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**LATE QUATERNARY VEGETATION HISTORY
AND CLIMATE CHANGE IN THE GOBI DESERT,
SOUTH MONGOLIA**

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**LATE QUATERNARY VEGETATION HISTORY
AND CLIMATE CHANGE IN THE GOBI DESERT,
SOUTH MONGOLIA**

By

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Dedication

I dedicate my research work to

- **My parents**

I can't repay the lessons that you taught when I was small
Or give you gift for gift the daily treasures I recall
I can't return encouragement and loving words of praise
In quite the way you did for me through all my childhood days
But there is one gift that I can give., it's all the love you've earned
For love is what you always taught. And love is what I learned.

- **My uncles and my cousins**

Abdul Rauf, Said Bacha, Nowsherawan, Muhammad zahir and Arshad iqbal
who are no more alive to see me prosperous. I shall say for them; everything
that has a beginning has an ending. ALLAH keeps their souls in peace and
hope that all will be well at their eternal lives

You never said we are leaving
you never said good bye
you were gone before I knew it
and only ALLAH knew why

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Foreword

The compilation of this thesis represents my PhD studies at the Albrecht-von-Haller-Institute for Plant Sciences, Georg-August University of Göttingen, Germany. The research work was carried out at the Department of Palynology and Climate Dynamics for the award of PhD degree in Biological diversity and Ecology for consecutive three years since June, 2008 to May, 2011. The project was completed under the supervision of Dr. Frank Schlütz, Prof. Hermann Behling and Prof. Markus Hauck.

The research work is a collaborative part to the project “Late Pleistocene, Holocene and ongoing Geomorpho-dynamics in the Gobi Desert., South Mongolia” under the supervision of Prof. Frank Lehmkuhl, RWTH Aachen (LE 730/16-1). The project was mainly funded by German Research Foundation (Deutsche Forschungsgemeinschaft, DFG). The Higher Education Commission (HEC) of Pakistan and Kohat University of Science and Technology, Kohat (KUST), Pakistan funded my three years scholarship including the AMS radiocarbon dating and palynological analysis of the project. The Mongolian Academy of Sciences (Prof. D. Dorjgotov, A. Tschimegsaichan) extended help during the field work to the visiting team (Prof. Frank Lehmkuhl, Dr. Frank Schlütz and Dr. Thomas Felauer).

The compilation of this dissertation is based on the present synthesis and the following three manuscripts.

1. Murad, W., Schlütz, F., Felauer, T., Mischke, S., Lehmkuhl, F. (submitted). First high resolution palynological record of climate history in the late Quaternary from the high continental Gobi desert of Mongolia.
2. Felauer, T., Schlütz, F., Murad, W., Mischke, S., Lehmkuhl, F. (2012). Late Quaternary climate and landscape evolution in arid Central Asia: A multiproxy study of lake archives Bayan Tohomiin Nuur, Gobi desert, southern Mongolia. *Journal of Asian Earth Sciences*.
3. Murad, W., Schlütz, F., Felauer, T., Mischke, S., Lehmkuhl, F. (in preparation). High resolution palynological record from lake Orog Nuur, southwestern Mongolia: An evidence of climate history during the last 50 ka.

All the results of the research work are presented in the above three manuscripts which are supported by the relevant tables and figures.

I hereby certify that I, as a co-author of the manuscript 2 carried out the pollen laboratory work, microscopic study, pollen data analyses, interpretation and discussion. I also produced the figures and the tables for the manuscript where necessary.

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First and foremost all praises to Almighty, All Gracious, All Compassionate “ALLAH” who blessed me to complete this project. I owe my sincere thanks to my supervisor Prof. Hermann Behling, Department of Palynology and Climate Dynamics, Göttingen for his friendly attitude and constant guidance throughout the duration of my research task.

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The author would like to convey thanks to the Higher Education Commission (HEC) and Kohat University of Science and Technology, Kohat (KUST), Pakistan for the grant of scholarship.

It is an honor for me to express my love and gratitude to my parents, brothers, sisters and all beloved family members; for their moral support and endless love throughout the duration of my studies. I have no suitable words to express my feelings and can fully describe everlasting love of my parents to me. I pay salute to my parents and pray that I may extend every possible help which they need throughout the rest of my life.

I owe my loving thanks to my wife and my son Sayed Muhammad Aayan. They suffered a lot due to my research abroad. It would have been impossible for me to finish this study without the encouragement and mutual understanding of my wife.

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Abstract

Southern Mongolia is a part of the arid to semiarid region of Central Asia and represents a transitional zone between the circulation systems of westerlies and associated North Atlantic Oscillation (NAO), the Asian summer monsoon and the Mongolian High Pressure System (MHPS). The sedimentary records from this geographically important region are a central key to understand past vegetation and climate changes, owing to variations in the intensity of the interacting climate systems. It is imperative to understand the palaeoclimate dynamics and landscape development of arid Central Asia based on past vegetation history and to get a notion about the future environmental conditions under the ongoing Global change.

The available palaeo-vegetation and palaeo-climate data from arid Central Asia are mainly conducted in Northwestern Mongolia and Northwestern China. The present research work focus on palaeo-ecological analyses of two lake archives of southern Mongolia (Bayan Tohomiin Nuur and Orog Nuur). The multidisciplinary analyses of these two sediment cores were carried out to reconstruct lake level changes, palaeo-vegetation and palaeo-climate dynamics and to expose the associated influencing biotic or abiotic factors during the last 50 kilo calibrated years before present (50 ka cal BP). Palynological and geochemical analyses of the Bayan Tohomiin Nuur revealed a detailed history of vegetation and landscape dynamics in continental Central Asia from 15 to 4 ka cal BP. The reconstructed arid climate phases between 12.3- 11.1 and 8.6- 7.6 ka cal BP can be correlated to the Younger Dryas and the 8.2 ka event respectively. Stable and relatively moist conditions occurred in the mid-Holocene from 6.3 to 4.9 ka cal BP. A mid-Holocene climate moisture maximum is attributed to the strengthening of the westerlies. However, the combined influence of the westerlies and summer monsoon caused a quite humid phase just before the Holocene climate optimum, while bordering areas in north and south of the investigation area were dry. The aridity in southern Mongolia increased after 3.8 ka cal BP as inferred from the geochemical record of the lake archive. The palynological study from the sediments of Orog Nuur show reconstructed vegetation and climate history during the last 50 ka. Generally semi humid conditions prevailed between 49.5 and 44.7 ka cal BP, correlating to Marine Oxygen Isotope stage 3 (MIS 3). It is followed by relatively a dry and cool climate from 44.7 to 23.2 ka cal BP corresponding to Marine Oxygen Isotope stage 2 (MIS 2). The increase in the concentration of green algae *Pediastrum* and *Botryococcus* indicate increase in semi arid conditions between 23.2 and 22.7 ka cal BP. The aridity of the climate increases since 18.9 ka cal BP till the onset of early Holocene. Our findings indicate continuous climate oscillations during the documented period of about 50 ka. Generally desert or desert steppe vegetation is prevailing as indicated by *Artemisia*, *Chenopodiaceae* and *Ephedra*.

Our findings show a general consistence to the palaeoclimate data with the surrounding regions of Central Asia. However, further multidisciplinary studies of palaeo-vegetation and palaeo-climate archives from the continental southern Mongolia are emphasized to gain a deeper understanding of the past environmental changes and to decode the complex spatial pattern of climate history of arid Central Asia during the late Quaternary. Such multidisciplinary approach will provide a base to understand the predictions for future environmental changes and will contribute information for nature conservation.

Chapter 1

General Introduction

1.1 Palaeo-climate research background

Mongolia is presenting a wide variety of terrestrial and aquatic habitats. It retains a substantial amount of its natural biodiversity. Two of the world's most biologically outstanding eco-regions, the Daurian steppes and the Altai-Sayan Mountains, lie partly within Mongolia (Bedunah et al., 2006). The country boasts centuries old tradition of nature conservation using protected areas (Johnstad and Reading, 2003). Mongolia is vulnerable to climatic extremes and variability with severe droughts. Climate change is observed at a pronounced pace in some regions of the globe (Chase et al., 2000) where as Gobi desert is climatologically very sensitive to future global change (Batima and Dagvadorj, 1998). Global change studies from the area observed a particularly high increase of temperature during the late 20th century and predict a further high increase of temperature in the 21st century (Dulamsuren et al., 2010). Summer temperature is projected to increase by 2 °C and winter temperature by 1 °C within the next 80 years (Sato and Kimura, 2006). Mongolia's mean annual temperature is increased by 1.8 °C over the last 40 years. This is more than twice the global average increase of 0.7 °C during the past 100 years (Batima, 2006; Trenberth et al., 2007). The late 20th century warming in Mongolia has already resulted the melting of glaciers (Kadota and Davaa, 2005). The rising temperature and uncertainties in precipitation intensity as well as duration associated with a changing climate are likely to increase the impact of climate variability and extremes (Nandintsetseg et al., 2007).

Relatively little is known about the long-term vegetation and climate history of the area or the relative impact of changes in land use, vegetation and climate in the region (Shinneman et al., 2010). The available palaeo-vegetation and palaeo-climate records from Mongolia are reported very recently (Jacoby et al., 2003; Nandintsetseg et al., 2007). These studies have revealed substantial differences in the availability of past moisture. The palaeo-climate records from arid Central Asia show substantial, temporal and spatial variability in the correlation between temperature and moisture availability. The climate models are inconsistent in predicting for future climate warming (Shinneman et al., 2010). Understanding regional vegetation and climate variability on spatial and temporal scales is important both for human and economic development. A better assessment of regional climate variability in Mongolia can reveal the range of climatic conditions experienced during Holocene. Such data can aid in resource management as well as contribute to a greater scientific understanding of such a climatologically unique area. This thesis contributes new proxy records of past ecological and climatic characteristics of the Gobi Altai and Gobi desert during the late Quaternary period. This improved multidisciplinary effort will lead to a better understanding of Central Asian vegetation and climate variability of the past and the underlying forcing mechanisms for vegetation and climate change. The current synthesis will also help to detect the future global changes and conservation managements.

1.2 Research goals and study outline

Mongolian plateau is very important for palaeo-vegetation and palaeo-climate data due to variations in the intensity of the Mongolian High Pressure System (MHPS) which has a strong control on the regional climate of Central Asia. The MHPS drives strong westerly wind system especially in Gobi desert and have reported to occur throughout Quaternary times (Owen et al., 1997). The region has very diverse and extreme continental vegetational and climatic conditions with steppe, dry steppe and desert regions and well forested Khangai, Khentein and Khuvsgul mountainous areas. The mean annual precipitation values are about 300-400 mm (occasionally exceeding 600). The mid-latitude westerlies affect the northwestern part of Central Asia and bring moisture to the western mountain ranges of southern Mongolia (Lehmkuhl and Haselein, 2000).

Interdisciplinary data collection on vegetation and climate change during the late Pleistocene and Holocene has been a focus of attention to understand the regional climatic variability. Although abrupt vegetation and climate changes during the late Quaternary period have been documented in northern Mongolia and northwestern China (An et al., 2000; Li et al., 2004; Qin et al., 2005; Chen et al., 2006; Wang et al., 2005, 2007; Sun et al., 2010) yet their reconstructed approach for vegetation and climate change remain controversial. The Mongolian plateau has relatively few extended records of palaeo-vegetation and palaeo-climatic data. Earlier studies (Fowell et al., 2003; Prokopenko et al., 2007; Rudaya et al., 2008; Schlütz et al., 2008; Wang et al., 2004, 2009) represent short time interval and restricted mainly to Holocene climatic records from lake sediments. These Holocene records were mostly carried out in northwestern and central Mongolia. Additionally, these multi-proxy studies brought up contradictory ideas about vegetation, climate and the associated environmental history. The Gobi desert (southern Mongolia) is of interest for palaeo-vegetation and palaeo-climate studies because it is situated in the triangle of SE Asian monsoon, Indian monsoon and the westerlies. It is a region of strong climatic change (Herzschuh, 2006) and fragile ecosystems. It is, therefore, an archive being very sensitive to any vegetation and climate change and the lake sediments of the region will provide a record of the palaeo-vegetation history and palaeo-climate development.

In general, the major goal of this thesis research is to investigate late Quaternary vegetation history and climate variability of southern Mongolia using the sediments of lakes Bayan Tohomiin Nuur, Orog Nuur and Olgoy Nuur. The main purpose of the research study is highlighted with the help of the following main research headings.

- A. The first scientific objective of our study is to investigate late Quaternary vegetation, climate and landscape history in arid Central Asia with the help of a multidisciplinary research of lake archive Bayan Tohomiin Nuur, Gobi desert, southern Mongolia.

The detail description of the subject above is narrated in chapter 2 and 3 as manuscript 1 and manuscript 2. The geochemical and granulometric analyses of a sediment core from Bayan Tohomiin Nuur have been carried out by Dr. Thomas Felauer; Department of Geography, RWTH Aachen University, Aachen. Waheed Murad; Department of Palynology and Climate Dynamics, Albrecht-von-

Haller Institute for Plant Sciences, University of Göttingen., analyzed palynological record where as ostracod analyses was conducted by Prof. Steffen Mischke., Freie Universität, Institute of Geological Sciences, Berlin. The multiproxy results contribute to investigate the complicated pattern of climate history of Central Asia based on vegetation history under the shifting control of westerlies and the monsoon system. The research task helps to improve the understanding of palaeo-climate development in southern Mongolia during the last ca.15 ka cal BP and reflects different climatic and associated environmental stages. Our high resolution multidisciplinary record from a climatically sensitive shallow lake seems to highlight a detailed history of vegetation and landscape dynamics in high continental Asia from about 15.3 to 3.8 ka cal BP. The reconstructed climatic phases can be correlated the Younger Dryas and the 8.2 ka event respectively. A mid-Holocene climate moisture optimum is attributed to a strengthening of the westerlies. Nevertheless, a combined influence of westerlies and the summer monsoon caused a quite humid phase just before the Holocene optimum, while bordering areas in the North and South were dry. However, further investigations in southern Mongolia are needed to verify such a peculiar climate phenomena for high continental Mongolia to contribute to a secret activity of the complex spatial patterns of climate history in Central Asia (Herzschuh, 2006).

B. The second main objective is to reconstruct late Quaternary vegetation, climate and landscape development in arid Central Asia: A multidisciplinary research of lake archives Orog Nuur, Gobi desert, southern Mongolia.

Detail description of palynological record is given in chapter 4 as manuscript 3 whereas the manuscript regarding the multiproxy study of geochemical, palynological and ostracod analyses is in the process of preparation. The research site has not been investigated so far for palaeo-vegetation studies. Our high resolution geochemical, granulometric, palynological and ostracod analyses of a 1333 cm long sediment core from Orog Nuur represents the first detailed history of vegetation and climate change during the last ca. 50 ka cal BP. The multidisciplinary research study will be providing a base line for further palaeo-vegetation and palaeo-climate research from a climatically sensitive region of continental Central Asia.

More specific objectives of the whole project are:

- i) To carry out the interdisciplinary pollen, non-pollen palynomorphs, geochemical and ostracod studies from Bayan Tohomiin Nuur (BTN) between 15.3 -3.8 ka cal BP (chapters 2 and 3).
- ii) To present the first high resolution palynological, geochemical and ostracod record from Orog Nuur (ONW-II) during the last ca. 50 ka cal BP (chapter 4 for palynological analyses).
- iii) To present the pollen record from Olgoj Nuur (OLG), central Mongolia (chapter 5).
- iv) The multidisciplinary study is also used to test different qualitative approaches suggested for the vegetation and climate reconstruction in the arid Central Asia and to apply the reconstruction methods to the detailed and adequately dated pollen record from Bayan Tohomiin Nuur and Orog Nuur.

- v) To investigate past pollen and fungal diversity of southern Mongolia.
- vi) To reconstruct climate, vegetation and land scape history based on pollen, fungal, geochemical and ostracod records.
- vii) To prepare a master key for pollen grain identified from Bayan Tohomiin Nuur, Orog Nuur and Olgoy Nuur, southern Mongolia (chapter 6).

1.3 General features

The general features about location, soil, water resources, vegetation and climate of the study region with a general overview of the core sites are described as under.

1.3.1 Location

Mongolia is located between 87° 41" and 119° 56" East longitude and 41° 35" and 52° 09" North latitude in the central region of North-East Asia. It stretches 1259 km from North to South and 2392 km from East to West. Mongolia is a vast country with about 1,560,000 km² area and sparsely populated central Asian nation of about 2.7 million people (Rudaya et al., 2008). In general, Mongolia mountains lie at elevations >1500 m whereas Mongolian plains having elevations between 800 to 1500 m. Mongolia has numerous mountain ranges throughout the country including the Great Sayan, Buteel, and Hentei Mountains in the north., Great Hingan highlands in the east., Mongolian Altai and Gobi Altai ranges in the southeast and south and Han-hohii and Hangai Mountains in the west. Mountain peaks >4000 m are concentrated in the Mongolian Altai (Mt. Huiten-Uul at 4374 m) and Hangai Mountains (Mt. Otgon-Tenger at 4031 m). The Gobi desert traverses the country along its southern border with China (Gunin et al., 1999; Jigjidsuren et al., 2003; Johnson et al., 2006; Ariunsuren et al., 2009).

1.3.2 Soil

The principal soil type is dry-steppe chestnut soil that covers some 40% of Mongolia. Other major soil types are brown desert-steppe and grey brown desert soils. Arable soils are generally dark chestnut and chestnut soils which are typically light, fine silty, around 20-30 cm deep with an organic matter content of 3-4% and pH of 6-7 (Batjargal et al., 1997).

1.3.3 Water resources

Mongolia is situated between the basins of the Arctic and Pacific Ocean and the closed depressions of Central Asia (Gunin et al., 1999). The water resources such as lakes, streams and rivers are very common in the northern part of the country. Rivers originating from the northern mountain ranges of Altai, Hangai, Hentei, and Hovsgul flow into the Pacific Ocean. There are about 3811 streams and rivers flowing in Mongolia, covering more than 67,000 km area in length across Mongolia. The Selenge is the largest river with a total length of 600 km. The Haraa and Eroo rivers converge with the Tuul river which originates on the southern slopes of the Hentei Mountains. The longest river draining into the Pacific Ocean is the Herlen river of which 1090 km flows through

Mongolia. The deepest rivers draining into the Pacific Ocean are the Onon and Ulz rivers. Tes, Hovd, Zavhan, Baidrag, Tuin, Ongi and Bulgan rivers are without any access to the sea (Johnson et al., 2006).

Mongolia has more than 3000 lakes and ponds of which 80% are saline. The largest lake is Huvsgul lake which is 134 km long and 35 km wide. Almost 65% of Mongolia has no open water sources, so livestock production in these areas critically depends on wells for watering livestock. About 35% of exploitable underground water sources are found in the Dornod plain, 25% in the Hangai-Hentei Mountains, 32% in the Gobi desert, and 8% in the Altai Mountains. This means that 70% of underground water resources in Mongolia occur in the Gobi desert and steppe zones. During the past several decades, water use for irrigation, mining and other human activities has increased. Deforestation and climate change have purportedly resulted in substantial reductions in river flows, flow regimes and water levels or in some cases complete drying of lakes and the lowering of groundwater tables (Batjargal et al., 1997; Maygmarjav and Davaa, 1999; Johnson et al., 2006).

1.3.4 Climate

The climate of Mongolia is highly continental. It is characterized by very long and cold winters with low precipitation, hot summers and high temperature fluctuations. Snow may fall in the North mountainous regions. It contributes less than 20% to total annual precipitation owing to long periods of clear skies in winter due to the high anticyclone. Soils are completely frozen due to low cover of snow. The annual average air temperature for Mongolia is 0.7 °C. It is 8.5 °C in the warmest regions of the Gobi and south Altai deserts and -7.8 °C in the coldest region of the Darkhad depression. The lowest monthly average temperatures of -15 °C to -35 °C are recorded in January. It is -30 to -34 °C in the valleys of the Altai, Khangai, Khuvsgul and Khentii mountains., -25 to -30 °C in the high mountainous area., -20 to -25 °C in the steppe and -15 to -20°C in the Gobi desert. July is the warmest month. The average air temperature in July is 12 °C in the Altai, Khangai, Khuvsgul and Khentii Mountainous. 15-20 °C in the valleys of Mountains and 20-25 °C in southern part of the eastern steppe and the Gobi desert (Nandintsetseg et al., 2007).

The mean annual precipitation decreases steadily from north-west to south-east which is a key factor in the distribution of vegetation formations. The highest mean annual precipitation values of 300-400 mm (occasionally exceeding 600 mm) may occur in the Khangai, Khentein and Khuvsgul mountainous region, 150-250 mm in the steppe and 100-150 mm in the steppe-desert. The Gobi desert has the lowest values of 50-100 mm and has periods without precipitation lasting several years. About 85% of total precipitation falls in summer. Although annual precipitation is low, its intensity is high. For example, an intense rainstorm of 40-65 mm may fall in a single hour (Batjargal et al., 1997; Batima et al., 2005; Ma et al., 2008).

1.3.5 Vegetation

Biogeographically, Mongolia is a transitional zone from Siberian taiga to dry steppe, steppe-desert and desert in Central Asia. The major portion of its territory lies in the steppe and forest-steppe zones (Ma et al., 2008).

The Daurian steppes and the Altai-Sayan Mountains are considered the world's most biologically outstanding eco regions which lie partly within Mongolia and the Mongolian steppe represents one of the largest contiguous unaltered grasslands in the world. The general zonation of the vegetation of Mongolia, based on floristic composition and physiognomy, is given by Walter (1974) in German language. Johnson et al. (2006) recognized six major vegetation zones of Mongolia on the basis of difference in altitude, temperature, rainfall distribution and soils. These vegetation zones and the percentages of land area occupied by each are: alpine tundra (3%), mountain taiga (4.1%), mountain steppe and forest steppe (25.1%), grass steppe (26.1%), desert steppe (27.2%) and desert (14.5%). About 10% of the land scape of Mongolia is covered by various types of forests. *Larix* (73.6%), *Cedrus* (13%), *Pinus* (8%), *Betula* (5%) and other species (*Abies*, *Populus*) dominating the northern part of the country. The *Haloxylon ammodendron* forests spread in the arid and semi-arid regions, accounting for 28% of the forest cover (Batjargal et al., 1997). A detailed knowledge of current vegetation in Mongolia is carried out by Hilbig (1995). He classified the vegetation of Mongolia along a south-north transect in correlation with precipitation and reported five vegetation zones of desert, desert-steppe, steppe, forest-steppe and mountain taiga vegetation as given below

Desert vegetation

Desert vegetation is found in East Gobi where a mean annual temperature is usually about 4-6 °C. Annual precipitation is usually less than 100 mm, almost exclusively in summer. Winters are cold and sunny. Common vegetation includes low shrubs and semi-shrubs, most of them belonging to the families Chenopodiaceae (*Anabasis*, *Haloxylon*, *Kalidium*, *Kochia*, *Iljinia*, *Salsola*, *Sympegma*, *Nanophyton*), Asteraceae (*Ajania*, *Artemisia*, *Asterothamnus*, *Brachanthemum*), Polygonaceae (*Atraphaxis*, *Calligonum*), Zygophyllaceae (*Nitraria*, *Zygophyllum*), Tamarucaceae (*Reaumuria*, *Tamarix*), Fabaceae (*Caragana*, *Oxytropis*), Rosaceae (*Potaninia*) and Convolvulaceae (*Convolvulus*). *Anabasis* and *Haloxylon* have a high degree of succulence (Fig. 1.1A and B).

Desert-steppe vegetation

Desert-steppe community is widespread in the northern parts of the East Gobi where the mean annual temperature is 3-4 °C and the mean annual precipitation is 100-200 mm. The vegetation is dominated by *Artemisia* species such as *A. xerophytica*, *A. caespitiosa*, *A. frigida* mixed with *Stipa* species like *Stipa krylovii*, *S. gobica*, representing *Artemisia-Stipa* desert-steppe community. The other common species include *Agropyrum sibiricum*, *Allium mongolium*, *Caragana pyhmaea*, *C. leucophloea*, *Convolvulus ammannii*, *Heteropappus hispidus*, *Scorzonera divaricata*, *Anabasis brevifolia*, *Salsola passerine*, *Kochia prostrata*, *Eurotia cerataide* *Reaumuria soongorica*, *Oxytropis*

aciphylla, *Peganum nigellastrum*, *Potaninia mongolica*, and *Tanacetum sibiricum*, *T. achillaeoides*, and *T. trifidum*, *Zygophyllum xanthoxylon*.



Fig. 1.1A: Picture showing Chenopodiaceae desert in the surrounding of BTN (source Frank Schlütz)

Fig. 1.1B: A common plant member of Chenopodiaceae in the study area (source Frank Schlütz)

Steppe vegetation

Steppe vegetation includes *Artemisia-Stipa* grass steppe and *Stipa-Leymus* steppe communities. They occupy the central and eastern Mongolia, at elevations between 950 and 1400 m. The trees do not survive anymore and grasses dominate the vegetation. The mean annual temperature in this region ranges from 3-2 °C and the annual precipitation in varies from 200-300 mm. Dominant species are *Stipa capillata*, *Cleistogenes squarrosa* and *Artemisia frigida*. Some other common species are *Agropyrum cristatum*, *Elymus chinensis*, *Carex durinacula*, *Artemisia adamsii*, *A. scoparia*, *A. plusfria*, *A. peatinata*, *Achnatherum splendens*, *Cymbaria dahurica*, *Leymus chinensis*, *Goniolimon speciosum*, *Kochina prostrate*, *Saussurea salicifolia* and *Peganum harmile*, *Caragana pygmaes*.

