC8 and all other samples, Cl content is especially elevated relative to Upper Crust Composition (UCC) values (Tab. 4-3), which may indicate the generally high saline / evaporite mineral contents in late Quaternary sediments (cf., Smith and Haines, 1964) of the dry endorheic Ejina Basin.

Furthermore, as illustrated in Fig. 4-9B and 9D, samples from the same sediment archive are more likely to aggregate together in the score plot. Thus, multivariate statistics of geochemical properties is a useful tool to discriminate the archive types. Outliers may be attributed to certain subjectiveness in field discrimination of archive types and GSD observations (Fig. 4-5).

4.5.3. Geochemical interpretation of sedimentary processes

As stated in Chapter 4.4.1, all sediments are dated to the (late) Quaternary. Although post-depositional processes e.g., hydrodynamic sorting and diagenesis may indeed exert an influence on the nature of geochemical compositions (Murray et al., 1992; Johnsson, 1993), in case of late Quaternary sediments (cf., Mid- to Early-Cenozoic desert alluvium in Walker et al., 1978 and Mesozoic sandstone and mudstone in Zhang et al., 2014b), the diagenesis...
induced elemental alteration stays more likely in the initial stages (see Stage I in Walker et al., 1978) and is therefore a negligible factor. On the other hand, the nature of parent rocks and tectonic settings need to be clarified. As illustrated in the ternary A-CN-K diagram (Fig. 4-6B), different archives exhibit generally a similar origin of mafic rocks which are close to the CN apex (i.e., hornblende and clinopyroxene). Thus, markedly diversified terrain sources and tectonic settings during the late Quaternary sedimentary processes can be ruled out.

Subsequently, elemental composition supplemented by XRD data from the key section HC8 can be employed to interpret the intriguing information of the sedimentary processes:

RF1 has relatively high loadings of felsic, ferromagnesian, mica and clay mineral source elements such as Ti, Fe, K, Cu, Zn, Ga, Rb and Th (Tab. 4-4), which are all from soluble or easily weathered minerals. These elements are commonly encompassed in clay minerals (cf., RF1 curve and clay mineral abundance in Fig. 4-10). Quartz is relatively stable and difficult to decompose, while feldspars (mainly K-rich orthoclase, while Na- and Ca-rich plagioclase are more likely to be attributed to RF2; Tab. 4-4) are more easily weathered to clay minerals (Chen et al., 2010). Fine materials have high enrichment of least durable minerals, e.g., sheet silicates such as micas (von Eynatten et al., 2012, cf. muscovite content in lacustrine clay and alluvial gravels in Fig. 4-4). Hence, RF1 may indicate the varied weathering intensity, albeit the magnitude is generally low throughout the sedimentary processes (cf., CIA in Fig. 4-10).

RF2 has high loadings of Si and negative loadings of Mg, Mn and Ca. The trend of RF2 is generally anticorrelated (Tab. 4-4; Fig. 4-10) with dolomite / dolostone variances, which is interpreted to precipitate within saline phase of playa basins (Last, 1990). Mg and Ca are generally enriched together in carbonate and metamorphic silicate minerals such as magnesite, dolomite, strontianite and pyroxene (Tucker et al., 1990). A possible origin may be the autochthonous production of the carbonates within the lake period (IJmker et al., 2012b) and allochthonous debris from aeolian sands (e.g., Ca in feldspathic sands, Divis and McKenzie, 1975; cf. aeolian sands in Fig. 4) during a non-lacustrine phase. Mg was particularly suggested as the most sensitive element to the paleolake depth (Shanahan et al., 2013). Thus, tectosilicates (e.g., quartz and feldspar / orthoclase) are assumed to be the predominant silicates in the aeolian U1, whereas clayey phyllosilicates (cf., RF1) e.g., kaolinite, illite and montmorillonite are assumed to be the prominent silicates in lacustrine period U2 (cf., muscovite / illite content in lacustrine clay in Fig. 4-4). Hence, RF2 may indicate still water level or in situ water budget (authigenic input) in lacustrine phases, whereas with indication of silicate-bearing sands input during aeolian phases.
RF3 has high loadings of Cl and Na, which displays correlation with calcareous evaporate minerals precipitated during the paleolake shrinkage (e.g., hydro-magnesite and halite, see halite content in lacustrine clay (Fig. 4-4), cf. RF3 and halite pattern in Fig.4-10). Furthermore, calcite can only be found in relatively high saline magnitude lacustrine periods, albeit calcite determined in aeolian phases may be attributed to the mineral provenance (intensive pedogenesis can be ruled here, see calcite and CIA in Fig. 4-10). Hence, RF3 can be referred to the salinity component of sediments.

RF4 has generally high loadings of Zr and Hf, which are usually from dust / airborne minerals e.g., quartz and feldspar (cf., aeolian sands in Tab. 4-3 and Chapter 4.5.2.2). Meanwhile, factor scores do not show a pronounced downcore trend along section HC8, suggesting a quasi-constant aeolian input into the basin systems throughout the late Quaternary.

In summary, the nature of bulk-compositions in the arid realm is governed by weak chemical weathering, authigenic minerals and aeolian sand input. In contrast, concerning the suite of late Quaternary sediments in this study, pedogenesis and diagenesis exert only very limited or no influence. In addition, it needs to be noted that the generally undiversified source terrain and tectonic settings during the sedimentary processes should be constrained as a prerequisite before any following interpretations.

4.6. Conclusions

A practical strategy is presented to discriminate sediment archive properties and thereafter sequence the controlling factors of sedimentary processes. The main conclusions are:

The considered records of northern Ejina Basin can be discriminated into three broad lithological units: basal aeolian strata, lacustrine strata and the uppermost poorly-sorted mixture of coarse sand and gravels.

Elemental characteristics in conjunction with the granulometric composition in different sediment archives in the northern Ejina Basin are obtained. Aeolian sands have high contents of Zr, Hf, Ba and Si. Especially Hf can be regarded as good indicator to discriminate the coarse sand proportion. Sandy loess has high contents of Ca and Sr which both exhibit broad correlations with medium to coarse silt proportions. Lacustrine clay has high contents of felsic, ferromagnesian and mica source elements. Fluvial sands have distinctly high contents of Mg, Cl and Na which are enriched in evaporate minerals. Alluvial gravels have especially high contents of Cr which may originate from nearby Cr-rich bedrock.
Multivariate statistical methods applied to geochemical compositions is a useful tool to discriminate archive types in our case. Considering the suite of late Quaternary sediments in the arid realm, temporal variation of the bulk-geochemistry can be well explained by four semi-quantified sediment components: (weak-) weathering intensity, silicate-bearing mineral abundance, saline / alkaline influence of sediments, and the quasi-constant aeolian input into the arid endorheic basin system. In contrast, pedogenesis and diagenesis exert only a limited influence.
It seems that these Heinrich events have left their signature in the Chinese loess record. This is consistent with simulations of the glacial climate, which imply that the climates of the North Atlantic and China were linked by the effect of westerly winds” (Stephen C. Porter and Zhisheng An, 1995)

5. Lake sediments documented late Quaternary humid pulses in the Gobi Desert of Mongolia: Vegetation, hydrologic and geomorphic implications

Kaifeng Yu 1, Frank Lehmkuhl 1, Frank Schlütz 2, Bernhard Diekmann 3, Steffen Mischke 4, Jörg Grunert 5, Waheed Murad 6,7, Veit Nottebaum 1, Georg Stauch 1

1 Department of Geography, RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany

2 Lower Saxony Institute for Historical Coastal Research, Viktoriastraße 26/28, 26382 Wilhelmshaven, Germany

3 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Telegrafenberg A43, 14473 Potsdam, Germany

4 Faculty of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavik, Iceland

5 Department of Geography, Johannes Gutenberg-Universität Mainz, Becherweg 21, 55128 Mainz, Germany

6 Department of Palynology and Climate Dynamics, Georg-August-Universität Göttingen, Untere Karspüle 2, 37073 Göttingen, Germany

7 Department of Botany, Kohat University of Science and Technology, 26000 Kohat, Pakistan

Considerable efforts have been devoted to decipher the late Quaternary moisture and thermal evolution of arid central Asia. However, disparate interpretations still exist concerning different proxies. The spatial and temporal heterogeneities have inhibited a holistic understanding of general patterns and underlying mechanisms. To address these issues, two parallel cores (ONW I, 6.00 m; ONW II, 13.35 m) were retrieved from lake Orog Nuur, in the Gobi Desert of Mongolia. An array of multidisciplinary investigations of geomorphological mapping, radiocarbon dating, geochemical and biotic studies embracing palynological and
ostracod valve analyses has enabled us to gain a comprehensive dataset for vegetation development and hydrological variability over the last ~50 ka. Ample evidence reveals a marked moisture pulse during the Marine Isotope Stage 3 (~36~24 ka) which might have induced the maximum last glacial expansion in the high elevated Khangai Mountains. A sharp transition of Termination I (~11 ka) is indicated by geochemical, palynological, and ostracod data. The lower area of the Orog Nuur catchment was dominated by *Artemisia* steppe in the late Pleistocene and gradually altered to Chenopodiaceae desert steppe in the Holocene. The early Holocene is also characterized by a relatively humid environment, albeit discordant downcore variability of moisture and thermal signals can be derived between palynological and bulk geochemical signals. The water body of the lake appears to be a distinct alkaline environment during the Holocene which was subjected to frequent allogenic input and disturbance of the anoxic states in relative to the late Pleistocene Epoch. These two humid pulses may be the trait of a larger scale of arid central Asia that is documented in a suite of archives. Considering kinetics, a coupled atmospheric component comprising both East Asian Summer Monsoon and strengthened westerlies moisture supply seems to be the driving mechanism. This coupled mode might have been modulated broadly by boreal insolation variances. On the other hand, four harsh climatic conditions were documented in the core at ~47 ka, ~37 ka, the global Last Glacial Maximum and the Younger Dryas as playa phases. An impeding of westerlies’ moisture conveying along with the retreated East Asian Summer Monsoon might have contributed to these playa phases in the Gobi Desert of Mongolia.

5.1. Introduction

Being a fragile ecological system, environmental change in arid central Asia exerts tremendous influence on a significant percentage of world population concerning nomadic migration and alternation of political regimes (Pederson et al., 2014). The Gobi Desert in southern Mongolia was recognized as one of the main dust sources for Chinese Loess Plateau and pelagic sediments in the northwest Pacific (Pye and Zhou, 1989; Xiao et al., 1997; Lu and Sun, 2000; Vandenberghe et al., 2006). Previously, general pattern of late Quaternary (in particular Holocene) paleoclimate signatures of arid central Asia were defined and reviewed by an array of works including Pachur and Wünemann (1995), Yang et al. (2004, 2011), Herzschuh (2006), Chen et al. (2008), An et al. (2008), Wang et al. (2010) as well as Wang and Feng (2013). These compilations have suggested a distinct moisture regime of middle and southern Mongolia in comparison to that of higher latitude Baikal catchments and East Asian Summer Monsoon (EASM) domain of China (Yang et al., 2004; Wang and Feng, 2013).
Fig. 5-1: Location of the study area and paleoclimate records mentioned in the text (1, Kanas Basin; 2, Darhad Basin; 3, Hovsgol Nuur; 4, Shaamar section; 5, Baikal Lake; 6, Kotokel Lake; 7, Wulagai Lake; 8, Manas Lake; 9, Luanhaizi Lake; 10, Wuliangsu Lake; 11, Japan Sea; 12, Lake Biwa; 13, Khangai Glacier; 14, Altai Glacier. More details refer to Tab. 5-3).

Panel A delineates schematic vegetation cover of Mongolia. Large-scale air mass controls are marked with arrows, comprising East Asian Summer Monsoon (EASM), Indian Summer Monsoon (ISM) and Westerlies. Ulaan Nuur (Lee et al., 2011, 2013) and Bayan Tohomin Nuur (Felauer et al, 2012) are the only two reported lacustrine archives in the central to southern Mongolia. Panel B exhibits north-south oriented topographic transect and corresponding vegetation patterns. The eastern parts of Khangai Mountains (higher reach of the Orog Nuur catchment) with altitudes between 3,500 m and 3,700 m a.s.l. have no modern
glaciers, while small ice-fields may reach down to 3,200 m a.s.l. in the western Khangai Mountains (Lehmkuhl and Lang, 2001).

On the Mongolian Plateau and adjacent arid central Asia, continuous lacustrine sequences are widely regarded as fundamental repository for paleoenvironmental signatures. A wealth of works has been reported concerning the late Quaternary moisture and thermal history. However, an array of paramount aspects still needs to be tackled. They are summarized as follows: (i) biased or even contradictory conclusions may occur due to the interpretations of different proxies. For instance, Schwanghart et al. (2009) advocated a warmer and wetter mid-Holocene in Ugi Nuur (nuur = lake; in central-northern Mongolia) as inferred from the mineral composition and bulk-geochemistry, while an arid mid-Holocene was reconstructed from palynological studies (Wang and Feng, 2013). (ii) Most of the works poured attention into the Holocene period, while only few records addressed the climate history during the Pleistocene (Pachur and Wünnemann, 1995; Grunert et al., 2000; Lehmkuhl and Haselein, 2000). (iii) Substantial spatial heterogeneity is also noteworthy. An amount of studies on lacustrine deposits were carried out in the Baikal area in Russia, in northern and western Mongolia and in northern China (Fig. 5-1A; Tab. 5-2; Rhodes et al. 1996; Prokopenko et al., 2001; Mischke et al., 2005; Hovsgol Drilling Project Members, 2009). Only two lacustrine sequences were hitherto conducted in southern Mongolia, namely from the Bayan Tohomin Nuur (Felauer et al., 2012) and the Ulaan Nuur (Lee et al., 2013) (Fig. 5-1A), albeit these two records cover only the last ~15 ka. Furthermore, climate reconstructions might be biased by uncertainties in the radiocarbon based age models due to lack of datable organic matter as well as varying hard water effects (Mischke et al., 2013).

Consequently, it is indispensable to perform multidisciplinary studies on a critically selected lacustrine sequence in attempting to gain a more unambiguous knowledge of the past environmental changes. Here, two parallel cores (ONW I; ONW II) were recovered from the western Orog Nuur Basin, in southern Mongolia. Based on previous investigations, a multidisciplinary study involving sedimentology, bulk-geochemistry, palynology and ostracod analyses were carried out, intending to:

(1) gain a compelling knowledge of moisture history in the Orog Nuur catchment over the last ~50 ka, and its governing atmospheric circulation;;
(2) elucidate the broad pattern of interrelated vegetation and hydrologic history of the Orog Nuur catchment;
(3) generate and refine understandings on the spatial and temporal traits of moisture and thermal signals in southern Mongolia, with aid of comparison with adjacent aeolian, pelagic and mountainous glacial expansion records.

5.2. Study Area

The Orog Nuur catchment lies in the Valley of Gobi Lakes in southern Mongolia (Fig. 5-1A). The Orog Nuur is a brackish habitat that is subjected to desiccation and it occasionally turns into a playa environment. Tuyn Gol (gol = river) is the main inflow that originates from the southern slopes of Khangai Mountains around 220 km north of the lake. The Orog Nuur has no conspicuous outflow, resulting in a hydrologically closed basin system.

Fig. 5-2: Geomorphological map of the Orog Nuur Basin, three sets of lake beaches were synthesized based on previous investigations. Section A1 is located at the third (highest) set of sand ridge, more details see Chapter 5.5.2.2. General content is adapted after J. Grunert and F. Lehmkuhl, and original cartography by T. Bartsch.

5.2.1. Geologic and geomorphic setting

The northwest-southeast orientated Valley of Gobi Lakes (ca. 1,400 to 1,800 m above sea level, a.s.l.) is an elongated intramontane depression between the Siberian Craton and the Tarim and Sino-Korean Cratons (Baljinnyam et al., 1993; Windley and Allen, 1993; Bardarch et al., 2000; Cunningham, 2013). The Valley of Gobi Lakes is bounded by the Khangai
Mountains in the north and Gobi Altai Mountains in the south (Fig. 5-1B). The maximum elevation of the Khangai Mountains is around 4,000 m a.s.l. at Otgon Tenger Uul in the west (4,008 m a.s.l.; 47°36’30”N, 97°33’09”E) and ca. 3,000 m a.s.l. at Erhet Hayrhan Uul in the east (3,037 m a.s.l.; 46°39’18”N, 101°13’56”E), whilst the summit of the Gobi Altai is in 3,957 m a.s.l. (Ikh Bogd Uul: 44°59’42”N, 100°13’51”E; uul = mountain). A left lateral strike-slip fault is located at the southern side of the Khangai Mountains (Tapponnier et al., 1979; Walker et al., 2007; Cunningham, 2013), while the southern part of the Orog Nuur watershed exhibits the tectonic escarpment of the Gobi Altai and gently inclined alluvial fans (Baljinnyam et al., 1993; Vassallo et al., 2011). The elongated forebergs of the Gobi Altai are markedly faulted, warped and partially uplifted by thrust faults (Owen et al., 1997). As an example, the 1957 earthquake (magnitude 8.3) caused a left-lateral displacement of 6 m and vertical displacements approached 1.5 m (Baljinnyam et al., 1993), demonstrating that tectonic movement may lead to some misinterpretations regarding shoreline ridges or terraces (Fig. 5-2). Paleozoic volcanic and plutonic rocks are exposed in the basin and some places are overlain by conglomerates. Previously, a much larger lake extents were reconstructed based on three sets of shorelines (Lehmkuhl and Lang, 2001; Komatsu et al., 2001; Grunert et al., 2009). These shorelines are situated 3 m, 10 m, 16 m (10 and 16 m = lake level 1, L.L.1) and 23 m (L.L.2) above the modern lake-level (Fig. 5-2). East-west oriented mobile dunes and cuspate bars lie in the vicinity of the Orog Nuur (Stolz et al., 2012).

5.2.2. Climatic and vegetation setting

Mongolia is dominated by a continental climate characterized by dry and cold winter and a precipitation maximum in summer (An et al., 2008). The mean annual precipitation along a north-south transect ranges from ~500 mm to <100 mm (Fig. 5-1A). 65-75 % of the precipitation occurs in summer due to the enhanced south-eastern cyclonic activity along the polar front (Kostrova et al., 2014). Only ~100 mm precipitation is delivered in the lower Gobi Desert of southern Mongolia, while the higher elevated Khangai Mountains can reach ~400 mm. According to records at Bayankhongor weather station near the Orog Nuur, the mean July and January temperature in the Gobi Desert are ~16 °C and ~−20 °C, respectively, while the mean annual temperature is about -2 °C to 5 °C (Felauer, 2012). In spring, dust- or sandstorms frequently occur with maximum wind speeds exceeding 20 m/s (Hempelmann, 2010; Felauer, 2012). There is generally no snow cover because of the immense winter dryness related to the predominant Siberian Anticyclone (Kostrova et al., 2014).
Fig. 5-3: Schematic lithologic column, photographs of sliced drilling core ONW II along with the reference logs. Abbreviations: cl, clay; fsi, fine silt; msi, medium silt; csi, coarse silt; fs, fine sand; ms, medium sand, cs, coarse sand. Mudstone or siltstone is represented in schematic colors according to core description. In general, greyish calcareous clays (upper fraction), siltstone and intercalated sandstones constitute the entire lacustrine sequence.

In general, the dominant soil types in central to southern Mongolia are dry-steppe Kastanozems. Other common soil types are Chernozems/dark Kastanozems in the forest-steppe zone as well as brown semi-desert soils (Tamura et al., 2012). The modern vegetation follows a north-south transect from mountain taiga, forest steppe, grass steppe, desert steppe...
and finally to desert communities (Fig. 5-1A; Hilbig, 1995; Gunin et al., 1999). Detailed modern vegetation of the Valley of Gobi Lakes see Felauer (2011). In the forest steppes of the Khangai and Altai Mountains, Larix sibirica is the dominating tree species on the northern and eastern slopes, while steppe prevail the sun-exposed southern and western slopes (Miehe et al., 2007). Pinus sibirica can be found in the restricted mountain taiga of the Khangai Mountains (Hilbig, 1995). The uppermost boundary of the alpine meadows is ~2,900 m a.s.l. (Lehmkuhl and Lang, 2001). Most of the lowland regions in the basin system are characterized by open desert steppes and bare gobi surface. Dwarf bushes and reed-halophytes are the dominant communities in the lower reaches of the Orog Nuur catchment (Murad, 2011).

5.2.3. Paleo- and modern glacial setting

As the depositional basin of Orog Nuur is linked to the higher Khangai Mountains via Tuyn Gol, Quaternary glacial variance may play a pivotal role in terms of water supply and the clastic delivery. In modern times, only the western Khangai has small ice caps and the average equilibrium line altitude (ELA) was estimated in a range from 3,900 to 4,000 m a.s.l. (Fig. 5-1B; Rother et al., 2014). The modern periglacial zone reaches down to 2,700 m a.s.l. (Lehmkuhl and Lang, 2001). A set of Last Glacial Maximum (LGM) moraines at an altitude of ~2,900 m. a.s.l. in the southern Khangai Mountains was dated thereafter to >21 ka (Lehmkuhl and Lang, 2001). In addition, Ritz et al. (2006) determined ages of alluvial sediments of the forelands of Gurvan Bogd (bogd = massif) by 10Be cosmogenic nuclides exposure dating and supposed an aggradation of sediments in the context of the global glacial terminations. In the Gobi Altai, permafrost developed at ca. 22-15 ka and degraded since ~13 ka, and was thereafter diminished since the early Holocene (Owen et al., 1998).

5.3. Material and methods

5.3.1. Cores retrieval and sampling strategy

Two parallel sediment cores (ONW I: 6.00 m, 45°03’48”N, 100°34’39”E; ONW II: 13.35 m, 45°04’28”N, 100°35’08”E, 1,219 m a.s.l.) are retrieved from the western part of Orog Nuur during the playa phase (Figs. 5-1A and 5-2). The core was opened, described and documented in the field. Samples were separated and transported to University of Göttingen, Free University of Berlin and the Alfred Wegener Institute in Bremerhaven for palynological, ostracod, X-ray fluorescence and X-ray powder diffraction analyses. The remaining material
of the cores is preserved at RWTH Aachen University for grain size and TOC analysis. The paleoenvironmental reconstruction is carried out primarily based on the longer core ONW II.

Table 5-1 The AMS $^{14}$C ages were calibrated to calendar years with 2 $\sigma$ standard deviation using the CALIB rev. 7.1 (Stuiver et al., 1998) with the latest IntCal13.14c (Reimer et al., 2013). According to the estimated real age based on the lithostratigraphy, raw radiocarbon ages are subtracted by a reservoir effect of ~3,400±2,100 a BP before computing to calibrated ages and generating the Bayesian age-depth model as given in Fig. 5-4.