Forest-steppe vegetation

The forest-steppe vegetation is distributed in the North and North-east of the Hangai and to the north-west, west and south of the Hentiy. The mean annual precipitation is usually 300- 400 mm. The mean annual temperature is 0 to -2 °C. This vegetation type separates the mountain taiga zone in the north from the steppe and desert-steppe zones in the south. The forest-steppe vegetation is consisting of a mosaic of patches of forest and grassland. Due to differences in topography there is a differentiation of the vegetation in forest on the north-facing slopes and higher parts and steppes on the south-slopes and in valleys (Hilbig, 1995). The plants such as *Stipa krylovii*, *Poa attenuata* and *Artemisia* species are the main species growing in forest steppe vegetation. With increase the forests steppe are built by *Larix sibirica* partly mixed with *Betula* and *Pinus sylvestris*. Other common herbaceous species include *Aster alpinus*, *Saussurea salicifalre*, *Thalictrum foetidum*, *Astragalus*

brevifolius, *Oxytropis pumila*, *Pulsatilla*, *Thymus serpyllum*, *Allium bidentatum*, *Arenaria capillaris*, *Bupleurum bicaule*, *Hedysarum pumilum*, *Iris potaninii*, *Pedicularis flava*, *Ptilotrichum canescens*, *Potentilla sericea*, *P. acaulis*, *Stellaria petraea*, *Stellaria chamaejasme* and *Sibbaldianthe adpressa*. Overgrazed spots of higher mountain steppe are dominated by *Carex duriuscula* with *Artemisia frigida*.

Mountain taiga vegetation

The mountain taiga vegetation is occupying the Hovsgol Nuur area. The mean annual precipitation is more than 400 mm. The characteristic plant species of mountain taiga include *Larix sibirica* (72% of total forest area), *Pinus sibirica* (12%), *Pinus sylvestris* (7%) and *Picea obovata* (0.25%) with shrub layer of *Rosa acicularis* and *Betula rotundifolia*. *Spiraea alpina*, *Lonicera altaica*, *Juniperus sibirica* and *Rhododendron* species prefer high altitude.

1.4 Sediment coring sites

The research was carried out on three sediment cores taken at Bayan Tohomiiin Nuur (BTN), Orog Nuur (ONW) and Olgoy Nuur (OLG) during two field excursions scheduled on August, 2007 and August, 2008. All these three core sites are situated at the transition zone between the Gobi desert and steppe of arid southern Mongolia, representing archives very sensitive to past vegetation, climatic changes and landscape development. The first high resolution multi-proxy analysis of the 700 cm long core taken from Bayan Tohomiiin Nuur and 1335 cm long core from Orog Nuur included the investigation of geochemical, granulometric, palynological and ostracod analyses. The multi-proxy data was used to reconstruct the geomorphologic, climatic and sedimentary processes at the catchment area of both lakes during the last ~15 ka and ~50 ka BP. respectively. The sediment samples, collected from different profiles of Olgoy Nuur, were also investigated for pollen analyses to reconstruct the vegetational and climatic change during late Pleistocene and Holocene. The detail of the pollen record sites is below.

The Bayan Tohomiiin Nuur, a dry lake, is located in Gobi desert region. The Gobi desert includes the semi arid and arid southern portion of Mongolia. This region has elevations ranging between 700 and 1400 m. Mean annual temperature of 0.0 °C to >2.5 °C with the coldest temperature in January (-20 °C) and warmest temperature (23 °C) in July. Mean annual precipitation is about 100 mm. Lack of snow as a water source is a major factor limiting livestock production in the Gobi desert region. Wind speed averages 2 to 8 m/sec. (Johnson et al., 2006).

Orog Nuur is located at 100° 34' E longitude, 45° 11' N latitude with about 1280 m elevation. It is situated in the valley of Gobi lakes, desert steppe sub region of Northwestern Mongolia (Yang et al., 2004) and is fed by the Tüin Gol from the Hangai Mountains, in addition to smaller drainages from the Ikh Bogd range of the Gobi Altai (Komatsu et al., 2001). The desert steppe region includes a broad treeless region in central and eastern Mongolia which is characterized by low knolls, hills and high plains. This region has elevations ranging from 900-2000 m. temperature drops to -20 °C in January

and may rise up to 22 °C in July. Mean annual precipitation of 150-250 mm. Snow depth ranges between 5-10 mm (Johnson et al., 2006).

The Olgoy Nuur lies at the southern side of the Hangai Mountains in the valley of Gobi lakes. The climate of the valley is extremely continental. The summers are very hot and arid where as winters are cold and dry. The mean annual temperature is 2 °C to -6 °C but can vary from -16 °C in January to 20 °C in July. The mean annual precipitation is about 250 mm (Tuvdendorzh and Myagmarzhav, 1985; Finch, 1996).

1.5 Materials and methods

1.5.1 Field work

Consecutive two field trips were arranged by Frank Schlütz., Department of Palynology and Climate Dynamics, University of Göttingen, Germany and Thomas Felauer., Department of Geography, RWTH Aachen University, Germany, in August, 2007 and August, 2008. During these two field excursions lake sediment cores were taken from Bayan Tohomiin Nuur (KEO-I), Orog Nuur (ONW-II) and Olgoy Nuur (OLG) in order to reconstruct vegetation, environmental and climatic history in the basins of the Gobi desert and Gobi Altai (Fig.1.2A and B). The OLG pollen analysis was carried out as a supplementary study (chapter 5.1).



Fig. 1.2A: Collection of sediment samples from BTN (source Frank Schlütz)

Fig. 1.2B: Collection of sediment samples from ONW (source Thomas Felauer)

A 7 m core (KEO-I) was taken from lake Bayan Tohomiin Nuur with a percussion corer (Nordmeyer GmbH and Co. KG, Germany) at the northern margin of the basin (43°34' N, 103°11' E, 1420 m elevation). Similarly a 1335 cm long sediment core (ONW-II) was also drilled at Orog Nuur, (100° 34' E longitude, 45° 11' N latitude, 1280 elevation), south Mongolia. In case of KEO-I the unconsolidated upper 200 cm (ten samples, 10 cm thickness each) were taken at the coring site for geochemical analysis. This upper part was not suitable for pollen analysis. The samples of KEO-I and OLG were preserved and transported in plastic tubes to Georg-August University, Göttingen where they were opened with an oscillating saw, cleaned and visually described. The extraction of samples of KEO-I

(700-200 cm) was done for palynological analyses. Steffen Mischke carried out the ostracod analysis at Department of Earth Sciences, Institute of Geographical Sciences, Freie Universität, Berlin where as XRF, grain size, CaCO₃, CNS and total organic carbon (TOC) were analyzed by Thomas Felauer at RWTH Aachen University, Aachen. The samples of OLG were analyzed for only pollen studies. The core fragments of ONW-II (1333 cm) were also preserved and transported in plastic tubes to Alfred Wegener Institute for polar and marine research (AWI), Bremerhaven where they were opened with an oscillating saw, cleaned and visually described. The extraction of samples for XRF, grain size, CaCO₃, CNS and total organic carbon (TOC) were analyzed by Thomas Felauer. The palynological study was conducted at the Georg-August University Göttingen where as the ostracod analysis was done at Department of Earth Sciences, Institute of Geographical Sciences, Freie Universität, Berlin by Steffen Mischke.

1.5.2 Laboratory work

A total of 211 sampling units were investigated from the sediment core of BTN (KEO-I, 56 samples), Orog Nuur (ONW-II, 123 samples) and Olgoy Nuur (OLG, 32 samples). Sediment samples of 0.5-2 cm³ were collected at every 5-10 cm interval depending upon the pollen concentration. All the samples were treated for pollen analysis with standard methods using KOH, HCl, HF and acetolysis (Erdtman, 1960; Moore et al., 1999). *Lycopodium* spores were added to each sample in order to calculate concentration (pollen grains/cm³), influx of pollen (pollen grains/cm²/yr) and charcoal. The suspensions were sieved in an ultrasonic bath through a 1.5 µm mesh and stored in glycerin.

1.5.3 Radiocarbon dating

In total, 17 bulk samples were taken from core KEO-I and ONW-II for Accelerator Mass Spectrometer (AMS) radiocarbon dating (Table 1.1). The bulk samples for AMS radiocarbon dates were processed at the University of Erlangen/Nürnberg, Germany and Poznań Radiocarbon laboratory, Poland for the determination of cores chronology. Radiocarbon ages have been calibrated with the online version of the program CalPal: <http://www.calpal-online.de/CalPal2007-HULU> (Weninger and Jöris, 2008) in order to construct age-depth models. The age depth models for the lake archives of BTN and Orog Nuur (ONW) were reconstructed using polynomial function (chapter 2 and 3) and linear interpolation (chapter 4).

1.5.4 Identification of pollen and spores

In arid environments the number of identified pollen taxa is limited (Herzschuh et al., 2004); therefore, a maximum number of about 400 pollen grains were counted in each sample. Pollen concentration in a few samples of both cores was very low. A total of about 140 different palynological taxa have been distinguished in the fossil pollen spectra of all the three sediment cores (Appendix I) of which almost 50 were pollen types, about 40 were identified as fungal spores. Other taxa include *Pediastrum*, *Botryococcus*, Volvocaceae, Chironomids, monolete and trilete spores, *Foraminifera*, *Filinia longesta* and eggs of *Trichuris*. About 40 fungal spores and algal types remained unknown.

Both pollen and spore taxa have been identified with the help of reference collection of Frank Schlütz and available literature (Vanky, 1994; Moore et al., 1999; van Geel et al., 2003; Beug, 2004).

Core name	Depth [cm]	Lab. No	¹⁴ C age and error [yr. BP]	$\delta^{13}\text{C}$ [‰]	Calibrated age and SD [cal. yr. BP]	material
BTN	247	Poz-37868	5495±35	-21.3	6299±24	bulk sample
BTN	253	Erl-13181	5880±46	-20.5	6709±45	bulk sample
BTN	353	Erl-12109	8697±56	-22.7	9674±85	bulk sample
BTN	367	Poz-37949	9270±50	-25.1	10441±88	bulk sample
BTN	367	Poz-37869	9320±60	-24.6	10523±90	bulk sample
BTN	526	Erl-13182	6037±47	-21.6	6884±64	bulk sample
BTN	536	Poz-37870	6920±40	-26.8	7222±36	bulk sample
BTN	674	Erl-12110	10661±56	-23.3	12661±65	bulk sample
BTN	665	Poz-37871	11170±70	-27.4	13073±125	bulk sample
ONW	94	ERL-15622	12581±103	-25.4	12973±323	bulk sample
ONW	199	ERL-15623	13242±85	-24.2	14223±413	bulk sample
ONW	271	ERL-15624	17733±149	-25.4	19215±354	bulk sample
ONW	392	ERL-15625	17713±180	-24.5	19192±379	bulk sample
ONW	571	ERL-15626	19738±179	-23.8	21670±348	bulk sample
ONW	778	ERL-15627	21501±217	-24.2	23714±444	bulk sample
ONW	1192	ERL-15628	46103±2281	-25.4	48072±3111	bulk sample
ONW	1272	ERL-15629	40429±1340	-25.92	42241±1147	bulk sample

Tab. 1.1: Results of the AMS ¹⁴C-datings of BTN and ONW and their calendric age-conversion (calibration) with 1 σ standard deviation (SD) using “CalPal-online” (Weninger and Jöris 2008)

1.5.5 Data presentation

The calculation of pollen and spore percentages is based on the pollen sum of about 400 pollen grains per sample containing all arboreal pollen (AP) and non-arboreal pollen (NAP) except Cyperaceae and aquatic plants. The palynological data are presented in the pollen diagram as percentages of the pollen sum. The software C2 version 1.5.1 was used to plot the pollen and spore data as stratigraphic diagram (Juggins, 2007). In diagram, all the palynological taxa are arranged according to their ecology and chronological order.

1.6 Pollen–climate indices

1.6.1 Introduction

The traditional interpretation of the individual pollen percentages and concentrations in sediment samples of arid and semi arid regions of Central Asia seem difficult to reconstruct past vegetation and climate history effectively because of poor pollen identification and the lack of good indicator taxa. The ratios of various pollen types have been applied as environmental indicators in arid regions in order to infer vegetation and climate change. The *Artemisia*/Chenopodiaceae (A/C) ratio has been introduced for the first time as a moisture indicator in the Middle East (El-Moslimany, 1990). This approach has also been used in Central Asia (Demske and Mischke, 2003; Herzschuh et al., 2004).

Herzschuh et al. (2006) introduced that the *Artemisia/Cyperaceae* (A/Cy) ratio can serve as a semi-quantitative measure for summer temperature changes on the central and eastern Tibetan Plateau. Herzschuh et al. (2004) also suggested *Ephedra fragilis*-type/ *Ephedra distachyia*-type (Ef/Ed) ratio and interpreted dry conditions based on high values of *Ephedra fragilis*-type in Ef/Ed ratio. Yu et al. (1998) and Cour et al. (1999) reported that Chinese desert areas yield A/C values below 0.5. Fowell et al. (2003) calculated a semi-quantitative ‘aridity pollen index’ expressed as a ratio of *Artemisia* + *Chenopodiaceae* by dividing the percentage of *Poaceae* to distinguish dry steppe from moist meadow steppe and forest-steppe vegetation in North-central Mongolia. The higher values of the index (>5) interpret arid conditions that favor desert-steppe where as low values (<5) are indicative of high moisture availability to support meadow steppe and forest-steppe vegetation. Similarly, several quantitative methods such as the response surface analysis and transfer function have been applied to modern pollen and vegetation for the reconstruction of climate variables. However, these methods cannot be effectively applied to the continental Mongolia due to the low availability of modern climatic data (Ma et al., 2008).

Poaceae pollen in extreme arid conditions are more abundant locally in the azonal vegetation communities, except in some areas that are disturbed by overgrazing. Owing to the possible distortion of *Poaceae* pollen abundance by human activities in these arid and semi-arid environments, the ‘aridity pollen index’ expressed as a ratio of desert-steppe (*Artemisia* + *Chenopodiaceae*) to steppe (*Poaceae*) taxa may not be an appropriate indicator to use for palaeoclimatic reconstruction (Herzschuh et al., 2004; Ma et al., 2008).

In our study, two new pollen-climate indices, a moisture index (M) and a temperature index (T), are introduced for Mongolia (Table 1.2). Both climate indices are calculated based on the ratios between groups of pollen taxa that represent different moisture or temperature conditions in the climate-sensitive study region.

The main pollen taxa were distinguished into six pollen groups based on their relationships to six major vegetation communities proposed by Ma et al., (2008). Group S1, containing *Chenopodiaceae*, *Nitraria* and *Zygophyllaceae* (*Tribulus terrestris*), is a representative of xeromorphic desert. Group S2 includes *Convolvulus*, *Anthemis*-type (*Matricaria*-type), *Ephedra* and *Liliaceae* (*Allium*) which occurs commonly in desert-steppe. Group S3 (*Artemisia*) represents meso-xeromorphic steppe. Groups S4 represent the birch forest/shrub land (*Betula*, *Rosaceae*, *Taraxacum*-type (Liguliflorae). Cold-moist needle-leaved forest (*Picea*, *Larix*, *Pinus* Haploxyton-type, *Pinus* Diploxyton-type, *Ranunculaceae* and *Caryophyllaceae*) is represented by Group S5 where as Group S6 is including *Cyperaceae*, *Polygonaceae*, is indicative of moderate hydro period steppe vegetation types. A total of 19 pollen taxa are considered to derive M and T climate indices. *Poaceae* is excluded from all six groups because its abundance could be distorted by human disturbance as discussed above.

The temperature index (T) and moisture index (M) is calculated as follows:

$$T = (PS1 + PS2 + PS3) / (PS4 + PS5 + PS6)$$

$$M = (PS5 + PS6) / (PS1 + PS2 + PS3 + PS4)$$

Group	Vegetation type	Main pollen taxa
S1	Xeromorphic desert	Chenopodiaceae, <i>Nitraria</i> , Zygophyllaceae, (<i>Tribulus terrestris</i>)
S2	Desert steppe	<i>Anthemis</i> -type (<i>Matricaria</i> -type), Liliaceae, <i>Ephedra</i> , <i>Convolvulus</i>
S3	Meso-xeromorphic steppe	<i>Artemisia</i>
S4	Birch forest/shrubs	<i>Betula</i> , Rosaceae, <i>Taraxacum</i> -type (Liguliflorae)
S5	Cold-moist needled forest	<i>Picea</i> , <i>Larix</i> , Ranunculaceae, Caryophyllaceae <i>Pinus</i> Diploxylon-type, <i>Pinus</i> Haploxylon-type
S6	Moderate hydro period steppe	Cyperaceae, Polygonaceae
	Pollen-climate indices	Calculation
T	Temperature index	$T = (PS1 + PS2 + PS3) / (PS4 + PS5 + PS6)$
M	Moisture index	$M = (PS5 + PS6) / (PS1 + PS2 + PS3 + PS4)$

Table 1.2: Selected pollen taxa in the pollen groups (S1-S6) used in the calculation of the pollen ratios which were ultimately used for the calculation of temperature index (T) and moisture index (M).

1.6.2 Methodology

Several semi quantitative methods have been tested to use the ratios of various pollen types as a tool for palaeo-environmental characteristics. Temperature (*T*) and moisture (*M*) indices were derived using the six pollen groups (S1-S6) for the calculation of the pollen ratios which represent different moisture or temperature conditions in the studied site. The pollen percentage of each pollen group (S1-S6) for each surface sample is calculated and plotted these values for all the samples along the curves for the moisture index as well as the temperature index to examine their spatial variation. We also plotted the A/C, A/A+Ch, A+Ch/Poa, Poa/A+Ch, A+Ch/Poa+Th+Cy, Poa+Th+Cy/A+Ch and *Ephedra*+*Glomus* pollen ratios along the transect, in order to test the validity of temperature and moisture indices curves with different ratios of various pollen types (Fig. 1.3 and Fig. 1.4 for BTN and Fig. 1.5 for ONW core).

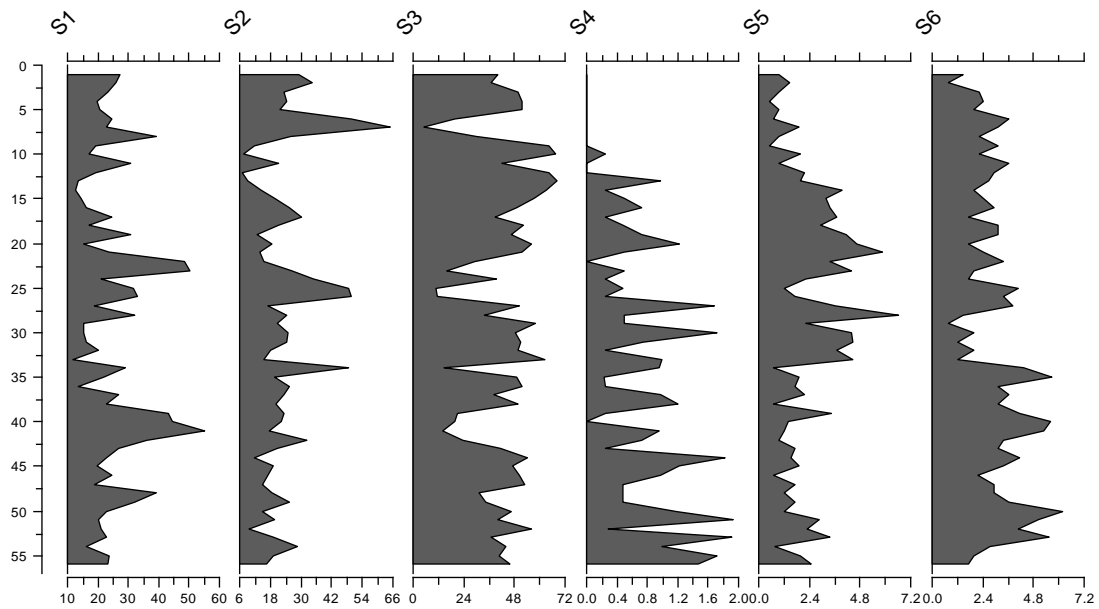


Fig.1.3: Grouped pollen percentages of the six pollen groups (S1-S6) from BTN core used in the calculation of pollen-climate indices

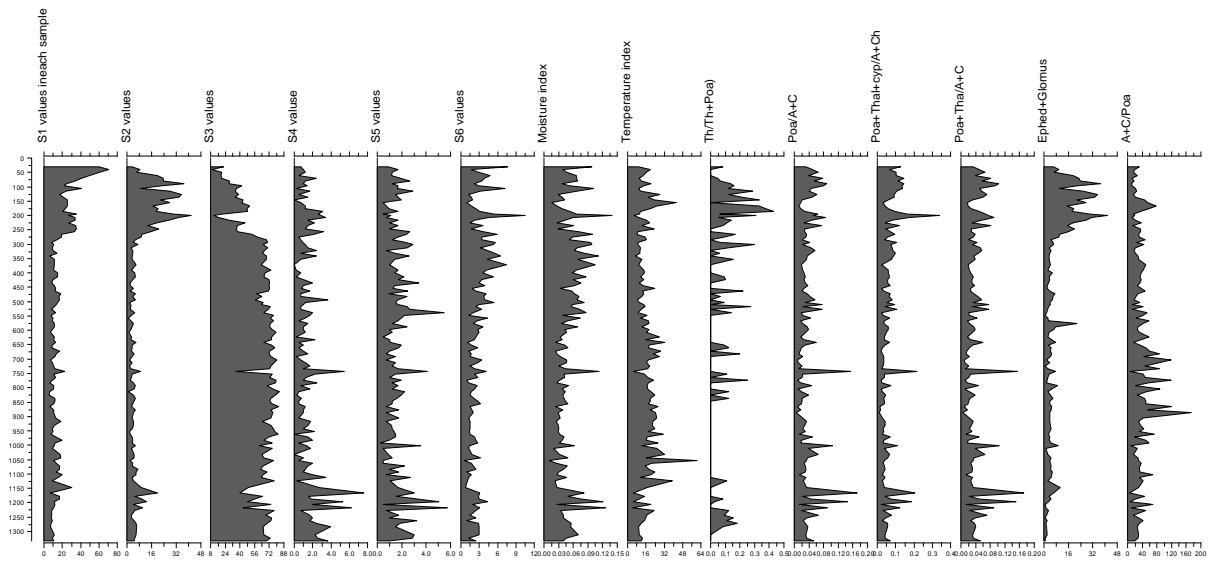


Fig.1.4: Grouped pollen percentages of the six pollen groups (S1-S6) from ONW sediment samples used in the calculation of pollen-climate indices

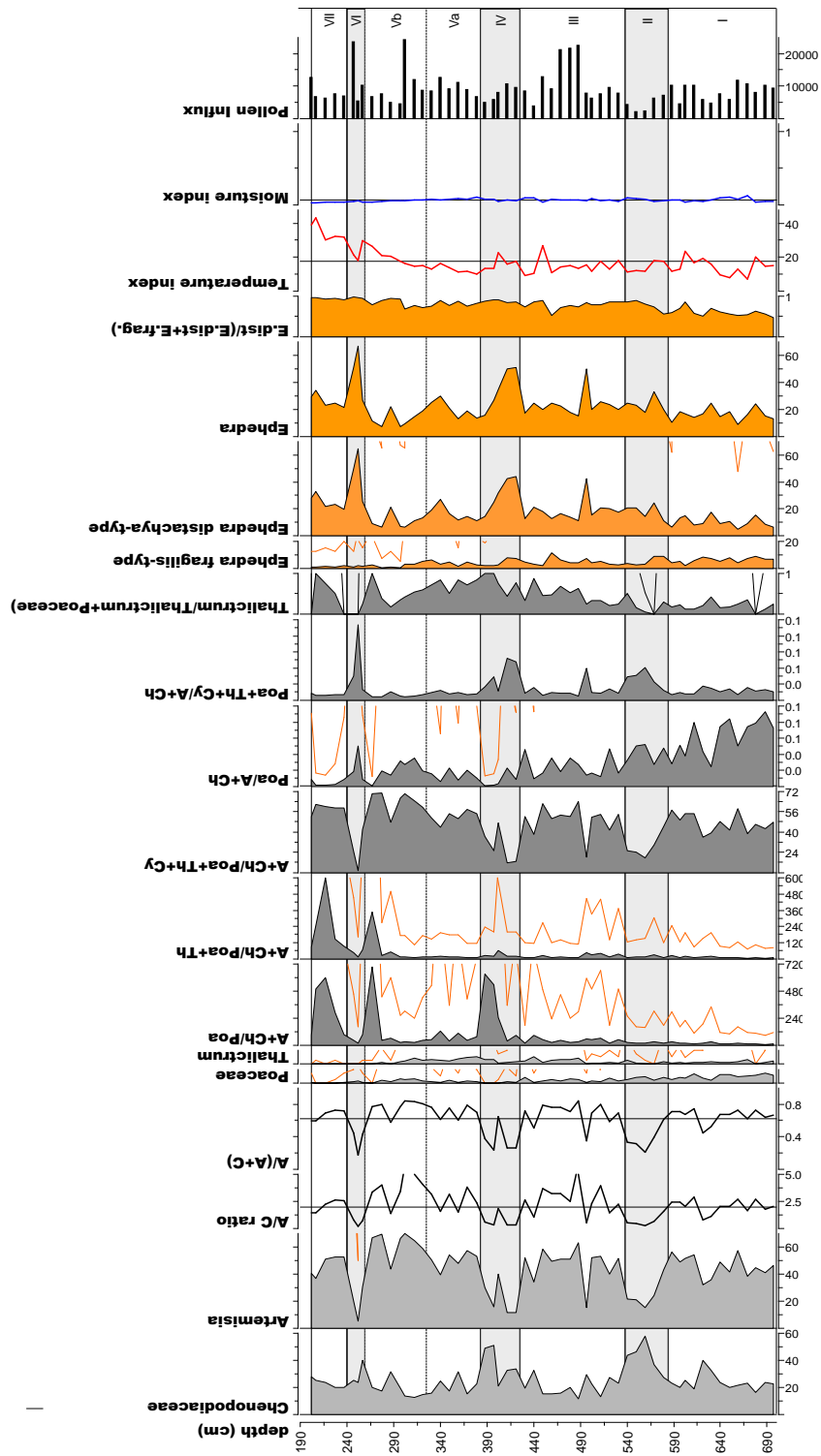


Fig.1.5: Temperature and moisture indices based on BTN sediment samples

1.6.3 General interpretation

We did not graph “(*Artemisia* + *Chenopodiaceae*) / *Poaceae*” but the reciprocal *Poaceae*/*(Artemisia + Chenopodiaceae)* curve because *Poaceae* pollen in extreme arid conditions are more abundant locally in the azonal vegetation communities, except in some areas that are disturbed by overgrazing. Owing to the possible distortion of *Poaceae* pollen abundance by human activities in these arid and semi-arid environments, the ‘aridity pollen index’ expressed as a ratio of desert-steppe (*Artemisia* + *Chenopodiaceae*) to steppe (*Poaceae*) taxa may not be an appropriate indicator to use for palaeoclimatic reconstruction (Herzschuh et al., 2004, Ma et al., 2008). *Poaceae* + *Thalictrum* + *Cyperaceae* represent forest steppe forb, alpine steppe, meadow steppe forb and moist/ wet conditions in contrast to *Artemisia* + *Chenopodiaceae* in the *Poa*+*Th*+*Cy*/*A* +*Ch* index. High *Ephedra* + *Glomus* values are showing very dry and cold climate causing severe erosion due to low vegetation cover *Ephedra* + *Glomus* curve does not fit to the temperature and the moisture indices because *Ephedra* is a typical desert species., however, low values of *Ephedra* pollen may not be a good vegetation indicator because it produces large amounts of pollen that are transported long distances. For example, *Ephedra* pollen has been documented in Midwestern North America, even though its parent plants are thousands of kilometers away in the deserts of the southwestern USA (Maher, 1964). Li et al. (2005) reported that in the eastern Alashan Plateau, eastern Qaidam Basin and part of Gansu Corridor, *Ephedra* pollen appears in most surface samples, even though no *Ephedra* plants are recorded in the surrounding communities. Therefore, *Ephedra* pollen in low abundance has limited climate information (Zhao et al., 2007).

The *Poa*+*Th*+*Cy*/*A*+*Ch* index curve is fitting best to the *Ephedra* + *Glomus* curve. The increasing trend is representing dry cold while increasing trend indicates moist warm conditions.

1.7 References

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Chapter 2

First high resolution palynological record of climate history in the late Quaternary from the high continental Gobi desert of Mongolia

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Vegetation History and Archaeobotany (under review)

Abstract

A 5 m long high resolution pollen and non-pollen palynomorphs (NPP) of the Bayan Tohomiiin Nuur (BTN), an almost dry lake in the Gobi desert of Mongolia, reveals a detailed history of the significant continental vegetation, environmental and climate change from about 15.3 to 3.8 ka cal B.P. Located in a semi-arid desert-steppe adjoining the desert today, pollen of *Artemisia*, Chenopodiaceae but also of the *Ephedra distachya*-type are abundant in the recovered sediments. Four semi-arid phases (*Artemisia* values 40-60%) of about 2.5 to 3 ka cal B.P. length were interrupted by arid spells (Chenopodiaceae 40-50%, A/C ratio <2) of 0.4 to 1.2 ka cal B.P. duration. During the arid phases high values of the *Glomus*-type (10 - 20%) indicates a stronger terrigenous input into the lake by erosion, reaching down into the rhizosphere of sparse catchment vegetation. A contemporaneous spreading of *Ephedra* shrubs is related to barren grounds. The first arid phase (12.3 -11.1 ka cal B.P.) correlates most probably with the Younger Dryas and the second one (8.6 – 7.6 cal B.P.) with the 8.2 ka event. An early short and slight climatic deterioration possibly reflects the Oldest Dryas. The most stable and relatively moist conditions (*Artemisia* steppe) occurred in the middle Holocene from 6.3 to 4.9 ka cal B.P. These inferences point to a climatic synchronicity with the Younger Dryas and 8.2 ka event of northern hemisphere and most possibly a stronger moisture input by the westerlies which probably caused the mid-Holocene climate optimum.

Pollen of trees, shrubs, grazing weeds, and spores of coprophilous and plant infecting fungi are present only in low quantities. Fossil eggs of the intestinal parasite *Trichuris* are reported for the first time from Mongolia.

Our results demonstrate the potential of pollen analysis on well selected small catchment archives to improve the current state of knowledge with respect to the climate history of Mongolia.

Key words: Mongolia, Gobi desert, Holocene, pollen, non-pollen palynomorphs

Introduction

Mongolia is situated in the heart of continental Asia and is in need of special attention from palaeoecologists and palynologists as reconstructions of the late Quaternary vegetation and environment are still sparse and regionally restricted. Studies have been carried out mostly in the

northwest of Mongolia (Gunin et al. 1999). The older publications summarized in Gunin et al. (1999) are originally published in Russian. Most of the more recent palaeoecological studies are also restricted to northern Mongolia, while the desert and steppe regions in the south are sparsely investigated (Fig. 2.1). Tarasov et al. (2000a) and Rudaya et al. (2009) reconstructed the Holocene environmental changes around the Hoton Nuur (*Nuur* meaning lake) in the Mongolian Altai in the northwest of Mongolia.

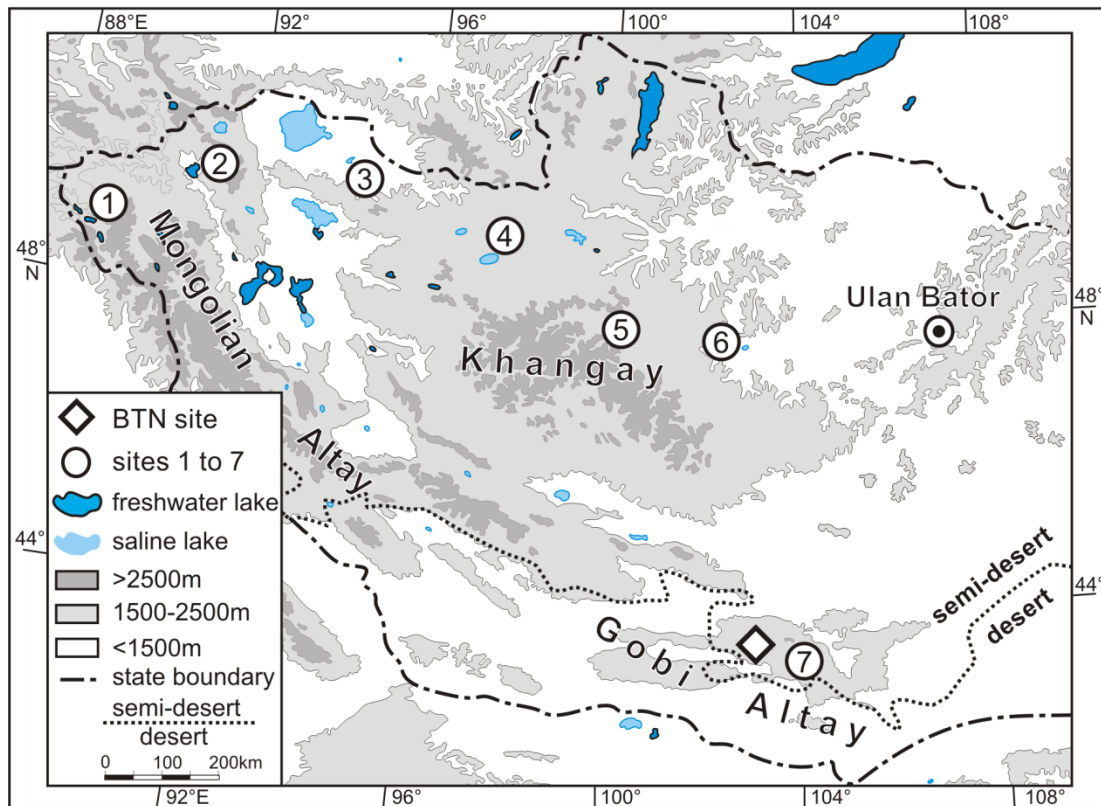


Fig. 2.1: Map of Mongolia with investigation site, sites mentioned in the text and the transition line from desert to semi-desert (*Artemisia* steppe). Sites mentioned in the text include: 1. Hoton Nuur (Tarasov et al., 2000 / Rudaya et al., 2009) 2. Archit Nuur (Gunin et al., (eds.) 1999) 3. Bayan Nuur (Grunert et al., 2000) 4. Telmen Nuur (Fowell et al., 2003 / Peck et al., 2002) 5. Daba Nuur (Gunin et al., (eds.) 1999) 6. Ugii Nuur (Wang et al., 2009, 2011 / Schwanghart et al., 2008, 2009) 7. Yolyn Am (Miehe et al., 2007)

Fowell et al. (2003) and Peck et al. (2002) worked on mid to late Holocene climate evolution at the Telmen Nuur in north-central Mongolia. Wang et al. (2009, 2011) investigated a Holocene vegetation and climate history record from the Ugii Nuur in central Mongolia. The same archive was studied by Schwanghart et al. (2008, 2009). The Last Glacial Maximum (LGM), mid Holocene and modern biomes have been reconstructed by Tarasov et al. (1999a, 1999b, 2000b) for the territory of the former Soviet Union and Mongolia based on pollen and plant macrofossils. Until now some of the local

results seem to contradict each other (Herzschuh, 2006), which may be due to a complex interplay of climatic influences changing over time from westerlies and summer monsoon as well as difficult geological and geomorphological features of the mainly vast catchment areas of the hitherto studied archives.

The lack of palaeoecological knowledge is most severe in the very dry southern part of Mongolia with missing up-to-date analyses. The Bayan Tohomiin Nuur (BTN) studied here occupies a small catchment area of only 1750 km² in the desert-steppe zone of southern Mongolia close to the Gobi desert. Due to its unique geographical location and small catchment area its sediments are a sensitive archive for vegetation and climate change. Here we present pollen and NPP records indicating several climatic fluctuations in the late Quaternary (15.3 to 3.8 ka cal B.P.). A detailed discussion of the sedimentological data is already published (Felauer et al. 2012). The closest palynological study was carried out on a terrestrial profile from the Gobi Altai (2390 m asl.) less than 100 km away comprising about the last 5 ka cal B.P. (Miehe et al. 2007).

Modern climate and vegetation

It is a general belief that Central Asia is slowly drying out (Wesche et al. 2005) but recent dendro-climatological studies suggest unchanged or even increasing annual precipitation for Mongolia in the 20th century (Jacoby et al. 2000). Because of the distance to the oceans, the climate is strongly continental with high yearly temperature amplitudes and relatively low precipitation.

Mountain barriers in the west and north-west intercept atmospheric flows bringing moisture from the west, while the moisture carrying East Asian summer monsoons fade rapidly in the very south-east of Mongolia. In the south the country is open to dry desert winds from Central Asia (Gunin et al. 1999). The present climate of the study area is semi-arid and extremely continental. The short growing season is limited in spring by low precipitation and by frost from September to May. Typical for desert regions, the precipitation varies strongly between years (Wesche et al. 2005). The winters are controlled by the Siberian-Mongolian high pressure cell, causing pronounced dryness with about only 10% of the mean annual precipitation. In spring time moisture is brought with strong winds from westerly directions. The altering influence of westerlies and the East Asian summer monsoon causes higher rates of rainfall (Feng et al. 2005). The mean annual precipitation is below 150 mm. The climate stations nearest the BTN (1420 m asl.) Dalandzadgad (1470 m asl.) and Bayandalay (1570 m asl.) recorded annual precipitations of 131 mm/a and 110 mm/a respectively. The mean temperatures are estimated for January at around -15°C and for July at >20°C (Geographic Atlas of Mongolia 2004; Wesche et al. 2005).

Mongolia is a transitional zone between the Siberian taiga and the deserts of Central Asia. The majority of its territory is covered by steppes and desert-steppes. Five main vegetation zones mostly running from west to east are recognized along a south-north transect (Hilbig 1995; Hilbig and Opp 2003; Ma et al. 2008; Wesche et al. 2005, von Wehrden et al. 2006). Desert vegetation occupies the

Gobi in the south between 750 to 1200 m asl. including low shrubs and semi shrubs of the Chenopodiaceae (*Anabasis*, *Haloxylon*, *Kalidium*, *Kochia*, *Nanophyton*, *Salsola*), *Artemisia*, *Calligonum*, *Nitraria*, *Ephedra* and *Convolvulus*. The zone to the north with a mean annual precipitation between 100 to 150 mm is mostly covered by an *Artemisia-Stipa* desert-steppe with Poaceae (*Stipa krylovii*, *S. gobi*, *Cleistogenes soongrica*) and subshrubs of several species of *Artemisia* and *Tanacetum*. Steppe vegetation is found in the majority of central and eastern Mongolia where the annual precipitation reaches 150 to 300 mm and is mainly dominated by grasses like *Stipa capillata* and *Cleistogenes squarrosa* and partly *Artemisia* (*A. frigida*). A forest steppe zone is distributed in altitudes above the grass steppe at about 1000 - 1600 m asl. where the effective moisture is higher. This zone is a patchwork of forests in mostly northern expositions of *Larix sibirica* with some *Betula* and *Pinus sylvestris* in a grass steppe (*Stipa krylovii*, *Poa attenuate*). A zone of mountain taiga with *Larix sibirica* and *Pinus sibirica* reaches up to over 2000 m elevation. Alpine vegetation occurs only in relatively restricted areas. Any zone of deciduous forests between conifer forests and steppe such as is found in most of Eurasia is not developed in Mongolia (Hilbig 1995; Walter 1975).

Materials and methods

A sediment core was obtained from the nearly dried-out BTN in the easternmost part of the Gobi Altai, southern Mongolia, at 43° 34' 23.8" N and 103° 11' 38.2" E (1420 m asl.). An extended lake existed here in a wide flat intramontane basin, which shrank during the later Holocene. The endorhehic catchment area covers about 1750 km² with ephemeral streams. The former extent of the lake is marked by a belt of small sand dunes fixed by *Achnatherum splendens* and a sandbar at about 9 m above the recent lake level (Grunert et al. 2009). A salt-meadow evolved on the gray silty lake sediments, covering the area at the core site.

A core of 5 m length was drilled from 2 to 7 m depth below surface. The upper 2 m of the core was unconsolidated and was not suitable for pollen analyses. In total 56 palynological samples of 0.5 or 1 cm³ were taken in 5 to 10 cm intervals. Sample preparation was carried out with standard methods (Erdtman 1960; Moore et al. 1999) including treatment with HCl, KOH, HF and acetolysis. *Lycopodium* spores were added as exotic marker to calculate the concentration (pollen grains/cm³) and influx of pollen (pollen grains/cm²/yr) and carbonized particles as well. The suspensions were sieved in an ultrasonic bath through a 1.5 µm mesh and stored in glycerin.

More than 400 pollen grains plus NPPs were counted for each sample and all percentages were calculated based on the sum of terrestrial pollen. Three samples (388, 550, 659 cm) contained less pollen grain (pollen sums 313, 269, 337). Pollen and spore types were identified with the reference collections of the Department of Palynology and Climate Dynamics at the University of Göttingen and relevant publications (Beug 2004; Moore et al. 1999; Van Geel et al. 2003; Van Geel and Aptroot 2006; Vanky 1994). Pollen clumps, denoting immature pollen grains sticking together, were recorded as an additional palaeoecological proxy (Schlütz and Lehmkuhl 2007).

The software C2 version 1.5.1 was used to present the selected palynological data as diagrams (Juggins, 2007). All observed palynological taxa occurring at least three times or with values of more than 0.5% are presented. The taxa are arranged according to their ecology and chronological appearance.

Stratigraphy and chronology

The core sediment consists of lacustrine fine silt (60 – 70%) and clay (25 – 35%), partly mixed with layers of coarse silt and fine sand. The sand fraction remains almost low (<5%). At the base (700 - 326 cm) the sediments are black and show faint lamination while the top (326-200 cm) is gray consisting of homogenous units with weak horizontal bedding.

Nine Accelerator mass spectrometry (AMS) ^{14}C measurements were completed on the TOC of bulk samples, as remains of terrestrial plants were very scarce or absent (Tab. 2.1). A first set consisting of two subsets of 2 samples each processed at the AMS-Laboratory of Erlangen University (Erl.) revealed

Depth [cm]	Lab. No	^{14}C age and error [yr. BP]	$\delta^{13}\text{C}$ [‰]	calibrated age and SD [cal. yr. BP]	material
247	Poz-37868	5495 ± 35	-21,3	6299 ± 24	bulk sample
253	Erl-13181	5880 ± 46	-20.5	6709 ± 45	bulk sample
353	Erl-12109	8697 ± 56	-22.7	9674 ± 85	bulk sample
367	Poz-37949	9270 ± 50	-25,1	10441 ± 88	bulk sample
367	Poz-37869	9320 ± 60	-24,6	10523 ± 90	bulk sample
526	Erl-13182	6037 ± 47	-21.6	6884 ± 64	bulk sample
536	Poz-37870	6920 ± 40	-26,8	7222 ± 36	bulk sample
674	Erl-12110	10661 ± 56	-23.3	12661 ± 65	bulk sample
665	Poz-37871	11170 ± 70	-27,4	13073 ± 125	bulk sample

Tab. 2.1: Results of the AMS ^{14}C -datings and their calendric age-conversion (calibration) with 1σ standard deviation (SD) using “CalPal-online” (Weninger and Jöris 2008)

Source: Felauer et al., 2012

a time inversion at 353 cm. A control set of 4 samples from about the same depths analyzed in the Poznań Radiocarbon Laboratory (Poz.) confirmed the previous results, with the doubtful sample (here 367 cm) being measured twice. All dates were calibrated with the online version of the program CalPal (Weninger and Jöris 2008).

To frame a sound age-depth model several possible influences on the measured ages should be assessed. One possible factor obscuring the real age of a given sample is the reservoir effect caused by old carbon incorporated by photosynthetic active water plants. As reported from Central Asia this can lead to an age overestimation of a few hundred to about 2000 years or more (Feng et al. 2005; Jiang et

al. 2006; Rickettsa et al. 2001). In the catchment area of the BTN carbonate rocks as a source of old carbon are unknown. Moreover, the BTN was probably always a large and flat lake with $\delta^{13}\text{C}$ of dissolved inorganic carbon in equilibrium with the atmosphere due to intense CO_2 exchange. Therefore, the results of AMS dating are probably not affected by the lake reservoir effect. Furthermore the low $\delta^{13}\text{C}$ values point to carbon of terrestrial origin, as large proportions of water plants would lead to high $\delta^{13}\text{C}$ values (Herzschuh et al. 2005, Stuiver and Polach 1977). For this reason a remarkable reservoir effect may be rejected.

A source of old carbon could be land snails whose shells occurred at about 360 cm depth but not within the range of the other samples for radiocarbon dating. The deepest datings could be influenced by carbon of redeposit fossils like foraminifera whose liners occurred between 640 and 690 cm. As a source of old carbon redeposited “charcoals” (Fig. 4: burnt plant fragments) should be taken in to account. Neglecting the doubtful ages of about 10 ka cal B.P. around 360 cm depth would result in an unrealistically high sedimentation rate (300 cm in less than 1000 years), that is lacking evidence in the sediment parameters (see Felauer et al. 2011 for detail) including the suitable high pollen concentration. Possibly the upper-most sample was influenced by modern carbon from the roots of the salt meadows leading to an age underestimation.

As clear conclusions are masked by the described, and possibly other, reasons, we used the radiocarbon dates without a reservoir or other corrections to establish a rather conservative age-depth model. Assuming a relatively young retreat of the flat lake, the surface level was included with its recent age. Because the time inversion prevents linear interpolation, a polynomial graph (Fig. 2.2) best fitting to the latest data set (Poz. 37868 – Poz. 37871) was chosen. The corresponding time frames of the BTN zones show convincing correlations to known events of climate history. This is for instance true for the length and timing of BTN 2 (12.3 – 11.1 ka cal B.P.), representing a dry period quite possibly equivalent to the Younger Dryas event as well as for the dry spell of BTN 4 (8.6 - 7.55 ka cal B.P.) that seems to represent the 8.2 ka event (this will be handled in more detail in the discussion). Apparently the contradicting influences of different sources of error seem to balance each other more or less.

Results and interpretation

About 80 different types of pollen and NPP (spores, algae, eggs) have been identified. *Artemisia*, Chenopodiaceae and *Ephedra distachya*-type are the most abundant with marked oscillations of amounts throughout the sediment core. Together they constitute more than 70% of the total pollen sum of each sample. The diagrams (Fig. 2.3) are divided into seven local zones (BTN 1 - 7) mainly based on changes in the *Artemisia*/Chenopodiaceae (A/C) ratio. The borders between zones are drawn

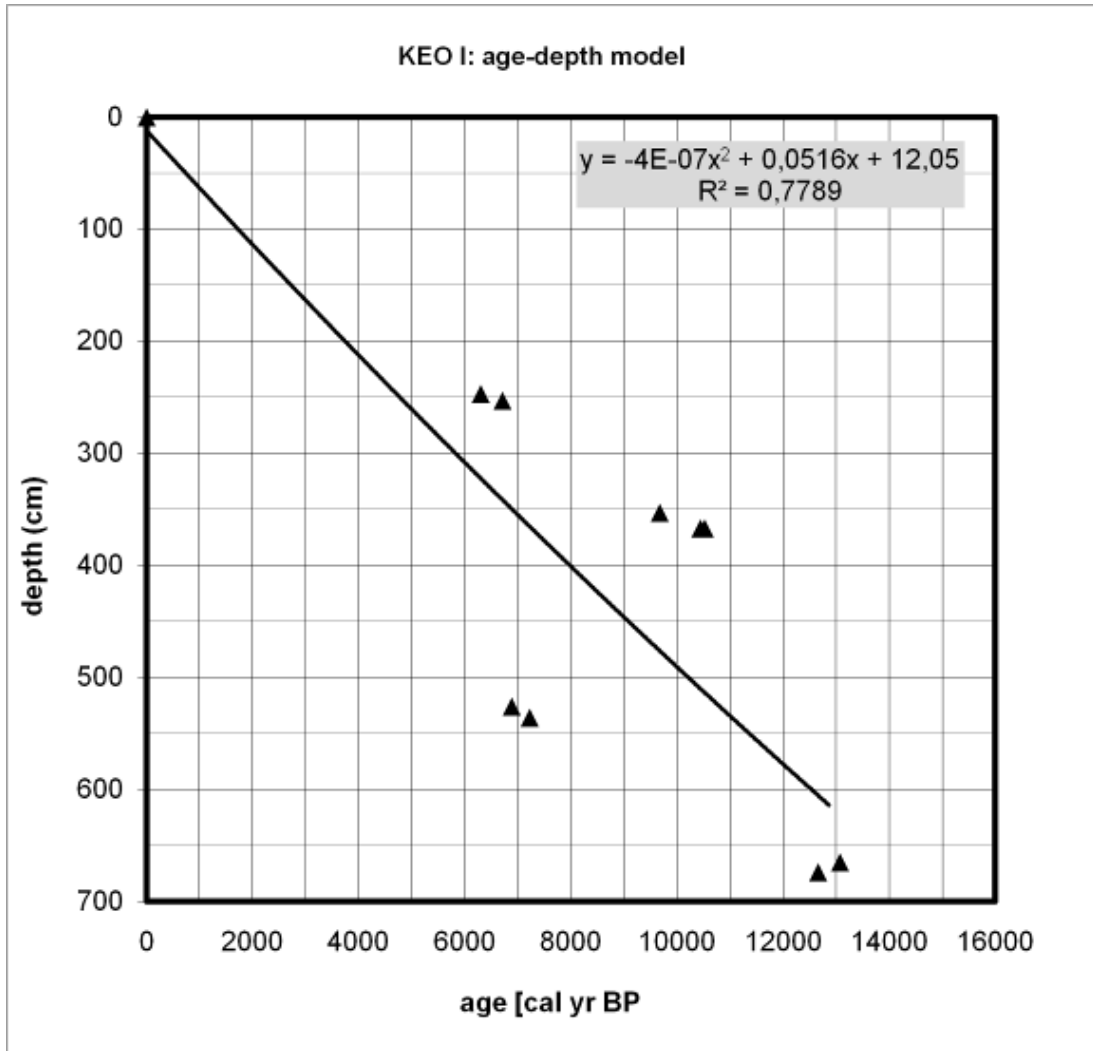


Fig. 2.2: Age-depth model of the Bayan Tohomiin Nuur site based on a polynomial graph best fitting to the calibrated latest data set (Poz. 37868 – Poz. 37871). Source: Felauer et al., 2012

where the A/C ratio exceeds values of about 2. The zones BTN 1, 3, 5 and 7 are characterized by high *Artemisia* values and consequently high A/C ratios. Zones BTN 2, 4 and 6 show high Chenopodiaceae values and A/C ratios below 1 coinciding with a prominent amount of the *Glomus*-type spores. In BTN 4 and 6 the *Ephedra distachya*-type rises up to 40% and 65% respectively. Pollen of trees and shrubs is very rare, with single taxa reaching 1% (*Hippophae*, *Salix*, *Betula*, *Ulmus*, *Pinus* Haploxyton- and *Pinus* Diploxyton-type).