<table>
<thead>
<tr>
<th>Core Nr.</th>
<th>Dept (cm)</th>
<th>Lab Nr.</th>
<th>Dating material</th>
<th>$^{14}$C ages (a BP)</th>
<th>$\delta^{13}$C (%)</th>
<th>Estimated real age according to lithostratigraphy (cal a BP)*</th>
<th>Calibrated Age based on Bayesian age-depth modelling (cal a BP)</th>
<th>Median Age based on Bayesian age-depth modelling (cal a BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONW II</td>
<td>94</td>
<td>Erl-15622</td>
<td>Bulk material</td>
<td>12,581±103</td>
<td>-25.4</td>
<td>-</td>
<td>-</td>
<td>5,054-16,854</td>
</tr>
<tr>
<td>ONW II</td>
<td>199</td>
<td>Erl-15623</td>
<td>Bulk material</td>
<td>13,242±85</td>
<td>-24.2</td>
<td>15,691-16,138</td>
<td>11,000-13,000</td>
<td>5,988-17,523</td>
</tr>
<tr>
<td>ONW II</td>
<td>271</td>
<td>Erl-15624</td>
<td>Bulk material</td>
<td>17,733±149</td>
<td>-25.4</td>
<td>21,042-21,819</td>
<td>13,000-18,000</td>
<td>10,905-22,893</td>
</tr>
<tr>
<td>ONW II</td>
<td>392</td>
<td>Erl-15625</td>
<td>Bulk material</td>
<td>17,713±180</td>
<td>-24.5</td>
<td>20,945-21,857</td>
<td>18,000-19,000</td>
<td>10,827-22,924</td>
</tr>
<tr>
<td>ONW II</td>
<td>571</td>
<td>Erl-15626</td>
<td>Bulk material</td>
<td>19,738±179</td>
<td>-23.8</td>
<td>23,344-24,150</td>
<td>-</td>
<td>13,528-25,249</td>
</tr>
<tr>
<td>ONW II</td>
<td>778</td>
<td>Erl-15627</td>
<td>Bulk material</td>
<td>21,501±217</td>
<td>-24.2</td>
<td>25,386-26,122</td>
<td>-</td>
<td>15,408-27,018</td>
</tr>
<tr>
<td>ONW II</td>
<td>1,19</td>
<td>Erl-15628</td>
<td>Bulk material</td>
<td>46,103±2,281</td>
<td>-25.4</td>
<td>44,908-49,914</td>
<td>-</td>
<td>37,748-49,716</td>
</tr>
<tr>
<td>ONW II</td>
<td>1,27</td>
<td>Erl-15629</td>
<td>Bulk material</td>
<td>40,429±1,340</td>
<td>-24.9</td>
<td>42,221-46,226</td>
<td>-</td>
<td>34,226-47,355</td>
</tr>
<tr>
<td>ONW I</td>
<td>386</td>
<td>Erl-12107</td>
<td>Bulk material</td>
<td>16,020±105</td>
<td>-28.1</td>
<td>19,049-19,560</td>
<td>18,000-19,000</td>
<td>-</td>
</tr>
<tr>
<td>ONW I</td>
<td>588</td>
<td>Erl-12108</td>
<td>Bulk material</td>
<td>17,642±112</td>
<td>-23.4</td>
<td>21,020-21,653</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* The reservoir effect is determined by taking average of the difference between the boldface ages in these two columns.

5.3.2. Lithology and chronology

In total ten radiocarbon ages were determined from bulk organic materials (Tab. 5-1) using accelerator mass spectrometry (AMS) at the University of Erlangen-Nürnberg and subsequently calibrated to calendar years using CALIB rev. 7.1 (Stuiver et al., 1998) with the latest IntCal 13.14c calibration curve (Reimer et al., 2013). All radiocarbon ages are presented as calibrated years (cal a BP) with a 2 $\sigma$ error bar. The upper 24 cm of the core ONW II were not retrieved. The R package “Bchron” (Parnell et al., 2008) was employed here to set up a Bayesian age-depth model for core ONW II (Fig. 5-4) including its calibration using the IntCal calibration curve mentioned above. Reservoir effects at different anchor points were assessed by (i) identifying Termination I in bulk-geochemical and palynological sequences, and (ii) comparing the Younger Dryas (YD) - related sand layer in Orog Nuur and Ulaan
Nuur (Fig. 5-1A; ~200 km northeast of Orog Nuur; Lee et al., 2011, 2013). All of the radiocarbon ages were first subtracted by the reservoir effect and then computed to calibrated calendar years and used in the establishment of the Bayesian age-depth model. Two radiocarbon ages from core ONW I (386 cm, 588 cm) are employed to compare timing of the stratigraphic units relative to ages of counterpart depths in core ONW II (Tab. 5-1; Fig. 5-4).

Fig. 5-4: Polylinear regression age-depth model of core ONW II generated from the radiocarbon ages. Reservoir effect is corrected by (i) late Pleistocene / Holocene transition (Termination I) as inferred from the suite of granulometric, palynological, ostracod and geochemical studies (marked as black triangle), and (ii) the Younger Dryas related sand layer (Ulaan Nuur, Lee et al., 2013). Frequency-dependent magnetic susceptibility ($\chi_{FD}$), electrical conductivity (EC), CaCO$_3$, TOC and C/N$_{atomic}$ ratios of parallel core ONW I are employed to cross-validate the age model of core ONW II. More details with respect to the lithostratigraphy and chronological framework see text in Chapter 5.4.1.

5.3.3. Grain size analysis

Grain Size Distributions (GSD) of all samples with 5 cm intervals (114 samples for ONW I; 258 samples for ONW II) were measured using a Beckman Coulter LS13320 laser diffraction particle size analyzer with a detection range of 0.04-2,000 µm. Preparation of samples follows Konert and Vandenberghe (1997). Before measuring, a parallel test (HCl/H$_2$O$_2$- and H$_2$O$_2$-only-treatment) was done to test the impact of possible incorporated calcium carbonate on the
resulting GSD, revealing however no pronounced differences (Schulte et al., 2016). Thus, all measurements were performed uniformly without hydrochloric acid treatment. For clayey sediments subsamples of 0.1 g and for coarse sands 1 g were utilized. 700 µl of 35 % hydrogen peroxide was added to remove the organic components. Samples were then dried at 70 °C for two days. Sodium polyphosphate was added afterwards to avoid coagulation. The Mie Theory was applied for GSD calculations (Özer et al., 2010; Schulte et al., 2016). The final GSD represents the average of two subsamples, each of which was measured twice to ensure reliability. In case notable offsets existed between subsamples, the measurement procedure was repeated for the sample.

Fig. 5-5: Lithologic units of the core ONW II, and corresponding granulometric, geochemical, and color variances. The grey bars depict the primary sand layers inferred from the granulometric and lithostratigraphic characteristics of the core.

### 5.3.4. Electrical conductivity and magnetic susceptibility measurements

Electrical conductivity (EC, here equals specific conductivity) and magnetic susceptibility (MS) were carried out exclusively on powder sediment from core ONW I as an environmental and salinity proxy. 50 ml water and 0.01 g KCl were added for each sample, the EC with 10 cm interval (1 cm thick each subsample) was measured after 30 min using a WTW LF 196 probe. MS at 1 cm interval was measured using a Barrington MS2 with a MS2 E sensor.
5.3.5. Carbon, nitrogen, sulfur, TOC and CaCO₃ analyses

Carbon (TC), nitrogen (TN), sulfur (TS) concentrations, and the Total Organic Carbon (TOC) content were determined, in order to gain a better understanding of the geochemical habitats of the former water sediment interface. Samples were dried at 36 °C for 24 hours. The samples in zinc capsules were subsequently analyzed in CHNS Analyzer EA3000. The Scheibler gas method (DIN 19684) was employed to calculate the CaCO₃ content, and 1-5 g samples were utilized respectively. Calculation equation is as follows:

\[
CaCO_3 (\%) = \frac{V \times p \times 0.1602}{(t + 273) \times E \times K}
\]

Where \( V \) is the volume of CO₂ (cm\(^3\)), \( p \) represents the atmospheric pressure (mm Hg), \( t \) denotes room temperature (°C), \( E \) is the loss of weight (g) and \( K \) exhibits the correction factor (here 2 is used). TOC was subsequently computed following Scheffer and Schachtschabel (2002). The C/N\(_{\text{atomic}}\) ratios throughout the ONW II core were computed and examined for further interpretations (Meyers and Teranes, 2001).

5.3.6. X-ray fluorescence analysis, color analysis and multivariate statistics

The X-ray fluorescence (XRF) analysis was carried out in Alfred Wegner Institute (AWI) for Polar and Marine Research in Bremerhaven, Germany, using an Avaatech XRF Core Scanner configured with Canberra X-Pips 1500-1.5 detector (slit 10 mm, 10, 30 keV, 300 and 700 μA). The scanning interval is 1 cm, resulting in 1,335 measurements for the core ONW II. Processes comprising subtracting a background curve, applying statistical corrections for physical processes in the detector and deconvolution of overlapping peaks were performed using scanner equipped WinAxil package (NIOZ and Avaatech, 2007). To gain a direct knowledge about the depositional environment of former sediment-water interface, two factors were computed based on the element dataset using factor analysis given in Yu et al. (2016). Thereby, high loading elements for each factor in conjunction with the factor scores provide intriguing insights into the sedimentary processes (Yu et al., 2016). In addition, X-ray diffraction (XRD) for 14 samples at different depths was performed to assess the general mineral composition and provide additional information for the interpretation of bulk elemental compositions. The sediment color (RGB model) was scanned using a CCD line scan camera.
Fig. 5-6: Diagram of analyzed taxa of pollen, fungal spores, aquatic algae and non-pollen palynomorphs through the core ONW II plotted against the age and depth. All taxa were aggregated into groups consist of arboreal plants (trees), shrubs, subshrubs/herbs/grasses, aquatics, as well as coprophilous fungi and Glomus.

5.3.7. Palynology

In total 123 sediment subsamples of 1-2 cm$^3$ were acquired in 5-10 cm intervals from core ONW II and treated with KOH, HCl, HF and subsequent acetolysis for palynological analyses (Erdtman, 1960; Moore et al., 1991). Lycopodium spores were added as exotic marker to calculate pollen concentration (n/ml). With few exceptions, at least 400 pollen of terrestrial plant were counted per sample. Pollen grains in clumps were counted separately (Schlütz and Lehmkuhl, 2007). A total of about 50 pollen and 40 non-pollen palynomorphs (NPP: spores, algae, etc.) were identified. Based on a variety of specific literatures (Müller, 1970; Vanky, 1994; Wang et al., 1995; Beug, 2004; Van Geel and Aptroot, 2006) and a collection of more than 5,000 type slides, selected taxa and groups are arranged and presented in ecological groups. All percentages of pollen and NPPs refer to the pollen sum of terrestrial plants. Beside presented (Fig. 5-6), the tree taxa also comprise low abundances of Quercus, Ulmus, Tilia and Alnus. The group of coprophilous fungi covers spore types related to the genera Arnium, Cercophora, Delitschia, Podospora, Sordaria, Sporormiella, and Trichodelitschia. In addition, the concentration of the pollen sum and of burnt plant particles (“charcoal”) as well the ratio of Artemisia to Chenopodiaceae (A/C ratio) are given (see supplementary material). The average of A/C ratio is marked by a line at 5.8 (Fig. 5-6). The pollen diagram was plotted using the software C2 version 1.5 (Juggins, 2007) and was based on changes in taxa.
abundance divided into 9 local pollen assemblage zone (LPZ), mostly in conformity with the stratigraphic units.

5.3.8. Ostracod analysis

A total of 131 sub-samples from core ONW II were collected at 10 cm intervals for ostracod analysis in order to examine and verify the paleohydrological conditions. The sediment was treated with 3 % H$_2$O$_2$ for 48 hours and washed through 0.25 and 0.1 mm meshes. All ostracod valves were picked from the dried sieved residues and identified according to Meisch (2000) and Mischke and Zhang (2011). Further inferences are mainly based on Hiller (1972), Hammer (1986), Meisch (2000) and Mischke et al. (2005).

5.4. Results

5.4.1. Bayesian chronology and lithostratigraphic units

According to the Bayesian age-depth model, the basal age of the core ONW II was determined to be between 38 and 52 ka (Fig. 5-4). For lacustrine deposits in the Valley of Gobi Lakes, lack of datable organic matter and old carbon effects may hamper the discerning of reliable chronological framework. The Termination I has manifested remarkable consistency in a complete set of palynological, geochemical and ostracod studies (i.e., abrupt increase of pollen concentration, CaCO$_3$ abundance, and ostracod valves, respectively after the Termination I; Figs. 5-4, 5-5, 5-6 and 5-8) on core ONW II, and thereby validate the onset of the Holocene stratigraphy in our age model. Thus, the sediments in a depth of ~205 cm are presumed to be ~11,000 a BP old), which is ~4,600 years younger than that in our model. In order to further corroborate the Termination I, Younger Dryas-related sand deposits in Ulaan Nuur sediments dated by optically stimulated luminescence (OSL) is applied (Fig. 5-1A). The chronology of the 600 cm Ulaan Nuur core was determined by 12 luminescence ages and the sand layer regarding the Pleistocene and Holocene transition was determined to ca. 13-11 ka (Fig. 5-4). Thereby, an age of 13,000 a BP could be assigned to sediments in ~248 cm depth, which is ca. 3,500 years younger than that in the age model. In the light of Lee et al. (2011) and Mischke et al. (2013), high reservoir effect in a scale of greater than 3,000 years in the Orog Nuur sediments is highly feasible. Likewise, based on the estimation of the real ages of the lithostratigraphy, the raw radiocarbon ages were subtracted by a reservoir effect of c. 3,400±2,100 yrs (Tab. 5-1) and then computed to calibrated calendar years and employed in the establishment of the Bayesian age-depth model (Fig. 5-4).
Subsequently, based on lithostratigraphic, together with granulometric, and geochemical characteristics, the entire sequence is delimited into nine units as follows (Fig. 5-3):

(1) Unit 1 (1,335-1,235 cm; ~50-~43 cal ka BP) is a greyish silty-clay layer with more than 50 % of silt and clay fraction. U1 is interbedded by a 20 cm (1,315-1,290 cm) predominant coarse sand layer. CaCO₃, C/N<sub>atomic</sub> along with TOC portray extremely low values with respect to the sand layer and gradually increase upward (Fig. 5-5).
(2) Unit 2 (1,235-1,120 cm; ~43--37 cal ka BP) is dominated by dark greyish clayey-silty sediments (60-80 % of silt to clay proportion) with several intercalated brownish sand layers (Figs. 5-3 and 5-4). CaCO$_3$ retains roughly stable within U2, while C/N$_{\text{atomic}}$ ratio manifests a more varied pattern, with values at gyttja-like laminae (~1,120 cm) greater than 20 (Fig. 5-5). The C/N$_{\text{atomic}}$ ratios together with S content in rest depth of the unit delineate generally low values.

(3) Unit 3 (1,120-1,057 cm; ~37--35 cal ka BP) is a light greyish silty-clay stratum with several intercalated brownish sand layers (Fig. 5-3). The C/N$_{\text{atomic}}$ ratios and TOC progressively attenuate upcore and increase slightly in the uppermost U3. S and N contents depict higher abundances than preceding units (Fig. 5-5).

(4) Unit 4 (1,057-660 cm; ~35--24 cal ka BP) is a dark greyish silty-clay stratum with intercalated sand layers at ~940 cm and ~840 cm, as well as several sinuously intercalated layers with light greyish color (~750-730 cm). TC and CaCO$_3$ concentration illustrate relative low values with slight variability. Two vigorous spikes of TOC and C/N$_{\text{atomic}}$ ratio occur at ~820 cm and ~720 cm (Fig. 5-5), albeit no counterpart phenomenon is manifested in lithofacies and granulometric composition (Figs. 5-3 and 5-4).

(5) Unit 5 (660-390 cm; ~24--19 cal ka BP) is a greyish silty-clay layer, which is intercalated by sand layers at ~540 cm and ~460 cm (Fig. 5-3). Unlike U4, the TOC and C/N$_{\text{atomic}}$ ratios represent quasi-constant values. In particular, the basal fraction of U5 is laminae of dark brownish gyttja-like sediment characterized by pronounced high S and TOC content (Fig. 5-5). Considering their counterpart stratigraphy in the core ONWI, spikes of magnetic susceptibility (MS) in conjunction with slightly higher EC values in the uppermost part of U5 are illustrated (Fig. 5-4).

(6) Unit 6 (390-350 cm; ~19--18 cal ka BP) is a salient brownish coarse sand layer which is also captured by the parallel core ONW I (Fig. 5-4). The sand fraction ranges from 91.5 % to 96.1 %. CaCO$_3$ abundance exhibits extremely low values whilst the C/N$_{\text{atomic}}$ ratios illustrate high values with oscillations (Fig. 5-5).

(7) Unit 7 (350-248 cm; ~18--13 cal ka BP) is a light greyish clayey-silty layer similar to U1. The sand fraction ranges from 10 % to 35 % with an abrupt decrease in the basal part of U7 to ~35 % and a subsequent decrease to 10 % at the depth of 283 cm. The CaCO$_3$ and C/N$_{\text{atomic}}$ ratio depict similar patterns as U1.

(8) Unit 8 (248-205 cm; ~13,000--11,000 cal a BP) is dominated by the sand fraction (50-90 %). This sand layer is also documented in the parallel core ONW I and the adjacent Ulaan Nuur (Fig. 5-1A). CaCO$_3$ abundance remains analogue to U7, while the C/N$_{\text{atomic}}$ ratio...
shows more fluctuations similar to the global LGM phase (U6). Throughout U8, S content exhibits remarkable low values (Fig. 5-5).

(9) Unit 9 (205-25 cm; ~11-? cal ka BP) is marked by fine sediments comprising the highest clay fractions (30-50 %) and the lowest sand proportion (1-10 %). An abrupt increase of the CaCO$_3$ (i.e., calcite, unpublished XRD data) and concomitantly diminished S content are represented in U9. C/N$_{\text{atomic}}$ ratios decrease from ca. 20 to <10 upward and increase incrementally approaching top of the core.

5.4.2. Bulk-geochemistry of the lacustrine sediments

Two factors were derived based on the multivariate analysis (Yu et al., 2016) on the bulk-geochemistry of the lacustrine sequence. Factor 1 denotes high loadings of Fe, Mn and Al, while factor 2 manifests particularly high loadings for Ca, Sr and Cl. Scores of each factor are given in Fig. 5-9. Four concurrent periods exhibiting low values of factors 1 and 2 are delineated in U1 (~1,300 cm), U2 (~1,120 cm), U6 (390-350 cm) and U8 (248-205 cm) (see yellow bars in Fig. 5-9). In the Holocene (U9), factor 1 has extremely low values while factor 2 exhibits high values. Compared with the uppermost portion, the basal part of U9 represents lower values for factor 1 and higher values for factor 2.

5.4.3. Palynological results

With values around 0.5 % tree pollen is infrequent throughout the whole archive and never reaching more than 3.5 % (Fig. 5-6). Findings of Hippophae shrubs are more abundant for most of the lower part at around 1.4 % (max. ca. 8 %) and Ephedra values exceed in the upper part over 45 %. The genus Artemisia, includes several species of subshrubs and herbs, is absolutely predominant with values around 70 % (max. 83.5 %). Chenopodiaceae are the second common taxon. Their values are around 12 % but increase to 71.5 % when Artemisia decreases at the top of the profile. For most of the profile the A/C ratio fluctuates between 0.13 and 14.5, but shows a clear trend to lower values and lower variability approaching the top. Beside Artemisia and Chenopodiaceae only Poaceae occur in every of the 123 samples, mostly with around 2.5 % and never but not reaching much more than 9 %. The pollen of sedges (Cyperaceae) and some groups of Asteraceae (Matricaria-type, Liguliflorae) occurs in about 120 samples respectively, while Rheum and Caryophyllaceae are represented in nearly 110 samples, Brassicaceae and the Senecio-type (Asteraceae) occur in around 100 samples. A maximum of more than 10 % is reached only by the Cyperaceae and the Matricaria-type. The pollen concentration is around 5,000 grains per ml (n/ml) but reaches up to greater than
41,000 n/ml in the upper part of the core (Fig. 5-6). In addition, nine local pollen zones (LPZs) are mostly in conformity with the stratigraphic units delimited in Chapter 5.4.1 (Fig. 5-6). Pollen concentration (n/ml) and A/C ratios are employed to generally constrain semi-quantified thermal (T) and effective moisture (M) anomalies (Fig. 9; Ma et al., 2008, 2013; Yang and Scuderi, 2010; Zhao et al., 2012).

5.4.3.1. Unit 1 (LPZ 1; 1,335-1,235 cm; ~50~~43 cal ka BP)

*Artemisia* dominates with pollen percentages at around 70 %, while Chenopodiaceae stay below 10 %. The A/C ratio increases, while percentages of spores (coprophilous fungi, *Glomus-type*) and aquatics (*Botryococcus, Pediastrum*) are low.

![Fig. 5-8: Absolute abundances of determined ostracod species, number of taxa and number of valves plotted against lithologic units.](image)
5.4.3.2. Unit 2 (LPZ 2; 1,235-1,120 cm; ~43--37 cal ka BP)

Chenopodiaceae increase to 30 %, *Artemisia* falls below 50% and the A/C ratio to 1.6. Values of spores and most aquatics increase considerably in the second half.

5.4.3.3. Unit 3 (LPZ 3; 1,120-1,057 cm; ~37--35 cal ka BP)

Values of *Artemisia* are around 70 %, Chenopodiaceae are below 20 %. Spores stay quite common, while some green algae (*Botryococcus*) and rotifer resting eggs (cf. *Trichocerca cylindrica*) decrease considerably. Other green algae (*Pediastrum*) remain on a low level and the amount of mandibles of Chironomidae is from now on recurrent over 1 %.

5.4.3.4. Unit 4 (LPZ 4; 1,057-660 cm; ~35--24 cal ka BP)

In general, the abundance of *Artemisia* increases slightly reaching values around 80 % while percentages of Chenopodiaceae decrease weakly, leading to some high A/C ratios in the middle of LPZ 4 (including the maximum A/C ratio of 14.5 through the core). After a short suspend the before sporadic finds of *Salix* pollen become more frequent. Aquatics like rotifer resting eggs (55 %) and *Pediastrum* (43 %) reach their absolute maxima before the middle of LPZ 4 and decrease substantially thereafter. In addition, only the upper boundary of the LPZ 4 shows slightly different depth compared with that of the Unit 4 in lithostratigraphy (Figs. 5-2 and 5-6). To provide a consistent outline in the following discussions, time slices of the lithostratigraphic units are employed given that there is no unambiguous boundary taxamarker through those depths.

5.4.3.5. Unit 5 (LPZ 5; 660-390 cm; ~24--19 cal ka BP)

Percentages of *Artemisia* are reduced around the middle of LPZ 5 while Chenopodiaceae values increase and therefore the A/C ratio falls to values below 4. Finds of green algae (*Botryococcus*, *Pediastrum*) and rotifer resting eggs (cf. *T. cylindrica*) strongly reduce or even disappear around the turn to LPZ 5. Short after spore values are reduced as well. The continuous finds of Chironomidae since LPZ 3 expires abruptly at the end of LPZ 5 for the rest of the record. The pollen grain concentration increases to values of greater than 8,000 n/ml and up to 17,000 n/ml short before the end of LPZ 5.
5.4.3.6. Unit 6 (LPZ 6; 390-350 cm; ~19--18 cal ka BP)

In Fig. 5-6, the LPZ 6 is represented by a single sample (372 cm) of low pollen concentration (400 n/ml) and a low pollen sum of 200 grains instead of more than 400 in the samples below and above. Due to insufficient pollen content, two further analyzed samples are not plotted. The amount of *Hippophae* pollen seems to be quite high in and around LPZ 6 and the low values of cf. *T. cylindrica* and *Pediastrum* continue the trend from the end of LPZ 5.

5.4.3.7. Unit 7 (LPZ 7; 350-248 cm; ~18--13 cal ka BP)

With values of some 10,000 n/ml, the pollen concentration is not only much higher than in LPZ 6 but even considerable higher than in LPZ 5. While the curves of *Artemisia* and *Hippophae* decline towards the end of LPZ 7 and the curve of *Salix* gets disrupted, pollen of *Ephedra*, including the *E. distachya*-type and the *E. fragilis*-type, increases for the first time to above 5 %. The A/C ratio drops markedly at the top of LPZ 7 below its mean level (5.8) and coprophilous fungi vanish for nearly the rest of the record. *Botryococcus* and *Pediastrum*, after reaching high values again, nearly disappear at the end of LPZ 7.

5.4.3.8. Unit 8 (LPZ 8; 248-205 cm; ~13--11 cal ka BP)

The pollen concentration is reduced and *Artemisia* and *Hippophae* drop to their lowest values till then while Chenopodiaceae pollen becomes much more common. The A/C ratio falls sharply to lowest values (0.4-1.7) so far and *Ephedra* increases for the first time to over 30 %. Algae and resting eggs are present in small numbers. Pollen of the *Sparganium*-type, here locally named *Typha angustifolia/australis*, increases drastically to its highest amounts (max. 13 %), while it occurred only very sporadically in the preceding record.

5.4.3.9. Unit 9 (LPZ 9; 205-25 cm; ~11-? cal ka BP)

After a sharp rise the *Artemisia* curve falls again and Chenopodiaceae become dominant resulting in A/C ratios <1 and <0.4 lastly. While the record of *Hippophae* ends with the onset of the LPZ 9, *Ephedra* curve reaches its highest values. *Tribulus terrestris*, sporadically till then, exhibits a more closed curve in LPZ 9, but never exceeds 1.5 %. Finds of the *Juniper*-type occur for the first time, but only very sporadically. After a strong increase, *Botryococcus* finds disappear. *T. angustifolia/australis* values decrease considerably and remain below 3 %.
Furthermore, a salient increase of the pollen concentration from some 5,000 n/ml to >41,000 n/ml occurs at the onset of LPZ 9 (Fig. 5-6).

5.4.4. Ostracod species and valve abundances

Valves of eight ostracod species were identified from the sediments of core ONW II: *Limnocythere inopinata* (unnoded valves of female and male specimens, and noded female specimens), *Ilyocypris cf. bradyi*, *Ilyocypris cf. inermis*, *Ilyocypris manasensis* var. *cornae*, *Sarscypridopsis aculeata*, *Pseudocandona cf. compressa*, *Candona neglecta* and *Leucocythere dorsotuberosa* (female and male valves) (Fig. 5-7). A total of nine samples did not contain any ostracod valves. The maximum abundance of 380 valves per sample is recorded at 187 cm. Valves of *L. inopinata* represent the dominant taxon throughout the core. The other taxa are only sporadically recorded (Fig. 5-8):

1. **Unit 1** (1,335-1,235 cm; ~50~43 cal ka BP): *L. inopinata* is the predominant species in U1. The number of valves displays an increasing tendency upcore and approaches 142 at 1,244 cm. Two carapaces of *L. inopinata* are preserved at 1,284 cm.

2. **Unit 2** (1,235-1,120 cm; ~43~37 cal ka BP): The ostracods exhibit minimum valve number at 1,158 cm (5) and a maximum at 1,124 cm (157). Eight carapaces of *L. inopinata* are recorded at ~1,190 cm.

3. **Unit 3** (1,120-1,057 cm; ~37~35 cal ka BP): U3 is marked by an incipient increase of the valve number (generally >150). One to sixteen valves of *I. cf. inermis* are recorded at the upper part of U3 (1,074-1,057 cm).

4. **Unit 4** (1,057-660 cm; ~35~24 cal ka BP): A significantly high valve number (309) is achieved in the basal part of U4 (1,034 cm). Specifically, *C. neglecta* and *L. dorsotuberosa* occur at 877-827 cm (Fig. 5-8). One valve of *I. cf. bradyi* appears at 794 cm and one valve of *I. cf. inermis* is represented at 683 cm.

5. **Unit 5** (660-390 cm; ~24~19 cal ka BP): Two carapaces of *L. inopinata* were recorded in the basal part of U5 (653 cm). a high valve number (312) was recorded at 415 cm. This layer is overlain by sediments with *I. cf. bradyi* at 407 cm.

6. **Unit 6** (390-350 cm; ~19~18 cal ka BP): U6 is marked by a low abundance of valves. One valve of *I. cf. inermis* is preserved at 373 cm. *L. inopinata* has vanished throughout this unit.

7. **Unit 7** (350-248 cm; ~18~13 cal ka BP): *L. inopinata* is recovered from the very beginning of U7, albeit the valve number remains relatively low. One valve of *I. cf. inermis* occurs at 285 cm and 257 cm, respectively.
(8) Unit 8 (248-205 cm; ~13~11 cal ka BP): U8 is marked by frequent appearance of I. cf. bradyi at 227-207 cm. A suite of species comprising I. manasensis var. cornae, S. aculeata and P. cf. compressa are represented for the first time in core at 207 cm.

(9) Unit 9 (205-25 cm; ~11~? cal ka BP): U9 is characterized by a transient increase of total taxa of ostracod as well as the number of valves (Fig. 5-8). The valve number per sample reaches its maximum (380) of the core at 187 cm. I. cf. bradyi and I. manasensis var. cornae are preserved at 202 cm. In the uppermost part of the core (31 cm), three valves of I. cf. bradyi are represented.

5.5. Discussion

5.5.1. Vegetation dynamics and hydrologic history of the Orog Nuur

Biomes and corresponding environmental conditions can be derived from palynofacies (Figs. 5-6 and 5-9; e.g., Tarasov et al., 2011). However, beside the ostracod fauna (Fig. 5-8), in terms of direct hydrological signals of the lacustrine sediments, bulk-geochemical fingerprints would be a vital indicator:

(1) For the high loading elements of factor 1 (i.e., Fe, Mn and Al), aluminosilicates and micas in clayey sediments were recognized as the main host (Millot, 1970). Considering the behavior of Mn in the pelagic realm, insoluble oxi-hydroxides (Mn³⁺ and Mn⁴⁺) are represented in oxygenated environments, while soluble Mn²⁺ occurs in anaerobic environments (Calvert and Pedersen, 2007). In terms of higher lake level i.e., suboxic/anoxic water bottoms, more soluble Mn will be readily engaged into carbonate lattices and thereby will share analogue variance pattern as CaO or CaCO₃, which seems largely untenable in this study (Ca has high loading for factor 2). This is consistent with the C/N atomic ratios of the bulk material, those values greater than 20 can be ascribed to the frequent input of allochthonous materials (Fig. 5-5; Meyers and Lallier-Vergès, 1999). In summary, factor 1 may point to the redox state of the depositional environment, from which higher scores indicate reduced environments.

(2) Those elements for factor 2 (i.e., Ca, Sr and Cl) are always associated with carbonates (Tucker and Wright, 1990). The analogue pattern between calcite and the CaCO₃ along with the absence of the dolomite and aragonite (unpublished XRD data) indicate that the carbonates in the Orog Nuur are mostly presented as calcite. As suggested by Wünneumann et al. (2010), calcite is practically authigenic precipitation in the lacustrine environment. In addition, Yu et al. (2016) suggest that the aeolian activity hasn’t been significantly
altered. This is also demonstrated by the largely unchanged quartz and K-feldspar contents determined by the XRD (see Chapter 6, and Fig. 6-3). Hence, factor 2 may indicate the downcore variability of the authigenic productivity.

Based on the entire dataset, a comprehensive view of vegetation dynamics, hydrologic history and climate developments are provided as follows:

5.5.1.1. Unit 1 (~50--43 cal ka BP): relatively humid Artemisia steppe around a shallow lake

As the amount of tree pollen is low and dominated by wind pollinated taxa, the wider area around the Orog Nuur was most likely treeless. Shrubs of sea buckthorn (*Hippophae*) were quite common and most probably growing on unconsolidated sand and gravels along the Tuyn Gol and other inflows and/or the Orog Nuur shore. The buckthorn may have been accompanied by some willows (*Salix*). Dry minerogenic habitats carried xeromorphic shrubs of *Ephedra* and *Nitraria*.

As for most of the late Pleistocene, steppes were the dominating vegetation type during Unit 1. They were very rich in *Artemisia*, accompanied by some Chenopodiaceae. Regarding to their potential high pollen representation due to wind transport, grasses (Poaceae, Cyperaceae) must have been quiet sparse while insect pollinated herbs like different kinds of Asteraceae (Liguliflorae, *Matricaria*-type, *Senecio*-type) and others (*Rheum*, Caryophyllaceae, Brassicaceae) must have been more common than the grasses.

The small amounts of green algae (*Botryococcus, Pediastrum*), rotifer resting eggs (cf. *T. cylindrica*) and chironomid mandibles (Chironomidae) suggest a lake environment. The monospecific occurrence of *L. inopinata* in the lowermost unit and samples without ostracod valves indicate a fluctuating and possibly temporary water body (Meisch, 2000; cf., grey horizontal bars in Fig. 5-5). Increasing valve numbers from the base to the top of the unit suggest a gradually increasing stability of the water body.
Fig. 5-9: Semi-quantified thermal, moisture and hydrogeochemical history as inferred from the palynological and geochemical studies. Palynological indices (curves a and b) are inferred from pollen concentration and Artemisia/Chenopodiaceae ratios, respectively, whilst the geochemical indices (curves c and d) i.e., factor scores, are entrained from multivariate statistics based on the bulk-geochemistry of the sediments (Yu et al., 2016). Fossil pollen concentration is linked to the thermal anomalies (e.g., Conroy et al., 2009). Considering the authigenic productivity, the Holocene may experience a distinct lacustrine phase with higher content of calcite and carbonates. In this study, the vertical blue bars depict humid pulses, while yellow bars denote the playa phase inferred from the granulometric and lithostratigraphic characteristics of the core. Furthermore, as stated in Chapter 5.4.3, the pollen assemblages preserved in the lacustrine archive may indicate merely local vegetation signals surrounding the lower catchment of the Orog Nuur. Therefore, inconsistency between the reconstructed effective moisture and lake level fluctuations may occur. Northern hemisphere temperature (e): Johnsen et al. (2001), H events: Bond et al. (1993), 45°N summer insolation (f): Whitlock and Bartlein (1997), west subtropical pacific SST (g) and sea level changes (h): Tudhope et al. (2001). In addition, the MIS 3/MIS 2 transition in this study is some 24 cal ka BP, which is largely in agreement with that in Martinson et al. (1987).

5.5.1.2. Unit 2 (~43~37 cal ka BP): relatively dry and fluctuating Artemisia steppe and water surplus to the lake

Regarding the decreasing and strongly fluctuating Artemisia curve, the overall climatic conditions in Unit 2 were unstable. While increases in Poaceae and Asteraceae indicate more humid pulses, a higher abundances of Chenopodiaceae point to dryer or locally more salty
conditions. The increase of aquatics hints at a more stable water body of the lake. The synchronously increase of spores of coprophilous fungi and spores of the *Glomus*-type document a higher water inflow, as those fungi spores are mostly transported into lakes by water (Ahlborn et al. 2015; Shumilovskikh et al. 2016).

The ostracod assemblage in Unit 2 is similar to those of Unit 1 apart from the general occurrence of *L. inopinata* valves in all samples. Slightly more stable conditions are suggested. Although it may be preserved in the catchment at any time in the past, the occurrence of carapaces of *L. inopinata* probably results from temporarily high sediment accumulation rates due to the sporadic delivery of large amounts of sediment during flood events. The higher water income as documented by aquatics, fungi spores and ostracods may indicate melt-water impulses either from the Khangai via the Tuyn Gol or by smaller streams from the neighboring Gobi Altai. A playa phase during the upper U2 (~37 ka) is also documented by oxidizing environment and low authigenic productivity (Fig. 5-9).

5.5.1.3. Unit 3 (~37~35 cal ka BP): relatively dry *Artemisia* steppe and lake stabilization

*Artemisia*-steppes are again the prevailing vegetation type. Fungi spores still indicate ongoing water inflow into the Orog Nuur. From now on, chironomids (Insecta: Diptera) became well established in the lake for most of the late Pleistocene, possibly indicating slightly less brackish conditions (Chen, 2009). As the A/C ratios during Unit 3 and in the prevailing time of Unit 2 are low, the river discharge documented by the fungi spores might be more generated by precipitation in the higher elevations of the catchment/pastures (Khangai, Gobi Altai) than in the low lands surrounding the lake.

*L. inopinata* reaches higher abundances in Unit 3, indicating a more stable environment and/or possibly a lower sediment accumulation rate. The portion of male valves of *L. inopinata* increases towards the top of the unit. More alkaline conditions were apparently established following a period with more Cl- or SO₄-dominated lake waters (see Chapter 6, and Fig. 6-2). Higher runoff to the lake might have probably caused a dilution of the more saline lake waters, which is also indicated by the occurrence of *I. cf. inermis* near the top of Unit 3. The species typically prefers spring habitats and waters flowing from springs (Victor and Fernando, 1981; Meisch, 2000; Mischke et al., 2005). Springs are situated today at the southern shore of the Orog Nuur fed by water from the flanking Gobi Altai.
Fig. 5-10: Synthesis and comparison of paleoenvironmental variability in Mongolia and adjacent regions since the Marine Isotope Stage 3 as developed in this study and other selected records from literatures: 1, Kanas Glacial (Xu et al., 2009; Zhao et al., 2013); 2, Manas Lake (Rhodes et al., 1996); 3, Darhad Glacial (Gillespie et al., 2008); 4, Hovsgol Nuur (Murakami et al., 2010); 5, Luanhaizi Lake core LH2 (Mischke et al., 2005b); 6, Baikal Lake (Williams et al., 1997; Prokopenko et al., 2001); 7, Kotokel Lake (Shichi et al., 2009); 8, Retreat of southern boundary of the Gobi Desert (Feng et al., 2007); 9, Shaamar Section (Ma et al., 2013); 10, Wulangsu Lake (Selvaraj et al., 2012); 11, Wulagai Lake (Yu et al., 2014); 12, Biwa Lake (Xiao et al., 1997); 13, Japan Sea (Nagashima et al., 2007); 14, Dust model in central Asian desert (Nilson and Lehmkuhl, 2001). Here, the vertical blue bars depict humid pulses, while yellow bars denote the playa phase inferred from the granulometric and
lithostratigraphic characteristics of the core. Calibrated radiocarbon ages were labeled as black triangles near the bottom axis. Climate intervals including the Younger Dryas (YD) and Last Glacial Maximum (LGM) were demarcated near the uppermost axis. More details concerning the proxies of each archive refer to Tab. 5-2 and locations refer to Fig. 5-1A.

5.5.1.4. Unit 4 (~35~24 cal ka BP): relatively humid Artemisia steppe and transition from maximum high to quite low lake levels

Higher A/C ratios point to somewhat less arid conditions in the landscape around. With regard to the spores, the water inflow into the lake underwent no substantial changes. In the first half of Unit 4 extremely high frequencies of rotifer eggs and Pediastrum point to an amelioration of living conditions for water organisms. This might especially include much less brackish conditions implying a fresh to oligohaline Orog Nuur of greater water depth (Jiang et al., 2006, Zhao et al., 2007; Kramer et al., 2010). I. cf. inermis is present at the base of the unit, suggesting substantial inflows and lower salinity levels (Victor and Fernando, 1981; Meisch, 2000; Mischke et al., 2005). The mostly monospecific ostracod assemblage and low valve abundance afterwards indicates a return to less stable lake conditions and a higher salinity. The few shells of C. neglecta and L. dorsotuberosa recorded at ca. 28 ka (Fig. 5-8) were possibly washed to the lake from neighboring habitats during floods or may represent a few species living at the extreme ends of their tolerance ranges.

The Orog Nuur experienced a higher lake level and somewhat fresh water conditions in the beginning of Unit 3 (~35 ka) until about 30 ka BP. This MIS 3 lake high stand seems to be a characteristic for arid central Asia as well as the Tibetan Plateau (Feng et al., 2007), albeit debate still exists as the ages may be biased as determined by different chronological methods (Lai et al., 2014; Long and Shen, 2015), which is out of the scope of this study. As the A/C ratios point to a relatively humid landscape, the effective moisture must have increased in general, possibly by lower temperatures documented in the altitudinal down move of the landscape belts (Fig. 5-11; e.g., Lehmkuhl and Haselein, 2000).

5.5.1.5. Unit 5 (~24~19 cal ka BP): Artemisia steppe and playa to shallow lake

While the A/C ratios indicate relative humid conditions, fungi spores point to lasting river water inflow, nevertheless low and respectively interrupted evidences of the aquatics hint at a deterioration of the lake environment in the beginning of Unit 5. Probably glaciers as water resource have diminished by the end of the prevailing Unit 4. The maximum peak of the
Glomus-type might document short-lived run-off events with fast soil erosion but overall low water surplus. Subsequent algae and rotifers were quite common again while chironomids seem to diminish during Unit 5 before they disappear permanently. Chironomids disappearance and the synchronous reduction of rotifers and Pediastrum may result from changes in the salinity. Slightly higher valve abundances in Unit 5 indicate a diminished sediment accumulation rate and/or slightly more stable environmental conditions. Lower abundances of male valves of L. inopinata closer to the top of Unit 5 probably result from an increase in salinity and predominance of Cl- or SO₄-dominated lake waters.

5.5.1.6. Unit 6 (~19~18 cal ka BP): Artemisia steppe and sand accumulation

From three pollen samples in Unit 6 only one (372 cm) yielded a minimum of palynological remains. The overall low pollen concentration coincides with sand accumulation in the lake. The relatively abundant pollen of Rheum might came with the sand by strong winds into the playa basin, as Rheum nanum and most other rhubarbs of Mongolia grow in desert habitats, from where sand is blown out (Hilbig, 1995; Grubov, 2001). As chironomids are eliminated and demanding aquatics (rotifers, Pediastrum) are low, the water quality and amount may have been limited, possibly caused by a decreasing inflow (low fungi spores). The almost monospecific occurrence of L. inopinata, lowest valve numbers and low numbers of male valves of L. inopinata suggest unstable conditions and Cl- or SO₄-dominated, relatively saline lake waters.

5.5.1.7. Unit 7 (~18~13 cal ka BP): Artemisia steppe, higher lake level and decreasing river influence

The landscape was still dominated by Artemisia steppes. Some amelioration of the lake ecosystem is indicated by higher Pediastrum abundance, while the stay away repopulation by chironomids point to quite salty conditions. One could speculate that an inhospitable brackish water body was seasonally overlaid by light fresh water, making a blooming of Pediastrum possible. At the end of Unit 7 the decrease of Hippophae and Salix together with the offset of coprophilous spores marks a strong decrease in river discharge into the western basin of the Orog Nuur. The contemporaneous increase in Chenopodiaceae and Ephedra indicates the end of Artemisia steppe dominance. The ostracod assemblage of Unit 7 is almost identical to those of Unit 6 and conditions apparently remained similar. A few valves of I. cf. inermis in the upper part of the unit probably result from sporadic flood events.
5.5.1.8. Unit 8 (~13–11 cal ka BP): Establishment of deserts around a strongly shrinking lake

Unit 8 stands for the displacement of *Artemisia* steppe by desert communities. The spreading of Chenopodiaceae reflect the desiccation of the wider landscape possibly including the establishment of salt tolerant Chenopodiaceae species on the salty playa enclosing the shrinking Orog Nuur. *Ephedra* includes typical desert species, which are less salt tolerant and often inhabit places with strong physical weathering like rocks and pebbles (Grubov, 2001; Schlütz and Lehmkuhl, 2007). The desertification of the landscape came together with low river influence (*Hippophae, Salix, Glomus*-type) leading to a nearly disappearing of algae and rotifers. The sudden spreading of *T. angustifolia* and/or *T. australis* - two highly salt tolerant cattails - and the only representatives of the *Sparganium*-type at the Orog Nuur (Hilbig, 1995) indicate marshlands near the core site. The occurrences of valves of *I. cf. bradyi*, *I. manasensis* var. *cornea*, *S. aculeata* and *P. cf. compressa* in the upper part of Unit 8 indicate a decreasing salinity in the lake and apparently wetter conditions. Recorded valves of *I. cf. bradyi* and *S. aculeata* suggest that flowing waters entered a relatively brackish lake. *I. cf. bradyi* is known as typical stream dweller whilst *S. aculeata* prefers slightly brackish (oligohaline to mesohaline) stagnant waters (Ganning, 1971; Meisch, 2000; Mischke et al., 2005). In summary, the YD event correlated phase is marked by a playa to shallow swamp habitat, influenced by sporadic pulses of fluvial inputs. This is corroborated by the low values of redox and authigenic productivity (Fig. 5-9).

5.5.1.9. Unit 9 (~11–? cal ka BP): desert steppe and a shallow lake of high salinity and alkalinity

The abruptly increased pollen concentration (Fig. 5-9) points to overall higher plant productivity. This may be associated to the improved climatic conditions and mark the inception of the Holocene period (Fig. 5-9; e.g., Mackay et al., 2012). Likewise, this is in concordance with the somewhat higher occurrence of trees probably indicating more effective moisture in higher elevations. While birches (*Betula*) may have grown in the nearby Gobi Altai, where small relics of *Betula* exist today (Fig. 5-11), pollen of conifers (*Pinus, Picea, Abies*) comes most probably from remote mountain areas (e.g., Ma et al., 2008). *Artemisia*-steppes recovered in the beginning, indicating higher effective moisture, but did not become dominating again. As documented by Chenopodiaceae and *Ephedra*, the lower elevations stayed arid. The reestablished steppe may have allowed a higher density of wild and/or domestic animals, leading to an increasing grazing pressure in the dry habitats documented by
the expansion of the ectozoochorous grazing weed *T. terrestris* (Miehe et al. 2007). In addition, Juniper shrubs (*Juniperus*-type) might have been favored by grazing (Miehe et al. 2009). In terms of ostracod records, the *I. cf. bradyi* and *I. manasensis* var. *cornea* occur only in the lowermost part of Unit 9, indicating relatively low salinities and higher runoff to the lake. Afterwards, the almost monospecific ostracod assemblage of *L. inopinata* valves, the absence of male valves of the species and a few samples lacking ostracod valves indicate harsh fluctuating environmental conditions and the establishment of generally Cl- or SO$_4^-$ dominated, relatively saline lake. In the modern context, note that the Tuyn Gol flows into the eastern main basin of the Orog Nuur until today, the offset of the *Hippophae* and *Glomus*-type finds may indicate the establishment of the recently active sediment barrier, segmenting the small western basin including the coring sites from the direct influence of the Tuyn Gol. Today the water in the western basin comes in addition from springs, located at the margin as well as inside the basin, and with a small creek fed by the precipitation in the Gobi Altai. To the end, our archive documents a strong decrease and the expansion of Chenopodiaceae deserts, the still today predominating vegetation (Fig. 5-1B).