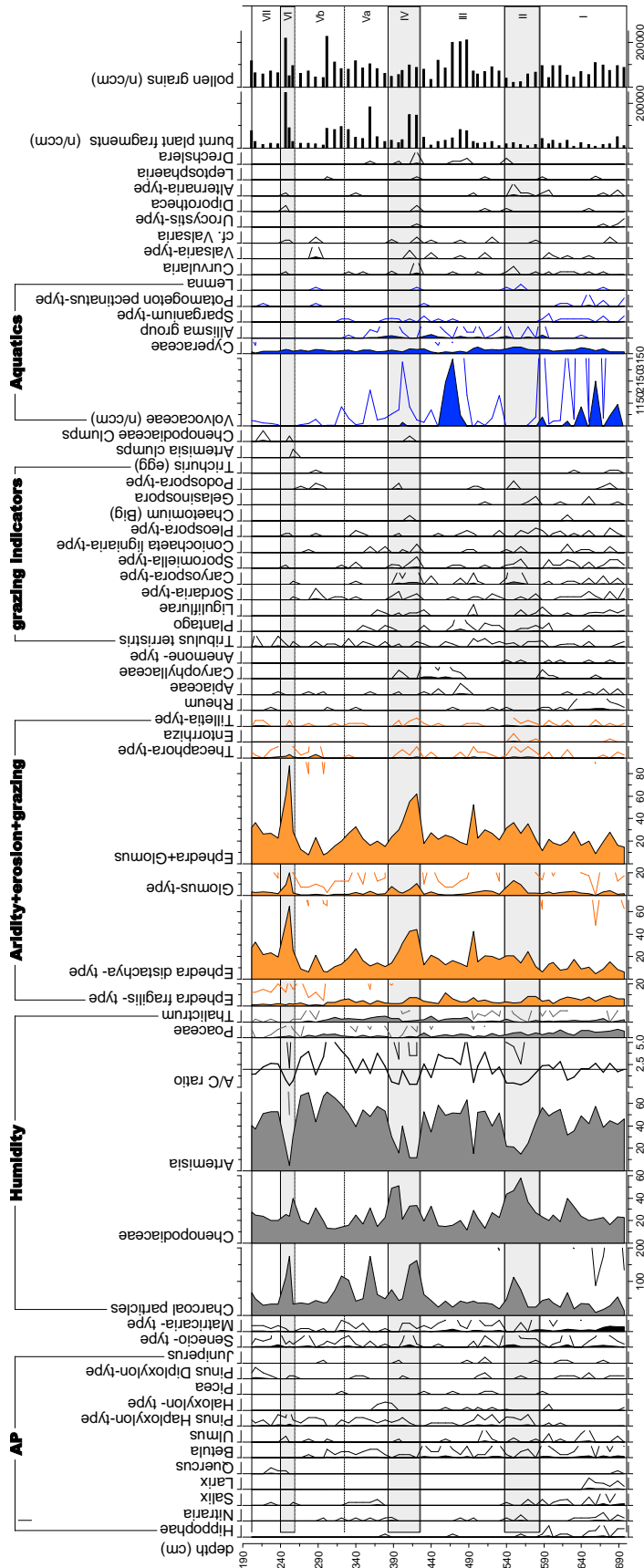


Fig. 2. 3: Pollen and non pollen palynomorphs percentage diagram of Bayan Tohomin Nuur, Gobi Altai, South Mongolia. A/C ratios and the concentration of Volvocaceae, burnt plant fragments and pollen grains are also shown.

BTN 1, 700 - 585 cm, 15.3 - 12.3 ka cal B.P.: Relatively dry *Artemisia* desert-steppe

Artemisia (45%), Chenopodiaceae (24%), the *Ephedra distachya*- (10%) and the *Ephedra fragilis*-type (6%) are the dominant pollen taxa. This and intermediate A/C ratios around 2 point most probably to an open *Artemisia* desert-steppe rich in *Ephedra* shrubs with Chenopodiaceae deserts nearby. The relatively high *Ephedra distachya*-/*Ephedra fragilis*-type ratios (Ef/Ed ratios) point to *Ephedra* species growing under dry conditions (Herzschuh 2007, Schlütz and Lehmkuhl 2007, Tarasov et al. 1996). With Poaceae values around 5%, *Stipa* and other grasses must have been of very low regional abundance. The *Glomus*-type spore, representing spores of mycorrhiza fungi, indicate that soils were eroded down into the rhizosphere (Miehe et al. 2009). Around 13.5 ka cal. B.P. a fall of the A/C ratios to values around 1 indicating a short expansion of desert.

Nitraria shrubs spread near the lake on sandy sites with brackish ground water and a few small trees and shrubs of *Hippophae* and *Salix* along the temporal rivers as well (Grubov 2001; Hilbig 1995). The BTN investigation site is situated at the western limit of the recent area of *Ulmus pumila* and a few trees with contact to the groundwater may have grown along the river beds in the region already 15,000 years ago (Wesche et al. 2011). Pollen of others trees and shrubs are more probably of long distance transport origin.

Beside the climate also grazing animals and fires (burnt plant fragments) affect the plant diversity. Low values of pollen from grazing weeds (*Tribulus terrestris*, Liguliflorae, *Plantago*), spores of coprophilous ascomycetes (*Sordaria*-, *Sporormiella*- and *Podospora*-type) and eggs of the intestinal parasite *Trichuris* reflect the presence of herbivores around the lake (Van Geel and Aptroot 2006, Miehe et al. 2007, 2009). Their diet, herbaceous plants and grasses, were affected by several species of smut fungi (*Thecaphora*-, *Tilletia*-, *Urocystis*-type) (Miehe et al. 2009; Vanky 1994).

The high peaks of Volvocaceae probably indicates phases of mesotrophic to eutrophic lake conditions with high organic productivity due to stronger nutrient input (Chen et al. 2003; Jin et al. 2006; Kramer et al. 2010; Feleauer et al. 2012). Pollen of aquatic plants (*Potamogeton pectinatus*-, *Sparganium*-type, *Allisma* group) and Poaceae point to submerged plants of shallow water and reed beds as found recently at the shore of the Orog Nuur, about 250 km to the north-west (Hilbig 1995).

BTN 2, 585 - 538 cm, 12.3 - 11.1 ka cal B.P.: Arid Chenopodiaceae desert

Highest Chenopodiaceae values of the record (58%), decreasing *Artemisia* percentages (<25%) and consequently low A/C ratios (0.5) indicate arid conditions. The increase in *Ephedra distachya*-type (>10 %) points to colder conditions and possible barren rocks with *Ephedra* shrubs growing in their crevices (Herzschuh 2007, Schlütz and Lehmkuhl 2007). Soil erosion due to the sparse vegetation is indicated by higher values of the *Glomus*-type (up to 13%) and the occurrence of spores of *Entorrhiza*, a smut fungi genus with species infecting the roots of Cyperaceae and Juncaceae. As indicated by the lowering of the Ef/Ed ratio the erosion increased under somewhat cooler climatic conditions.

Ascomycetes (*Coniochaeta ligniaria*-type) were probably involved in the subaerial decay of woody material, and water ascomycetes of the genus *Caryospora* or relatives (*Caryospora*-type) probably enhanced decay within the lake after subaqueous deposition. The absence of *Potamogeton pectinatus*-type points to a shrunken or more salty lake with a decreased productivity indicated by lower values of TOC and CaCO₃ (see Feleauer et al. 2012 for detail).

BTN 3, 538 - 430 cm, 11.1 - 8.6 ka cal B.P.: Semi-arid *Artemisia* steppe

A steep rise of *Artemisia* (>50%) and a strong reduction of Chenopodiaceae (A/C ~4), indicate a semi-arid *Artemisia* desert steppe again. A rise of *Thalictrum* may hint to the development of meadow-steppe-like vegetation types under more humid conditions in higher altitudes (Grubov 2001). Reduced amounts of Fe, Ti, *Glomus*-type and Rb/Sr and K/Ca ratios are evidence for a quite dense vegetation cover (see Feleauer et al. 2012 for detail). Few reversals of these erosion and detrital influx-indicators coincident with high amounts of Volvocaceae, TOC and N. High N values combined with a low persistence of *Glomus*-type point to the in wash of nutrient rich litter and/or topsoil.

BTN 4, 430 - 383 cm, 8.6 – 7.6 ka cal B.P.: Chenopodiaceae desert with *Ephedra* shrubs

The climatic conditions became arid again (low A/C ratios). A first phase characterized by exceptionally high values of the *Ephedra distachya*-type (>40%) represents the time of a very open vegetation cover with areas of barren ground dominated by *Ephedra* shrubs. A deep reaching soil erosion is demonstrated by the *Glomus*-type. In a second phase, shrubs of *Ephedra* were partly replaced by Chenopodiaceae, but erosion remained high. Intermediate cooler conditions indicated by almost disappearing *Thalictrum* values (meadow-steppes at higher elevations) in the second part of the BTN 4 could have caused the *Ephedra* shrub phase. Nevertheless, *Ephedra distachya*-type percentages of more than (10-) 20% are hard to interpret as they have no recent analogs in Mongolia (Ma et al. 2008), Inner Mongolia (Liu et al. 2006; Wang et al. 1996) as well as in other parts of Central Asia (Herzschuh 2007; Tarasov et al. 1998; Yu et al. 2001). Thus further research on surface samples is needed for a more sound palaeoecological understanding.

Zone BTN 5, 383 - 260 cm, 7.6 - 4.9 ka cal B.P.: Most wet with *Artemisia* desert-steppe to steppe

A sharp rise in the *Artemisia* percentages demonstrates again a rapid change from arid to semi-arid conditions. The zone can be divided into two sub zones. In the beginning (BTN 5a) the landscape status resembles very much that of BTN 3 (*Artemisia* desert-steppe). At around 6.3 ka cal B.P. (325 cm) the start of the rise of the *Artemisia* curve to over 70% (A/C >4) marks the onset of the most stable and humid conditions for the entire sediment core, possibly representing a semi-humid *Artemisia* steppe in BTN 5b. Very low values of erosion indicator (*Glomus*-type) suggest a dense vegetation cover. The soil stabilization during this climatic amelioration was in contrast to the other relatively less arid periods of BTN 3 and BTN 5a. Nevertheless, synchronously occurring slightly higher values of

Chenopodiaceae and *Ephedra distachya*-type (one sample) and a reduced carbonate precipitation (two samples) may point to a short lived cold event without notable long-term consequences for erosion.

The dense vegetation offered a substantial food supply for the existing herbivores (*Tribulus terrestris*, *Podospora*-type, *Trichuris*) lowering the relative grazing pressure. This and/or a change in composition or density of the herbivore fauna may have led to the lasting reduction of typical grazing weeds such as Liguliflorae and *Plantago*.

BTN 6, 260 - 240 cm, 4.9 - 4.5 ka cal B.P.: Cool and arid *Ephedra* shrub vegetation

Highest values of *Ephedra distachya*- (65%) and *Glomus*-type (20%) for the entire record show that the loss of soil by erosion and the portion of barren ground reached probably their greatest extents. High concentrations of burnt plant particles point to frequent fires under dry climatic conditions (A/C ratio 0.2). The same is true for BTN 4. Such fires may have significantly supported the abundance of *Ephedra* shrubs. However, concurrent extremely high concentrations of burnt plant particles and pollen grains could be the result of an unobstructed surface runoff (Hartmann and Wünnemann 2009). Also the occurrence of pollen clumps in the sediment may be a result of water transport. Overall, the ecological conditions resembled those in the first phase of BTN 4, with BTN 6 being probably too short for a subsequent succession to a Chenopodiaceae desert.

BTN 7, 240 - 200 cm, 4.5 – 3.8 ka cal. B.P.: Relatively dry *Artemisia* desert-steppe

A/C ratios around 2 and high *Artemisia* abundance imply a relatively dry *Artemisia* desert-steppe as in BTN 1, which was slightly richer in *Ephedra* shrubs. Parallel to the increase of the *Ephedra distachya*-type, the (aeolian) clastic input grew (Ti, Fe) once more. Very low values of grazing indicators possibly result from a strongly reduced animal population. As spores of coprophilous fungi are dispersed only over very short distances, higher values may denote to water transport, thus lower values may point to the drying out of the lake.

Discussion

Regarding the given age-depth model, the recorded alteration of arid, semi-arid and semi-humid climatic conditions correlate well to the traits of supraregional climatic patterns (Tab. 2.2).

BTN zone	Time period (Ka cal. B.P.)	Vegetation and sedimentological derivations	Climate	Duration (ka)
7	4.5 - 3.8	<i>Artemisia</i> desert-steppe with <i>Ephedra</i> shrubs, erosion low, lake shrinking	semi-arid	0.7
6	4.9-4.5	<i>Ephedra</i> shrub dominated Chenopodiaceae desert, <i>Glomus</i> -type, erosion very high	(cold-)arid	0.4
5b	6.3 - 4.9	dense <i>Artemisia</i> steppe, erosion lowest	semi-humid	1.4
5a	7.6 - 6.3	<i>Artemisia</i> desert-steppe with <i>Ephedra</i> shrubs, erosion relative low	semi-arid	1.3
4	8.6 - 7.6	succession from a <i>Ephedra</i> shrub land to a Chenopodiaceae desert, <i>Glomus</i> -type, erosion high	warm-arid cold-arid	1.0
3	11.1 - 8.6	<i>Artemisia</i> desert-steppe, erosion low	semi-arid	2.5
2	12.3 - 11.1	Chenopodiaceae desert with <i>Ephedra</i> shrubs, <i>Glomus</i> -type, erosion high	(cold-)arid	1.2
1	15.3 - 12.3	<i>Artemisia</i> desert-steppe with few <i>Ephedra</i> shrubs, low erosion	semi-arid	3.0

Tab. 2.2: Synopsis of vegetation, landscape and climate evolution at the Bayan Tohomiin Nuur site, Gobi Altai, South Mongolia

Late Glacial

The record starts at about 15.3 ka cal. B.P. with the pollen-based reconstruction of a relatively dry *Artemisia* desert-steppe near to Chenopodiaceae deserts lasting until about 12.3 ka cal. B.P. (**BTN 1**). This period was followed by a pronounced climatic deterioration (**BTN 2**), suggesting that the **BTN 1** may be the high continental equivalent of the late glacial stadials Meiendorf, Bölling and Alleröd known from northern Europe and north-east China as phases of forest reestablishment and increased $\delta^{18}\text{O}$ values in ice cores from Greenland (Litt and Stebich 1999, Stebich et al. 2009). This lateglacial warm period lasted in NE-China until 12.5 ka cal. B.P. (Schettler et al. 2006).

With 1200 years of arid conditions the **BTN 2** (12.3 – 11.1 ka cal. B.P.) apparently corresponds to the Younger Dryas period which is represented by a dry phase in most parts of Central Asia lasting from about 12.8 to 11.5 ka cal. B.P. (Herzschuh 2006) and marked by a forest decline in north-east China dated by varved sediments to 12.7 to 11.65 ka cal. B.P. (Stebich et al. 2009). The relative delay of the **BTN 2** of about 400-500 years can be ascribed to uncertainties in the age-depth model. A short return to dry conditions in the **BTN 1** at around 13.5 ka cal. B.P. possibly correlate to the colder and/or dryer Oldest Dryas (13.9 - 13.8 ka cal B.P.) occurring in north-east China, where an Older Dryas equivalent (ca. 13.5 ka cal. B.P.) was not recorded so far (Stebich et al. 2009).

Holocene

The Holocene is mostly represented by relatively humid conditions interrupted by dryer oscillations (Tab. 2.2). The early Holocene starts at about 11.1 ka cal. B.P. with a climatic amelioration lasting almost 2500 years (**BTN 3**). These more humid conditions coincide with the onset of higher effective moisture in continental Asia at around 11.5 ka cal. B.P. due to an abrupt intensification of the summer monsoon system driven by a steep rise in air temperature as documented in Greenland ice cores (Herzschuh 2006). A strengthening of the North Atlantic Oscillation enhanced the westerlies drawing more moisture from the sea to the interior of Eurasia. Thus the effective moisture in Central Asia increased due to strong westerlies and an enhanced summer monsoon as well (Morrill et al. 2003; Qin and Yu, 1998; Tarasov and Harrison 1998; Wang et al. 2004).

Wang et al. (2007) also discussed an enhanced summer monsoon at about 11 ka cal B.P. in India, western Asia, western Africa and the Sahara, placing the moisture-driven climatic optimum into the early Holocene. In contrast to monsoon-controlled areas, the early Holocene in the Gobi Altai was not the period of maximum moisture availability. However, the temperatures increased in all mentioned areas as well as in northern Eurasia (Andreev and Tarasov, 2007) and the precipitation must have been notably higher in the early Holocene compared to the cooler conditions of the BTN 1 to result in relatively high effective moisture.

The semi-arid conditions during the early Holocene were followed by an abrupt climatic deterioration from 8.6 to 7.6 ka cal. B.P. (**BTN 4**). The vegetation succession from *Ephedra* shrubs to a Chenopodiaceae desert points to a climatic shift from more cold and dry to warm and dry conditions. This succession can be probably related to some extent to the 8.2 ka event known from the Greenland ice cores as a strong climatic reversal lasting about 150 years (Kobashi et al. 2007; Thomas et al. 2007). The 8.2 ka event was the middle part of a longer climate deterioration of 400 to 600 years (Jin et al. 2007; Lal et al. 2007; Prasad et al. 2006; Rohling et al. 2005; Wang et al. 2005). Despite the dating uncertainties, the relatively long period of 1000 years and the climatic evolution reflected at the BTN site may be peculiarities under a high continental climate.

The abrupt change to moister conditions marks the onset of a mid-Holocene climatic amelioration lasting from 7.6 to 4.9 ka cal. B.P. (**BTN 5**). Following the review of Feng et al. (2006), the western part of southern Mongolia experienced a generally wet climate from 7.5 to 4.0 ka cal B.P. (Chinese province Xinjiang). To the east of Mongolia in the Chinese province Inner Mongolia a dry early Holocene was followed by a wet middle Holocene from 7.4 to 4.5 ka cal. B.P. as well. In contrast, in the south of Mongolia this period was dry (Feng et al. 2006; Chen et al. 2003). In northern Mongolia, a drought took place between 6.5 to 4.8 ka cal B.P. (An et al. 2008) and in NE-China the summer monsoonal rainfall reached a minimum at around 6.4 ka cal B.P. (Schettler et al. 2006). Extreme spatial climate differences in Central Asia during the Holocene were already pointed out earlier (i.e. An et al. 2008, Herzschuh 2006). With the help of the new information from the BTN area a supraregional pattern characterized by a relatively wet belt stretching west-east over more than 30° of

latitude and a few hundred kilometers south-north bordered by dry regions in the north and south may be derived. Possibly the confluence of westerly and monsoonal air masses led to atmospheric and resulting precipitation while in the south and north the sole marginal influence of each of these two climate systems was relatively weak (Feng et al. 2005). Thus the asynchronous climate developments in the region were the result of a complex and combined influence of the westerlies and the monsoon (Jiang et al. 2007; Schettler et al. 2006).

The most humid phase inferred from our record lasted from 6.3 to 4.9 ka cal. B.P. (**BTN 5b**) and was characterized by a well proliferated *Artemisia* steppe which represents the Holocene climate optimum in the Gobi Altay. This is in accordance with the rising lake level of the Telmen Nuur between 6.3 and 4.4 ka cal. B.P. (Peck et al. 2002) and the maximum of tree pollen at the Bayanchagan lake in Inner Mongolia some 1000 km east of the BTN (Jiang et al. 2006). As the monsoonal influence in Asia decreased since at least 7 ka cal. B.P. the moisture optimum in the Gobi Altai must have been steered by northern hemispheric processes (An et al. 2000; Herzschuh et al. 2006; Jiang et al. 2006; Li et al. 2004). The climatic optimum was suddenly terminated by a short climatic reversal to arid and possibly colder conditions from 4.9 to 4.5 ka cal. B.P. (**BTN 6**). A minimum in the summer monsoon rainfall in NE-China at around 4.9 ka cal. B.P. (Schettler et al. 2006) and a hiatus in the sediments of the Bayanchagan lake (Jiang et al. 2006) point to an temporal regional moisture deficit during this time. At least the subsequent 700 years (**BTN 7**) were semi-arid again.

Some of the climatic changes can be correlated to the climate of the northern hemisphere pointing to teleconnections with the North Atlantic (Chen et al. 2010, Vandenberghe et al. 2006). For instance, the increase in moisture from the westerlies depends on an increase in evaporation over the north Atlantic driven by a higher summer insolation (Feng et al. 2006). As the summer monsoon is also controlled by orbital forcing, coeval changes took place. Thus not all observed changes in the BTN record can be attributed to one or the other climate system, as also links between the North Atlantic and the summer monsoon regions exist (Gupta et al. 2003, Wang et al. 2005).

Conclusions

The palynological record of the Bayan Tohomii Nuur of southern Mongolia Gobi desert revealed a detailed history of vegetation and landscape dynamics in high continental Asia from about 15.3 to 3.8 ka cal BP. The reconstructed climatic phases can be correlated within dating errors to typical features of the Northern Europe climate patterns such as the Younger Dryas and the 8.2 ka event. A mid-Holocene timing of the moisture optimum is attributed to a strengthening of the westerlies. Nevertheless the combined influence of westerlies and the summer monsoon caused a relatively humid phase just before the Holocene optimum, while bordering areas in the south and north were dry.

The overall high correlation with supraregional climate dynamics seems to be a peculiarity of the BTN record, while most of the Mongolian archives stress small-scale differences obscuring outreaching commonalities to some extent. We can conclude that the small catchment area of the BTN, its location

at the transition from desert to semi-desert and the shallow character of the lake led the sediments of the BTN to become a highly sensitive and representative archive for climate and landscape change. Our results emphasize the need for further detailed interdisciplinary studies of well selected archives of Mongolia to contribute to a decryption of the complex spatial patterns of climate history in central Asia

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Chapter 3

Late Quaternary climate and landscape evolution in arid Central Asia: A multiproxy study of lake archive Bayan Tohomin Nuur, Gobi desert, southern Mongolia

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Abstract

A 7 m sediment core from the Bayan Tohomin Nuur dry lake located in southern Mongolia was investigated by a multidisciplinary study to reconstruct the history of climate and palaeoenvironmental conditions during the late Quaternary. The geochemical, granulometric, palynological and ostracod results show a graduation of at least nine climatic units during the last 15 ka cal. BP. The climate during the late Glacial changed from wet towards more dry conditions, representing the beginning of the Younger Dryas period. At 11 ka cal. BP a rise in temperature and precipitation could be reconstructed, marking the onset of the Holocene. The humid period of the Holocene lasted until about 4 ka cal. BP, interrupted by shorter dry/cold reversals at 8.5 – 7.5 ka cal. BP and 5 – 4.5 ka cal. BP. The aridity in southern Mongolia increased afterwards accompanied by the strengthening of aeolian processes, dune remobilization and lake desiccation.

Keywords: paleoclimate, sedimentology, palynology, late Pleistocene, Holocene

1. Introduction

In paleoclimate research lake sediments have proved to serve as good archives for reconstruction of climatic changes during the Pleistocene and Holocene. Due to the low disturbance and the evident stratification of many lacustrine sediments palaeoenvironmental conditions may be reconstructed using continuously accumulated lake sediment archives.

On two expeditions in the years 2007 and 2008, lacustrine sediment cores were taken at three different sites (Bayan Tohomiin Nuur, Khongoryn Els, Orog Nuur) in order to reconstruct environmental and climatic processes in the basins of the northern Gobi. In this paper we present our findings concerning the sedimentary and geochemical evolution of the Bayan Tohomiin Nuur area during the transition from Pleistocene to Holocene. The Bayan Tohomiin Nuur dry lake is located in continental Central Asia (Mongolia) in the present transition zone between the Gobi desert and desert-steppe, therefore representing a very valuable archive sensitive to past climatic changes. The multiproxy analysis of the 7 m core included the investigation of geochemical, granulometric, palynological and ostracod analyses used to reconstruct the geomorphologic, climatic and sedimentary processes within the small

local catchment of the lake during the last 13 ka. Detailed palynological analyses of the core are in preparation. Therefore only selected palynological results are presented here.