Likewise, in the perspective of bulk-geochemistry, sediments exhibit particularly high authigenic productivity in the early Holocene and slightly decreased afterwards (Fig. 5-9). The higher authigenic productivity is characterized by high abundance of Ca and Sr in the sediments. The Holocene water body is presumably an alkaline habitat with higher concentrations of cations that can be bound to chloride. However, this high alkalinity or salinity in the water body may not necessarily result from high temperatures. As illustrated in Fig. 5-9, the reconstructed thermal condition of the Holocene appears to be slightly better than that during the MIS 3. This mild temperature typically favors the flourishing of *Betula* in northeastern Asia biomes (Fig. 5-6; Heusser, 1989). Hence, rather than temperature, a significant change of the sediment provenance might have contributed to the distinctive saline and alkaline environment in the Holocene, albeit assessment of the provenance change is out of the scope of this study. On the other hand, the supply of the meltwater may provide abruptly increased riverine inflows into the sedimentary basin and thereby destroy the former established suboxic habitats, and invoke low values of redox conditions through the Holocene (Fig. 5-9). In summary, the relatively higher lake level in the early Holocene might be explained by climate-induced higher meltwater flux from ice, snow and frozen ground in the higher catchment, and subsequent drying till today as a result of diminishing inflow and higher evaporations.
Tab. 5-3: Synthesis of lacustrine, pelagic, aeolian and glacial sequences (spanning at least the MIS 3) in the vicinity of the Gobi Desert. For locations of each site refer to Fig. 5-1A.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Archive</th>
<th>Lat. (°N)</th>
<th>Long. (°E)</th>
<th>Chronology</th>
<th>Time span</th>
<th>Analytical techniques and proxies</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Kanas Basin</td>
<td>G</td>
<td>48°41'</td>
<td>87°01'</td>
<td>OSL</td>
<td>0-50 ka</td>
<td>M</td>
<td>Xu et al. (2009); Zhao et al. (2013)</td>
</tr>
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<td>2</td>
<td>Darhad Basin</td>
<td>G</td>
<td>51.3°</td>
<td>99.5°</td>
<td>14C, CRN</td>
<td>0-150 ka</td>
<td>ELAs, sh</td>
<td>Gillespie et al., (2008)</td>
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<tr>
<td>3</td>
<td>Hovsgol Nuur</td>
<td>L</td>
<td>51°53'</td>
<td>100°21'</td>
<td>14C</td>
<td>0-27 ka</td>
<td>ICP-MS, AAS, TOC</td>
<td>Fedotov et al. (2008); Hovsgol Drilling Project Members (2009); Murakami et al. (2010)</td>
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<td>Shaamar Section</td>
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<td>0-35 ka</td>
<td>p, ms, gs, CaCO₃</td>
<td>Feng et al. (2007); Ma et al. (2013)</td>
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<td>52°32'</td>
<td>106°12'</td>
<td>14C, mag</td>
<td>0-75 ka</td>
<td>d, BSi</td>
<td>Prokopenko et al. (2001)</td>
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<td>108°05'</td>
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<td>0-50 ka</td>
<td>p, ch, BSi</td>
<td>Shichi et al. (2009)</td>
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<td>117°29'</td>
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<td>0-48.5 ka</td>
<td>loi, gs</td>
<td>Yu et al. (2014)</td>
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<td>0-37.8 ka</td>
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<td>101°12'</td>
<td>14C, TIMS</td>
<td>0-50 ka</td>
<td>os, ICP-AES, thmag</td>
<td>Mischke et al. (2005)</td>
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<td>0-36.5 ka</td>
<td>ms, gs, XRF, CaCO₃</td>
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<td>134°42'</td>
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<td>0-144.4 ka</td>
<td>ESR, CI, ms</td>
<td>Nagashima et al. (2007)</td>
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<td>136°01'</td>
<td>tephro</td>
<td>0-145 ka</td>
<td>EQF, SEM, gs</td>
<td>Xiao et al. (1997)</td>
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<td>96°-103°</td>
<td>CRN</td>
<td>0-45 ka</td>
<td>M</td>
<td>Rother et al. (2014); Lehmkuhl et al. (2015)</td>
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<tr>
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<td>Altai Glacier</td>
<td>G</td>
<td>46°-52°</td>
<td>82°-95°</td>
<td>-</td>
<td>0-132 ka</td>
<td>ELAs</td>
<td>Lehmkuhl et al. (2011)</td>
</tr>
</tbody>
</table>

Notes:

- **a** Archives: L, lacustrine; G, paleoglacial; A, aeolian loess and interbedded paleosol; O, oceanic material.

- **b** Chronology methods: mag, paleomagnetic events/reversals; OSL, optical stimulated luminescence dating; IRSL, infrared-stimulated luminescence dating; CRN, beryllium-10 cosmogenic nuclide dating; TIMS, thermal ionisation mass spectrometry.

- **c** Analytical techniques and proxies: d, diatom abundance; BSi, biogenic silica content; loi, loss on ignition; gs, grain size distribution; p, pollen spectra; m, glacial moraines; ch, charcoal; os, ostracod; thmag, thermomagnetic measurements to check the Curie Temperature of each sample; XRF, X-ray fluorescence analysis; XRD, X-ray diffraction analysis; ms, mass magnetic susceptibility; AAS, atomic absorption spectrometry; ICP-MS, inductively coupled plasma mass spectrometer; ICP-AES, inductively coupled plasma atomic emission spectroscopy. ELAs, equilibrium-line altitudes; sh, paleolake shoreline; SEM, scanning electron microscopic photographs; TOC, total organic carbon; ESR, electron spin resonance; CI, crystallinity of quartz; EQF, aeolian quartz flux.
Notably, the palynofacies (i.e., local pollen zones/LPZs in Chapter 5.4.3) employed here may only reveal the vegetation evolution in the lower catchment surrounding the lake. Direct hydrologic signatures could merely be referred from algae, ostracod specimens and bulk-geochemical characteristics of the lacustrine sediments. Hence, not surprisingly, geochemical and palynological indices may occasionally result in inconsistent or controversial interpretations regarding the past environmental changes (Fig. 5-9). This specious mismatch between palynological and geochemical signals may be attributed to a nonlinear response of the catchment biomes to the orbital scale insolation modulations (Schwanghart et al., 2009; Wang and Feng, 2013). For instance, in the Holocene, high temperature induced higher evaporation may reduce the annual moisture and thereby the A/C ratios. However, the thermal characteristics may exert only limited impacts on lakes levels and accompanied geochemical nature of the core sediments. A holistic view of different proxies as well as geomorphological features is therefore indispensable in attempts to reconcile the inconsistency, and interpret sound and reliable paleoenvironments. On the other hand, in contrary to the multiproxy reconstruction for the hydrological/moisture conditions, credible paleo-thermal reconstruction in the lacustrine or terrestrial realm still awaits novel techniques. The testified functions as given in Ma et al. (2008, 2013) seem not applicable in this study due to lack of pivotal taxa. Apart from the palynomorph- (Fig. 5-9), chironomid-, and diatom-based reconstructions, pilot studies on (i) fluid inclusions (Lowenstein and Brennan, 2001) and (ii) organic signatures of branched glycerol dialkyl glycerol tetraethers (brGDGTs; Tierney et al., 2010) preserved in lacustrine sequences would be practical and promising in achieving sound thermal signals, albeit the following discussions have focused more on moisture signals in terms of the broadly arid condition in the Gobi Desert of Mongolia.

### 5.5.2. Geomorphic evidence of the past environmental change in the Orog Nuur catchment

In the scenario of Orog Nuur catchment, past glacial moraines in the higher elevated Khangai Mountains and shorelines of the Orog Nuur in lower catchment area (Figs 5-1 and 5-2) are pivotal aid that could be employed in paleoenvironmental reconstructions.

#### 5.5.2.1. Glacial advances in the higher reaches of the Orog Nuur catchment

Glaciology and permafrost study is an essential complement to gain a more comprehensive knowledge of the past environment in the higher reach of Orog Nuur catchment (Fig. 5-1B). In the Khangai Mountains (above 3,000 m a.s.l.), as determined by the cosmogenic nuclide
dating of the terminal moraine boulders (Lehmkuhl et al., 2016), the oldest detected glacial advance was dated in the westernmost part of the Khangai to ~40 ka, which roughly corresponds to the uppermost of U2 (Fig. 5-11). Thus, in the western Khangai Mountains, ca. 40 ka marked the inception of the glacial advance in MIS 3. In addition, two granite erratic boulders (47.85°N, 97.31°E; 47.68°N, 97.21°E) from terminal moraines of Otgon Tenger in the western Khangai were dated using $^{10}$Be/$^{26}$Al exposure dating, yielding an age of 30.5±1.4 ka and 37±2.7 ka (Lehmkuhl et al., 2016). Moreover, the MIS 3 glacial advances were also suggested in (i) western Khangai (Rother et al., 2014), (ii) Chinese Altai (Xu et al., 2009; Zhao et al., 2013), and in (iii) Darhad Basin (Fig. 5-1A; Gillespie et al., 2008), implying that these MIS 3 glacial advances may be a common phenomenon in a greater spatial scale in the arid central Asia. Interestingly, the glacial expansion during the MIS 3 interstadial is even larger than that during the LGM (Rother et al., 2014), albeit the MIS 3 is a relatively warm interstadial (Dansgaard et al., 1993). During the MIS 3, the time span of the glacial advance is in phase with the lacustrine period in this study, whereas the LGM and YD glacial advances are accompanied by playa phases as inferred from the core and the accumulation of dune sediments in the adjacent sections of the Orog Nuur (Section A1 in Fig. 5-2; Figs. 5-10 and 5-11). For the Khangai Mountains and adjacent regions, a suite of the compilations from Lehmkuhl et al. (2011, 2016) and Rother et al. (2014) have implied that nival and periglacial features together with major glacial expansions occurred between 28 and 24 ka, and thereafter a dry and cold phase (24-15 ka) accompanied by loess accumulations is inferred. Consequently, the considerable humid pulse during the mid- to late-MIS 3 (~36~24 ka as in this study) may be the main driving mechanism for MIS 3 glacial advance, whereas it is not pertained in case of the paucity of moisture in the LGM, when lower temperature in particular in the high elevated eastern Khangai Mountains would have been the main forcing factor (Rother et al., 2014; Lehmkuhl et al., 2016). On the other hand, no glacial advance was detected in the higher eastern Khangai Mountains, where merely patches of undated periglacial remains were observed (Fig. 5-11), which may be attributed to the unfavored thermal amelioration and hence the elevated ELA since the early Holocene. In southern mountain ranges (i.e., Gobi Altai) of the Orog Nuur, the degradation of permafrost since Termination I was concluded by Owen et al. (1998), which coincides with the fewer occurrences of periglacial features on the southern slopes of eastern Khangai Mountains (Fig. 5-11).
5.5.2.2. Ancient shorelines of the Orog Nuur

Although it might be slightly altered by neotectonic events, evidences of former sand beaches of the Orog Nuur can still shed light on the paleohydrologic conditions of the lake. The oldest remnants of beach sediments can be found 57-62 m above the present lake-level (L.L.3). Section A1 (Fig. 5-2; 45°11’N, 100°46’E) provides two luminescence ages, namely HDS 047 and HDS 049 (at depth of ~0.5 m and ~3 m, respectively; Lehmkuhl and Lang, 2001). The age of ~70 ka (HDS 047: 75±14 ka; HDS 049: 71±11 ka) serves as evidence for the highest former lake level (L.L.3, 1280 m a.s.l.). Hence, the highest beach ridges may indicate high lake levels in the early part of the last glacial or even the Eemian period, and these phases are also supported by floodplain sediments in the Mongol Els (300 km west of the Orog Nuur; Stolz et al., 2012). Consequently, the reconstructed MIS 3 lake level may be slightly lower than the early last glacial paleolake. Considering the lower sand ridges in Fig. 5-2, recessional beach lines reveal that the shrinking of the lake can be identified at 20 m (L.L.2), 10-16 m (L.L.1) and 3 m above the modern lake-level. The L.L.2 and L.L.1 may be indicative of a more or less stable lake corresponding to MIS 3 and early Holocene humid pulses, respectively, albeit no detailed chronology is available here. Moreover, in the study of Komatsu et al. (2001), based on the remote sensing investigations of the paleoshorelines in the catchment and nearby basins, the stable paleolakes were estimated at MIS 3. In addition, in the Valley of Gobi Lakes, Owen et al. (1997) suggest that more humid conditions have prevailed between 40 and 23 ka. On the southern slopes of the eastern Khangai Mountains, as concluded by Lehmkuhl and Lang (2001), high humidity-induced slope processes such as sheet wash was stronger in the early Holocene.

5.5.3. Regional synthesis - humid pulses inferred from different archives in the vicinity of the Gobi Desert

In the Orog Nuur, two chief humid pulses (~36--24 ka, ~11--? ka) and four relatively short playa phases (~47 ka, ~37 ka, ~19 ka and ~13--11 ka) were determined (Figs 5-9, 5-10 and 5-11). Several more thin coarse-grained sediment layers can be identified through the MIS 3 humid pulses, they are however less significant as aforementioned playa phases (Fig. 5-5). Furthermore, rather than pure aeolian sediments, this layers might be attributed to fluvial materials as determined by geochemical compositions (see Chapter 6.5.2.4, and Fig. 6-3), albeit their granolometric composition share similar characteristics with aeolian sands (Yu et al., 2016). In order to gain a holistic paleoenvironmental view in a greater spatial scale, an array of studies in the proximity to the Gobi Desert is compiled and evaluated (Fig. 5-10).
5.5.3.1. Marine Isotope Stage 3

Humid conditions during the middle and late MIS 3 were recorded in northern Chinese deserts and northern Mongolia by several works based on diverse archives and proxies (Herzschuh, 2006; Yang et al., 2011). As illustrated in Fig. 5-10, the higher moisture signals along with glacial advances during mid- to late MIS 3 are documented in the Kanas Basin (Xu et al., 2009; Zhao et al., 2013), Manas Lake (Rhodes et al., 2006), Darhad Basin (Gillespie et al., 2008), Wuliangsu Lake (Selvaraj et al., 2012), Wulagai Lake (Yu et al., 2014), Biwa Lake (Xiao et al., 1997) and Shaamar loess section (Feng et al., 2007; Ma et al., 2013). This entire set of records hints at a humid pulse during the MIS 3 in arid northern China and northwest Pacific (Tab. 5-2; Figs. 5-1 and 5-10). Considering other records in Tengger Desert and drylands of northern China, most of the high lake-level periods have also been dated to the main interstadial of the last glaciation i.e., MIS 3 (Pachur and Wünnemann, 1995; Lehmkuhl and Haselein, 2000), albeit age difference may occur as determined by different chronological methods (Lai et al., 2014; Long and Shen, 2015). More specifically, a higher lake level at Gaxun Nur was determined to 41-33 ka (Fig. 5-1A; Wünnemann and Pachur, 1998). Likewise, a marked expansion of needle-leaved forest in the southern Mongolian Plateau and northern China in the late MIS 3 were suggested by several studies (Pachur and Wünnemann, 1995; Ma et al., 2013). This MIS 3 humid pulse is also corroborated by low dust supply as suggested by the model of Nilson and Lehmkuhl (2001) and in the northwest Pacific (Leinen, 1989) (Fig. 5-10). However, whether the high lake levels of Qinghai Lake have to be assigned to MIS 3 or MIS 5 still remains elusive (Colman et al., 2007; Madsen et al., 2008; Liu et al., 2010).

On the other hand, in the Baikal catchments and northern Mongolia, Baikal core GC-1 (Williams et al., 1997; Prokopenko et al., 2001), Kotokel Lake (Shichi et al., 2009) and Hovsgol Nuur (Murakami et al., 2010), no humid pulses during the MIS 3 is displayed, suggesting a distinct moisture pattern compared with those in northern China and northwest Pacific (Fig. 5-10).

In summary, aquatic organisms such as *Pediastrum* and *Botryococcus*, as well as relative haigh A/C ratios have revealed a humid pulse during the MIS 3 (Fig. 5-6; Unit 4 in the core sequence), albeit this phase is not well presented in other plynological and geochemical fingerprints (Fig. 5-9). Although there exist certain inconsistency between all this suites of imprints, we need to focus on the direct signals such as aquatic organisms in order to better discern the hydrological state of the Orog Nuur in the past.
5.5.3.2. Marine Isotope Stage 2

A fluctuating shallow lake together with a moisture deficit in the LGM and YD were implied in the studies of Manas Lake (Rhodes et al., 1996), Luanhaizi Lake (Mischke et al., 2005), Wuliangsu Lake (Selvaraj et al., 2012), Wulagai Lake (Yu et al., 2014), Biwa Lake (Xiao et al., 1997) and Schaamar loess section (Feng et al., 2007; Ma et al., 2013) (Fig. 5-10). Arid LGM conditions were previously suggested for the Asian interior by numerous works (Lu and Sun, 2000; Bush, 2004). After the LGM, a stepwise climate amelioration was conceived by Herzschuh (2006) as such can be correlated to U7 in our study (Fig. 5-9). Interestingly, the reconstructed authigenic productivity curve (Fig. 5-9) exhibit broadly similar downcore variability as west Subtropical sea surface temperature (SST) and sea level variances (Tudhope et al., 2001), indicating certain links between the moisture supply in the Gobi Desert and the northwest Pacific, both of which lie beneath the pathways of the boreal westerlies and EASM throughout the late Quaternary period (Nagashima et al., 2007).

5.5.3.3. The Holocene

As illustrated by geochemical indices (Fig. 5-9), the higher effective moisture and authigenic productivity in the early Holocene corroborates the lake expansion phase postulated in Lehmkuhl and Lang (2001). This is also in line with a suite of studies in Luanhaizi Lake (Mischke et al., 2005), Baahr Nuur (Feng et al., 2005), Khyaraany loess-paleosol sequence (Feng, 2001), Qilian Mountain loess sequences (Nottebaum et al., 2015), Yili loess-paleosol sequence (Li et al., 2011) and other westerlies domain signals (Arz et al., 2003; Ilyashuk and Ilyashuk, 2007), albeit Herzschuh (2006) synthesized the palynological signals in this area and conceived that the early Holocene optimum may not be a uniform phenomenon in the entire westerlies domain. However, as reconstructed by palynofacies (Fig. 5-9), the increasing temperature and decreasing moisture in the early Holocene is concordant with the Altai region (Demske et al., 2005; Rudaya et al., 2009). To gain a broad view, a wealth of palynological studies with focus on Mongolia was carried out by Tarasov et al. (2000, 2007), assembling the vegetation history of Mongolia and Baikal catchment and reconstructing a broadly warm and humid early Holocene and a deteriorated climate since the mid-Holocene. Likewise, Miehe et al. (2007) investigated forest patches in the Gobi Altai and concluded a shift from dark taiga to a steppe environment over the last 5 ka. In the Holocene, the greatest dust fluxes from Asia into the northwest Pacific are estimated to be in the mid-Holocene (Leinen, 1989). A dry mid-Holocene mega-thermal that may favor dust storms was also evidenced in studies in Inner Mongolia (Chen et al., 2003). Moreover, late Holocene dune sediments were uncovered in the
sections around the Orog Nuur catchments during our field investigations (Fig. 5-2), indicating a less favored environment after the mid-Holocene and in modern times. However, due to the absence of at least the late Holocene sediments (the uppermost 24 cm of core ONW II), interpretations for this time slice in our study are restricted.

In addition, as aforementioned, the high temperature induced higher evaporation might have reduced the annual moisture in the catchment, shifted the vegetation to desert steppe (e.g., the increases in *Ephedra*, Chenopodiaceae, and *Nitraria*; see supplementary materials) and thereby reduced the A/C ratios in the Holocene (Yang et al., 2010; Zhao et al., 2012). However, the thermal characteristics may exert only limited impacts on lakes levels and accompanied geochemical nature (higher contents of carbonate) of the core sediments (Fig. 5-9).

### 5.5.4. Potential driving mechanisms for the late glacial climate change in the Gobi Desert

From an arid central Asia perspective, the moisture signature is of particular importance with respect to the dust activity in the Asian interior as well as for the northwest Pacific (Duce et al., 1980; Leinen, 1989; Pye and Zhou, 1989; Nakai et al., 1993; Nilson and Lehmkuhl, 2001; Nagashima et al., 2007). A general assertion is that the moisture signatures here have an out-of-phase relationship with the EASM domain (Chen et al., 2008). At least in the western part of arid central Asia, the moisture signal is believed to be brought by the westerlies (Vandenberghe et al., 2006; Chen et al., 2008). Nonetheless, recently, based on the analysis of modern precipitation signals, Huang et al. (2015) demonstrated that the Gobi Desert of southern Mongolia is outside of the core region of westerlies-dominated arid central Asia (50-90 °E, 36-54 °N). In their study, the southern Mongolian Plateau portrays a modern precipitation variation pattern analogue to the EASM-influenced China, while an anticorrelated relationship is obtained in contrast to the core region of the westerlies (50-90 °E, 36-54 °N). The early Holocene moisture optimum is at odds with the dry pattern in the westerlies-dominated Hovsgol Nuur (Fig. 5-1; Prokopenko et al., 2007; Rudaya et al., 2009). On the other hand, the reconstructed indices (Fig. 5-9) imply intimate connections between hydrochemical conditions of the Orog Nuur and the west subtropical Pacific signals. Hence, partially contrary to the envisaged assertion, it is likely that thermal and moisture signals in the Gobi Desert may not be driven by unitary mechanisms. In other words, the Gobi Desert is rather affected by an atmospheric mode comprising both the EASM and the westerlies, which as a dynamically coupled system, is governed by the nature of boreal insolation variances (Fig. 5-9).
Fig. 5-11: Synoptic compilation of hydrologic, vegetation and geomorphic history of the Orog Nuur catchment over the last ~50 ka. Playa & dune phase is recovered from the granulometric and lithostratigraphic characteristics of the core ONW II. More details see Chapter 5.5.1. Glacial advance in Khangai Mountains refer to Rother et al. (2014) and Lehmkuhl et al. (2016). As mentioned in Chapter 5.5.3.3, in the Holocene, the high temperture induced higher evapouration might have triggered lower annual moisture in the catchment (see A/C ratios in Fig. 5-9), it has however less impacts on the better hydrological condition of the water body as revealed by higher authigenic productivity (Fig. 5-9) in the more alkaline water column (see Chapter 6.5.2.2, and Fig. 6-6).

5.5.4.1. Humid pulses in the Gobi Desert

The asynchronous Holocene optimum of East Asia was demonstrated by An et al. (2000), Kerr (2003) and Chen et al. (2008), concluding that the moisture from the northwest Pacific can be transported into continental Asia. On the other hand, the westerlies were also suggested as a feasible moisture supplier. For instance, a weakening of the Siberian winter anticyclone coupled with a retreat of the northern hemisphere ice sheet would have acted as a
forcing factor that permits more moisture to penetrate into the Asian interior by both Atlantic cyclone activity and the EASM (cf., Moros et al., 2004; Peltier and Fairbanks, 2006). Boyle and Keigwin (1987) reported the connection between the north Atlantic thermohaline circulation - namely Atlantic meridional overturning circulation (AMOC) - and temperature in high-latitude regions. In the scale of the last glacial period, the massive iceberg discharges may trigger global scale climate change via alteration of the AMOC (Bond et al., 1993; Broecker, 1994; Porter and An, 1995; Böhm et al., 2015). The prominent decay of ice sheets and concomitant weakening or shutdown of AMOC (Ding et al., 1995) were demonstrated to be the conceivable driving mechanism for the global scale transition during the last deglaciation (Rodwell et al., 1999; Rahmstorf, 2002; Liu et al., 2009; Clark et al., 2012). Furthermore, the moisture history of the north Atlantic may exert fundamental impacts on the EASM signals via the teleconnected interactions (Ivanova, 2009). In this study, the higher lake level in the MIS 3 and early Holocene implies a broadly resembling pattern with the higher values of 45°N summer insolation (Fig. 5-9; Whitlock and Bartlein, 1997). Likewise, further western Altai depicts a similar and only slightly lagged pattern compared with the boreal insolation curve (Eichler et al., 2009). Interestingly, this early Holocene optimum is also documented in the Indian Monsoon domain (Sirocko et al., 1993; Fleitmann et al., 2003; Gupta et al., 2003; Liu, 2011), leading to our assumption that, the Gobi Desert is governed by a coupled Asian monsoon system that is largely modulated by boreal insolation variances. Presumably, in the mid-latitudes, higher insolation forcing during the MIS 3 and early Holocene has supplied more moisture into the Asian interior via pathways of EASM or westerlies (Cheng et al., 2016).

5.5.4.2. Playa phases in the Gobi Desert

Considering the aridity of the Asian interior, Bush (2004) suggests that the arid conditions in the LGM may result from significantly declined moisture transferred from the North Atlantic Ocean due to the orographic blocking (establishment of the northern European ice sheet) of the westerlies. Meanwhile, the weakening or shutdown of the AMOC may induce the mitigation of the ocean-continental pressure gradients (Rodwell et al., 1999) and thereafter diminish the moisture delivered by both the westerlies and EASM (Wu and Wang, 2002; Ivanova, 2009). It is postulated that, during the YD event, the relationship between the Rossby wave pattern of the upper-level westerlies and the tropical convection intensity may exert an influence on the precipitation regime over the low latitude Asia and thereby promote widespread droughts (Staubwasser and Weiss, 2006). Moreover, impeded moisture conveying
by the westerlies (Chiang et al., 2015) along with the southward displacement of summer mean latitudinal position of Inter Tropical Convergence Zone (ITCZ) (Haug et al., 2001; Fleitmann et al., 2003; Broccoli et al., 2006; Yancheva et al., 2007) would have exerted a pivotal influence on the less moisture supply of the Asian monsoon system. Furthermore, in this study, the four playa phases exhibit broadly concurrent phases of low values on northern Hemisphere temperature and insolation curves (see yellow bars in Fig. 5-9), suggesting moisture deficits in response to the coupled oceanic circulation and boreal summer insolation variances.