Investigations of the late Pleistocene climatic development focused mainly on the northern parts of Mongolia, analyzing changes in lake levels, deposition of glacial sediments, phases of aeolian activity and the spreading of vegetation (Lehmkuhl 1997, Lehmkuhl, 1998, Naumann 1999, Walther 1999, Grunert et al. 2000, Schlütz 2000, Tarasov 2000, Peck et al. 2002, Fowell et al. 2003, Walther et al. 2003, Grunert and Lehmkuhl 2004, Wang et al. 2004, Prokopenko et al. 2007, Gillespie et al. 2008). These surveys concluded that a moist and relatively cold climate prevailed between about 45-30 ka. During that time many lakes in northern Mongolia maintained high lake levels (Walther 1999, Grunert and Dasch 2000, Grunert et al. 2000, Lehmkuhl and Lang 2001). Between 25 ka and 13 ka arid-cold conditions prevailed in most parts of Central Asia as reconstructed from low lake levels, vegetation changes, dust deposition, dune formation and glacier advances (Owen et al. 1997, Owen et al. 1998, Walther 1999, Fedotov et al. 2000, Grunert et al. 2000).

Holocene climate reconstructions show regional variations and uncertainties and the differentiation between local signals and regional climatic patterns is difficult (Fowell et al. 2003, Chen et al. 2008). At theUvs Nuur basin two Holocene phases of high lake levels were reconstructed for the periods from 11.2-9.6 ka and 7.3-3.2 ka (Walther 1999, Grunert and Dasch 2000, Grunert et al. 2000). Peck et al. (2002) and Fowell et al. (2003) inferred a general rise in lake level at Telmen Nuur during the Holocene. At lake Ugii Nuur humid conditions were reconstructed from sedimentological analyses for 7.9-4.2 ka and 2.8 ka (Schwanhardt et al. 2008), whereas Wang et al. 2009 reconstructed based on pollen analyses a dry and warm climate between 8-3.2 ka and 1.6-0 ka for Central Mongolia interrupted by wet and cold conditions. Investigations on paleosoils in loess sections (northern Mongolia) indicate humid and warm conditions at around 6 ka and 3 ka (Feng et al. 2005, Lehmkuhl unpubl. data).

Paleoclimatic research in southern Mongolia has only rarely been conducted. Investigations of beach bars of Orog Nuur and Adgiyn Tsagaan Nuur show low lake levels between 25-15 ka (Komatsu et al. 2001). High lake levels were reconstructed between 10-6 ka and 1.5-1.4 ka (Komatsu et al. 2001, Lehmkuhl and Lang 2001, Yang et al. 2004). Degradation of permafrost during the Holocene was analyzed in alluvial fan sediments of the Gobi Altai by Owen et al. (1998). The formation of alluvial fans in the Gobi was discussed by Owen et al. (1997), Lehmkuhl (2000) and Vassallo et al. (2005). The sediment core at the Bayan Tohomiiin Nuur therefore provides further data to improve the understanding of paleoclimate development in southern Mongolia during the Holocene.

2. Regional setting

Bayan Tohomiiin Nuur dry lake (43°34'N, 103°11'E, 1410 m a.s.l.) is situated in the northwestern Gobi desert within a small NW-SE striking basin (area ~300 km²) at the eastern termination of the Khongoryn Els dune field (Fig. 3.1). The basin is framed by NW-SE striking mountain ranges, which

are part of the Gurvan Saihan island arc terrane. These ranges are composed of Silurian and Devonian metasedimentary rocks, being elevated during Cenozoic faulting as part of the Bogd-Fault system. They consist of left lateral strike-slip and thrust faults (Mineral Resources Authority of Mongolia 1998).

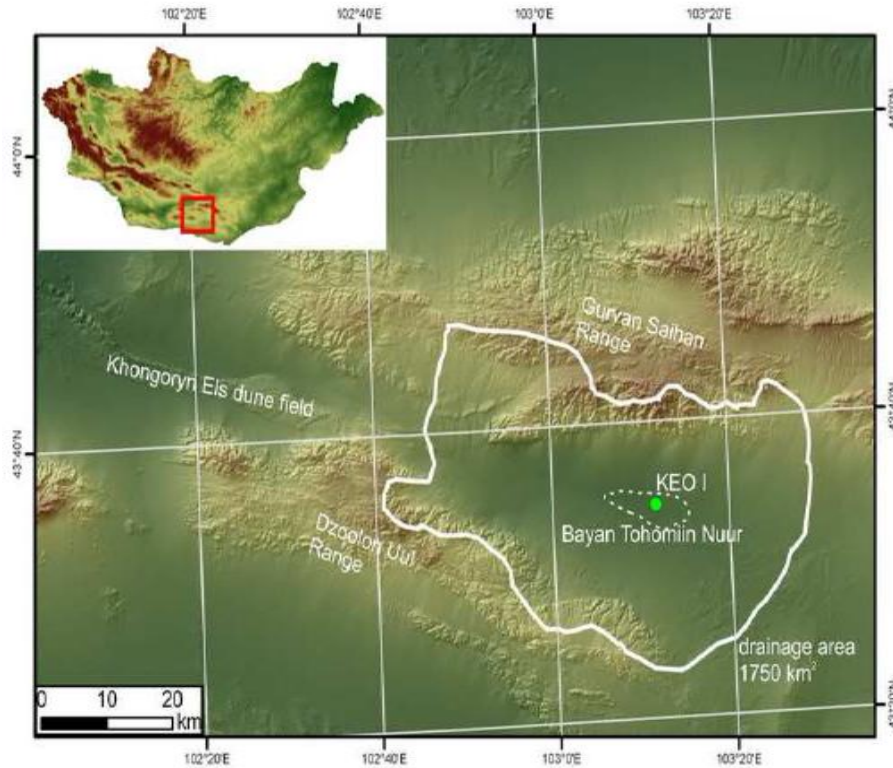


Fig. 3.1: Location of the Bayan Tohomiin Nuur core; the dashed line illustrates the lake area and the bordered line shows the drainage area of the lake

Surrounding mountains reach altitudes of 2600 m a.s.l. at the northern Gurvan Saihan Range and 2400 m a.s.l. at the southern Dzoolon Uul Range. The mountain front is covered by several relief generations of alluvial fans and fanglomerates (20-30 km length) building the transition to the endorheic basin, filled with Quaternary sediments. The basin sediments are composed of lacustrine silt and clay, alternating with fluvial slope deposits and aeolian sediments. The Khongoryn Els dune field originates from a large basin located 150 km to the north-west and covers the bottom of a graben with an area of approximately 1000 km² and an extent of 180 km. The Khongoryn Els is characterized by several generations of complex dunes reaching up to 100 m height (Baasan 2004). At the eastern expiration of the Khongoryn Els, the dunes decrease and pass into the lacustrine sediments of Bayan Tohomiin Nuur.

The catchment of the Bayan Tohomiin Nuur occupies an area of 1750 km², consisting of ephemeral streams prograding from the ranges and alluvial fans into the basin. Due to the low amount of precipitation and the high evaporation the basin is mostly dried up, leaving a salt meadows area at the center mostly fed by groundwater from the alluvial fans. The dried lake area is surrounded by a belt of

small dunes (< 2 m) fixed by *Achnatherum splendens* (Poaceae). A beach bar at 9 m above the present surface marks a former expansion of the lake area (Grunert et al. 2009).

Present climate is extremely continental with a high amplitude of mean temperatures ranging from -15 °C in January to 21 °C in July. Rainfall is highly variable with mean annual precipitation rates of 127 mm (National Statistical Office of Mongolia 2004). During the winter months the climate is influenced by the Siberian-Mongolian high pressure cell, which causes low temperatures and dryness (only 10% of the mean annual rainfall). The alternating occurrence of the East-Asian summer monsoon and westerlies during the summer months causes high temperatures and higher rates of precipitation (Feng et al. 2005).

The vegetation within the catchment area is characterized by desert steppe species of *Artemisia* and Chenopodiaceae, thus indicating the transition to the desert in the southern part of Mongolia (Barthel 1988, Administration of Land Affairs 2004).

3. Materials and methods

A 7 m core (KEO I) was taken with a percussion corer (Nordmeyer GmbH & Co. KG, Germany) within the northern margin of the former lake basin (43°34'N, 103°11' E, 1410 m a.s.l.) during an expedition in August 2007. From the unconsolidated upper 200 cm ten samples (10 cm thickness) were taken at the coring site. The lower drilled sediments (700-201 cm) were transported in plastic tubes to RWTH Aachen University where they were opened with an oscillating saw, cleaned and visually described. The drilling was stopped due to technical reasons and deeper lake sediments have to be expected. XRF, grain size, CaCO₃, CNS and total organic carbon (TOC) were analyzed at RWTH Aachen University on one half of the core. Palynological analyses and extraction of samples for ostracod analysis was done on the second half of the core at the Georg-August University Göttingen.

Element concentrations of Ti, Mn, Fe, V, Rb, Ca, Sr and K were measured on the core with a mobile X-ray fluorescence scanner (Analyticon, Xlt 700) at 2 cm intervals and the element ratios of K/Ca and Rb/Sr were calculated. Grain size, CaCO₃, CNS and total organic carbon (TOC) were analyzed at sediment samples of 2 cm, taken at 5 cm intervals.

For grain size analysis the samples were air-dried. To remove the organic matter the samples were treated with 0.3 ml 30 % H₂O₂ at 70 °C for 24 hours. The carbonates were not removed in order to provide the possibility of also measuring agglomerated aeolian particles, which are cemented by carbonate (Kilibarda et al. 2008). For keeping the particles in dispersion the samples were treated with 0.25 ml Na₄P₂O₇ for 12 hours. The grain size measurement was done with a Laser Diffraction Particle Size Analyzer (Beckman Coulter LS 13 320) calculating the mean diameters of the particles within a size range of 0.04 - 2000 µm and an error of 2 %. Each sample was measured nine times in order to exclude a deviation of the results. The grain size distribution (GSD), mean grain size and volume percentage of clay, silt and sand were calculated with the Beckman Coulter LS Software. The contents of carbon, nitrogen and sulphur were measured with a CNS analyzer (Eurovector EA3000) after air-

drying and grinding of the samples. CaCO_3 was determined volumetrically whereas the TOC was calculated as $(\text{C} - (\text{CaCO}_3 * 0,12)) * 1,72$ (Scheffer and Schachtschabel 2002).

For palynological studies 56 sediment samples of 0.51 cm^3 were taken from 700 to 200 cm at 5 to 10 cm intervals. The samples were treated with standard methods using HCl, KOH, HF and acetolysis (Erdtman 1960, Moore et al. 1999). The suspensions were sieved in an ultrasonic bath on a $1.5 \mu\text{m}$ mesh and stored in glycerin. *Lycopodium* spores were added before HCl treatment as exotic markers to calculate the concentration and influx of pollen grains and burnt plant fragments („charcoals“). Identification and nomenclature of pollen and spore types was relied on the reference collections of the department of Palynology and Climate Dynamics in Göttingen and relevant literature (Vánky 1994, Moore et al. 1999, van Geel et al. 2003, Beug 2004). In all except three samples the counted pollen sum was about 400 pollen grains excluding Cyperaceae and water plants. All values of pollen and spore taxa are related to this sum. The software C2 version 1.5.1 was used to illustrate the results (Juggins 2007). Around a quarter of the nearly 100 recorded pollen and spore taxa are presented in Fig.5. Small values are displayed by an additional exaggeration line (10x). The taxa are arranged according to their ecology and chronological appearance. Sub-samples for ostracod analysis were collected at 4 cm intervals, treated with 3 % H_2O_2 for 48 hours and washed through 0.25 and 0.1 mm meshes at the Institute of Geological Sciences at the Freie Universität Berlin. All ostracod shells were picked from the dried sieve residues and identified.

AMS radiocarbon dating was performed on eight samples which were measured by the AMS ^{14}C laboratory in Erlangen (Germany) and the Poznań Radiocarbon Laboratory (Poland). The calendric age-conversion of the resulting radiocarbon ages was performed with the online version of the program CalPal using the calibration curve CalPal2007-HULU (Weninger and Jöris 2008).

4. Results

4.1. Chronology

Eight AMS ^{14}C datings were performed on bulk material due to missing terrestrial plant remains. A first set of four samples processed at the AMS-Laboratory of Erlangen University (Erl.) revealed a time inversion in 353 cm (Tab.3.1). A control set of another four samples adjacent to the samples measured in Erlangen was analyzed in the Poznań Radiocarbon Laboratory (Poz.) which confirmed the previous results. The sample at a depth of 367cm was measured twice in order to verify the results (Tab. 3.1).

In order to frame an acceptable age-depth model several possible influences on the measured ages are to assess. One factor obscuring the real age of a given sample is the reservoir effect caused by old carbon being incorporated by photosynthetic active water plants. As reported from central Asia this can lead to an age overestimation of a few hundred to about 2000 years (Rickettsa et al. 2001, Feng et al. 2005, Guo et al. 2007). In the catchment area of the Bayan Tohomiin Nuur carbonate rocks as

Depth [cm]	Lab. No	¹⁴ C age and error [yr. BP]	δ ¹³ C [‰]	calibrated age and SD [cal. yr. BP]	material
247	Poz-37868	5495 ± 35	-21,3	6299 ± 24	bulk sample
253	Erl-13181	5880 ± 46	-20.5	6709 ± 45	bulk sample
353	Erl-12109	8697 ± 56	-22.7	9674 ± 85	bulk sample
367	Poz-37949	9270 ± 50	-25,1	10441 ± 88	bulk sample
367	Poz-37869	9320 ± 60	-24,6	10523 ± 90	bulk sample
526	Erl-13182	6037 ± 47	-21.6	6884 ± 64	bulk sample
536	Poz-37870	6920 ± 40	-26,8	7222 ± 36	bulk sample
674	Erl-12110	10661 ± 56	-23.3	12661 ± 65	bulk sample
665	Poz-37871	11170 ± 70	-27,4	13073 ± 125	bulk sample

Tab. 3.1: Results of the AMS ¹⁴C-datings and the calendric age-conversion (calibration) with 1 σ standard deviation (SD) using “CalPal-online” with calibration curve CalPal2007-HULU (Weninger and Jöris 2008).

source of old carbon are unknown. Moreover the Bayan Tohomiin Nuur as a flat and temporary desiccating lake should be in an isotopic equilibrium with the atmosphere by intense CO₂ interchange. Therefore the age data should not be affected in this way. The low amounts of δ¹³C point to a predominantly terrestrial origin of the dated carbon, as remarkable contributions of water plants to the dated material could be identified by higher δ¹³C values (Stuiver and Polach 1977, Herzschuh et al. 2005). For that reasons all dating results seem to be more or less free of the reservoir effect.

A source of old carbon causing the observed age inversion could have been land snails, which occurred at about 360 cm depth. Redeposit ‘charcoals’ (Fig. 5 burnt plant fragments) can also be considered as a source of old carbon. Neglecting the ages of about 10 ka cal B.P. around 360 cm depth for any reasons, would result in a very high sedimentation rate of nearly 300 cm in less than 1000 years. That high sedimentation rate is missing any evidence in the sediment parameters including the suitable high pollen concentration.

As clear decisions are masked by the depicted and possibly other reasons, we considered to use the given dates without reservoir or other correction to build a tentative age-depth model. Assuming a relatively young retreat of the flat lake the surface was included with its recent age into the model. Because the time inversion expels a linear interpolation the age-depth model (Fig. 3.2) is based on a polynomial graph best fitting to the calibrated latest data set (Poz. 37868 – Poz. 37871). This age-depth model dates the profile base to around 15 ka cal B.P.

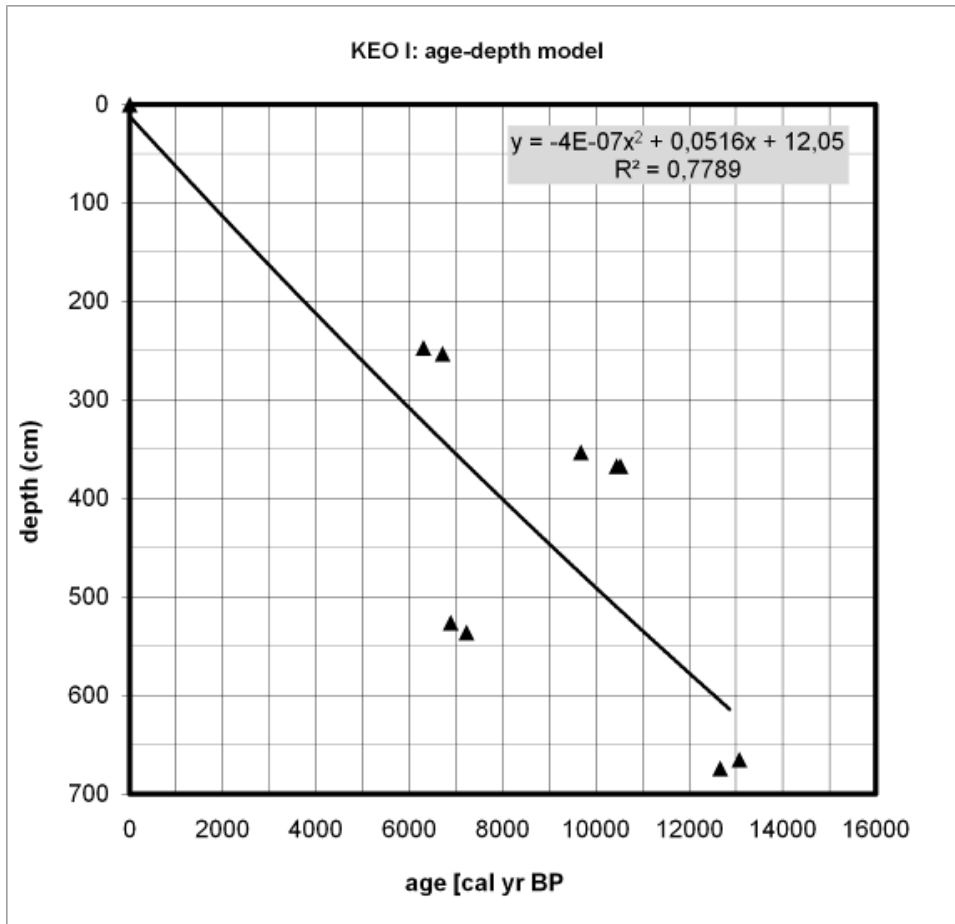


Fig. 3.2: Age-depth model of the core Bayan Tohomiin Nuur based on a polynomial graph best fitting to the calibrated latest data set (Poz. 37868 – Poz. 37871)

4.2. Sediment analysis

The sediment core is composed of lacustrine fine silt and clay, partly interbedded with layers of aeolian fine sand and coarse silt. Based on variations of the palynological and sedimentological data nine stratigraphic units from bottom to top were identified (I – IX) (Fig. 3.3). The sediments of units I - IV (below 383 cm) are black-coloured and show a faint lamination, whereas those of units V – IX (above 383 cm) are grey-coloured and consist of homogeneous units with a weak horizontal bedding.

The grain size analysis of the sediment core yielded two different types of deposits. Most of the samples (75%) feature means grain sizes between 6 and 14 μm . The grain size distribution (GSD) of these sediments shows a unimodal distribution (GSD1) with a peak at the fine sediment fraction (2-10 μm) and a low sand content (Fig. 3.3). The second type of sediment occurs as peak value of the mean grain size ($>15 \mu\text{m}$), caused by an increasing sand content. Grain size analyses of these sediments show the appearance of two peaks, one at the clay and silt fraction (2-10 μm) and one at the sand fraction (63-200 μm), resulting in a bimodal distribution (GSD2).

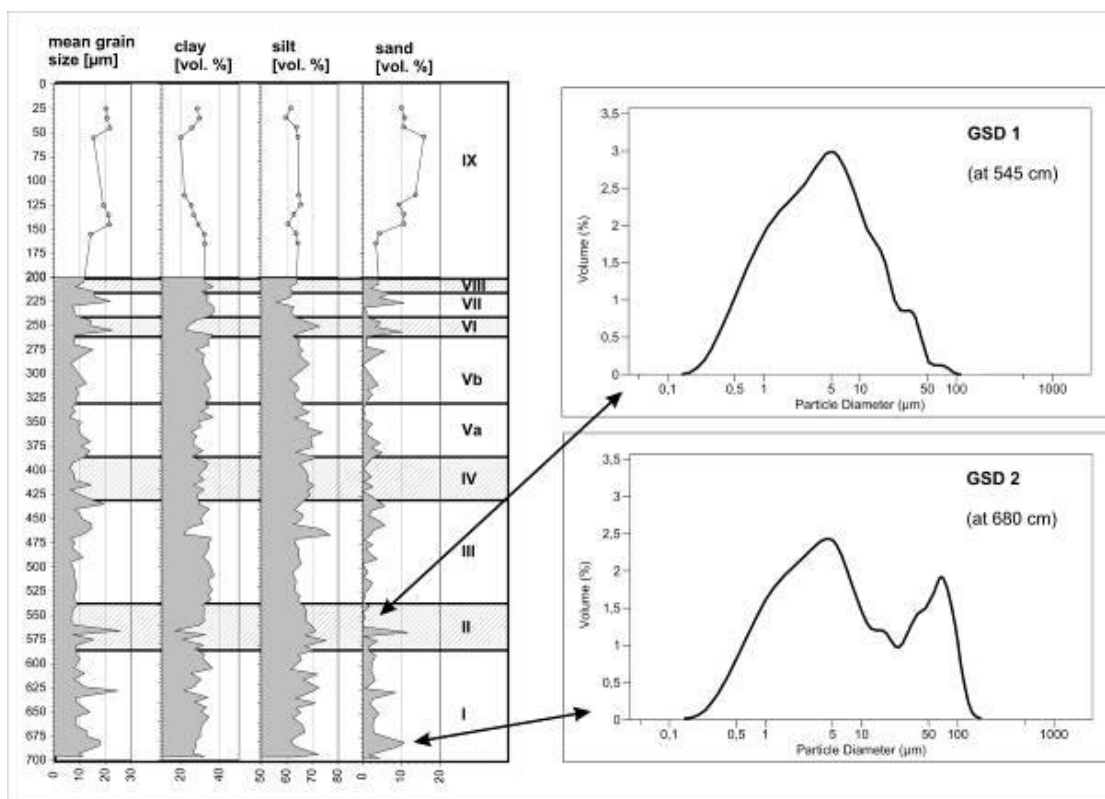


Fig. 3. 3: Results of the grain size analysis: The volume percent of the clay, silt and sand-sized fraction is displayed with the mean grain size. GSD 1 shows a representative grain size distribution with a peak at clay and silt sized particles (unimodal distribution). GSD 2 is composed of two peaks (bimodal distribution), one occurring at the clay and silt fraction the second at the sand fraction.

The element concentrations of Ti, Fe, Mn, K and Rb show consistent trends with low values at units I, III, Vb, VII (Ti: 2000–3000 ppm; Fe: 18000-20000 ppm) and increased values at units II, IV, Va and VI (Ti: 3000–4000 ppm; Fe: >20000 ppm) (Fig.4). This corresponds to K/Ca and Rb/Sr ratios which also show low values at units I, III, Vb, VII and high values at units II, IV, VI. Sr, Ca and CaCO₃ show an increasing trend from bottom to top (CaCO₃ unit I: 16 %, unit IX 20-40 %) with higher values at units I, III and Vb and lower concentrations at II, IV and VI. Variations of C_{total}, TOC, N and TOC/N are consistent to changes of Sr, Ca and CaCO₃, yielding lower amounts at unit II, IV and VI and higher concentrations at units I, III and Vb (Fig. 3.4). The concentration of sulphur shows high values from unit I to V, being interrupted by lowered values at the beginning of unit III and the unit Va. The S content in the upper parts of the core (Units VI – IX) remains low.