5.6. Conclusions

A multidisciplinary investigation is conducted on a 13.35 m lacustrine core retrieved from Orog Nuur, in the Gobi Desert of Mongolia. Methods embracing sedimentological, geochemical, palynological and ostracod studies are combined with geomorphological evidence (sets of dated terrace ridges and moraines) in order to illustrate the vegetation development and hydrologic history during the last ~ 50 ka. For the first time, in the Gobi Desert, semi-quantified moisture and thermal sequences that trace back to the MIS 3 are presented. The main conclusions are summarized as follows:

In Gobi Desert of Mongolia, the MIS 3 experienced sufficient moisture supply in particular between ~36 ka and ~24 ka; MIS 2 was subjected to cool temperature and moisture-deficient, which was interrupted by two exceedingly cold and dry playa phases related to the LGM and YD event; the early Holocene exhibited ameliorated climatic condition characterized by higher lake levels. Moreover, the merely local vegetation imprints (palynological spectrums) may be responsible for the inconsistency or even controversy between the palynologically and geochemically reconstructed hydrological signals. Thus, in this arid realm, a holistic view of different proxies in conjunction with the consideration of geomorphological features surrounding the lake as well as in the higher catchment is necessary. Furthermore, we need to bear in mind that palynological imprints indicate merely the vegetation characteristics in the catchment. Geochemical factors suggest the redox and antigenic state of the core sediments, they are however not direct fingerprints of the lake level variances. In order to better discern hydrological states, direct imprints such as aquatic organisms need to be focused on.

A sharp transition from the late Pleistocene to the Holocene (i.e., Termination I) is illuminated by palynological and geochemical imprints. Lower area of the Orog Nuur catchment was dominated by Artemisia steppe in the late Pleistocene and was altered to Chenopodiaceae
desert steppe in the Holocene. The water body in the Holocene appears to be a distinct alkaline environment which was subjected to frequently allogetic input and disturbance of the late Pleistocene anoxic states.

The main humid pulse in MIS 3 might have been the main driving mechanism for the MIS 3 glacial advance, while the pronounced low temperature in the higher elevated catchment in the eastern Khangai Mountains is presumably the forcing factor for the LGM glacial advance. The early Holocene in the Gobi Desert experienced the other humid pulse, which was concurrent with lacustrine conditions and the degradation of the permafrost features as well as the glacial retreat.

Four major arid playa phases (~47 ka, ~37 ka, ~19 ka and ~13~11 ka) were determined, of which the latter two sand layers (i.e., the LGM, YD event, respectively) may provide an opportunity to be labelled as chronological benchmarks for other lacustrine sequences in the Gobi Desert of Mongolia. Nonetheless, further investigations still need to be carried out to test its reliability in a larger spatial scale.

In the central to southern Mongolia, the late Quaternary moisture and thermal history may be modulated, if not controlled, by coupled atmospheric components embracing both westerlies and the propagation of the East Asian Summer Monsoon into the Asian interior, albeit more details with respect to the quantified contribution from these systems remain an open question.
Fig. 5-S1: Diagram of analyzed taxa of pollen, fungal spores, aquatic algae and non-pollen palynomorphs through the core ONW II plotted against the age and depth. All taxa were aggregated into groups consist of panel (A) arboreal plants, humidity indicators, aquatic algae, and panel (B) aridity indicators and grazing indicators.
“It is now clear that lacustrine sediments and sedimentary rocks represent one of the best archives for paleoenvironmental information available within the entire realm of terrestrial settings” (William M. Last and John P. Smol, 2002)

6. Geochemical imprints of coupled paleoenvironmental and provenance change in the lacustrine sequence of Orog Nuur, Gobi Desert of Mongolia

Kaifeng Yu 1*, Frank Lehmkuhl 1, Bernhard Diekmann 2, Christian Zeeden 1, Veit Nottebaum 1, Georg Stauch 1

1 Department of Geography, RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany

2 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Telegrafenberg A43, 14473 Potsdam, Germany

In the arid environment, due to the scarcity of a continuous terrestrial archive, lacustrine sequences are often employed as a paleoenvironmental repository. However, numerous spatial and temporal heterogeneities exist concerning previously studied sites in arid central Asia. Furthermore, surveys using a XRF core scanning technique on lacustrine sequences retrieved in hyperarid desert settings are largely rare. Hence, two parallel sediment cores (ONW I; ONW II) were retrieved from Orog Nuur, in the Gobi Desert of Mongolia. Continuous, high-resolution elemental abundances at a 1 cm scanning step size were examined in core ONW II using XRF core scanning. Based on multivariate statistical evaluation, the bulk-geochemistry of the core sediments are governed by (i) grain-size composition, (ii) authigenic productivity (Ca, Cl, CaCO₃) in an alkaline environment, (iii) allochthonous organic material (TOC and C/N atomic), and (iv) terrigenous input via fluvial inflows, as well as quasi-constant aeolian input through the late Quaternary (Al, Si, K, Ti, and Fe). To constrain the data quality, elements with high error margins relative to measured peak areas and those elements/proxies below the significance level during the multivariate statistics are excluded for environmental/provenance implications. Disparate source lithotypes, as well as authigenic productivity of the lake system existed before and after Termination I. The Holocene was dominated by a distinct high productivity alkaline environment with more felsic and alkaline input relative to the late Pleistocene. This might be attributed to an increased hydrodynamic
strength of riverine inflow and/or intensified erosion and weathering of felsic source rocks in the upper catchment of the Orog Nuur. Therefore, in order to gain a better understanding of the bulk-geochemistry of lake sediments, the coupled provenance and environmental signatures, as well as land surface processes in the catchment need to be systematically discerned. Thus, the XRF core scanning data obtained in this study would have practical and complimentary merit for other lacustrine studies focused on the desert realm across the globe.

6.1. Introduction

Lacustrine sequences are critical archives for the reconstruction of climate and provenance signatures. In particular, in arid central Asia, due to a scarcity of continuous loess-paleosol or oceanic archives, lacustrine records were often employed as Quaternary paleoenvironmental repositories (Boyle, 2001; Mischke et al., 2005). Southern Mongolia is located on the margin of the westerlies-dominated arid central Asia and the East Asian Summer Monsoon domain of eastern Asia (Chen et al., 2008). Acquisition of a continuous and chronologically reliable past environmental record in this region is of substantial importance in refining our understanding of comprehensive paleoenvironmental patterns and possible driving mechanisms. However, numerous spatial and temporal heterogeneities exist concerning the lacustrine sequences here. Compared with more intensively studied lake records in northern China and northern Mongolia/Lake Baikal catchment of Russia, due to the remoteness of the region, only two continuous lacustrine records were previously reported in the Gobi Desert of Mongolia, namely Bayan Tohomin Nuur (nuur = lake; Felauer, 2011) and Ulaan Nuur (Lee et al., 2011). Nonetheless, these two cores cover only the last ~15 ka. Furthermore, a commonly high reservoir effect (contributing to $^{14}$C dating uncertainty) of the non-varved lacustrine sediments, as well as a lack of datable organic material in this arid context have largely hampered a robust age-depth reconstruction (Felauer, 2011; Lee et al., 2011). A longer record along with a well constrained chronological model (for instance using Bayesian age-depth modelling) is therefore indispensable in providing a complementary repository to unravel the aforementioned issues.
Fig. 6-1. Present-day distribution of geologic terranes in the Orog Nuur catchment. Panel A: simplified land cover transect of Mongolia: mountain taiga, forest steppe, steppe, desert steppe, and Gobi Desert in the south. Panel B: schematic geological setting of the catchment, which is marked by dashed line. Northern region of catchment is dominated with Devonian-Triassic felsic quartz syenite, granite, plagiogranite, and alkaline sediments, accompanied by patchy intermediate mafic fractions. The southern region of Orog Nuur exhibits more of mafic/ultramafic basalt and andesite-basalt rocks relative to the northern catchment. Alkaline syenite occurs sporadically in the lower reach of Orog Nuur catchments. The depositional basin is bounded by eastern Khangai in the north and the Gobi Altai Mountains in the south.

Among a suite of multidisciplinary studies on argillaceous sediments, geochemistry appears to be a promising tool for deciphering the interplay between environmental change, source lithotypes and sediment bulk-composition (Boyle, 2001). When considering late Quaternary
lacustrine sediments, the bulk-geochemistry may be controlled by source terranes, authigenic or allogenic input, which may be modulated by past environmental conditions, while pedogenesis and diagenesis exert merely limited overprints (Yu et al., 2016). Knowledge of the downcore variability of major, trace, and minor element abundance along with field investigation and careful examination of previous geologic mapping will enable us to decipher the climate-induced provenance change throughout the depositional processes. On the other hand, surveys considering the bulk-geochemistry and corresponding environmental interpretations in the marine realm have been systematically reviewed (Calvert and Pedersen, 2007), whilst elucidations of the elemental fingerprints incorporated in the lacustrine sediments still await more investigation (Roser and Korsch, 1988; Norman and De Deckker, 1990; Sinha et al., 2006). In particular, in contrast to conventional XRF measurement using pressed pellets, the application of high resolution, time saving, and continuous XRF core scanning to lake sediments has only attracted limited attention in the less than ten years since its earlier applications in the marine realm (Melles et al., 2012). The XRF scanning technique has not yielded a complete consensus on how the provenance, depositional environment, and corresponding earth surface processes affect a suite of elements in different lacustrine settings (Richter et al., 2006; Shanahan et al., 2008). A recent review by Davies et al. (2015) highlights that several studies have been conducted to interpret elements, ratios and associated environmental interpretations in the lacustrine realm. However, those implications should not be taken as universally applicable, as there is to date rare XRF core scanning data that has been generated in the hyperarid (desert) setting where largely no varved laminae can be observed in the lacustrine sequences.

This work aims to provide a complementary XRF scanning logged record to fill in the gaps in the above mentioned spatial/temporal heterogeneity of data repositories in the hyperarid desert setting. In this study, major and trace element contents accompanied by calcium carbonate concentration and C/N\textsubscript{atomic} ratios of the Orog Nuur lacustrine sequence are examined in an attempt to: (i) test the possible plots of element ratios that could be employed to extract the broad pattern of diversified source regions throughout the depositional period; and (ii) ultimately evaluate the set of multi-proxy fingerprints and parse out the interplay between the coupled past environmental processes, land surface processes, and provenance change in the arid depositional system of the Orog Nuur catchment.
6.2. Regional setting

The Orog Nuur (45°01’-45°04’N 100°33’-100°53’E; ~1,219 m a.s.l.) is located in a hydrologically closed basin system in the Valley of Gobi Lakes (Fig. 6-1). It is a brackish lake subject to desiccation and occasionally turns into playa system. The Tuyn Gol (gol = river) is the main inflow originating from the southern slopes of the Khangai Mountains around 220 km north of the lake. The continental climate of Gobi Desert is characterized by a dry / cold winter with limited snow. More than 65% of the rainfall occurs in the summer. Annual precipitation reaches ~100 mm in the vicinity of the Orog Nuur in the Gobi Desert of Mongolia, while the higher elevated Khangai Mountains receive up to ~400 mm/a. The mean annual air temperature is -2 to 5 °C. The mean air temperatures during July and January in the Gobi Desert are ~16 °C and ~-20 °C, respectively (Felauer, 2011). The Valley of Gobi Lakes (1,400-1,800 m a.s.l.) is an elongated intramontane depression between the Siberian Craton and the Tarim and Sino-Korean Cratons (Baljinnyam et al., 1993; Cunningham et al., 2005). Paleozoic volcanic and plutonic rocks are exposed in the basin (Fig. 6-1). The southern part of the Orog Nuur watershed is represented by the tectonic escarpment of the Gobi Altai, as well as gently inclined alluvial fans (Baljinnyam et al., 1993). As illustrated in Fig. 6-1, the northern catchment (Tuyn Gol watershed) is dominated with Devonian-Triassic felsic quartz syenite, granite, plagiogranite, and alkaline sediments, accompanied by minor proportions of (intermediate) mafic rocks. The southern watershed exhibits more mafic to ultramafic basalt and andesite-basalt rocks relative to the northern catchment. The Orog Nuur might have occupied a much larger area in the Eemian and Marine Isotope Stage 3 (Lehmkuhl and Lang, 2001).

6.3. Material and methods

6.3.1. Core retrieval and Bayesian age-depth modelling

During the playa phase in 2007 and 2008, two parallel sediment cores (ONW I: 6.00 m, 45°03’48”N, 100°34’39”E; ONW II: 13.35 m, 45°04’28”N, 100°35’08”E, 1,219 m a.s.l.) were recovered from the western part of Orog Nuur (Fig. 6-1B). The core was opened, described and documented in the lab. Samples were separated and transported to (i) RWTH for grain size and TOC analyses, and (ii) AWI Bremerhaven for X-ray fluorescence scanning and X-ray powder diffraction analyses. The study here is conducted primarily on the longer core ONW II.
Fig. 6-2. Lithostratigraphy and Bayesian age-depth modelling for core ONW II. R package Bchron (Parnell et al., 2008) was employed. Gray shaded area represents maximum and minimum age-depth estimates based on 100,000 smooth spline fits through the calibrated age distributions (95% highest density region). The Bayesian age-depth model was further cross-validated by several independent approaches: (i) two ages from the parallel core ONW I (marked as black rectangles), (ii) sand layer and luminescence-determined age model of Ulaan Nuur (Lee et al., 2011), (iii) downcore variance of CaCO₃ concentration.

In total ten radiocarbon ages were determined from bulk materials (Tab. 6-1; Fig. 6-2) using accelerator mass spectrometry (AMS) at the Erlangen-Nürnberg University and subsequently calibrated to calendar years using CALIB rev. 7.1 (Stuiver et al., 1998) with the latest IntCal 13.14c calibration curve (Reimer et al., 2013). All radiocarbon ages are presented as calibrated years (cal a BP) with a 2σ error bar (Tab. 6-1). The upper 24 cm of the core ONW II were not retrieved. The R package “Bchron” (Parnell et al., 2008) was employed here to set up a Bayesian age-depth model for core ONW II (Tab. 6-1; Fig. 6-2) including its calibration using the IntCal calibration curve mentioned above. Reservoir effects at different anchor points were assessed by (i) identifying Termination I in bulk-geochemical (sharp increase of Ca peak areas, and CaCO₃ %; Lauterbach et al. 2011) and palynological sequences (sharp increase of pollen grains/concentration; Murad, 2011), and (ii) comparing the Younger Dryas-related sand layer in Orog Nuur and Ulaan Nuur (Fig. 6-1A; Lee et al., 2011). All of the radiocarbon ages were first subtracted by the reservoir effect and then computed to calibrated
calendar years and used in the establishment of the Bayesian age-depth model (Tab. 6-1; Fig. 6-2). The exact implementation procedures can be reproduced using appended R script. In addition, two radiocarbon ages were determined for core ONW I (386 cm, 588 cm) to compare and validate the timing of stratigraphic units of the counterpart depths in core ONW II (Fig. 6-2).

**Table 6-1** The AMS $^{14}$C ages were calibrated to calendar years with 2 $\sigma$ standard deviation using the CALIB rev. 7.1 (Stuiver et al., 1998) with the latest IntCal13.14c (Reimer et al., 2013). According to the estimated real age based on the lithostratigraphy, raw radiocarbon ages are subtracted by a reservoir effect of $\sim$3,400±2,100 a BP before computing to calibrated ages and generating the Bayesian age-depth model as given in Fig. 6-2.

<table>
<thead>
<tr>
<th>Core Nr.</th>
<th>Dept h (cm)</th>
<th>Lab Nr.</th>
<th>Dating material</th>
<th>$^{14}$C ages (a BP)</th>
<th>$\delta^{13}$C (%)</th>
<th>2$\sigma$ (cal a BP) (95.4 %)*</th>
<th>Estimated real age according to lithostratigraphy (cal a BP)*</th>
<th>Calibrated Age based on Bayesian age-depth modelling (cal a BP)</th>
<th>Median Age based on Bayesian age-depth modelling (cal a BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONW II 94</td>
<td>Erl-15622</td>
<td>Bulk material</td>
<td>12,581±103</td>
<td>-25.4</td>
<td>14,325-15,192</td>
<td>-</td>
<td>5,054-16,854</td>
<td>10,697</td>
<td></td>
</tr>
<tr>
<td>ONW II 199</td>
<td>Erl-15623</td>
<td>Bulk material</td>
<td>13,242±85</td>
<td>-24.2</td>
<td>15,691-16,138</td>
<td>11,000-13,000</td>
<td>5,988-17,523</td>
<td>11,499</td>
<td></td>
</tr>
<tr>
<td>ONW II 271</td>
<td>Erl-15624</td>
<td>Bulk material</td>
<td>17,733±149</td>
<td>-25.4</td>
<td>21,042-21,819</td>
<td>13,000-18,000</td>
<td>10,905-22,893</td>
<td>17,703</td>
<td></td>
</tr>
<tr>
<td>ONW II 392</td>
<td>Erl-15625</td>
<td>Bulk material</td>
<td>17,713±180</td>
<td>-24.5</td>
<td>20,945-21,857</td>
<td>18,000-19,000</td>
<td>10,827-22,924</td>
<td>17,046</td>
<td></td>
</tr>
<tr>
<td>ONW II 571</td>
<td>Erl-15626</td>
<td>Bulk material</td>
<td>19,738±179</td>
<td>-23.8</td>
<td>23,344-24,150</td>
<td>-</td>
<td>13,528-25,249</td>
<td>19,604</td>
<td></td>
</tr>
<tr>
<td>ONW II 778</td>
<td>Erl-15627</td>
<td>Bulk material</td>
<td>21,501±217</td>
<td>-24.2</td>
<td>25,386-26,122</td>
<td>-</td>
<td>15,408-27,018</td>
<td>21,685</td>
<td></td>
</tr>
<tr>
<td>ONW II 1,192</td>
<td>Erl-15628</td>
<td>Bulk material</td>
<td>46,103±281</td>
<td>-25.4</td>
<td>44,908-49,914</td>
<td>-</td>
<td>37,748-49,716</td>
<td>45,303</td>
<td></td>
</tr>
<tr>
<td>ONW II 1,272</td>
<td>Erl-15629</td>
<td>Bulk material</td>
<td>40,429±1,340</td>
<td>-24.9</td>
<td>42,221-46,226</td>
<td>-</td>
<td>34,226-47,355</td>
<td>40,873</td>
<td></td>
</tr>
<tr>
<td>ONW II 386</td>
<td>Erl-12107</td>
<td>Bulk material</td>
<td>16,020±105</td>
<td>-28.1</td>
<td>19,049-19,560</td>
<td>18,000-19,000</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>ONW I 588</td>
<td>Erl-12108</td>
<td>Bulk material</td>
<td>17,642±112</td>
<td>-23.4</td>
<td>21,020-21,653</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*The reservoir effect is determined by taking average of the difference between the boldface ages in these two columns.

**6.3.2. Grain size analysis**

The grain size distributions (GSDs) of 258 samples from ONW II and 114 samples from ONW I at a 5 cm interval were determined using a Beckman Coulter LS13320 Laser Diffraction Particle Size Analyzer. All measurements were performed uniformly without hydrochloric acid treatment (Felauer, 2011; Schulte et al., 2016). 700 $\mu$l of 35% $H_2O_2$ was added to remove the organic components. Samples were subsequently dried at 70 °C for two days. Sodium pyrophosphate was added to avoid coagulation. The final GSD represents the average of two subsamples. Each of them was measured twice to ensure the reliability. In any
case of conspicuous offsets exist between subsamples, the procedure was repeated for the sample (Schulte et al., 2016).

6.3.3. TOC, CaCO$_3$ and C/N$_{\text{atomic}}$ analyses

![Diagram of elemental distribution](image)

**Fig. 6-3.** Downcore variance of abundance of the major and trace elements expressed by integrated peak areas (total counts per second), accompanied by the C/N$_{\text{atomic}}$ ratios, CaCO$_3$ content, Rb/Sr ratio (lower values= higher catchment weathering; Davies et al., 2015), Al/Si ratio (lower values=higher coarse-grained sands; Davies et al., 2015), and the XRD determined minerals in sparser intervals. Silicon and K share similar patterns as Al, whilst Mn and Co share similar patterns as Fe. Further details are presented in the supplementary material of this paper. The grey bars depict the sand layers inferred from the granulometric and lithostratigraphic characteristics of the core, and the dashed line mark the transition of Termination I. The consistency between the grey bars and the elements spikes implies that the sand fractions (Factor 1 as determined by robust statistics; Fig. 6-4) have played a pivotal role in the alteration of bulk-geochemistry of the lacustrine sediments.

In total 258 samples (ONW II) were dried at 36 °C for 24 hours. The prepared samples in zinc capsules were analyzed in a CHNS Analyzer EA3000. The Scheibler gas method (DIN 19684) was used to calculate the CaCO$_3$ content. Total organic carbon (TOC) was computed following Scheffer and Schachtschabel (2002). The C/N$_{\text{atomic}}$ ratios of core ONW II were calculated for the following discussion (Meyers and Lallier-Vergès, 1999).
6.3.4. X-ray fluorescence scanning and X-ray powder diffraction analysis

The X-ray fluorescence (XRF) analysis was conducted using an Avaatech XRF Core Scanner configured with a Canberra X-Pips 1500-1.5 detector (20 s dwell time, slit 10 mm, 10, 30 keV, 300 and 700 µA) (Richter et al., 2006) at the AWI Bremerhaven. For core ONW II, in total 1,335 results at a 1 cm scanning step size were retrieved. Subtraction of a background curve, application of statistical corrections for physical processes in the detector, and deconvolution of overlapping peaks were performed using a scanner equipped WinAxil package (NIOZ and Avaatech, 2007). Element abundance is given in integrated peak areas (total counts per second or cps). To help discern their environmental and/or provenance implications, the whole set of elements were further divided into four groups based on robust multivariate statistics as outlined in next chapter (Fig. 6-3).

To further interpret the bulk-geochemical composition of samples from different sedimentological settings, a standard X-ray diffraction (XRD) technique using a Philips X’Pert MPD diffractometer with a divergence slit using array Cu Kα radiation (40 kV, 50mA) was employed to detect the bulk mineralogical composition of 14 samples at the depth of 50, 200, 300, 350, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300 cm, respectively (Fig. 6-3). Minerals were identified from XRD patterns of samples at 3.34 Å (quartz), 3.24 Å (K-feldspar), 3.19 Å (plagioclase), 3.024 Å (calcite), 6.15 Å (mica), 14/7.02/4.72 Å (kaolinite-chlorite/chlorite), 3.57 Å (kaolinite) 8.47 Å (hornblende), and minor spikes at 10/5 Å (illite). The measurement was performed from 2-35° 2θ with scan speed of 0.02° 2θ/2 sec. The integrated peak areas (total counts) of the above mineral groups were calculated and transformed into mineral percentages using the freeware MacDiff (Petschick et al., 1996). A suite of original measurements of Stein et al. (1994) and Vogt (1997) that were previously carried out at AWI were compared to ensure the comparability between the peak areas and percent calculations.

6.3.5. Robust multivariate statistics

To provide a quantitative manner in which to segregate the whole set of multi-proxies into detailed assemblages, a robust multivariate statistical analysis is computed using the R package “Robustfa” (https://cran.r-project.org/web/packages/robustfa/robustfa.pdf). A detailed computing process and the manner of data interpretation were given in Yu et al. (2016). The robust evaluation parameters for each factor and sediment sample are presented in Tab. 6-2. Those elements with high positive or negative (> 0.75) loadings are shown in
boldface and will be included for further discussion regarding their integrated environmental processes, provenance, and land surface processes.

Table 6-2 Standard deviation, variance/cumulative proportion, multi-proxies loading for each factor, and communalities for each proxy generated by robust multivariate statistics. High positive or negative (> 0.75) loadings are marked in boldface. Blank values represent those loadings which are under significance level in robust multivariate statistics. Communalities for each element are computed by taking sum of the squared loadings, it can be referred to the length of the element arrows in loadings plot (Fig. 6-4A), a value greater than 0.90 suggests a well representative of this proxy in the statistical model. Factors 1 (26.4%) and 4 (25.9%) explain more than have of the variance, they are therefore illustrated in the biplots of Fig. 6-4 for further implications. More details concerning the statistics refer to Yu et al. (2016).

<table>
<thead>
<tr>
<th>Multi-proxies</th>
<th>Factor 1: Sand fraction</th>
<th>Factor 2: Authigenic productivity</th>
<th>Factor 3: Organic material</th>
<th>Factor 4: Terrigenous input</th>
<th>Communalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>-0.249</td>
<td>-0.129</td>
<td>-</td>
<td>0.930</td>
<td>0.944</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>-0.117</td>
<td>-</td>
<td>0.911</td>
<td>0.844</td>
</tr>
<tr>
<td>S</td>
<td>-</td>
<td>-0.448</td>
<td>-</td>
<td>-</td>
<td>0.201</td>
</tr>
<tr>
<td>Cl</td>
<td>-0.340</td>
<td>-0.756</td>
<td>-</td>
<td>-0.118</td>
<td>0.585</td>
</tr>
<tr>
<td>K</td>
<td>-0.340</td>
<td>-</td>
<td>-</td>
<td>0.935</td>
<td>0.990</td>
</tr>
<tr>
<td>Ca</td>
<td>-0.494</td>
<td>0.780</td>
<td>-</td>
<td>-</td>
<td>0.852</td>
</tr>
<tr>
<td>Ti</td>
<td>-0.459</td>
<td>-0.105</td>
<td>-</td>
<td>0.826</td>
<td>0.904</td>
</tr>
<tr>
<td>Cr</td>
<td>-0.243</td>
<td>0.197</td>
<td>-</td>
<td>0.194</td>
<td>0.135</td>
</tr>
<tr>
<td>Fe</td>
<td>-0.554</td>
<td>-</td>
<td>-</td>
<td>0.773</td>
<td>0.904</td>
</tr>
<tr>
<td>Rb</td>
<td>-</td>
<td>-0.367</td>
<td>-</td>
<td>0.675</td>
<td>0.590</td>
</tr>
<tr>
<td>Sr</td>
<td>-0.108</td>
<td>0.697</td>
<td>-</td>
<td>-0.153</td>
<td>0.521</td>
</tr>
<tr>
<td>Zr</td>
<td>-</td>
<td>-0.109</td>
<td>-</td>
<td>0.724</td>
<td>0.536</td>
</tr>
<tr>
<td>N (CNS)</td>
<td>-0.804</td>
<td>-0.147</td>
<td>0.280</td>
<td>0.141</td>
<td>0.766</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>-0.548</td>
<td>0.779</td>
<td>-</td>
<td>-0.244</td>
<td>0.967</td>
</tr>
<tr>
<td>TOC</td>
<td>-0.382</td>
<td>-</td>
<td>0.954</td>
<td>-</td>
<td>1.056</td>
</tr>
<tr>
<td>C/Natomic</td>
<td>-</td>
<td>-0.818</td>
<td>-</td>
<td>-</td>
<td>0.669</td>
</tr>
<tr>
<td>Mean grain-size</td>
<td>0.914</td>
<td>-0.242</td>
<td>-</td>
<td>-0.234</td>
<td>0.949</td>
</tr>
<tr>
<td>Clay fraction</td>
<td>-0.780</td>
<td>0.470</td>
<td>-</td>
<td>-</td>
<td>0.829</td>
</tr>
<tr>
<td>Silt fraction</td>
<td>-0.926</td>
<td>0.122</td>
<td>-</td>
<td>0.269</td>
<td>0.945</td>
</tr>
<tr>
<td>Sand fraction</td>
<td>0.934</td>
<td>-0.258</td>
<td>-</td>
<td>-0.212</td>
<td>0.984</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>5.281</td>
<td>3.097</td>
<td>1.685</td>
<td>5.172</td>
<td>-</td>
</tr>
<tr>
<td>Variance proportions/%</td>
<td>26.4</td>
<td>15.5</td>
<td>8.4</td>
<td>25.9</td>
<td>-</td>
</tr>
<tr>
<td>Cumulative proportions/%</td>
<td>26.4</td>
<td>41.9</td>
<td>50.3</td>
<td>76.2</td>
<td>-</td>
</tr>
</tbody>
</table>

6.4. Results

6.4.1. Lithostratigraphic units and Bayesian chronology

According to the Bayesian age-depth model, the basal age of the core ONW II was determined to be between 38 and 52 ka (Fig. 6-2). Termination I manifests as a remarkable transition in geochemical patterns in core ONW II (Fig. 6-3), namely an abrupt increase of CaCO₃, indicating the onset of the Holocene unit in the age model (Fig. 6-2) (Lauterbach et
al., 2011). To further corroborate the depth of Termination I, a luminescence-constrained Younger Dryas sand layer in Ulaan Nuur sediments (Fig. 6-1A) is used. In this adjacent core, the sand layer was determined to be some 13-11 ka (Fig. 6-2). Thus, ~205 cm is presumed to be ~11,000 a BP, which is ~4,900 years younger than that in the age model. The age of sediment at ~248 cm is assigned to ~13,000 a BP, which is ~3,000 yrs younger than in the Bayesian age model. Likewise, based on the estimation of the real ages of the lithostratigraphy, the raw radiocarbon ages were subtracted by a reservoir effect of c. 3,400±2,100 yrs (Tab. 6-2) and then computed to calibrated calendar years and employed in the establishment of the Bayesian age-depth model (Fig. 6-2). In light of Felauer (2011) and Lee et al. (2011), a reservoir effect of greater than 3,000 yrs in the Orog Nuur cores is highly feasible. Furthermore, the lowermost two ages are near the limit of radiocarbon dating. However, the application of the newly established calculation curve IntCall13, as well as the employment of the Bayesian modeling still assures a relatively reliable basal age that is younger than ~50 ka (Tab. 6-1; Fig. 6-2).

On the basis of lithostratigraphic, granulometric, and geochemical characteristics, the entire sequence is delimited into five units:

*Unit I (1,335-390 cm; ~50--~19 cal ka BP)*

Unit I is dominated by greyish clayey-silty sediments (on average 60-80%; Fig. 6-2) with intercalations of several brownish sand layers that are marked as grey bars in Fig. 6-3. CaCO$_3$ remains generally stable with low values (~10%) within Unit I, while the C/N$_{\text{atomic}}$ ratio displays a relatively varied pattern (Fig. 6-3) with several laminations with values greater than 20.

*Unit II (390-350 cm, ~19--~18 cal ka BP)*

Unit II is a salient brownish coarse sand layer which is also captured by the parallel core ONW I (Fig. 6-2). The sand fraction ranges from 91.5% to 96.1%. CaCO$_3$ abundance exhibits extremely low values while C/N$_{\text{atomic}}$ ratios display high values with oscillations (Fig. 6-2).

*Unit III (350-248 cm; ~18--~13 cal ka BP)*

Unit III is a dark greyish clayey-silty layer similar to Unit I. The sand fraction ranges from 10% to 35% with an abrupt increase in the basal part of Unit III to ~35% and a subsequent decrease to 10% at 283 cm. The CaCO$_3$ and C/N$_{\text{atomic}}$ ratio depict similar patterns to Unit I.
Unit IV (248-205 cm; ~13-11 cal ka BP)

Unit IV is dominated by the sand proportion (50-90%). The sand layer is also present in the parallel core ONW I and the adjacent Ulaan Nuur (Fig. 6-1; Lee et al., 2011). CaCO₃ content remains similar to Unit III, while the C/N atomic ratio shows more fluctuations similar to Unit II. Throughout Unit IV, the S content exhibits low values (Fig. 6-3).

Unit V (205-25 cm; <~11 cal ka BP)

Unit V is characterized by fine sediments with the highest clay proportion (30-50%) and the lowest sand fraction (1-10%). A sharp increase in CaCO₃ (calcite; Fig. 6-3) and concomitantly diminished S contents are present in Unit V. C/N atomic ratios decrease from ~20 to <10 upward and increase incrementally approaching the top of the core.

6.4.2. Elements/minerals downcore variance and multi-proxy assemblages revealed by multivariate statistics

The major and trace element concentrations, as well as mineral compositions throughout the core ONW II were plotted against the depths and stratigraphic units (Fig. 6-3). In light of the multivariate statistics (Fig. 6-4; Tab. 6-2), the whole set of elemental compositions and other proxies are evaluated using a robust factor analysis. They are divided into four factors: (1) Factor 1 (variance proportion: 26.4%) is positively correlated with mean grain-size and sand percentages of the sediments and negatively correlated with the N content and silt/clay fraction of the sediments. (2) Factor 2 (15.5%) exhibits significantly high loadings of Cl, Ca and CaCO₃ content. In general, Ca and Sr concentrations display a unique pattern that resembles CaCO₃ and hornblende, with relatively low abundances throughout the late Pleistocene and sharp increases after Termination I. Cl exhibits a long-term trend of upcore increase along with superimposed fluctuations. In general, the factor is an indicator for the authigenic productivity of the lake system (see following discussion). (3) Factor 3 (8.4%) delineates higher loadings for TOC and C/N atomic and an insignificant correlation with elemental compositions and grain-size composition. (4) Factor 4 (25.9%) has significantly high loadings of Al, Si, K, Ti, and Fe. This set of elements exhibits higher abundance in Units I, III and V (relatively lower in Unit I), while the contents in Units II and IV are markedly lower. They share broadly similar patterns to mica and chlorite. This factor is explained as terrigenous input brought by two pathways: (i) riverine inflows via Tuyn Gol, and (ii) quasi-constant aeolian inputs. In addition, note the relatively high variability of the element
concentrations of, in particular, Unit I (Fig. 6-3), which may result from the frequently occurrence of sand layers as illustrated by the grey bars in Fig. 6-3. In this scenario, insight into the bulk-geochemistry of each unit is more readily obtained in the dispersion plots, wherein Units I and III share broadly similar median values and upper / lower quartiles (Fig. 6-3; supplementary figure). Factors 1 (26.4%), 4 (25.9%), and 3 (15.5%) explain ~70% of the multi-proxy variations; they are the primary governing factors for the sediment bulk-geochemistry.

Fig. 6-4. Loadings and scores plot of the multi-proxy data set. Panel A: loading plot of the robust Factor 1 (grain-size) vs. 4 (terrigenous input). Panel B: score plot of the robust Factor 1 vs. 4. In multivariate statistics, the maximum direction of variance is regarded as axes. Rotation is performed to get varimax rotated axis (x- and y-axis in Panel A) during the analysis attempting to archive a higher loading for each elements (Tab. 6-2). Cosine of the angle between the proxies and varimax rotated axes are factor loadings, length of the arrows are corresponding to the proxy communalities. In panel B, all units of samples are defined based on their lithostratigraphic units.

In terms of the minerals, mica, chlorite, quartz, plagioclase, K-feldspar, hornblende, and calcite are determined at coarser intervals throughout the core ONW II (Fig. 6-3). Amongst those minerals, (1) quartz and plagioclase display only minor variation through the core; (2) mica and chlorite exhibit a highly coupled pattern that has higher values in the lake phases (Unit I, III, and V); (3) calcite and hornblende have a similar pattern with higher values specifically in the Holocene (Unit V) relative to the Pleistocene units; (4) K-feldspar denotes
a broadly reversed pattern compared with that of mica and chlorite, and appears to have a higher content corresponding to the sand layers (grey bars in Fig. 6-3). In general, the set of XRD data shed light on the general mineralogical composition of the studied core, and thereby aid in further interpretation of the XRF scanning data.

6.5. Discussion

6.5.1. Evaluating the quality of the X-ray scanning data

As mentioned above, the retrieved XRF core scanning data are expressed in semi-quantified integrated peak area/total counts per second (cps) without conversion to oxide wt % or molar abundance.

Amongst the entire suite of elements, Ni, Cu, Zn, Ga, Br, Au, Pb, and Bi have a relatively high error margin compared to their measured peak areas. They are therefore removed from the multivariate statistics (for detailed data and error margin see the supplementary material of this paper). In the statistical report (Tab. 6-2), the proxies that are under significance level are ruled out for the following discussions as well. The remaining set of elements show measured peak areas that are well above the theoretical detection limit of the Avaatech XRF scanning infrastructure (Richter et al., 2006; NIOZ and Avaatech, 2007). Certain low count rates (in particular for light elements such as Si) may be ascribed to intervals with very coarse-grained sediments such as those in Unit II and Unit IV in this core (Richter et al., 2006; Shanahan et al., 2008; Weltje and Tjallingii, 2008; Ohlendorf et al., 2015). However, as demonstrated in the recently published monograph concerning the XRF scanning technique and its applications on marine, fluvial, and lacustrine sediments (Bertrand et al., 2015), in general, the precision of data obtained by XRF core scanning is not significantly altered by grain-size variations. They correct the XRF peak areas for water content and grain-size, which only slightly improves the correlation between XRF peak areas and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) determined bulk-geochemistry concentrations. This improvement is, however, relatively minor; the difference between the correlation coefficients is never significant at $p < 0.05$ level (Bertrand et al., 2015). Furthermore, Schillereff et al. (2015) demonstrate for the first time that the employment of different XRF scanning instruments (mainly Avaatech and Itrax, etc.) yields similar elemental patterns, implying a robust and sound quality of the retrieved data. Meanwhile, Dulski et al. (2015) analyzed parallel subsamples using XRF scanning and ICP-MS, also revealing a systematic relationship between the scanned data and element concentrations.
In terms of late Quaternary lacustrine sediments, although diagenesis may indeed exert certain influence on the fate of bulk-composition (Johnsson, 1993), it is, however, a less crucial aspect compared with the alteration of paleoenvironment and source lithotypes in the entire catchment system. Pettijohn (1973) concluded that due to the limited burial time, calcite cements along with the negligible quartz overgrowths are virtually the only diagenetic overprints. Thus, source terranes, paleoenvironment-induced weathering and transportation adaptations are more likely the governing factors for the late Quaternary lake sediments. On this account, the following discussion is generally demarcated and outlined in twofold: (i) the paleoenvironmental (weathering, land surface processes) implications, and (ii) provenance signals.

6.5.2. Governing factors for sediment bulk-geochemistry

In the marine realm, researches have been systematically undertaken to examining the sediment bulk-geochemistry and its environmental interpretations (Calvert and Pedersen, 2007; Diekmann et al., 2008; Martinez-Ruiz et al., 2015). It has been suggested that assemblages of the elements exhibit specific indications of the redox condition (Mn and Co), diagenetic processes (Fe), authigenic productivity (Al and Ba) and the alloigenic aeolian/fluvial inputs (Zr and Rb) during sedimentary processes. Here, in the lacustrine realm, a holistically refined view of the governing factors of sediment bulk-geochemistry, taken in consideration of other multidisciplinary proxies, is employed using robust multivariate statistics as a prerequisite for the following discussions.

6.5.2.1. Factor 1 (26.4%): Grain-size variation of the lacustrine sediments

This factor has the highest proportion, 26.4%, as determined by the factor analysis (Tab. 6-2). In arid central Asia, aeolian sand plays a primary role in the terrestrial context (Kazancı et al., 2016) and the northwest Pacific pelagic sediments (Pye and Zhou, 1989). The abundance of the sand percentage (63-2,000 µm fractions) is also well presented as spikes for Al, Fe, and Al/Si ratios (Fig. 6-3). In order to examine the sand-induced influence on the bulk-geochemistry, all samples are plotted in the scores plot based on the multivariate statistics (Fig. 6-4B). Samples with a great contribution from (aeolian/fluvial) sand fractions particularly approach the positive end of Factor 1, while those samples of clay or silty-clay sediments are scattered at intermediate to negative positions on the Factor 1 axis. Interestingly, all coarse-grained samples from the Unit II (LGM) strata are relatively clustered, while those from the Unit IV (YD) are more scattered. This may be because the
Unit IV strata correspond to a playa phase that is more frequently influenced by the riverine input (mixture of both fluvial sands and finer suspended river sediments; Fig. 6-2), instead of predominantly coarse-grained sands as in Unit II. In summary, the coarse sands have a large influence on the sediment bulk-geochemistry via (i) fluvial inflows, and (ii) direct aeolian inputs. However, it must also be remembered that the sediment bulk-geochemistry is not solely a reflection of the sediment grain-size composition, indicated by the fact that that no elements in Factor 1 are well above the significance level (Tab. 6-2).

6.5.2.2. Factor 2 (15.5%): Authigenic productivity of the saline/alkaline lacustrine environment

Factor 2 has significantly high loadings of Cl, Ca, and CaCO₃ (Tab. 6-2). Ca is generally included in carbonates which are also common minerals in lacustrine environment (Tucker and Wright, 1990). Calcite, low-Mg calcite, and rarely occurring aragonite are generally authigenic precipitates in lake sediments while dolomite (along with quartz and feldspar) could be regarded as detrital input (Sinha et al., 2006; Wünneemann et al., 2010). In core ONW II, the abundance of calcite, Ca and CaCO₃ share analogous patterns, implying that in this study Ca is present mainly as calcite, and Unit V (Holocene) depicts notably higher authigenic productivity relative to the late Pleistocene epoch (Fig. 6-3). In contrast, Al and Si display lower values in the Holocene, acting as an analogue for plagioclase and K-feldspar (Fig. 6-3), suggesting a non-productivity signature. Therefore, compared with the marine pelagic realm, Al is not an indicator for the authigenic productivity. On the other hand, Sr has relatively high loadings, but its content variation is still under significance level (Tab. 6-2). Sr behaves quite similarly to Ca due to their similar hydro-geochemical characteristics (Calvert and Pedersen, 2007; Kylander et al., 2011). Likewise, Davies et al. (2015) also suggest that the presence of Ca and Sr is commonly associated with authigenic carbonate minerals in catchments located in arid and carbonate environments. In the lacustrine realm, halite is a ubiquitous species that may partly be generated by re-precipitation from pore solutions (Sinha et al., 2006). Similar to halite, the halogen element bromine may also be readily incorporated in halide salts. The upcore increase of these halogen elements (Fig. 6-3) implies a higher salinity/alkalinity approaching the upper part of core ONW II. Particularly in the Holocene, this high salinity and/or alkalinity are corroborated by the significantly elevated CaCO₃ abundance (Fig. 6-3).

In addition, Sulfur is in part negatively correlated with the Factor 2, albeit under the significance level (Tab. 6-2). Sulfur might be present as sulfate (gypsum and anhydrite), sulfide, and pyrite (Millot, 1970). As illustrated in Fig. 6-3, S exhibits higher content in Units
I-III, low values in Unit IV and is slightly elevated in the uppermost unit. In the late Pleistocene units, the less disturbed lake states may have led to a relatively higher content of sulfide and pyrite precipitation at the sediment-water interface. The sulfide minerals were then almost entirely oxygenated when exposed in the sand/playa layer and subsequently produced sulfate precipitation in the alkaline environment of Unit V. Alternatively, the sporadically deposited gypsum and mirabilite in such a cold, dry lake system may also account for these S spikes determined in Fig. 6-3. However, above all, the insignificance level of S loading for Factor 2 (Tab. 6-2) suggests that sulfide or sulfate mineral genesis is of minor importance for the bulk-geochemistry. This is also corroborated by clear evidence that above mentioned minerals are not detected by the XRD analysis in this study (Fig. 6-3).

6.5.2.3. Factor 3 (8.4%): Organic material content

Factor 3 is represented by significantly high loadings of TOC and C/N$_{atomic}$ (Tab. 6-2). The TOC content incorporated in the core sediments is relatively low (Fig. 6-2). The coupled variation of TOC and C/N$_{atomic}$ values implies that the lacustrine system has merely minor biogenic activity, and that the low content of the organic matter incorporated in the core was brought into the depocenter via allogenic fluvial processes, given that C/N$_{atomic}$ ratios greater than 20 indicate allochthonous input into the lacustrine system (Meyers and Lallier-Vergès, 1999).

6.5.2.4. Factor 4 (25.9%): Terrigenous components via riverine input and quasi-constant aeolian input

Factor 4 has high loadings for Al, Si, K, Ti and Fe (Tab. 6-2). Clay or silty-clay is the predominant sediment in the lacustrine environment (Millot, 1970). The fine detrital matrix formed mainly from the weathering decomposition of the primary aluminosilicates, which are the main host for Al (Calvert and Pedersen, 2007). On the other hand, Al may also be incorporated in feldspar and micas (Millot, 1970). In core ONW II, Al and Si display broadly identical patterns (Fig. 6-3), indicating a close link due to similar host minerals in fine sediments, either in a feldspathic structure or as a set of clay minerals in water bodies (Millot, 1970). In addition, in an arid context such as the Gobi Desert, in situ evaporated alkaline water was reported to be rich in Si and depleted in Al (Millot, 1970), which may account for the lower Al abundance in Unit V when calcite or carbonates are the predominant minerals in the water body (Fig. 6-3). In addition, several works suggest that the organic content in a lacustrine environment may exert strong influence on the Al abundance (Davies et al., 2015).
However, in the arid context of the Orog Nuur, the TOC values are broadly no greater than 2-3% (Fig. 6-2), thus making the above Factor 2 less important.

Due to the complex characteristics of its provenance ranging from fine clays to coarse sands (Yu et al., 2016), Si presents an unclear indication of the grain-size composition (unpresented in Factor 1; Tab. 6-2). Indeed, aeolian sands exhibit higher amounts of SiO$_2$ (Yu et al., 2016). However, in this context in Orog Nuur, Units II and IV may not be ascribed to purely aeolian sand. Grain-size alone cannot be used precisely to conform that the coarse-grained layers in this study are purely aeolian sands (Confroy et al., 2013). In a recent study on the Gobi Desert archives, SiO$_2$ content was found to be 71% (aeolian sands), 55% (lacustrine clay), 47% (fluvial sands), 69% (sandy loess), and 36% (alluvial gravels), respectively (Yu et al., 2016). This relatively lower Si content in the coarser-grained fluvial sand layer is also suggested by Dulski et al. (2015) based on scanning of the Piànico paleolake sequence. Likewise, Hunt et al. (2015) also demonstrate that increasing grain-size composition will not necessarily result in an elevated Si value. Thus, the fluvial sands may indeed display lower Si abundance relative to lacustrine clays in the core. In addition, as given in Yu et al. (2016), the sand fraction of the fluvial sands may be as high as that of the aeolian sand, albeit more spikes in finer fractions may be observed in the granulometric curves of fluvial sands. Thus, the complex provenance of lacustrine sediments from both coarse sands and alluminosilicate clays leads us to assume that the relatively coarse-grained layers (Units II and IV) may be largely attributed to fluvial transportation, rather than purely aeolian sands. On the other hand, in this aeolian sand and silt source region, the fluvial system normally experiences multi-cycle deposition of the coarse material. The SiO$_2$ values in this aeolian material show a significant decrease through long-term weathering processes (Bridge and Demicco, 2008), rendering a considerably lower SiO$_2$ abundance of the fluvial sands detected by the core scanning in this study. Multi-cycle deposition would account for the relatively lower SiO$_2$ values in those coarse-grained layers relative to the lacustrine clays in other units. Furthermore, the various Al/Si ratios through the core indicate that the Si pattern is also not governed by the terrigenous aluminosilicate constituents (Fig. 6-5; Richer et al., 2006), demonstrating a twofold, mixed provenance for Si: (i) quartz in aeolian sands, and (ii) fine-grained terrigenous aluminosilicates.
Fig. 6-5. Bivariate plots of major and trace elements in peaks areas (y-axis) against Al/Si (x-axis) according to their stratigraphic units. Al/Si ratios indicate generally the grain-size compositions of the bulk sediments, which display lower values/spikes according to the coarse-grained sand layers (Fig. 6-3). The biplot of Ca vs. Al/Si seems like a useful tool to properly discriminate the instinct (i) source rocks changes, and (ii) authigenic productivity in comparison with the late Pleistocene units. This distinct Holocene samples characteristics are more clearly elaborated in the scores plot of Fig. 6-4B.