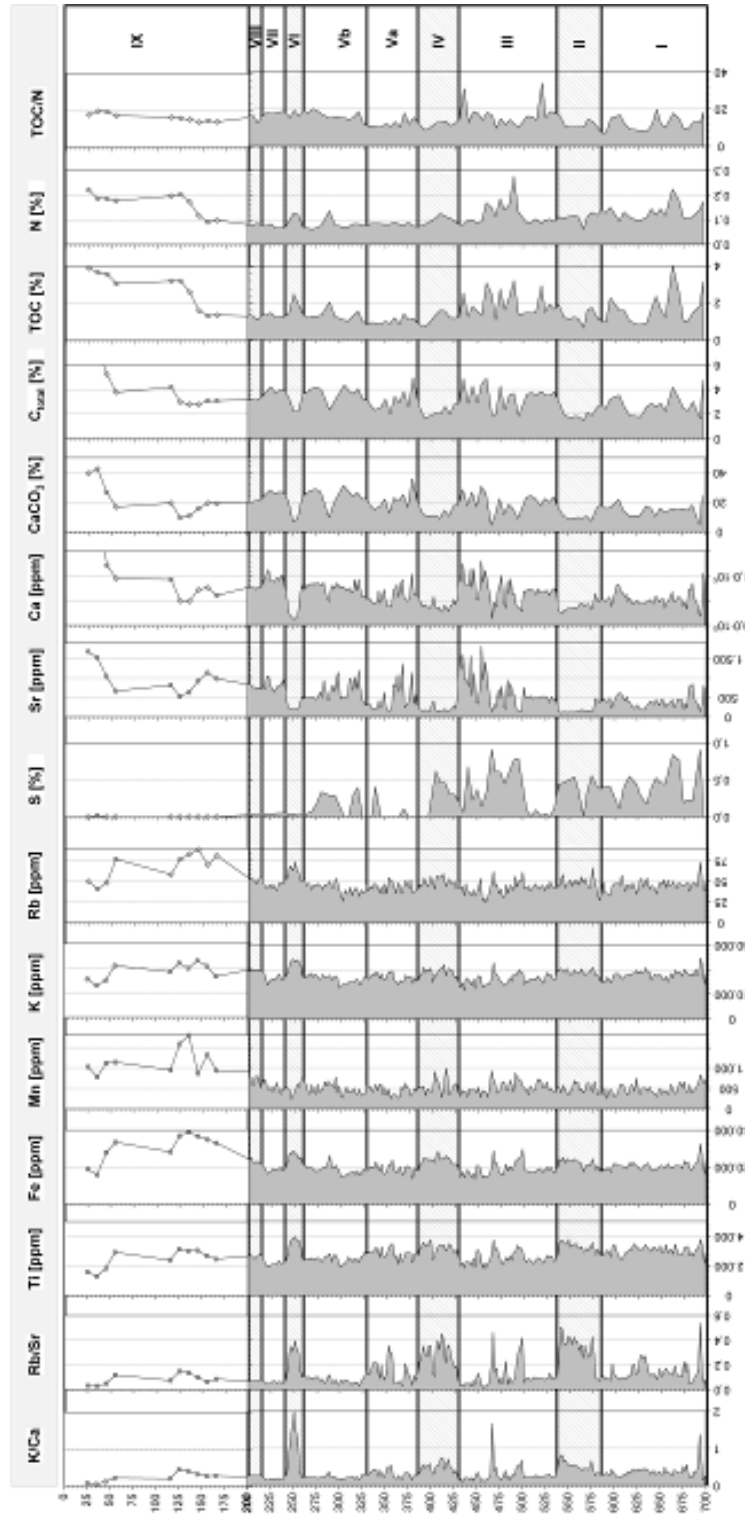


Fig. 3.4: Sedimentological proxies of the Bayan Tohomim Nuur core (KEO I) divided into nine sedimentary units

4.3. Palynological and ostracod analysis

Palynological analyses were restricted to the well preserved material of units 1 to VIII (200 – 700 cm). The pollen taxa *Artemisia* and Chenopodiaceae along with *Ephedra* are dominating throughout the whole diagram (Fig. 3.5). *Artemisia* and Chenopodiaceae exhibit opposite alternating low and high values of up to 70% and 58%. Consequently, the *Artemisia*/Chenopodiaceae (A/C) ratio ranges from 0.2 to 5.5, being low in the units II, IV, VI, VIII. Generally, phases with higher values of Chenopodiaceae (mean values: unit II/42%, unit IV/38%, unit VI/30%, unit VIII/26%) are accompanied by an increasing abundance of *Ephedra* (II/24%, IV/36%, VI/48%, VIII/32 %) and spores of *Glomus* (II/7%, IV/6%, VI/10%, VIII/3%). The aforementioned pollen and spore values of 0-0.75 % in units VII and VIII are low. The ostracod data yield low concentrations of shells throughout the taxa show low abundances in the odd-numbered units I, III, V and VII, while mean values of *Artemisia* are high (I/45%, III/48%, V/57%, VII/52%). The mean values of Chenopodiaceae (I/24%, III/20%, V/20%, VII/21%) and *Ephedra* (I/16%, III/24%, V/16%, VII/23%) are low and *Glomus* occurs with about 2% in those units. The Poaceae show a slight and gradual decrease from bottom to top with a maximum of 7.25% in unit I and core, although two sections with higher shell frequencies can be identified (Fig. 5).

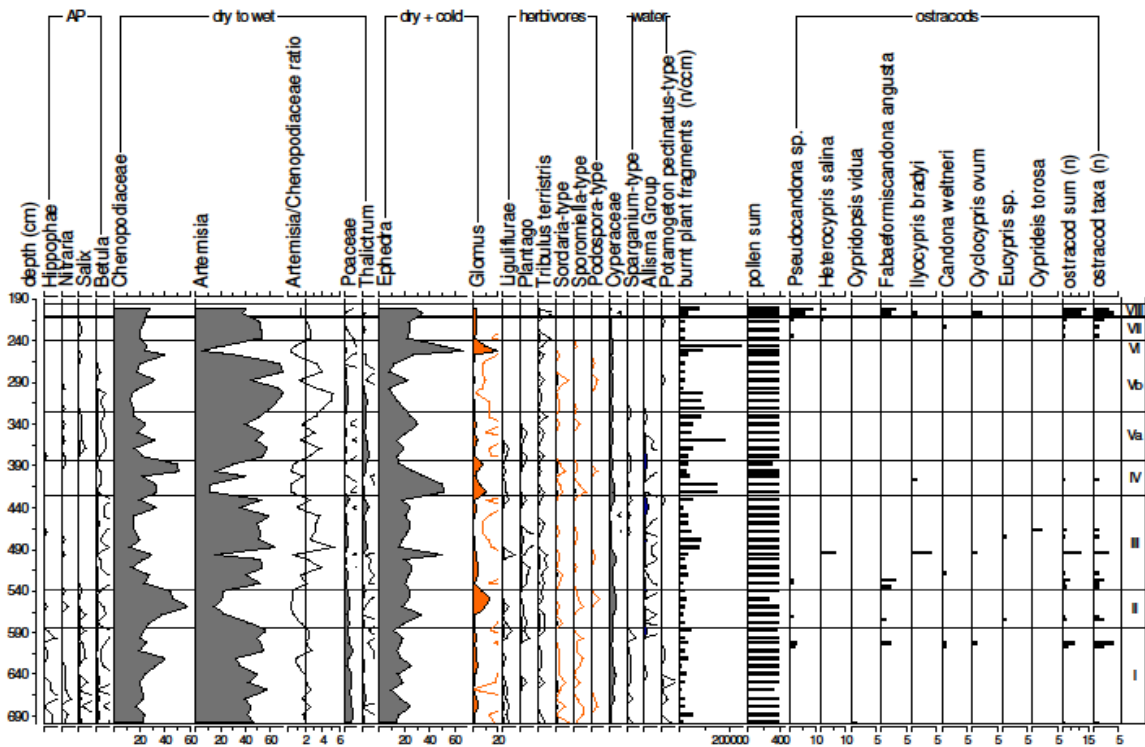


Fig. 3.5: Palynological proxies in percentages, ratio, concentration and absolute ostracod abundances.

AP: arboreal pollen (shrubs and trees)

Between 607 and 495 cm (upper unit I to lower unit III) shells of *Candona weltneri*, *Fabaeformiscandona angusta*, *Cyclocypris ovum* and *Cyprideis torosa* occur. The second section with a higher frequency of ostracod shells is found at 215-203 cm (unit VIII) and is characterized by shells of *Heterocypris salina*, *Cyclocypris ovum*, *Fabaeformiscandona angusta*, *Ilyocypris bradyi* and *Candona weltneri*.

5. Discussion

5.1. Core interpretation

The distinction between different mechanisms of sedimentation is helpful to receive information about past environmental and climatic conditions. Therefore, the multi-proxy analysis may provide information about vegetation changes, weathering and sedimentation processes, transport distance and source area. Due to the alteration between dry lake, shore vegetation and shallow lake the Bayan Tohomiin Nuur represents a sensitive archive for different sedimentation processes triggered by changing climatic conditions. The given ages are based on the age-depth model (chapter 4.1) in order to get an impression of the timing of the different processes although we were not able to establish a precise chronology as we do not know if there is a possible reservoir effect.

Late Glacial

Unit I (700-585 cm; 15-12 ka cal BP): relatively wet and cold climate, *Artemisia* steppe

The lowermost unit consists of well stratified, black coloured sediments deposited in anoxic conditions. This is in consistence with a high concentration of S, also pointing towards an anoxic milieu (Peck et al. 2002, Banks et al. 2004, Tomkins et al. 2005, Melles et al. 2007). Grain size analyses show the dominance of clay and silt-sized particles. The occurrence of largely unimodal GSD of the sediments (675-630 cm, 620-585 cm) is indicative of shallow lake sediments and fluvial sediments being deposited in distal environments (Prins et al. 2000). At 690-685 cm and 628-624 cm an increase of sand and coarse silt could be observed. GSD of these sediments show the appearance of a second peak at the 36-200 μm fraction, thus indicating a further transport and deposition process being responsible for the bimodal distribution. A fluvial origin of the second peak is thought to be unlikely because in this case the particle size distribution would show a unimodal and gradual trend (Prins et al. 2000). Therefore the coarse silt – fine sand peaks may represent aeolian input connected to the Khongory Els dune field, indicating short phases of dune activity (Hempelmann 2011). Low K/Ca and Rb/Sr ratios and low values of Ti, Fe, Mn, K and Rb in unit I are attributed to the lithogenous sediment fraction, indicating a marginal input of clastic sediments (Wünnemann et al. 1998, Fedotov et al. 2000, Mischke et al. 2003, Mischke et al. 2005, Jin et al. 2006, Schwanghardt et al. 2008). This points to towards stable and dry climatic conditions without significant slope wash, which is consistent with increasing values of C_{total} , N and TOC (2-3 %) (Fig.4), indicating an increased productivity of the

lake and a dense vegetation cover within the catchment area (Chen et al. 2003, Jin et al. 2006). TOC/N values around 15-20 show the dominance of autochthonous organic matter with only few input from the catchment of the lake (Horiuchi et al. 2000, Chen et al. 2003, Wang et al. 2004, Herzs Schuh et al. 2005, Jin et al. 2006, Guo et al. 2007). The occurrence of shells of *Candona weltneri*, *Fabaeformiscandona angusta* and *Cyclocypris ovum* points to freshwater or oligohaline conditions. The relatively low contents of CaCO₃ (16-20 %), Sr and Ca are used as indicators of temperature and moisture (Guo et al. 2007). Accordingly, low contents of CaCO₃, Sr and Ca point to a low rate of carbonate precipitation, caused either by a low water temperature or by large discharge to the lake and an extension of the lake volume. Therefore a low temperature and a less dry climate conditions can be assumed. At a depth of 695 cm a short period of enhanced slope wash is recorded by peaks of K/Ca, Rb/Sr, Ti, Fe, Mn, K and Rb. Consistent low values of C_{total} and TOC (1.8 %) indicate a reduction of lake productivity and vegetation cover.

During unit I *Artemisia* occurs with about 45% and Chenopodiaceae with around 24%. Accordingly, the *Artemisia*/Chenopodiaceae ratio (A/C ratio) yields moderate values around 2, indicating neither very dry nor very moist growing conditions in the area (Fig. 5). The landscape was probably covered by an *Artemisia* steppe with shrubs of *Ephedra*, growing on a rocky or gravelly surface. Shrubs or small trees of *Hippophaë* may have grown along the streams and *Nitraria* shrubs at sandy sites with efflorescent salts. Beside climate and soil properties, the vegetation biodiversity was also affected by grazing animals and fires as indicated by burnt plant fragments. The herbivores are indicated by pollen of grazing weeds (Liguliflorae, *Tribulus terrestris* and *Plantago*) as well as by spores of coprophilous ascomycetes (*Sordaria*-, *Sporormiella*- and *Podospora*-type) living on their dung. Pollen grains of *Potamogeton pectinatus*-type, *Sparganium*-type and relative high Poaceae values denote to a vegetation zonation at the lake shore with submersed plants in shallow waters and reed beds similar to Lake Orog Nuur at present (Hilbig 1995).

Unit II (585-538 cm; 12-11 ka cal BP): dry and cold climate, Chenopodiaceae desert

The dominance of black laminated lacustrine clay and high contents of S suggest a continuing anoxic lake-bottom environment. The sediments largely consist of clay and silt (approx. 95%), therefore indicating lacustrine or distal fluvial deposition as the main process (Prins et al. 2000). At 565 cm a short phase of aeolian deposition can be derived from an increasing sand content (> 12%) and a bimodal GSD pattern. An increased input of clastic sediments is inferred from high Rb/Sr and K/Ca ratios and increased contents of Ti, Fe, Mn, K and Rb. Furthermore, reduced values of TOC (1.0-1.5%), N and C_{total} indicate a declining lake productivity and a reduction of soil and vegetation cover within the catchment area (Fig.4). Low TOC/N values also indicate a lower input of allochthonous organic matter. While low Ca, Sr and CaCO₃ (7-10%) contents indicate the prevalence of cold conditions, increased sediment input and reduced lake productivity as well as the occurrence of aeolian sand probably result from an increased aridity.

The low A/C ratio and high *Ephedra* values point to a Chenopodiaceae desert under very dry conditions with extensive barren ground, dotted with *Ephedra* shrubs growing in rock cleavages caused by physical weathering (Schlütz and Lehmkuhl 2007). Due to the low vegetation cover probably accompanied by uneven casual torrential rain falls, the soil erosion and input of minerogenic material into the lake increased consequently, which is indicated by the high values of spores of the mycorrhizal fungi (*Glomus*-type). The absence of water-plant pollen (*Potamogeton pectinatus*-, *Sparganium*-type) points to a shrunken or even temporarily desiccated lake.

Late Pleistocene to Holocene

Unit III (538-430 cm; 11-8.5 ka cal BP): more wet and instable climate, *Artemisia* steppe

Sediments of unit III show prevailing anoxic lake-bottom conditions (black colour, lamination, high S content). The deposits of the lower part (538-460 cm) consist of lacustrine clay and silt, whereas a rising amount of sand (up to 8%) occurs between 460 cm and 435 cm (Fig.3). This points towards a further period of aeolian sediment input. Rising amounts of TOC (2-3%), N and C_{total} indicate an increased vegetation cover and probably soil formation within the lake catchment. The contribution of allochthonous organic matter in this period is indicated by a raised TOC/N ratio (30-40). Low Rb/Sr and K/Ca ratios and low Ti, Fe, Mn, K and Rb values result from a reduced input of clastic sediments. Therefore a more humid environment with increased vegetation cover and a reduced fluvial sediment transport can be assumed. The rising aeolian sedimentation indicates a strengthening of wind speed during this period. Increased contents of CaCO₃ (16-28%), Ca and Sr point to a higher rate of carbonate precipitation probably in conjunction with a higher temperature (Guo et al. 2007). The occurrence of *Fabaeformiscandona angusta*, *Ilyocypris bradyi* and *Candona weltneri* points towards freshwater or oligohaline conditions of the lake whilst the low shell number and sporadic pattern reflects the predominance of anoxic conditions at the lake bottom. The record of *Cyprideis torosa* shells at 467 cm core depth indicates more saline conditions of a permanent lake. Variations of the vegetation and clastic sediment proxies between 500 cm and 460 cm hint to unstable conditions and short-term fluctuations towards a dryer environment.

The sharp reversal to *Artemisia* dominated pollen spectra and A/C ratios higher than 2 document significantly wetter climatic conditions during unit III. The increases in *Thalictrum* pollen may indicate even the establishment of some meadow-steppe like vegetation and underline the higher effective moisture (Hilbig 1995, Grubov 2001).

Unit IV (430-383 cm; 8.5-7.5 ka cal BP): dry and cold climate, Chenopodiaceae desert

Black coloured and laminated lacustrine clay indicates prevailing anoxic bottom conditions of the lake. Thus decreasing concentrations of S point towards a rising oxygen content which is also an indicator of a lower lake level (Peck et al. 2002, Melles et al. 2007). The grain size data shows the dominance of clay and silt sized particles, while the amount of sand remains low (2-3%) (Fig. 3), thus indicating a

reduced aeolian input. High Rb/Sr and K/Ca ratios and high amounts of Ti, Fe, Mn, K and Rb point towards an increased input of clastic sediments which refers to dry conditions. Low values of C_{total} , TOC (0.8-1.5%) and N indicate a reduction of lake productivity and vegetation cover. Low TOC/N values around 10 document a mainly autochthonous source of TOC, which is consistent with a reduced vegetation cover of the catchment. Low contents of $CaCO_3$ (10-12%), Ca and Sr hint towards a reduced carbonate precipitation, probably indicating a decline of the water temperature.

Low A/C ratios indicate the dominance of dry climatic conditions during unit IV, while raised *Ephedra* values are indicative of a cold environment. The occurrence of burnt plant fragments and a high content of *Glomus*-type spores points to an increased input of eroded soil material.

Unit V (383-260 cm; 7.5-5 ka cal BP): most wet and warm climate, *Artemisia* steppe

Due to gradual changes in geochemistry and palynology unit V is divided into two subunits Va and Vb. The lower subunit Va is characterized by black coloured and laminated lacustrine sediments composed of clay and silt. A change of sediment structure and colour towards grey weakly stratified clay occurs at 325 cm (subunit Vb) and was probably caused by a decline of the lake level, thus facilitating processes of oxidation and turbation (Peck et al. 2002). The GSD of the samples show unimodal distributions with high contents of clay (30-40%) and silt (60-70%), while the amount of sand remains low (< 5%) (Fig.3). This refers to a dominance of lacustrine sedimentation processes during unit V, while the aeolian contribution is low. In subunit Va low concentrations of C_{total} , TOC (1%) and N indicate a low lake productivity. A change towards higher amounts of C_{total} , TOC (1-2%) and N in subunit Vb (Fig. 4) can be connected to an increasing productivity of the lake and an increase of the vegetation cover. The elements Ti, Fe, Mn, K and Rb yield low concentrations in subunits Va and Vb, while Rb/Sr and K/Ca show a decreasing trend from Va to Vb (Fig.4). This supports the assumption of an increasing lake productivity and vegetation cover, thus reducing the surface runoff and the input of clastic sediments (Wünnemann et al. 1998, Fedotov et al. 2000, Mischke et al. 2003, Mischke et al. 2005, Jin et al. 2006, Schwanghardt et al. 2008). The content of $CaCO_3$ shows variable concentrations in subunit Va ranging between 10% and 25%. Concentrations of Ca and Sr are similarly variable. This indicates changes in carbonate precipitation. At Vb high concentrations of $CaCO_3$ (20-30%), Ca and Sr probably imply a higher water temperature.

During subunit Va (383-325 cm; 7.5-6.5 ka cal BP) the precipitation increased (high *Artemisia* values) and relatively high *Thalictrum* values indicate the establishment of meadow-steppes () with *Ephedra* values suggesting relatively cool conditions. In subunit Vb (325-260 cm; 6.5-5 ka cal BP) the increase of moisture continued, leading to A/C ratios of more than 5 and to the highest *Artemisia* values of the whole pollen record (up to 70%). Additionally low values of *Ephedra* and *Glomus* indicate a closed vegetation cover inhibiting erosion. Thus unit V represents a climatic moisture optimum that probably reflects the increase of the summer monsoon as reported by Schettler et al. (2006).

Unit VI (260-240 cm; 5-4.5 ka cal BP): dry and cold climate, Chenopodiaceae desert

A strong oscillation of most proxies during this unit indicates a significant change of the environmental conditions which lasted only for a short period. A peak of K/Ca, Rb/Sr, Ti, Fe, Mn, K and Rb indicates an increase of clastic sediment input connected to surface processes. This is corresponding to the deposition of dark brown coloured sediments with increased TOC (>2 %) and N contents, indicating a period of soil erosion during dry climatic conditions. Low contents of C_{total}, CaCO₃ (10%), Ca and Sr probably suggest a low water temperature and a low lake productivity. The occurrence of aeolian sand and silt (silt: 75%, sand: 10%) at 255 cm points towards another activation phase of the nearby dune field.

The *Artemisia* curve reaches its minimum level in unit VI while values of *Ephedra* and *Glomus* and the abundance of burnt plant fragments are the highest of the whole diagram, reflecting an extremely dry and cold climatic reversal. The growing conditions were apparently even harsher than at the end of the late Glacial (unit II). Under the dry climate the sparse vegetation was effected by fires. The extreme high influx of burnt plant fragments and the high concentration of pollen grains may be seen as the result of an undammed surface runoff (Hartmann and Wünnemann 2009).

Unit VII (240-212 cm; 4.5-4 ka cal BP): wet and warm conditions, Artemisia steppe

The core sediments between 240 and 212 cm consist of grey, weakly stratified clay, deposited in a shallow lake environment. Increasing contents of C_{total}, TOC (1-1.5%), N, CaCO₃ (20-30%), and Ca and Sr are similar to unit V probably indicating a higher water temperature, a higher lake productivity and a relatively dense vegetation cover within the catchment. This is consistent with high TOC/N ratios indicating a larger incorporation of allochthonous material into lake sediments. Low values of K/Ca, Rb/Sr, Ti, Fe, Mn, K and Rb indicate wetter conditions with a reduced accumulation of clastic sediments. At 225 cm increased amounts of sand (> 10%) hint to a further spell of dune activity.

During unit VII the A/C ratio rises to values slightly above 2 with *Ephedra* having moderate values, indicating wetter conditions. The absence of spores of coprophilous ascomycetes (*Sordaria*-, *Sporormiella*-and *Podospora*-type) may point to decreased influx of grazing herbivores.

Unit VIII (212-195 cm; 4-3.5 ka cal BP): dry and cold conditions, Chenopodiaceae desert

The sediments of this unit consist of grey, weakly stratified clay and silt. The occurrence of shells of *Heterocypris salina* and *Cyclocypris ovum* also hint towards a shallow lake environment, whereas *Fabaeformiscandona angusta*, *Ilyocypris bradyi* and *Candona weltneri* indicate more or less freshwater conditions. Therefore, the existence of a permanent shallow lake during this period is inferred. The sand content is low (2-3%) and the unimodal GSD pattern is prevailing (Fig. 3), representing a low aeolian input. Increased concentrations of Ti, Fe, Mn, K and Rb indicate a strengthening of surface runoff caused by a reduced vegetation cover. This is consistent with lower amounts of C_{total}, TOC and N, suggesting dry climatic conditions. Reduced contents of CaCO₃ (20%),

and Ca and Sr are related to a lower carbonate precipitation, probably indicating a lower water temperature (Fig.4).

At the turn to unit VIII the A/C ratio declines below 2 while *Ephedra* and burnt plant fragments become more frequent, indicating the beginning change to a dryer and colder climate again.

Unit IX (200-0 cm; 3.5-0 ka cal BP): dry and warm climate, desiccation of the lake, increasing dune activity

The upper 200 cm of the core cannot be divided into units because of the fragmentary sediment recovery and missing palynological data. However, some general features can be discussed. Grey, weakly stratified clay with a high amount of sand and silt can be observed throughout. GSD of the sediments show bimodal distributions, indicating an increasing accumulation of aeolian material. This points towards a desiccation of the lake, accompanied by the formation of the dune belt which persisted until present. Between 160 cm and 110 cm a change towards dry conditions can be inferred from increasing K/Ca, Rb/Sr, Ti, Fe, Mn, K and Rb values, indicating an enhanced input of clastic sediments. A simultaneous decrease of CaCO₃ (10-20%), and Ca and Sr indicates a reduction of the lake productivity, which can be caused by a shrinking of the lake. Peak values of TOC (3.7%), N and C in this part of the core (130-20 cm) are probably caused by soil formation and vegetation cover within the transition zone between salt meadows and dune belt. This is also reflected by high TOC/N values. High amounts of CaCO₃ (42%), and Ca and Sr at the top of the core indicate the formation of evaporites near the dune belt. This hints towards dry climatic conditions which were similar to the present situation. Low amounts of K/Ca, Rb/Sr, Ti, Fe, Mn, K and Rb indicate a low clastic sediment input, which is not consistent with the dry environment. We assume that the clastic sediment input during this dry period is blocked by the dune belt.

5.2. Paleoclimatic implications

The geochemical, palynological and granulometric properties of the sediments from Bayan Tohomiin Nuur revealed several short-term changes during the transition from late Glacial to middle Holocene. These changes in sedimentation processes, input of pollen and accumulation of aeolian material reflect different climatic and environmental stages (Tab. 3.2).

For the first documented part of late Glacial cool and wet conditions could be affiliated within the catchment area (unit I: 15 – 12 ka cal BP). This is consistent with high lake levels of Uvs Nuur (Walther 1999) and other lakes in northern Mongolia (Komatsu et al. 2001) as well as increased vegetation productivity at Bayan Nuur (Krengel 2000). In northern Mongolia higher lake levels are coupled to a retreat of the glaciers and an increase of the river discharge connected to the high mountain areas. An input of melt water can be excluded here as the catchment of the Bayan Tohoomin Nuur lacks any significantly elevated areas. We therefore assume that the lake level could be influenced by permafrost, thus reducing the infiltration within the basin and providing a supply of

water from the slopes. The decreasing S content within the core reflects the change from anoxic towards oxic conditions, which can be connected to a degradation of the permafrost (increased exchange of oxygen within the sediments after melting of the ice). This degradation of permafrost at the transition from Pleistocene to Holocene was also reconstructed for this region by Owen et al. (1998).

Sediment unit II is characterized by a short phase of dry and cold conditions, lasting from 12 - 11 ka cal BP. This change from more wet conditions between 15 – 12 ka cal BP towards a dryer environment may represent the high continental equivalent to the change from the late glacial interstadials towards the Younger Dryas (Litt and Stebich 1999, Herzschuh 2006, Stebich et al. 2009).

The transition from unit II to unit III around 11 ka cal BP is characterized by a rise of temperature and humidity, reflecting the climatic amelioration at the turn from the Pleistocene to the Holocene. This is in agreement with high lake levels and humid conditions at Uvs Nuur during the onset of the Holocene (Grunert et al. 2000). In northwestern China an increase of temperature and moisture was also reported by Pachur et al. (1995), Wang et al. (2004), Mischke et al. (2005) and Chen et al. (2006). This points to a strengthening of the Summer Monsoon and the westerlies as well leading to higher effective moisture in most parts of northern Asia (Komatsu et al. 2001, Morrill et al. 2003, Walther et al. 2003, Herzschuh 2006, Andreev and Tarasov 2007).

A change from wet/cool to dry/cold conditions at around 8.5 ka cal BP (unit III/IV) marks a short climatic reversal in the early Holocene belonging to a sequence of alternating long and wet and short and dry phases appearing until 3.5 ka cal BP. Several lake records from NW China and Mongolia indicate moist and warm conditions between about 7 – 5 ka cal BP (Walther et al. 2003, Wünnemann et al. 2003, Jiang et al. 2007). The dry/cold conditions during unit VI (5 – 4.5 ka cal BP) are in agreement with the single mid-Holocene regression of lake Boston Hu (NW-China) dated to 5.5 ka cal BP indicating a weakening of the westerlies (Wünnemann et al. 2003). The palaeoclimatic records from northern China and Mongolia show large inconsistencies in the timing of moisture supply and the change of temperatures. This can be interpreted as strong spatial climatic variability in this area due to the combined influence of the west wind system and the Asian monsoon (Mischke et al. 2005, Schettler et al. 2006, Jiang et al. 2007). Additionally the records are controlled by different further factors like rivers and glaciers, thus creating complicated mixed signals. The fractional data of the upper sediment sequence (unit IX), comprising the middle and late Holocene (since 3.5 cal ka BP), indicate a clear trend towards lake desiccation and a strengthening of the aeolian activity. This trend is corresponding to the aridization of southern Mongolia and adjacent areas of China during the late Holocene (Chen et al. 2003, Jiang et al. 2003, Walther et al. 2003, Wünnemann et al. 2003, Peng et al. 2005). Due to an increasing influence of pastoralism in Central Asia since the middle Holocene also a human impact on dune (re-)activation and landscape degradation has to be considered (Lehmkuhl et al. 2000, Schlütz 2000, Schlütz and Lehmkuhl 2009).

Unit	Unit period (ka cal. BP)	authigen proxies	terrigen proxies	lake status	aeolian input	ostracods	vegetation	climate	Unit
IX	3.5 - 0	high (lower near base)	low (higher near base)	oxic lake bottom, desiccation	continuous aeolian activity	no data	no data	dry/warm	IX
VIII	4 - 3.5	low	high	oxic lake bottom, moderate water temperature	short phase of aeolian activity	<i>Heterocypris salina</i> , <i>Cyclocypris ovum</i> .	Chenopodiaceae desert, <i>Ephedra</i> shrubs, <i>Glomus</i>	dry/cold	VIII
VII	4.5 - 4	high	low	oxic lake bottom, increased water temperature	weak activity	no data	<i>Artemisia</i> steppe with <i>Ephedra</i> shrubs	wet/cool	VII
VI	5 - 4.5	very low	very high	oxic lake bottom, low water temperature	strong aeolian activity	no data	Chenopodiaceae desert, <i>Ephedra</i> shrubs, <i>Glomus</i>	most dry/cold	VI
Vb	7.5 -(6.5) -5	high	low	change to oxic bottom, turbation, higher water temperature	weak aeolian activity	no data	<i>Artemisia</i> steppe, few <i>Ephedra</i> shrubs	most wet/warm*	Vb
Va		low	moderate	anoxic bottom, moderate water temperature	weak aeolian activity	no data	<i>Artemisia</i> steppe with <i>Ephedra</i> shrubs	wet/cool	Va
IV	8.5 - 7.5	low	high	anoxic bottom, low water temperature	weak aeolian activity	no data	Chenopodiaceae desert, <i>Ephedra</i> shrubs, <i>Glomus</i>	dry/cold	IV
III	11 - 8.5	high	low	anoxic bottom, increasing water temperature	weak aeolian activity	no data	<i>Artemisia</i> steppe with <i>Ephedra</i> shrubs	(instable) wet/cool	III
II	12 - 11	low	high	anoxic bottom, low water temperature	aeolian activity after transition I - II	<i>F. angusta</i> , <i>Ilyocypris bradyi</i> , <i>C. wellneri</i>	Chenopodiaceae desert, <i>Ephedra</i> shrubs, <i>Glomus</i>	dry/cold	II
I	15 - 12	intermediate	low	anoxic bottom, low water temperature	short phases of aeolian activity	<i>Candona wellneri</i> , <i>Fabaeformiscandona angusta</i>	<i>Artemisia</i> steppe with <i>Ephedra</i> shrubs	wet/cool	I

Tab. 3.2: Summary of the reconstructed climatic and environmental changes in the Bayan Tohomiin Nuur area.

6. Conclusion

The multiproxy study of the Bayan Tohomiin Nuur, comprising sedimentological, palynological and ostracod parameters, represents the first high resolution lake archive from southern Mongolia, revealing a high consistence of the different palaeoclimatic data. Our trans-disciplinary approach elucidated nine phases of landscape development and climate dynamics during the late Glacial and the Holocene. A change from wet/cool to dry/cold conditions for the late Glacial probably represents the Younger Dryas period. From the beginning of the Holocene at around 11 ka cal BP wet conditions prevailed until about 3.5 ka cal BP, interrupted by three dry /cold reversals. Since 3.5 ka cal BP aridity increased, leading to a higher dune activity and lake desiccation. The results of this investigation show a general consistence with palaeoclimatic data from surrounding regions of central Asia. Due to a different initiation and characteristic of climatic events as well as different regional influences within central Asia a comparison to short term climatic changes in northern Mongolia, Russia and China is not always possible. Our study underlines the need of further detailed studies of well selected lake archives of small catchment areas to reconstruct the complex spatial climatic pattern of central Asia being concurrently controlled by the westerlies and the monsoon system. Therefore, and to understand the role of climate phenomena known from oceanic regions, further studies are required especially in continental Mongolia.

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Chapter 4

High resolution pollen record from lake Orog Nuur, southwestern Mongolia: An evidence for climate history during the last 50 ka

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Abstract

High resolution pollen and non pollen palynomorphs records from the sediments of lake Orog Nuur, located in the semiarid Gobi-Altai transition zone in the valley of lakes, was used to reconstruct vegetation and climate history during late Quaternary. This paper provides a record of climate change for this key region located on the margin of summer monsoon and westerlies. The palynological results indicate that the pollen of *Artemisia* and Chenopodiaceae dominate the whole profile during the last 50 ka cal BP. Seven major episodes of climate change are reconstructed in the record in response to palaeovegetation. *Artemisia* steppe desert prevailed between 49.5 and 44.7 ka cal BP, indicating relatively warm (interstadial) and semi humid conditions correlating to Marine Oxygen Isotope stage 3 (MIS 3). Relatively dry and cool climate is dated between 44.7 to 23.2 ka cal BP corresponding to Marine Oxygen Isotope stage 2 (MIS 2). It is followed by a rise of temperature with semi arid conditions between 23.2 and 22.7 ka cal BP. This interval indicates the initiation of glacier retreat during the early kataglacial stage (late glacial times). The aridity of the climate was still in progress from 22.7 ka cal BP till the late Holocene. From about 18.9 ka cal BP, xeromorphic taxa increased in abundance, indicating that the conditions became arid and cold. The further decrease in precipitation and changes in the vegetation towards desert are reflected by the increase in the frequency of Chenopodiaceae and *Ephedra* shrubs from about 11 ka cal BP.

More high resolution palaeovegetation and palaeoclimate data is needed to observe short lived events.

Key words: Late Quaternary, pollen, vegetation and climate history, Gobi-Altai

1. Introduction

Mongolia is a part of the arid to semiarid Asian region. This region is controlled by the Asian monsoon and the North Atlantic Oscillation (NAO) associated westerlies (Visbeck, 2002; Vandenberghe et al., 2006; Wang et al., 2009). These westerly winds affect the northern and western part of Central Asia and bring moisture to the Mongolian and Gobi Altai of southwestern Mongolia (Lehmkuhl and Haselein, 2000). Herzsuh (2006) proposed that Mongolia represents a transitional zone between the circulation system of summer monsoon and westerlies whereas Chen et al. (2008) stated that the westerlies are a dominating climate system for Mongolia. The geographical location of

Mongolia and sedimentary records from this region would be a central key to understand past vegetation and climate changes, owing to the mid-latitude westerlies.

The variations in the intensity of the Mongolian High Pressure System (MHPS) in southern Mongolia during late Quaternary times (Owen et al., 1997) draw attention of palaeoecologists. The MHPS has a strong control on the regional climate of Central Asia and drives strong westerlies in the Gobi desert and adjacent regions (Owen et al., 1997; Herzschuh, 2006). In order to understand the interacting history of NAO, MHPS and Asian monsoon climate systems, a detailed reconstruction of late Quaternary palaeoenvironment including past vegetation and climate change in the southern Mongolia is urgently needed.

Several multi-proxy studies have been carried out during the last decade in northwestern and central Mongolia (Grunert et al., 2000; Peck et al., 2002; Fowell et al., 2003; Wang et al., 2004; Feng et al., 2007; Prokopenko et al., 2007; Schlütz et al., 2008; Rudaya et al., 2009; Wang et al., 2009, 2011). Most of these studies are focused only on Holocene vegetation and climate history. These records brought contradictory ideas about Holocene vegetation and climate change and their driving forces. Therefore, more work is emphasized to assess the stability of Holocene and late Quaternary vegetation and climate reconstruction. Pollen records from lakes in the arid and semi arid regions of Mongolia are one of the best proxies for vegetation history and environmental response to the global climate change.

In general it has to be considered that studies on late Quaternary vegetation and climate in Mongolia are still rare and are mostly based on poorly dated pollen records (Gunin et al., 1999). In this paper, a detailed reconstruction of vegetation and climate changes during the late Quaternary is presented by a first high-resolution pollen record from lake Orog Nuur (ONW) in southwestern Mongolia.

2. Regional setting

2.1. Geography

Mongolia is situated in the northern part of Central Asia and has an area of more than 1,500,000 km², with an average population density of less than two people per km² (Rudaya et al., 2009; Dulamsuren et al., 2010). It stretches 1,259 km from North to South and 2,392 km from East to West (Fig. 4.1). It has a net work of the Hangai and Hentii Mountains in the North and Khangai Mountains in central Mongolia. The Mongolian Altai lies in the West and the Gobi Altai is in the Southeast of the country (Johnson et al., 2006).

2.2. Current climate

The continental climate of Mongolia receives low precipitation and is far away from the Oceanic influences. The mean annual country wide precipitation is only 230 mm and about 90% of the

precipitation is returned to the atmosphere through evapotranspiration. Only 3% of the total annual precipitation is potentially available as soil moisture. Mean annual precipitation decreases from the Northwest to the Southeast. The annual highest precipitation values, exceeding 600 mm, is recorded locally in the Hovsgol region of northwestern Mongolia while the Southeast Gobi desert receives the lowest annual precipitation of about 50 mm (Batjargal, 1997; Ma et al., 2008). The summer temperature is high and consequently high moisture deficit occurs during the vegetation period. The

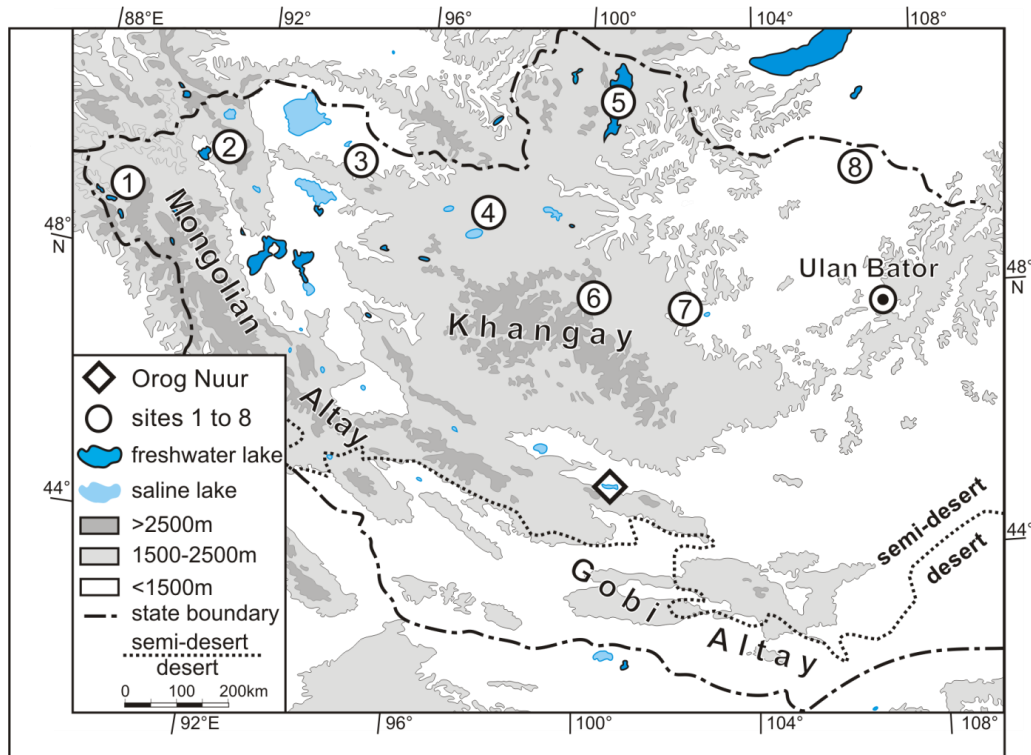


Fig. 4. 1. Map of Mongolia with investigation sites mentioned in the text and the transition line from desert to semi-desert (*Artemisia* steppe). Sites mentioned in the text are: 1. Hoton Nuur (Rudaya et al., 2009) 2. Archit Nuur (Gunin et al., (eds.) 1999) 3. Bayan Nuur (Grunurt et al., 2000) 4. Telmen Nuur (Fowell et al., 2003; Peck et al., 2002) 5. Hovsgol Nuur (Prokopenko et al., 2007) 6. Daba Nuur (Gunin et al., (eds.) 1999) 7. Ugii Nuur (Wang et al., 2009; Wang et al., 2011) 8. Gun Nuur (Wang et al., 2004).

mean annual temperature is about -2 to 5 °C with low average temperature of -24 °C in January and high average temperature of 22 °C in July (Ariunsuren et al., 2009). The climate becomes drier and warmer from the Northwest to the Southeast. Strong winds, with relative low air humidity and very low precipitation, are blowing during the spring time. A fierce dust and sand storms are observed during the early afternoon hours (Tuvdendorzh and Myagmarzhav, 1985).

2.3. Current vegetation

The major part of Mongolia covers the steppe and forest-steppe zones. The Mongolian steppe represents one of the largest contiguous unaltered grasslands in the world (Bedunah et al., 2006; Ma et al., 2008). More than 70% of Mongolia's forest is covered by *Larix sibirica* (Gunin et al., 1999). Forests are mostly found in the northern and eastern slopes of high mountains. Grasslands dominate the sun exposed southern and western slopes, whereas steppe vegetation covers the plains; such areas are classified as forest steppe. Steppes also occur on sun exposed slopes of the mountain taiga, north of the forest steppe belt (Dulamsuren et al., 2005). The distribution of major vegetation zones is controlled by variations in altitude, temperature, rainfall distribution and soils of Mongolia. Based on these different climatic and environmental factors, the vegetation of Mongolia follows north-south gradient with alpine tundra (3%) in the North, followed by mountain taiga (4%), mountain steppe and forest steppe (25%), grass steppe (26%), desert steppe (27%) and desert (15%) in the South (Dulamsuren et al., 2005; Bedunah et al., 2006; Johnson et al., 2006).

2.4. Study site

Lake Orog Nuur is located at 45° 2' 60 N longitude and 100° 42' 0 E latitude in the valley of Gobi lakes (Fig. 4. 2). The studied lake currently covers an area of approximately 129 km² and is situated at about 1280 m in elevation. The climatic conditions in the lake region have winter temperatures below -20 °C and summer temperatures exceeding 15 °C. Mean January temperature of Bayankhongor at 1900 m elevation is -18.3 °C and mean July temperature is 16.3 °C. The mean annual precipitation is usually <150 mm, exceeding 400 mm in the surrounding higher mountain areas of the valley (Academy of Sciences of Mongolia and Academy of Sciences of USSR, 1990; Komatsu et al., 2001; Lehmkuhl and Lang, 2001; Yang et al., 2004).

The valley is bounded by the Khangai Mountains to the northeast of the study site and the Altai Mountains to the southwest. The largest mountainous range of Mongolia, the Mongolian Altai, lies in the north-western part of the valley. The valley has a net work of many other lakes namely Boon Tsagaan Nuur, Taatsyn-Tsagaan Nuur and Ulaan Nuur. Lake Orog Nuur is fed by the river Tüin Gol from the Khangai mountain range (Komatsu et al., 2001; Lehmkuhl and Lang, 2001; Yang et al., 2004). The valley and its surrounding mountain ranges comprise a wide variety of terrestrial and an aquatic habitats but very little is known about the vegetation and climate history of the region. The highest peaks of the Khangai mountain range is covered by *Salix* (willow), *Potentilla fruticosa*, *Betula* (birch), *Pinus sibirica* (Siberian stone pine) and *Larix* (larch). The lower slopes and plains in the northern part of the valley are located in window shadow and has dry desert climate. These slopes contain a mixture of high mountains and steppe vegetation whereas the plains are characterized by desert steppe with such as Chenopodiaceae, *Artemisia absinthium* and Poaceae. The plains are dissected deeply by small rivers originating from Khangai mountain range and enter to Orog Nuur. Sedges and forb-sedges communities are growing on flood plains. In the meadow steppe, cushion

plants with *Kobresia* and *Carex* form the major vegetation types of the Mongolian Altai. Its north facing slopes are covered by very sparse patches of *Larix* stands but the southwestern slopes have small forest fragments of *Larix*, *Pinus sibirica* and *Picea* (spruce) species (Gunin et al., 1999; Miehe et al., 2007).

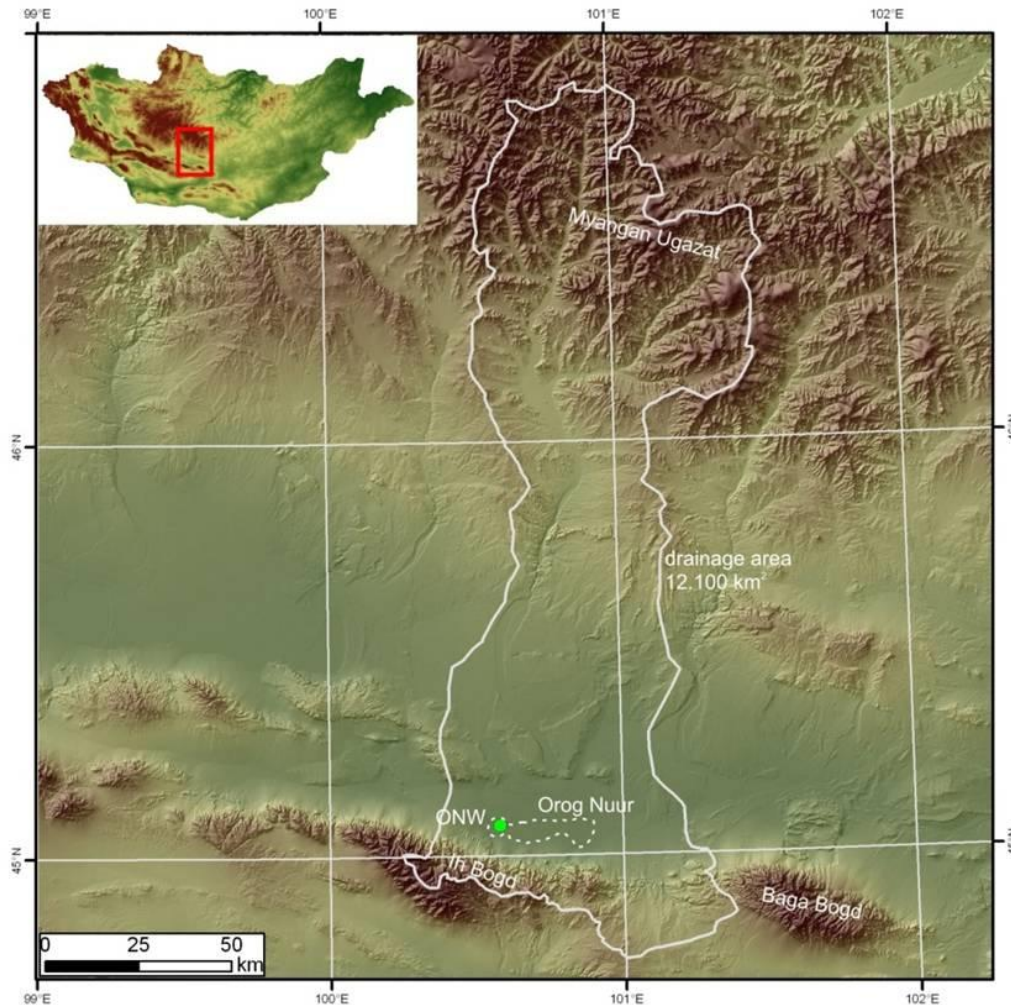


Fig. 4. 2. Map of Mongolia showing the investigation site (Orog Nuur)

The southern part of the valley is limited by tectonic escarpment of the Gobi Altai with gently inclined plains, sandy hills and intermittent Orog Nuur. Desert steppe taxa such as feather grass (Poaceae) - onion (*Allium polyrrhizum*) at inclined plains, wormwood (*Artemisia*) - dwarf bushes in sandy hills and Reed-halophytes are common plant communities near Orog Nuur. Semi fixed stands with single *Haloxylon* (Chenopodiaceae) trees are observed along Orog Nuur. Such a landscape feature reflects that the lake was formerly occupying a very large area and is now desiccating (Gunin et al., 1999). The intermountain basins of Gobi Altai are dominated by desert steppe such as *Stipa* species, *Anabasis brevifolia* and *Allium polyrrhizum*. At high altitude between 2300-2700 m the vegetation changed to mountain steppe like *Stipa krylovii*, *Artemisia frigida* and *Agropyron cristatum*. The *Betula*

and *Salix* forests are bordered by a narrow belt of meadow steppe. *Betula* is found occasionally, pointing the replacement of forest by meadow steppe (Miehe et al., 2007).

Due to water deficit the density of human population in the valley is very low and mostly employed in cattle ranching (Dgebuadze, 1995). Despite very harsh conditions many pastoral nomads find a livelihood with their herds of camels, sheep and goats in these semi desert regions. Desert feather grasses and various types of pea shrubs provide grazing to livestock. The wild camel and the saiga antelope which is found here are some of the rarest species in the world (Onon et al., 2004).

3. Materials and methods

A 1333-cm-long sediment core was drilled in the dried out western part of the lake Orog Nuur (ONW). Sediment samples of 1 or 2 cm³ were taken for pollen analyses at 5 to 10 cm intervals along the core. In total 123 samples were obtained and treated with KOH, HCl, HF and acetolysis. The pollen grains were extracted with standard techniques (Erdtman, 1960; Moore et al., 1999). Before processing *Lycopodium* spores were added as exotic marker to calculate the pollen concentration (grains/cm³) and pollen influx (grains/cm²/yr) as well as spores and charcoal particles. The suspensions were sieved in an ultrasonic bath through a 1.5 µm mesh and stored in glycerin.

At least 400 pollen grains, excluding Cyperaceae, aquatic pollen and spores, were counted in each pollen sample. However, pollen concentration in few samples was low, but the number of counted pollen reaches at least 200 per sample. A total of 50 pollen and 40 spore types were identified. Pollen clumps, denoting immature pollen grains sticking together, were also observed as palaeoecological parameter (Schlütz and Lehmkuhl, 2007). Pollen and spore types were identified with available literature (Vanky, 1994; Moore et al., 1999; Van Geel et al., 2003; Beug, 2004) and the reference collection of the Department of Palynology and Climate Dynamics in Göttingen. The identified taxa were grouped into Arboreal plants (AP), pollen and spores indicating humid conditions, grazing, soil erosion and aquatic environment.

Amaranthaceae/Chenopodiaceae (A/C) ratios were calculated for the pollen record. A/C ratio in arid and semi arid areas of Asia help to distinguish steppe and desert vegetation based on pollen analyses and used it as a moisture indicator (El-Moslimany, 1990). This approach is based on the observation that higher Chenopodiaceae percentages characterize desert plants while higher *Artemisia* percentages point to steppe vegetation (Herzschuh et al., 2006a).

The software C2 version 1.5.1 was used to plot a percentage diagram of the selected palynological data (Juggins, 2007). The pollen and spore taxa are arranged according to their ecology and chronological sequence. The pollen and spore types that appeared in more than 3 samples throughout the record or having values above 0.50% are displayed in the pollen diagram.

4. Chronology

The age depth model is based on eight bulk samples obtained for AMS ^{14}C dates (Tab. 4.1). All the bulk samples were determined at the Accelerator Mass Spectrometry (AMS) laboratory of the University of Erlangen, Germany. The ages were calibrated with online program CalPal (<http://www.calpal-online.de/CalPal2007-HULU>; Weninger and Jöris, 2008). The temporary desiccating lake should be in an isotopic equilibrium with the atmosphere by intense CO_2 interchange. The low amounts of $\delta^{13}\text{C}$ point to a predominantly terrestrial origin of the dated carbon as remarkable contributions of water plants to the dated material could be identified by higher $\delta^{13}\text{C}$ values (Herzschuh et al 2005; Stuiver and Polach 1977). Keeping in view the aforementioned facts, all dating results seem to be more or less free of the reservoir effect. Therefore the age depth model represents an interpolation of the eight AMS dates and an assumed recent surface age (Fig. 4.3). The age inversion at 1192 cm and 1272 cm can be caused by the limit of the AMS method and the increased deviation of the measured ages.