In this study, K displays a divergent variance pattern compared with Ca and reveals convergent characteristics with Si, Al and Fe (Figs. 6-3 and 6-4). The behavior may result from mechanisms suggested by Millot (1970), namely, in young aqueous sediments, Ca is preferentially fixed into carbonates while K enters silicates. Furthermore, as illustrated in Fig. 6-3, the most likely host for K in the Orog Nuur sediments is K-feldspar with partial contributions from micas or chlorite, which may all be associated with allogenic fluvial inputs, as well as the aeolian processes (Costa et al., 2014).

In core ONW II, hornblende and micas are the potential hosts for Iron (Fig. 6-3). In general, hornblende is the main constituent of certain mafic source terranes in the catchments (Fig. 6-1B) and has weak resistance to weathering (Millot, 1970). Consequently, decomposed and retained hornblende together with micas all concentrate in fine clay sediments which are liable to be transported into the Orog Nuur by hydraulic flow and/or mass movement (Nesbitt
and Young, 1996) from southern alluvial fans (Fig. 6-1). In general, Fe has two modes of occurrence, namely the trivalent state and bivalent state when it accompanies Mg or K (Millot, 1970). As illustrated in Fig. 6-3, Fe acts in a manner analogous to Al and Si. Thus, rather than primary hornblende, Fe is mainly found in the micas and chlorite in the clayey sediments, which seems to be the same case with Ti, Rb and Co (Fig. 6-3). Due to the short burial time and resulting weak diagenetic influence, Fe may not be an indicator of diagenetic processes in the lacustrine realm.

Furthermore, several other elements share similar patterns as that of the above elements, they illustrate insignificant loadings for Factor 4. (1) Zirconium: there is ample evidence that Zr is relatively stable and is almost exclusively mechanically transported and fractionated (Pettijohn et al., 1973). Mukherji (1970) determined that in an acid aqueous media, Zr may also exist in polymeric species, e.g., zirconyl halides in the case of higher Cl anion abundance (Fig. 6-3). However, in terms of alkaline environments with higher concentrations of calcite or carbonate (higher abundance of $[\text{HCO}_3^-]+2[\text{CO}_3^{2-}]$; Chilingar et al., 1979; Dapples, 1979), zirconyl halides seem not to be the host for Zr. Here, the downcore Zr variance reveals no association between sand fractions and Zr abundance. However, it displays certain links with the quartz, plagioclase and K-feldspar abundance throughout the core, implying that Zr may be correlated to the precursor lithotype-governed allogenic fluvial clastic input, but is not necessarily a faithful recorder of aeolian input (Sinha et al., 2006). (2) Manganese: in spite of the two sand layers (Units II and IV), the lacustrine phase throughout the core depicts quasi-constant Mn abundance. In general, insoluble oxo-hydroxides (Mn (III) and Mn (IV) ion) occur in oxygenated environments while soluble Mn (II) occurs in anaerobic environments (Calvert and Pedersen, 2007). Thus, in terms of higher lake levels with suboxic to anoxic water bottoms, more soluble Mn will be readily incorporated into the carbonate lattice and thereby share variance patterns similar to Ca or CaCO$_3$, which seems largely untenable in this study (Fig. 6-3). The Orog Nuur therefore represents a frequently riverine inflow-disturbed shallow hydrological environment, rather than a stagnant water body. (3) Cobalt: the element Co behaves similarly to Mn and is generally enriched in clayey deposits (Costa et al., 2014). Both Mn and Co are therefore depleted in sand layers (Fig. 6-3). A slightly lower value in Unit V can be observed with respect to Co, albeit the broad pattern remains analogous to Mn. This lowering may be ascribed to the sensitive response of the elements to the slightly decreasing mica abundance (Fig. 6-3).
In summary, Factor 4, represented by Al, Si, K, Ti, and Fe, indicates the allochthonous input into the lacustrine system. This terrigenous input implication is consistent with several other works, including Kylander et al. (2011) and Davies et al. (2015).

6.5.3. Biplots of elements and scores plot as indicators of a distinct provenance signal and high authigenic productivity of the lake system in the Holocene

There is broad consensus that rare earth elements (REE), which are rarely influenced by diagenesis and metamorphic processes, are common indicators for provenance change (Pettijohn et al., 1973). Here, in terms of the dominating mudstone, ratios between major and trace elements were computed in an attempt to examine the possible lithotype signatures (Fig. 6-5). As postulated by Pettijohn et al. (1973), the Al/Si ratio is the commonly applied value in discriminating the provenance of sandstone and mudstones. In general, higher Al/Si denotes more clayey or detrital aluminosilicates while the quartz-rich sandstones have low Al/Si ratios due to the virtual absence of clay-bearing silicates (Davies et al., 2015).

Distinct assemblages related to the lithostratigraphic units are discriminated in the biplots against Al/Si (Fig. 6-5). Three main groups have been recognized: (i) Fe (K with similar pattern) abundances are broadly altered by silicate contents in authigenic mud and allogetic fluvial clastics brought by the Tuyn Gol. Due to the lack of a clay fraction, the Last Glacial Maximum (LGM) sediments (Unit II) are distinctly distributed with low Fe and Al/Si values, whereas the mud dominant sediments from Units I and III occupy the opposite end of the biplot. Furthermore, apart from the lacustrine sediments in this study, the quasi-linear regression (r=0.66-0.97; $R^2=0.43-0.97$) pattern between Al/Si and Fe was also delineated in the sandstones and argillites, wherein both depositional conditions and provenance fingerprints might have been incorporated (Roser and Korsch, 1988); (ii) Mn (Zr and Co with similar patterns), similarly, is also governed by clay and silt fractions. However, through sand-dominated sediments may confound the pattern of Mn (Fig. 6-5), data points of the LGM sediments (Unit II) are more scattered compared with those of Fe. The entire set of data points is therefore less linearly correlated (r=0.18-0.70; $R^2=0.03-0.57$) relative to the first group of elements. In addition, as stated above, the whole suite of samples in the biplot of Zr vs. Al/Si present a slightly more horizontal and scattered regression (r=0.36-0.61; $R^2=0.13-0.38$), implying that Zr is hosted in both clay enriched and depleted sediments, which might have complicated the biplot pattern; (iii) Ca appears to be the distinct element that allows us to discriminate between late Pleistocene and Holocene signatures. Before Termination I, the sediments exhibit a virtually linear regression (r=0.06-0.97; $R^2=0.00-0.95$) in a manner
analogous to Fe, suggesting a quasi-consistent alteration kinetics governed by the clay and silt fraction input (Fig. 6-5). Nevertheless, although they share similar granulometric compositions, the Holocene sediments in Unit V exhibit distinctly higher Ca values relative to the granulometrically similar Units I and III ($r=-0.42$; $R^2=0.17$) (Fig. 6-5). On the other hand, the LGM and Younger Dryas sand layers (Units II and IV) represent distinctly different patterns, namely the Younger Dryas sediments are more scattered relative to LGM sediments regarding the Al/Si axis. Unlike the dominantly playa condition during the LGM, the Younger Dryas may have been subject to frequent riverine inflows, resulting in a broader covering of mud-, silt- to sandstone suites (Fig. 6-2). As a consequence, compared with those in Unit II, the set of Unit IV data points is more scattered in Fig. 6-5.

6.5.3.1. The disparate provenance signatures and authigenic productivity of the Holocene sediments

The set of late Pleistocene sediments exhibits coherent regression patterns in the biplots (Fig. 6-5), indicating insignificantly alteration of source lithotypes through Units I-IV. This quasi-constant provenance delivery/authigenic productivity through Unit I to IV is also documented in the broadly unbiased quartz, plagioclase, hornblende and minor biased Rb/Sr ratios (catchment weathering) throughout the late Pleistocene (Fig. 6-3). Apart from Ca, all of the above three groups of elements display a tendency of quasi-linear regression which is altered by the amount of clay and silty-clay proportions, albeit Zr is slightly biased and scattered due to contributions from both finer and coarse sand fractions. The constant delivery of riverine inflows during the lake phase may have transported the felsic and weathered intermediate or mafic plutonic rocks into the Orog Nuur (Fig. 6-1B), although this phase was interrupted by two desiccated playa periods (the local LGM and Younger Dryas) with a sporadic or cessation of riverine inflows. Alternatively, in this hyperarid environment, airborne material is a permanent, vital input for the catchment depocenter. The minor variance of quartz and plagioclase content implies that the aeolian activity that conveyed coarse-grained sediments into the Orog Nuur catchment basin was quasi-constant through the late Quaternary. Likewise, as demonstrated by robust multivariate statistics, in the context of the Eijina Basin, there is no sharp variation of aeolian sands input through the late Quaternary (Yu et al., 2016), albeit the LGM might have been subject to a slightly higher aeolian deflation in the arid central Asia (Nilson and Lehmkuhl, 2001). This amount of airborne material was thus incorporated into the sediment trap at a quasi-constant rate, in spite of the lacustrine setting,
playa, or other land surfaces. Thus, the sharp increase of Ca since the very beginning of the Holocene seems not to have been caused solely by the quansi-constant aeolian activity.

From the onset of the Unit V, both hornblende and CaCO$_3$ demonstrate a coeval abrupt increase. This phenomenon is also documented in calcite and Ca (peak areas) (Fig. 6-3). The distinct behavior of Ca in the Holocene sediments is also properly depicted in the biplot against Al/Si (Fig. 6-5), as well as the scores plot revealed by robust multivariate statistics (Fig. 6-4B). All of the evidence corroborates the theory that the past environment is not the sole governing factor exerting influence on the sediment bulk-composition, and that prominently different source lithotypes and/or higher authigenic productivity may have existed before and after Termination I. This different provenance may be attributed to twofold pathways given that the catchment basin is intimately linked to the higher catchment via the Tuyn Gol: (i) in the stadial (Younger Dryas event) of the late glacial period, the glacial-pluvial debris accumulated in the higher Khangai Mountains may not have been subject to abrasion and transport into the Orog Nuur. Subsequently, immediately after Termination I, due to climate amelioration-induced deglaciation and the hydrodynamically strengthened riverine inflows, abrupt increases of clastic minerals were available for transport into the Orog Nuur (Fig. 6-1B), resulting in a sharp increase of the Ca, calcite, and hornblende abundance in the Holocene, as well as the distinct biplot pattern of Ca vs. Al/Si (Figs. 6-3 and 6-5). Furthermore, this increased weathering and fluvial input is corroborated by the negative values of Factor 4 (high terrigenous input) of the Holocene samples in the scores plot (Fig. 6-4B) and the decreased Rb/Sr ratios of the Holocene samples (Fig. 6-3; Davies et al., 2015).

(ii) Due to the temperature amelioration and better moisture conditions, markedly intensified chemical weathering (decrease of Rb/Sr) and denudation (increased mica, chlorite and hornblende contents) occurred in the upper catchment of Orog Nuur, where the source terranes were broadly occupied by felsic/alkaline and patchy mafic plutonic rocks (Fig. 6-1B and 6-3). In addition, as suggested by Millot (1970), when hypersaline brines reach saturation, alkaline earth carbonates will be the first precipitates followed by calcite and aragonite. Thus, an immense amount of alkaline carbonates and subsequent authigenic calcite have been generated from the felsic and alkaline precursors, causing a distinct alkaline environment (higher authigenic productivity) in the Holocene. Thus, only the biplot of Ca vs. Al/Si has rendered a sound and distinct picture of conditions of the Holocene relative to late Pleistocene sediments.
Fig. 6-6. Schematic model of the integrated past environmental change, land surface processes and provenance signals (carbonate geochemistry) of the Orog Nuur catchment over the last ~50 ka. The eastern parts of Khangai Mountains (higher reach of the Orog Nuur catchment) with altitudes between 3,500 m and 3,700 m asl. have no modern glaciers. More details regarding glacial and vegetation developments in the catchment are given in Lehmkuhl and Lang (2001), Rother et al. (2014), and Lehmkuhl et al. (2016). Distinct geochemical signals for each phase also refer to the table in supplementary material of this paper.

In summary, influences from the integrated past environment (weathering and land surface processes) and provenance signals cannot be separately discerned in the arid context. They more likely represent inherently intercorrelated mechanisms regarding the bulk-geochemistry of the lacustrine sediments (Fig. 6-6).
6.5.4. Summary of coupled paleoenvironmental, weathering, catchment land surface processes, and provenance signals over the past ~50 ka BP in the Orog Nuur catchment

The overall knowledge gained above has allowed gleaning of the hydro-geochemical implications of the Orog Nuur water body, as well as the reconstruction of paleoenvironmental conditions and provenance signals in the drainage catchment (Fig. 6-6).

6.5.4.1. Unit I (~50--19 cal ka BP): shallow to lentic water body, moderate catchment weathering

Ample proxy and modelling evidence illustrates that it was generally humid in arid northwestern China over MIS 3 (Herzschuh, 2006; Yu et al., 2007). It has been suggested that this may have been caused either by the strengthening of the Asian moisture-laden monsoon or by a strengthened moisture supply by the westerlies (Yang and Scuderi, 2010). This enhanced moisture supply is documented in the Orog Nuur sediment core by high amounts of clay and silt, and is also indicated by a high abundance of the minerals mica and chlorite that are fluvially transported to the lake. Factor 4 elements, plagioclase, and K-feldspar retain generally high levels in Unit I, indicating allogenic fluvial input linked to adjacent source lithotypes in the catchment (Fig. 6-6). On the other hand, however, several intercalated sand layers with corresponding spikes in the C/N$_{atomic}$ ratio point to sporadic desiccation of the water column and abrupt fluvial-induced allogenic terrestrial input. The depths of these sand layers (playa phases) exhibit broad consistency with the spikes in the elemental variances and the Al/Si ratio (Fig. 6-3). Apart from the sand layers, most phases in Unit I reveal a slightly reducing environment as inferred from the Mn abundance (Fig. 6-3). A moderate weathering rate is demonstrated by the largely higher values of the Rb/Sr ratios throughout Unit I. In summary, Unit I developed in a humid environment with regular riverine inflows of the Tuyn Gol. Throughout the time period of Unit I, the water body was generally shallow and sporadically converted into playa conditions (Fig. 6-6). This generally humid phase in MIS 3 is corroborated by low dust supply in the northwestern Pacific pelagic sequences (Leinen, 1989; Nilson and Lehmkühl, 2001).

6.5.4.2. Unit II (~19--18 cal ka BP): playa phase and minor riverine inflow

This unit, related to the global LGM, is represented by a massive sand layer that marks an abrupt deterioration of the hydro-environment in the catchment (Fig. 6-6). The Orog Nuur was completely desiccated and changed to a playa environment, which served as an allogenic
dust sink with ephemeral alluvial/fluvial deposition. In a modern context, aeolian silts and mobile dunes were generally accumulated in the (winter monsoon) downwind direction, namely the southeastern section of the Orog Nuur (Lehmkuhl and Lang, 2001). The Factor 4 elements, mud clay, and fluvial elastic bearing minerals mica, chlorite, plagioclase, and hornblende all exhibit drastically declining contents due to the virtual absence of argillaceous sediments (Fig. 6-3). Conversely, allogenic K-feldspar displays an abrupt increase related to the sharply increased contribution of feldspar-bearing sand. The $C/N_{atomic}$ ratios with broadly greater values than 20 also suggest a more frequent input of allogenic matter. The slightly reduced redox condition was broken down, as shown by extremely low concentrations of Mn (Calvert and Pedersen, 2007; Wirth et al., 2013). The \textit{in situ} weathered materials from the higher catchment in the Khangai Mountains were preserved locally due to reduced fluvial transport capacity, and thus were seldom transported into the Orog Nuur.

6.5.4.3. Unit III (~18--13 cal ka BP): shallow saline lake, moderate weathering in higher catchment

This period corresponds with the commencement of the last deglaciation in the southern Mongolian Plateau. Climate amelioration after the LGM led to the melting of glaciers (Rother et al., 2014) in the higher Khangai Mountains and resulted in a significantly raised amount of riverine inflows into the Orog Nuur (Fig. 6-6; $C/N_{atomic}$ exhibits slightly higher values relative to Unit I). The water body was instantly recovered to a state that is comparable with hydrological conditions prior to the LGM. The relatively stagnant environment is also demonstrated by high Mn abundance and low $C/N_{atomic}$ ratios (Fig. 6-3). The Factor 4 elements Si, Al, and Fe exhibit similar abundances relative to those in Unit I, suggesting analogous hydro-geochemical and moderately higher catchment weathering conditions (Figs. 6-4B and 6-6). A slightly increased Cl abundance implies raised salinity of the water body in contrast to Unit I (Sinha et al., 2006). In contrast, Factor 2 proxies Ca, calcite, and CaCO$_3$ are low compared to the older late Pleistocene units, indicating a broadly unchanged authigenic condition within the lake system. Furthermore, similar Rb/Sr ratios relative to those in Unit I also reflect a largely unchanged weathering intensity in the catchment.

6.5.4.4. Unit IV (~13--11 cal ka BP): playa phase with slightly more riverine inflows relative to LGM

This unit again, as in the LGM, is represented by a sand layer (Fig. 6-4B). It corresponds to a climate deterioration episode associated with the late glacial Younger Dryas event. Although
the Orog Nuur system did not completely turn into a playa system as during the LGM (Unit II; Fig. 6-4B), it experienced repeated desiccations giving rise to the deposition of coarse sands brought in by fluvial and aeolian processes (Fig. 6-6). The sharp decrease in clay and silt-clay is displayed by exceedingly low abundances of Fe, Mn and Co, whereas marked fluctuations in C/N\textsubscript{atomic} ratios hint at the frequent occurrence of allogenic fluvial inputs into the playa system (Fig. 6-3). In addition, the (i) sand layer, (ii) reduced run-off input, and (iii) varved sediments altered to unvarved strata related to the Younger Dryas are also documented in the nearby lacustrine sequence of Ulaan Nuur in the Valley of Gobi Lakes (Fig. 6-1A; Lee et al., 2011), in the Lake Tana in northern Ethiopia (Lamb et al., 2007), and in the Lake Mondsee in Europe (Lauterbach et al., 2011), respectively. These features presumably characterize a benchmark lithofacies in the lacustrine sequences in the Gobi Desert of Mongolia or even on a larger northern hemispheric scale. In particular, this YD event-related Ca depletion with sharp boundaries at c. 11,500 and 12,500 cal a BP is also clearly recorded in the varved lacustrine core from Lake Mondsee (Luterbach et al., 2011), albeit the corresponding archive is not a sand layer as in this study in the desert realm.

6.5.4.5. Unit V (<~11 cal ka BP): lentic hypersaline lake with abruptly increased terrigenous inputs and authigenic productivity

An abrupt recovery of lacustrine conditions marks the termination of the late glacial stage as a chronological benchmark in the Orog Nuur catchment. This rapid increase of Ca abundance linked to the ameliorated Holocene climate is also recorded in Lake Mondsee in the northeastern Alps (Lauterbach et al., 2011). The granulometric composition is akin to that of Units I and III with slightly higher clay and silt concentrations (Fig. 6-2; Al/Si ratio in Fig. 6-3). The most remarkable feature of the Holocene phase is the amount of hornblende and calcite corresponding to high Ca and CaCO\textsubscript{3} concentrations that are significantly greater relative to late Pleistocene units (Fig. 6-5). This feature suggests a considerably different hydro-geochemical habitat associated with paleoclimatic amelioration. The characteristic presence of carbonate indicates a predominant alkaline environment (higher Cl content) with abundant moisture supply and raised authigenic productivity (Wünnemann et al., 2010). This postulation is reinforced by the distinct assemblage of Ca in the biplot against Al/Si (Figs. 6-4B and 6-5; Norman and De Deckker, 1990). Another reason for its occurrence, however, is that the calcite may also result from its recrystallization from detrital precursors (neogenic calcite; Pettijohn et al., 1973). In this case, more eroded clastic materials from the northern felsic and alkaline source terranes were brought into the Orog Nuur (Figs. 6-1B and 6-6).
However, in terms of late Quaternary terrestrial (lacustrine) sediments, this diagenesis (recrystallization) may only have exerted limited influence on the bulk-geochemistry relative to the climate-induced calcite precipitation as well as allochthones input (Pettijohn, 1973; Yu et al., 2016). Furthermore, the significantly increased input of weathering materials is also demonstrated by the sharp increase of the Rb/Sr ratio (Fig. 6-3). In general, the higher Holocene lake level is in agreement with that from Lehmkuhl and Lang (2001). In the Baikal catchment further to the north (Fig. 6-1A), a wealth of palynological signals was assembled and assessed by Tarasov et al. (2007), who revealed a broadly warm and humid early Holocene as well as a deteriorated climate since the mid-Holocene. Nonetheless, in this study, due to the loss of the uppermost 24 cm of sediments and a relatively high uncertainty in the Holocene age in the Bayesian age model (Fig. 6-2), a feasible interpretation for the late Holocene signals is difficult to construct. Accordingly, the lentic hypersaline habit proposed here might be restrained to the early- to mid-Holocene period.

In summary, the distinct Holocene water body is attributed to (i) a more intensively weathered felsic/alkaline material transported from the higher catchment into the Orog Nuur depocenter, and (ii) sharply increased authigenic productivity of the alkaline environment thereafter.

6.6. Conclusions

We present a continuous, high-resolution elemental record attained in the lacustrine sequence of Orog Nuur, southern Mongolia. An integrated paleoenvironmental and provenance history in the Gobi Desert that trace back to the MIS 3 are outlined for the first time.

To constrain the data quality, elements with high error margins relative to measured peak areas, and those elements/proxies under a significance level during the robust multivariate statistics are ruled out for further implications. As determined by robust multivariate statistics, the bulk-geochemistry of the Orog Nuur core sediments are governed by Factor 1 (grain-size composition), Factor 2 (authigenic productivity in the saline/evaporitic environment: Ca, Cl, CaCO₃, Factor 3 (allochthonous organic material input: TOC, C/Natomic, and Factor 4 (fluvial terrigenous input, as well as quasi-constant aeolian input through the late Quaternary period: Al, Si, K, Ti, Fe, chlorite, and hornblende). As inferred from the biplot of Ca vs. Al/Si, disparate source lithotypes along with authigenic productivity existed before and after Termination I. In contrast to the late Pleistocene, the Holocene was dominated by a distinctly high productivity alkaline environment due to the increased hydrodynamic strength of riverine inflow and intensified source rock weathering/erosion in the upper catchments of Orog Nuur.
In order to gain a better understanding of the bulk-geochemistry of lake sediments, the coupled provenance and environmental signatures, such as weathering and land surface processes in the catchment, need to be systematically discerned. Thus, considering the bulk-geochemistry of lacustrine sediments, paleoclimate would not be the sole governing factor; the coupled alteration of precursor rocks and accompanying decomposition / denudation intensity, as well as the transportation process may exert pivotal influences.

In the arid realm of Gobi Desert of Mongolia, two coarse sand layers corresponding to the LGM and Younger Dryas are present. In the Gobi Desert, these two layers provide a potential opportunity to act as chronological benchmarks. However, more investigation needs to be carried out to test the reliability of these beds on larger spatial scales and their synchrony in time.

**Table 6-S1** Synoptic description of the coupled paleoenvironmental and provenance signatures during the past ~50 ka BP as inferred from the lacustrine sequence of Orog Nuur. A schematic model comprising these factors is proposed in Fig. 6-6 in the main text.

<table>
<thead>
<tr>
<th>Lithostratigraphic units</th>
<th>Corresponding ages (cal ka BP)</th>
<th>Water column and climatic interpretations</th>
<th>Broad source lithotypes and land surface processes</th>
<th>Distinct bulk-geochemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>~50--19</td>
<td>shallow to lentic water body</td>
<td>Weathering of felsic and few mafic plutonic rocks</td>
<td>High S, Al, and Si; low Cl, Ca, calcite and hornblende</td>
</tr>
<tr>
<td>II</td>
<td>~19--18</td>
<td>arid playa phase</td>
<td>Intensified aeolian sands deposited in fluvial coarse-grained sediments</td>
<td>High K-Feldspar, C/N ratio; low terrestrial elements, mica, chlorite, and calcite</td>
</tr>
<tr>
<td>III</td>
<td>~18--13</td>
<td>shallow saline lake</td>
<td>Felsic and few mafic plutonic rocks similar like phase I</td>
<td>High S and Co; low Ca, calcite and hornblende</td>
</tr>
<tr>
<td>IV</td>
<td>~13--11</td>
<td>arid playa phase</td>
<td>Intensified aeolian sands input and seldom fluvial activity</td>
<td>High C/N ratio; low terrestrial elements and Ca/CaCO$_3$</td>
</tr>
<tr>
<td>V</td>
<td>&lt;~11</td>
<td>lentic &amp; hypersaline water body</td>
<td>alkaline, felsic, and few mafic plutonic rocks, together with intensive erosion of bedrocks</td>
<td>High Ca, Cl, calcite, mica, chlorite and hornblende; low S, quartz, plagioclase, and K-feldspar</td>
</tr>
</tbody>
</table>
Fig. 6-S1. Dispersion plots of the major and trace element concentrations (peak areas) according to their stratigraphic units. Numbers of observations for each unit are marked on the upmost axis. The median values are linked with dash lines, while the upper and lower quartiles are marked as error bars.
7. Synthesis: Paleoclimatic implications from late Quaternary terrestrial archives in the Gobi Desert

This dissertation presents results from the multidisciplinary study on terrestrial archives embracing aeolian, fluvial, alluvial and lacustrine sediments in the arid realm, and their corresponding thermal and moisture implications. To close the loop of this dissertation, main thermal and moisture history of the Gobi Desert of Mongolia is illustrated in Fig. 7-1. The core part is summarized as follows, reflecting the significant findings in this research.

Fig. 7-1: Synoptic compilation of hydrologic, vegetation and glacial history of the Orog Nuur catchment over the last ~50 ka. Playa & dune phase is recovered from the granulometric and lithostratigraphic characteristics of the core ONW II. Likewise, this late Glacial high lake levels are also recorded in the Ejina Basin as lacustrine facies.

7.1. Bulk-geochemistry of different terrestrial archives in the arid realm and their corresponding implications for the paleoenvironmental, pedogenesis and diagenesis processes

A practical strategy is presented to discriminate sediment archive properties and thereafter sequence the controlling factors of sedimentary processes. The considered records of northern Ejina Basin can be discriminated into three broad lithological units: basal aeolian strata, lacustrine strata and the uppermost poorly-sorted mixture of coarse sand and gravels.
Elemental characteristics in conjunction with the granulometric composition in different sediment archives in the northern Ejina Basin are obtained. Aeolian sands have high contents of Zr, Hf, Ba and Si. Especially Hf can be regarded as good indicator to discriminate the coarse sand proportion. Sandy loess has high contents of Ca and Sr which both exhibit broad correlations with medium to coarse silt proportions. Lacustrine clay has high contents of felsic, ferromagnesian and mica source elements. Fluvial sands have distinctly high contents of Mg, Cl and Na which are enriched in evaporate minerals. Alluvial gravels have especially high contents of Cr which may originate from nearby Cr-rich bedrock.

Multivariate statistical methods applied to geochemical compositions is a useful tool to discriminate archive types in our case. Considering the suite of late Quaternary sediments in the arid realm, temporal variation of the bulk-geochemistry can be well explained by four semi-quantified sediment components: (weak-) weathering intensity, silicate-bearing mineral abundance, saline / alkaline influence of sediments, and the quasi-constant aeolian input into the arid endorheic basin system. In contrast, pedogenesis and diagenesis exert only a limited influence.

7.2. Sedimentological, palynological and ostracod studies of the lacustrine sediments and their references to the paleohydrological and vegetation history

A multidisciplinary investigation is conducted on a 13.35 m lacustrine core retrieved from Orog Nuur, in the Gobi Desert of Mongolia. Methods embracing sedimentological, geochemical, palynological and ostracod studies combined with sets of dated terrace ridges and moraines were conducted to illustrate the vegetation development, hydrologic and paleoglacial history during the last ~ 50 ka. For the first time, in the Gobi Desert, semi-quantified moisture and thermal sequences that track back to the MIS 3 are presented.

In Gobi Desert of Mongolia, the MIS 3 experienced sufficient moisture supply in particular between ~36 ka and ~24 ka; MIS 2 was subjected to cool temperature and moisture-deficient, which was interrupted by two exceedingly cold and dry playa phases related to the LGM and YD event; The early Holocene exhibited ameliorated climatic condition characterized by higher lake levels. In addition, a sharp transition of Termination I is illuminated by palynological and geochemical imprints. Lower area of the Orog Nuur catchment was dominated by Artemisia steppe community in the late Pleistocene and altered to Chenopodiaceae desert steppe in the Holocene. Water body in the Holocene appears to be a
distinct alkaline environment which was subjected to frequently allogenic input and disturbance of the late Pleistocene anoxic states.

The main humid pulse in MIS 3 might have been the main driving mechanism for the MIS 3 glacial advance, while the pronounced low temperature in the higher elevated catchment in the eastern Khangai Mountains is presumably the forcing factor for the LGM glacial advance. The early Holocene in the Gobi Desert experienced the other humid pulse, which was concurrent with the lacustrine condition and the degradation of the permafrost features as well as the glacial retreat. On the other hand, four arid playa phases (~47 ka, ~37 ka, ~19 ka and ~13~11 ka) were determined, of which the latter two sand layers (i.e., the LGM, YD event, respectively) recorded in the Orog Nuur may provide an opportunity to be labelled as chronological benchmarks for other lacustrine sequences in the Gobi Desert of Mongolia. Nonetheless, further investigations still need to be carried out to test its reliability in a larger spatial scale.

In the central to southern Mongolia, the late Quaternary moisture and thermal history may be modulated, if not controlled, by coupled atmospheric components embracing both Westerlies and the propagation of the East Asian Summer Monsoon into the Asian interior, albeit more details with respect to the quantified contribution from these systems remain an open question.

7.3. Geochemical imprints of the lacustrine sediments and integrated paleoenvironmental and provenance implications

Based on a continuous, high-resolution elemental records attained in the lacustrine sequence of Orog Nuur, Gobi Desert of Mongolia, the coupled paleoenvironmental and provenance history are outlined. Due to the predominant sediments of mud- to siltstone, Al and Si display broadly identical pattern in the lake sediments. Ca behaviors may be ascribed to the authigenic calcite abundance. As equally applicable to pelagic sediments, Mn and Co may act as indicator for the redox condition in lacustrine realm. On the other hand, owing to the short burial time and weak diagenetic influence, Fe is not an indicator to the diagenetic processes. Likewise, Zr may be associated to fluvial clastic in relation to the lithotypes but not necessarily linked to the aeolian sands concentration as in the pelagic realm. Furthermore, S in lake sediments may denote the redox condition and K is more likely linked to the K-feldspar which is associated with the allogenic fluvial inputs.
The two sand laminations corresponding to the LGM and YD are dominated by coarse sands. In the Gobi Desert of southern Mongolia, these two laminations provide a potential opportunity to be regarded as chronological benchmarks. However, more investigation needs to be conducted to test its reliability in larger spatial scales.

As inferred from the biplot between Ca and Al/Si, disparate source lithotypes may exist before and after the Termination I. The Holocene appears to be a distinct alkaline environment relative to the late Pleistocene. This may be ascribed to either strengthened hydrodynamic strength of the riverine inflows and/or intensified source rocks erosion in the upper catchments of Orog Nuur. In order to gain a better understanding of the bulk-geochemistry of lake sediments, the coupled provenance and environmental signatures need to be properly discerned. On the other hand, in arid realm as Gobi Desert of Mongolia, sands may exert a considerable influence on the bulk-geochemistry of lacustrine sediments.

In summary, considering the bulk-geochemistry of lacustrine sediments, paleoclimate would not be the solely governing factor, the coupled alteration of precursor rocks and decomposition intensity may exert pivotal influences.

7.4. Outlook

For the upcoming decades, several pivotal but challenging tasks need to be carried out to better decipher the paleoclimate signals and controlling atmospheric circulations in the arid central Asia, on perspectives of both terrestrial and pelagic archives. A fundamental step is to refine the understandings concerning the proxies and their corresponding paleoenvironmental implications. The tasks are assembled as follows:

(1) As the purposes of the paleoclimatologist are primarily high resolution and longer time spanning of the repository, it is therefore indispensable to take part in IODP / ECORD excursion in e.g., NW Pacific, retrieving continuous, high resolution and well constrained chronological framework pelagic sequences;
(2) Get innovative methods, e.g., neodymium or other isotopes signals incorporated in the pelagic sediments, to discriminate Westerlies signals from EASM, and build thereby robust Westerlies Intensity indices. Eventually, compare with our published arid central Asia data in this dissertation. Thereafter, it is possible to define and decipher the moisture provenance in the Gobi Desert of Mongolia;
(3) Investigate long time scale lacustrine core retrieved in southern Mongolia, from where
great scarcity of paleoenvironmental repository exists. Alternatively, terrestrial drilling
project (e.g., lacustrine, loess-paleosol sequences) could be carried out underneath the
pathway of the mid-latitude Westerlies. Compared to the pelagic sequences,
environmental interpretations concerning those elements such as trace and REE elements
abundance as well as non-conventional isotopes signals in lacustrine realm are less studied
and understood. A time spanning of greater than the late glacial period is in urgent need in
order to gain a comprehensive understanding of the kinetics of central to eastern Asian
paleoclimate patterns;

(4) Gain robust and quantitatively defined indices for thermal and moistures signals.
Promising proxies are geobiology (pollen / ostracod / diatom), geochemistry (elements,
minerals and non-conventional isotopes) and geophysics (paleomagnetic), of which the
paleomagnetic is of special importance because of its application of refinement of the
surface sediments’ age model and thereafter the estimation of reservoir effect from the
radiocarbon determined age model;

(5) In particular, the geologic repository may not illustrate complete consistency with the
numerical simulation results (e.g., Jiang et al., 2012). It is therefore indispensable to
provide high resolution, (semi-) quantified proxy sequence as parameters for the modelers.
In turn, the high resolution simulation results should be taken into account in trying to
better understand the atmospheric patterns and underlying mechanisms of the
paleoclimate changes.

The fulfillment of above points will largely fill the knowledge gaps in the arid central Asia
and therefore benefit the paleoclimatological communities.
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Appendix

Tab. A1: Ratios from major elements to oxides and corresponding functions.

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Name</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂O</td>
<td>Sodium Oxide</td>
<td>1.3480</td>
</tr>
<tr>
<td>MgO</td>
<td>Periclase</td>
<td>1.6583</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Corundum</td>
<td>1.8895</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Quartz</td>
<td>2.1393</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>Phosphorus Pentoxide</td>
<td>2.2914</td>
</tr>
<tr>
<td>K₂O</td>
<td>Potassium Oxide</td>
<td>1.2046</td>
</tr>
<tr>
<td>CaO</td>
<td>Calcium Oxide</td>
<td>1.3992</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Rutile</td>
<td>1.6685</td>
</tr>
<tr>
<td>MnO</td>
<td>Manganosite</td>
<td>1.2912</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>Hematite</td>
<td>1.4297</td>
</tr>
</tbody>
</table>

\[ b_n = a_n \times r_n/10^4 \quad \text{Eq. (A.1)} \]

\[ b_n' = b_n \times 100/\sum_{n=1}^{10} b_n \quad \text{Eq. (A.2)} \]

In Eq. (A.1), \( a_n \) denotes original major elements abundance in ppm. \( b_n \) denotes oxide data. \( r \) is ratio in above table. \( n \) ranges from 1 to 10, i.e., ten major elements, respectively. In Eq. (A.2), \( b_n' \) is the normalized oxides in wt %, which is used in the multivariate statistics.
R script employed in the dissertation

# this script is part of the manuscript ‘Discriminating sediment archives and sedimentary processes in the arid endorheic Ejina Basin, NW China using a robust geochemical approach’ by Yu et al. in *Journal of Asian Earth Science*, and manuscript ‘Geochemical imprints of coupled paleoenvironmental and provenance change in the lacustrine sequence of Orog Nuur, Gobi Desert of Mongolia’ by Yu et al.

# load the 'boot' package, which must be installed
library(boot)
library(Hmisc)

# read in element data from clipboard, as in S3.
data<-read.table("clipboard",dec="",header=TRUE,sep='\t')

# row names of archive types and sequence number

# column names of elements (raw data set)
names2<-c("Na","Mg","A1","Si","P","K","Ca","Mn","Fe","Ti","S","Cl","V","Cr","Ni","Cu","Zn","Ga","As","Rb","Sr","Y","Zr","Nb","Ba","Nd","Hf","W","Pb","Th")
rownames(data)=make.names(names1,unique=TRUE)
colnames(data)=make.names(names2)
data # shows the data matrix with specific row names

# read in grain size AND element data from clipboard, as in S3.
data_all<-read.table("clipboard",dec="",header=FALSE,sep='\t',stringsAsFactors = FALSE)
data_all <- do.call(rbind, data_all)
data_all2 <- apply(data_all, 1,as.numeric)
data_all2 <- t(as.numeric(data_all))

# [R,P] = corr(data_all, data_all)
Cor<-rcorr(data_all2) # generate correlation matrix and corresponding P values
dlmwrite('R1.txt',Cor$r)
dlmwrite('P1.txt',P) # imported into Excel>>R<-read.table("clipboard")
P <- read.table("clipboard")

mysub <- function(x) {sub("",".",x)} # create a function to replace "," with ".

dataR <- apply(R, 2, mysub)

dataR <- data.frame(apply(dataR, 2, as.numeric)) # change the matrix as numeric

dataP <- apply(P, 2, mysub)

dataP <- data.frame(apply(dataP, 2, as.numeric))

R <- R1
P <- P1

data_matrix <- (R)

data_matrix2 <- matrix(nrow = length(P), ncol = length(P))

for (C in 1:40) # 40 can be dim(data[40])
{
    for (Ro in 1:40)
    {
        if (P[Ro, C] < 0.05) {data_matrix2[Ro, C] <- data_matrix[Ro, C]}
        # set criterion: P<0.05, can be set different, criterion here, >.5, this need to be improved later
    }
}

data_heatmap <- heatmap(data_matrix2, Rowv = NA, Colv = NA, col = topo.colors(256), scale = "column", margins = c(5, 10))

install.packages("lattice")

library(lattice)

levelplot(data_matrix2, col.regions = topo.colors(256))
circle <- function(center = c(0, 0), npoints = 100) {r = 1
+ tt = seq(0, 2*pi, length = npoints)
+ xx = center[1] + r * cos(tt)
+ yy = center[1] + r * sin(tt)
+ return(data.frame(x = xx, y = yy))
+ }

corcir = circle(c(0, 0), npoints = 100)

loadings_16 <- as.data.frame(vRFs)

arrows = data.frame(x1 = c(0, 0, 0, 0), y1 = c(0, 0, 0, 0), x2 = loadings_16$vRF1, y2 = loadings_16$vRF2)

ggplot()
+ geom_path(data = corcir, aes(x = x, y = y))
+ geom_segment(data = arrows, aes(x = x1, y = y1, xend = x2, yend = y2))
> robustfa_30 <-
factorScorePfa(sum, factors=4, covmat=covwt, cor=TRUE, rotation="varimax", scoresMethod="regression")

> rownames(robustfa_30$loadings) = make.names(names2, unique=TRUE)
> scores_30 = as.data.frame(robustfa_30$scores)

> ggplot(data=scores_30, aes(x=Factor1, y=Factor2, label=rownames(scores_30))) + geom_hline(yintercept=0) + geom_vline(xintercept=0) + geom_text(colour="tomato", alpha=0.8, size=4) + ggtitle("Scores Plot")  # scores plot

> arrows_30 = data.frame(x1=c(0,0), y1=c(0,0), x2=loadings_30$RF1, y2=loadings_30$RF2)
> ggplot()+geom_path(data=corcir, aes(x=x, y=y))+geom_segment(data=arrows_30, aes(x=x1, y1=x2, yend=y2))+geom_text(data=loadings_30, aes(x=RF1, y=RF2, label=rownames(loadings_30)))+geom_hline(yintercept=0)+geom_vline(xintercept=0)+geom_text(x="Robust Factor 1", y="Robust Factor 2") + ggtitle("Loadings Plot")  # loadings plot for robust data

> RF1 <- robustfa_16$scores[,1]
> RF2 <- robustfa_16$scores[,2]
> labs_robustfa <- rownames(robustfa_16$scores)
> RF_scores <- data.frame(cbind(RF1, RF2))
> rownames(RF_scores) <- labs_robustfa

> ggplot(RF_scores, aes(RF1, RF2, label=rownames(RF_scores))) + geom_text()
> scores_16 = as.data.frame(robustfa_16$scores)

> ggplot(data=scores_16, aes(x=Factor1, y=Factor2, label=rownames(scores_16))) + geom_hline(yintercept=0)+geom_vline(xintercept=0)+geom_text(colour="tomato", alpha=0.8, size=4) + ggtitle("Scores Plot")  # scores plot for robust data
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Abstract

Considerable efforts have been devoted to disentangle the late Quaternary moisture and thermal evolution of arid central Asia. However, an array of paramount aspects has inhibited our complete understanding of the broad pattern of Quaternary moisture and thermal history of arid central Asia and underlying mechanisms.

The Ejina Basin, with its suite of different sediment archives, is known as one of the main sources for the loess accumulation on the Chinese Loess Plateau. In order to understand mechanisms along this supra-regional sediment cascade (aeolian, fluvial and alluvial sediments), it is crucial to decipher the archive characteristics and formation processes. Five sediment archives from three lithologic units exhibit geochemical characteristics as follows: (i) aeolian sands have high contents of Zirconium and Hafnium, whereas only Hafnium can be regarded as a valuable indicator to discriminate the coarse sand proportion; (ii) sandy loess has high Calcium and Strontium contents which both exhibit broad correlations with the medium to coarse silt proportions; (iii) lacustrine clays have high contents of felsic, ferromagnesian and mica source elements e.g., Potassium, Iron, Titanium, Vanadium, and Nickel; (iv) fluvial sands have high contents of Magnesium, Chlorine and Sodium which may be enriched in evaporite minerals; (v) alluvial gravels have high contents of Chromium which may originate from nearby Cr-rich bedrock. Temporal variations can be illustrated by four robust factors: weathering intensity, silicate-bearing mineral abundance, saline / alkaline magnitude and quasi-constant aeolian input. In summary, the bulk-composition of the late Quaternary sediments in this arid context is governed by the nature of the source terrain, weak chemical weathering, authigenic minerals, aeolian sand input, whereas pedogenesis and diagenesis exert only limited influences. Hence, here demonstrates a practical geochemical strategy to discriminate sediment archives and thereafter enhance our ability to offer more intriguing information about the sedimentary processes in the arid central Asia.

On the other hand, two parallel cores (ONW I, 6.00 m; ONW II, 13.35 m) were retrieved from lake Orog Nuur, in the Gobi Desert of Mongolia. Ample evidences reveal a marked moisture pulse during the Marine Isotope Stage 3 (~36~24 ka) which might have induced the maximum last glacial expansion in the high elevated Khangai Mountains. A sharp transition of Termination I (~11 ka) is illuminated by geochemical, palynological, and ostracod data. Lower area of the Orog Nuur catchment was dominated by Artemisia steppe community in the late Pleistocene and altered gradually to Chenopodiaceae desert steppe in the Holocene. The early Holocene is also characterized by relatively humid environment, albeit discordant
downcore variability of moisture and thermal signals can be derived between palynological and bulk-geochemical signals. Water body in the Holocene appears to be a distinct alkaline environment which was subjected to frequent allogenic input and disturbance of the late Pleistocene anoxic states. These two humid pulses may be the trait of a larger scale of arid central Asia that would be documented in a suite of archives. Considering kinetics, a coupled atmospheric component comprising both East Asian Summer Monsoon and strengthened Westerlies moisture supply seems to be the driving mechanism, and this coupled mode might have been modulated broadly by boreal insolation variances. On the other hand, four major harsh climatic phases were documented in the core at ~47 ka, ~37 ka, ~19 ka (gLGM) and ~13–~11 ka (Younger Dryas) as playa phases. Reduced conveying of the Westerlies moisture along with the retreated East Asian Summer Monsoon might have contributed to these playa phases in the Gobi Desert.

Continuous, high-resolution elemental abundances at a 1 cm interval were examined on core ONW II. Due to the predominant clay or silty-clay fraction in the sediments, Aluminium and Silicon display broadly identical pattern. Calcium behaviors may be ascribed to the authigenic calcite variance. Manganese and Cobalt act as sound indicator for the redox condition. Owing to the short burial time and weak diagenetic influence, Iron is not an indicator to the diagenetic processes. Likewise, Zirconium may be associated to fluvial clastic in relation to the lithotypes but not necessarily linked to the aeolian sands relative to that in the pelagic realm. Furthermore, Sulfur in lake sediments may denote the redox condition and Potassium is more likely linked to the K-feldspar which is associated with the allogenic fluvial inputs. The two sand layers corresponding to LGM and YD event were dominated by coarse sands. In the Gobi Desert of Mongolia, these two laminations provide an opportunity to be regarded as potential chronological benchmarks. As inferred from the biplot between Ca and Al/Si, disparate source lithotypes may exist before and after Termination I. The Holocene appears to be a distinct alkaline environment compared with the late Pleistocene. This may be ascribed to strengthened fluvial morphodynamics of the riverine inflows and intensified erosion of source rocks in the upper catchment of the Orog Nuur. In exceptionally arid realm, sands may exert significant influence on bulk-geochemistry of the lake sediments. In summary, considering the bulk-geochemistry of lacustrine sediments, paleoclimate would not be the solely governing factor, the coupled alteration of precursor rocks and decomposition intensity may also exert pivotal influences.
Zusammenfassung

Beachtliche Versuche sind unternommen worden, um die hygrische und thermische Entwicklung des ariden Zentralasiens im Spätquartär zu entschlüsseln. Allerdings sind das allgemeine Schema der hygrischen und thermischen Entwicklung des ariden Zentralasiens im Quartär sowie die zugrundeliegende Mechanismen noch nicht umfassend verstanden.


Zwei parallele Kernbohrungen (ONW I, 6.00 m; ONW II, 13.35 m) vom Orog Nuur (Nuur = See) See in der Gobi Wüste der Mongolei wurden näher analysiert. Es gibt viele Belege für einen ausgeprägten Feuchtigkeitsimpuls während des marinen Isotopenstadiums 3 (MIS 3; ~36–24 ka), welcher auch den maximalen letztglazialen Eisvorstoß im Khangai Gebirge hervorgerufen haben könnte. Ein scharfer Übergang am Ende der letzten Eiszeit (~11 ka) wird mittels geochemischen, palynologischen und Ostrakoden daten nachgewiesen. Das untere