Depth [cm]	Lab. No	^{14}C age and error [yr. BP]	$\delta^{13}\text{C}$ [‰]	Calibrated age and SD [cal. yr. BP]	material
94	ERL-15622	12581±103	-25,4	12973±323	bulk sample
199	ERL-15623	13242±85	-24,2	14223±413	bulk sample
271	ERL-15624	17733±149	-25,4	19215±354	bulk sample
392	ERL-15625	17713±180	-24,5	19192±379	bulk sample
571	ERL-15626	19738±179	-23,8	21670±348	bulk sample
778	ERL-15627	21501±217	-24,2	23714±444	bulk sample
1192	ERL-15628	46103±2281	-25,4	48072±3111	bulk sample
1272	ERL-15629	40429±1340	-25,92	42241±1147	bulk sample

Tab. 4.1. Results of the AMS ^{14}C -datings and their calendric age-conversion (calibration) with 1σ standard deviation (SD) using “CalPal-online” (Weninger and Jöris 2008).

5. Results and interpretation

5.1 Pollen analyses

Seven pollen zones (ONW 1-7) are recognized based on variations in the pollen stratigraphy and the deduced palaeoecological changes (Fig. 4.4). *Artemisia* and *Chenopodiaceae* are the most common pollen which occurs throughout the diagram. Both pollen taxa together constitute more than 65% per sample, exceeding up to 90% in zone ONW 3 and ONW 5. *Ephedra* shows high frequency in the upper two zones. *Poaceae* and *Liguliflorae* have a constant existence of ca. 4-7% through the whole record. *Caryophyllaceae*, *Brassicaceae* and the *Hippophaë*-type pollen gradually disappear to missing in pollen zone ONW 6 and ONW 7 respectively. Arboreal pollen such as *Quercus*, *Nitraria*, *Salix* and the *Pinus* Haploxylon-type occur regularly in low percentages (<1%). The green algae *Botryococcus* and *Pediastrum* are recorded frequently in zones ONW 3 and ONW 5 where as *Volvocaceae* and *Sparganium* dominate in the upper two zones. Mandibles of Chironomids are mainly found in the

sediment samples of ONW 3. Brief characteristics of the ONW pollen zones from bottom to top are given below.

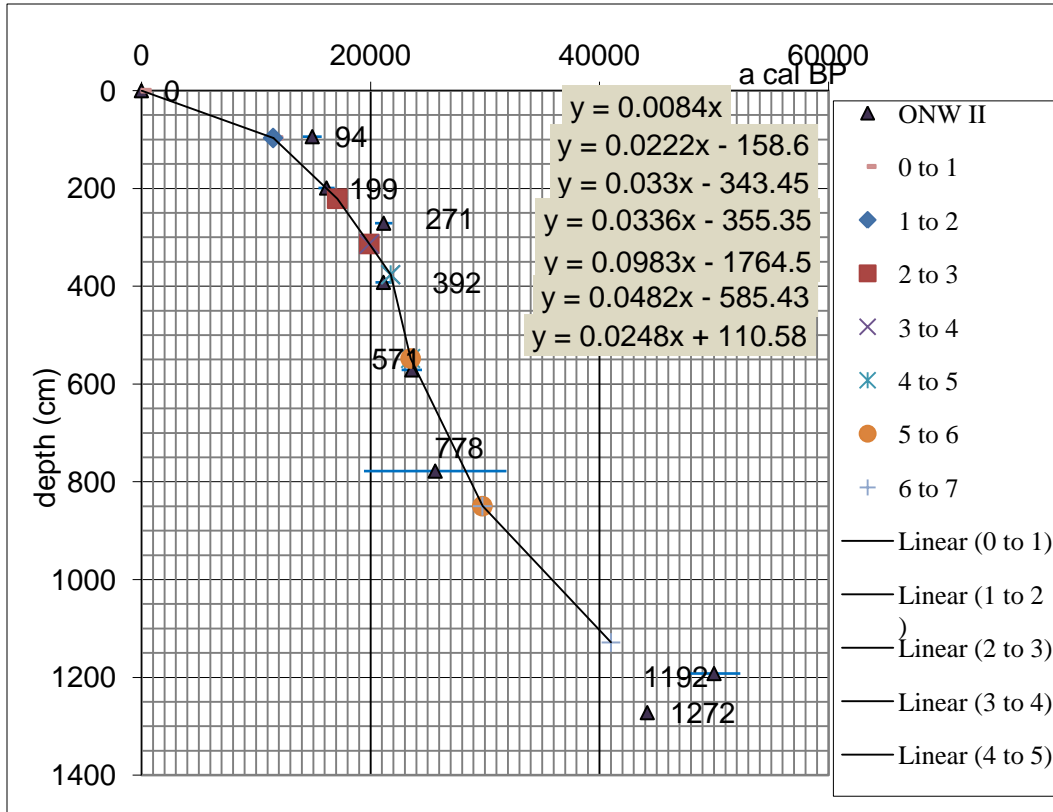


Fig. 4. 3. Age-depth model of lake Orog Nuur.

5.1.1.1. Zone ONW 1 (1333 - 1222 cm, 49.5 – 44.7 ka cal BP): semi humid *Artemisia* steppe

High *Artemisia* (71%) and minimum Chenopodiaceae (9%) pollen percentages are recorded during this zone. *Artemisia*/Chenopodiaceae ratios (A/C ratios) are around 8. The pollen proportion of Poaceae (3%), Brassicaceae (3%), Caryophyllaceae (2%) and *Thalictrum* (1%) are found relatively high. Arboreal pollen such as the *Hippophaë*-type, *Picea* and *Quercus* occurs in frequencies up to 2%. The pollen of Liguliflorae and Apiaceae constitute (1-2%). The *Sporormiella*-type spores exist with low percentage value, lower than 1%.

The pollen data indicate that the landscape was covered by *Artemisia* steppe, suggesting sub desert and warm conditions. The relative high frequency of the aforesaid herbaceous taxa shows that these species have grown along the springs near the lake. Heliophilous shrubs or small trees of *Hippophaë* have grown at some favourable habitats of the landscape beside the temporal rivers (Hilbig, 1995; Grubov, 2001). The increase of *Quercus* and *Picea* at the beginning of the zone suggests the transport of these pollen from Mongolian Altai (northwestern Mongolia) through westerlies or denote a short precipitation spell near the Orog Nuur lake. The pollen of grazing weeds like Liguliflorae and

Apiaceae (1%) and spores of coprophilous ascomycetes such as the *Sporormiella*-type (Van Geel et al., 2003) infer to the existence of wild herds.

5.1.2. Zone ONW 2 (1222 - 1133 cm, 44.7 – 41.2 ka cal BP): semi arid *Artemisia* steppe

Artemisia (57%) still dominates the pollen assemblages. Chenopodiaceae is found in small amounts (14%) and A/C ratios are about 4. The frequency of *Ephedra* (up to 5%) is slightly higher in the upper samples of the core. Liguliflorae (4%) and the *Matricaria*-type (8%) pollen increase. Pollen influx values are very low. The frequency of herbaceous pollen such as Poaceae (4%), Brassicaceae (2%) and Caryophyllaceae (2%) remains similar as in the previous zone. Pollen clumps (2%) generally increase while *Artemisia* pollen clumps alone indicate marked peaks up to 11%. The frequency of fungal spores (the *Glomus*-, *Delitschia*- and *Sporormiella*-type) and the concentration of the green algae *Botryococcus* and *Pediastrum* slightly increase. The concentration of charcoal increases at the end of the zone.

The decrease of A/C ratios compared to previous zone suggests a marked decrease of moisture. *Artemisia* with a relative gain of *Ephedra* shrubs reflects desert steppe vegetation (Herzschuh et al., 2006a; Zhao et al., 2007). The high values of the insect transported *Matricaria*-type suggests that the water level was low with Asteraceae growing near the drilling site. The pollen concentration decreased under semi desert climatic conditions. Poaceae and Caryophyllaceae fluctuate regularly with clear maxima, suggesting climatic instability. This is consistent with the existence of pollen clumps that reveals a strong disturbance of the vegetation as a result of climatic variation (dry/cold events) or shortening of the growing season and /or grazing impact (Schlütz and Lehmkuhl, 2007). The low values of *Pediastrum* and *Botryococcus* suggests low lake levels (Jiang et al., 2006; Medeanic and Correa, 2010; Zhao et al., 2007) and a cooler climate (Kramer et al., 2010; Jankovská and Komařek, 2000). The high input of *Glomus* in the upper samples of the zone reveals soil erosion under dry conditions and supports the notion of thin vegetation cover that is certified by the high concentrations of charcoal (fires). Owing to extreme environment, grazing indicating pollen (Liguliflorae) and fungal spores (the *Delitschia*- and *Sporormiella*-type) further expose the pressure of wild herbivores on vegetation in the catchment area of the lake. The presence of grazing indicating pollen and fungal spores might give the strength to the suggestion of Komatsu et al. (2001) about the initial human entry into the area prior to 40,000 years ago and possibly as early as the last interglacial (ca. 125,000 B.P.).

5.1.3. Zone ONW 3 (1133 - 515 cm, 41.2 – 23.2 ka cal BP): semi humid *Artemisia* steppe

Artemisia shows its highest values exceeding up to 85%. Chenopodiaceae is about 12% and the resulting A/C ratios spans to 7. The frequency of herbaceous pollen shows a little change to the values of the previous zones. Tree pollen such as *Nitraria*, *Salix*, the *Hippophaë*- and *Pinus* Haploxylon-type occur in low frequencies (<1%). The concentration of *Pediastrum* and *Botryococcus* oscillate regularly with well marked maxima. Smut fungi such as the *Thecaphora*-type (2%) and mycorrhizal fungus like

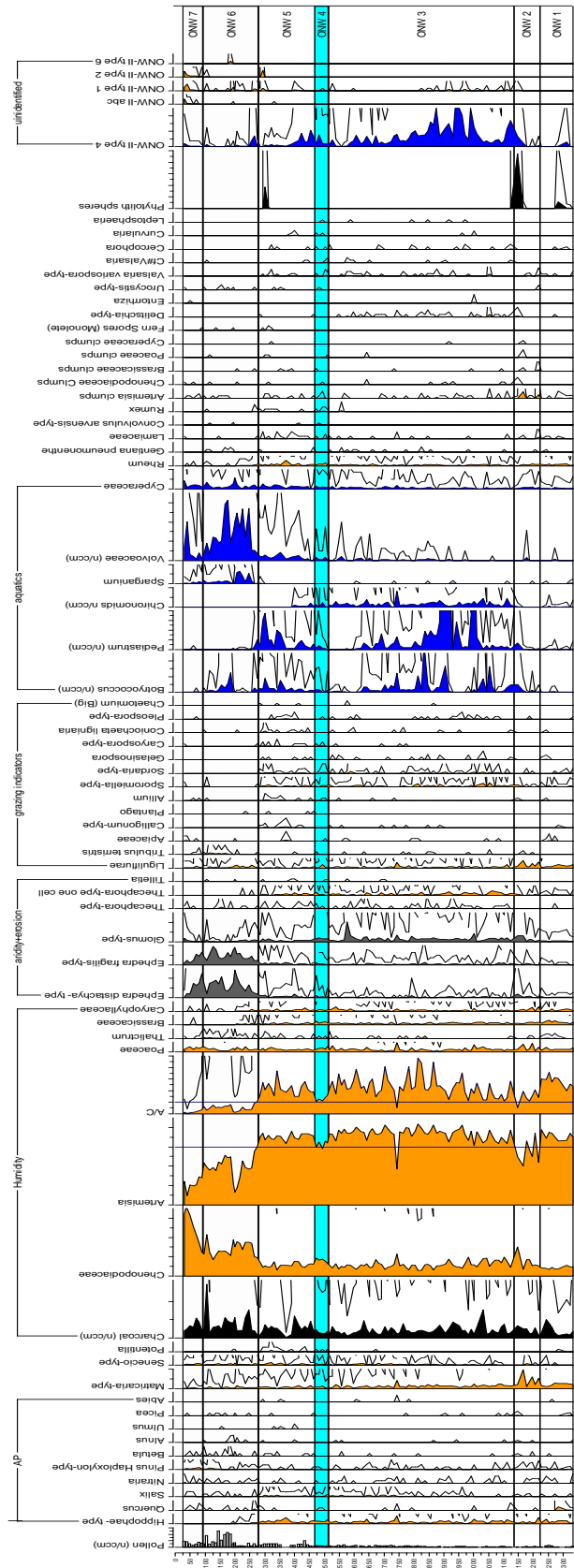


Fig. 4. Pollen and non pollen palynomorphs percentage diagram of Orog Nuur, Gobi Altai, South Mongolia. A/C ratios and the concentration of *Pediatrum*, *Botryococcus*, *Volvocaceae*, burnt plant fragments and pollen grains are also shown.

the *Glomus*-type (3%) attain highest frequencies. The ascospores of coprophilous fungi such as *Gelasinospora*, *Sordaria*-, *Pleospora*-, *Delitschia*- and the *Sporormiella*-type appear with slightly higher values (1%). The mandibles of Chironomids have their maximal frequency (3%).

The dominance of *Artemisia* with a smaller representation of herbaceous pollen led to the establishment of steppe vegetation, reflecting sub desert but cold conditions in the research area. Increase in A/C ratios point to an increase of moisture conditions. Arboreal plants like *Nitraria* might have grown on sandy wet areas near the lake whereas the *Salix*, and *Hippophaë* along the banks of temporal rivers (Hilbig, 1995; Grubov, 2001). Pine pollen seems to transport from the nearby Khangai mountains. The highest input of *Pediastrum* attests high lake levels (Jiang et al., 2006; Kramer et al., 2010; Medeanic and Correa, 2010; Zhao et al., 2007). The sporadic presence of *Botryococcus* reveals cold lake conditions (Jankovská and Komařík, 2000). The relative high values of the *Thecaphora*- and *Glomus*-type suggest soil erosion in sub desert conditions. The increase in coprophilous spores especially the *Sporormiella*-type is an indication of dung produced by herbivores (Cugny et al., 2010). The maxima of Chironomids mandibles designate that enough food (aquatic plants) was available for herbivores.

5.1.4. Zone ONW 4 (515 - 469 cm, 23.2 – 22.7 ka cal BP): semi arid *Artemisia* steppe

Artemisia pollen (63%) decreases compared to previous zone but still dominates while Chenopodiaceae (16%) increase slightly. The A/C ratios drop to 4. Poaceae (4%), Brassicaceae (3%) and Caryophyllaceae (2%) pollen are comparatively high. The *Hippophaë*-type pollen shows maximum values (3%). The concentration of *Pediastrum* and *Botryococcus* is very low. The fungal spore *Glomus*-type is showing the same values as in zone ONW 3.

The comparative low A/C ratios suggest decrease in climate humidity. The pollen data imply *Artemisia* steppe with dry and warm conditions. The herbaceous pollen might have grown at high altitude with better growing conditions. *Hippophaë* shrubs have grown beside the lake. The lake level seems to be low reflected by the extremely low values of green algae.

5.1.5. Zone ONW 5 (469 - 280 cm, 22.7 – 18.9 ka cal BP): semi humid *Artemisia* steppe

This zone contains a high proportion of *Artemisia* pollen (70%) compared to zone ONW 4. Chenopodiaceae occurs at values of around 12% and A/C ratios are about 6. The frequency of the *Hippophaë*-type (3%) is similar to the pervious zone. A slight increase has been observed in *Pediastrum*, *Botryococcus* and Volvocaceae. Grazing indicator pollen and spores are present with low frequency (usually <1%) and include Liguliflorae, Apiaceae, *Plantago*, *Allium*, the *Calligonum*- and *Potentilla*-type as well as *Coniochaeta ligniaria*, the *Pleospora*- and the *Caryospora*-type.

The high A/C ratios indicate steppe vegetation with relative humid climatic conditions. The comparative high precipitation supported the growth of *Hippophaë* shrubs. The relative increase of the green algae such as *Pediastrum* (high water level) and *Botryococcus* confirms (cold) moderate cool

climate while Volvocaceae attest eutrophic to mesotrophic lake conditions (Kramer et al., 2010) and high organic productivity due to stronger input of nutrients to the lake. This input of nutrients might be enhanced by herbivore animals as reflected by the existence of grazing indicating pollen and spores.

5.1.6. Zone ONW 6 (280 - 92 cm, 18.9 – 11.0 ka cal BP): relative dry *Artemisia* desert-steppe

Pollen of *Artemisia* (38%) declines and Chenopodiaceae (29%) attains a higher frequency in this zone. The A/C ratios decrease to values of ~1 whereas the *Ephedra distachya*- (13%) and *Ephedra fragilis*-type (10%) increase. Pollen concentration is high. Arboreal pollen such as *Quercus*, *Alnus* and *Betula* occur occasionally. The frequency of grazing indicating pollen and spores like Liguliflorae and *Thecaphora*-type, respectively, is comparatively high. *Tribulus terrestris* appear with its highest frequency in the upper samples of the zone. *Sparganium* with its local maxima (4%) appear for the first time. Volvocaceae attains highest concentration. The spores of green algae such as *Pediastrum* and *Botryococcus* almost disappear.

The low A/C ratios and highest *Ephedra* values point probably a mixed patches of *Artemisia* desert-steppe and Chenopodiaceae desert with *Ephedra* shrubs. These features may illustrate the onset of drier and colder conditions in the study area. High Chenopodiaceae and high pollen concentration reflect regional vegetation cover around the lake and attest extreme climatic conditions (Grubov, 2001; Shen et al., 2005; Chen et al., 2006). The sporadic occurrence of *Quercus*, *Alnus* and *Betula* contemplate that these pollen transported with westerlies from the high mountain ranges of northwestern Mongolia as a result of strong pressure gradient. *Tribulus terrestris*, Liguliflorae and the *Thecaphora*-type are indicative of herbivores. The appearance of *Sparganium* might indicate that the core site is near the lake shore and lake desiccation is observed (Jiang et al., 2007) on the onset of last glacial period. The highest concentration of Volvocaceae and lowest concentration of *Pediastrum* and *Botryococcus* might indicate lake water alkalinity. *Pediastrum* and *Botryococcus* prefer an environment with low pH values and acidic water bodies (Kramer et al., 2010; Hermann, 2010). Low pH can be obtained when concentrations of free carbon dioxide are relatively high. High concentrations of CO₂ occur in cold water bodies and at low photosynthetic activity (Kramer et al., 2010). It is assumed that *Pediastrum* and *Botryococcus* could not survive any more in high pH of lake water, might be conducive for Volvocaceae.

5.1.7. Zone ONW 7 (92 - 25 cm, 11.0 – 3.0 ka cal BP): Arid Chenopodiaceae desert

Chenopodiaceae attains maximum values of the record (50%) whereas *Artemisia* has minimum values (22%). The A/C ratio declines to <1. The frequency of *Ephedra* pollen (18%) is as high as in the previous zone. Arboreal pollen like the *Pinus* Haploxylon-type occurs in low proportion (1%) while the *Hippophaë*-type pollen is missing. Poaceae (4%) pollen increases while the pollen proportion of *Sparganium* and the concentration of Volvocaceae decrease. *Pediastrum* and *Botryococcus* are completely missing.

The low A/C ratios denote a saline Chenopodiaceae desert (Cour et al., 1999) with *Ephedra* shrubs growing in the rock cleavages after the soil cover was eroded (Schlütz and Lehmkuhl, 2007) This points to very extreme (arid) environment than the previous zone. The low proportion of the *Pinus* Haploxylon-type (1%) might indicate cooling phase or transported from the Khangai mountains due to low vegetation cover. The relative high value of Poaceae with the low pollen proportion of the aquatic plant *Sparganium* indicates shallow water and the lake level was near the core site to support the regional abundance of the grasses and aquatic flora. Low concentration of Volvocaceae determines low input of nutrients to the lake and thus low lake productivity in a very dry climate (Kramer et al., 2010). Owing to very arid (low A/C ratio) and cold (high *Ephedra* shrubs values) conditions, *Hippophaë*-type pollen, the green algae *Pediastrum* and *Botryococcus* disappear and do not exist anymore.

6. Discussion

The pollen analyses from the sediments of Orog Nuur interpret vegetation and climate variations during the late Quaternary from southwestern Mongolia (Tab. 4. 2). *Artemisia* and Chenopodiaceae are the major plants of steppe, semi-desert, and desert vegetation of Mongolia (Hilbig, 1995; Gunin et al., 1999; Fowell et al., 2003). El-Moslimany (1990) applied the A/C ratio to arid and semi arid areas of Asia in order to distinguish steppe and desert vegetation based on pollen analyses and used it as a moisture indicator. This approach is based on the observation that higher Chenopodiaceae percentages characterize desert plants, indicating pronounced aridity, while higher *Artemisia* percentages point to steppe vegetation (Herzschuh et al., 2006a). It was reported that A/C ratios of <0.5, 0.5 to 1 and >1 represent a typical desert community, steppe-desert and typical steppe vegetation respectively (Zhao et al., 2007) in the arid and semi arid regions of China. Cour et al. (1999) identified that the saline desert (western Taklimakan), montane desert (Kunlun), and montane steppe or sub-desert (Karakorum) were respectively represented by A/C ratio of <1, 1 to 2 and >2. Our fossil pollen analyses have also shown a significant potential of using A/C ratios during the last 56 ka cal BP. The late Quaternary pollen record of Orog Nuur has been used to infer the vegetation and climate changes of the last 56 k BP.

The results of the initial pollen zone ONW 1 (49.5 – 44.7 ka cal BP) indicate steppe vegetation and suggest semi humid and warm climate. Sun et al. (1997) also implied warm-temperate and sub humid climate between 54.5 to 46.2 ka cal BP from loess plateau in China.

The humid phase is followed by relatively short climate deterioration of semi desert and cool conditions (ONW 2). Similar mirror image of cool conditions has presented by Swann et al. (2005) from 43.2 until 39 ka BP from lake Baikal, south east Siberia based on diatoms and geochemical analyses.

ONW zones	Time period (Ka cal. B.P.)	Vegetation derivations	Climate	Duration (ka)
7	11.0-3.0	<i>Ephedra</i> shrub dominated Chenopodiaceae desert	(cold-)arid	8.0
6	18.90-11.0	<i>Ephedra</i> shrub dominated Chenopodiaceae desert	semi-arid (cold)	7.9
5	22.70-18.90	<i>Artemisia</i> desert-steppe with <i>Pediastrum</i> and <i>Botryococcus</i>	semi-humid (cool)	3.80
4	23.20-22.70	<i>Artemisia</i> desert-steppe	semi-arid (warm)	0.50
3	41.25-23.20	<i>Artemisia</i> desert-steppe with green algae <i>Pediastrum</i> and <i>Botryococcus</i> , erosion high	semi-humid (cold)	18.05
2	44.70-41.25	<i>Artemisia</i> desert-steppe with <i>Ephedra</i> shrubs, <i>Glomus</i> -type, erosion	semi-arid (cool)	3.45
1	49.50-44.70	<i>Artemisia</i> desert-steppe	semi-humid (warm)	4.8

Tab. 4. 2. Synopsis of vegetation and climate evolution at Orog Nuur, valley of Gobi lakes, South Mongolia.

A change from semi desert to sub humid climatic conditions is observed between 41.2 to 23.2 ka cal BP (zone ONW 3). Such vegetation change represents a signal of semi humid and cold climatic conditions. This is consistent with the findings from palaeoenvironmental records of lake Baikal, western China and western Mongolia (Chen and Bowler, 1986; Liu, 1991; Lehmkuhl and Haselein, 2000). Most of the high lake level periods in lake basins of Mongolia and northwestern China have been dated to the interstadial of last glaciation (Marine oxygen isotope stage 3; MIS 3) at about 40-30 ka (Lehmkuhl and Lang, 2001). Hövermann and Süssenberger, (1986) used the term “Anaglacial” for the beginning of the last glacial cycle, characterized by wet and cold conditions. Chen and Bowler, (1986) inferred lake expansion between ~40 to 25 ka from the lacustrine sediments of Qaidam Basin, northern Tibet. Liu (1991) recognized freshwater conditions and humid climate between 38.6 to 28.7 ka from Qarhan salt lake, Qaidam Basin, China. Lehmkuhl and Haselein (2000) reported humid and cold conditions between 32-24 ka cal BP from western China and western Mongolia. Humid climate is recorded between 40 and 23 ka by Yang et al. (2004). Pachur et al. (1995) recorded humid/cool conditions from ~39 to 23 ¹⁴C ka, followed by drier conditions, on the basis of palaeoshore-lines and the geochemistry of Ostracoda in lacustrine sediments in the Tengger Desert, north of the Qilian Mountains where as Owen et al. (1997) suggested similar humid conditions between 40 to 23 ka based on observation of alluvial fans in the Gobi desert, Mongolia and correlated the drying trend in central China to changes in sedimentological analyses in alluvial fans in the Gobi –Altai.

The time period from 23.2 to 22.7 ka BP is characterized by warm and dry conditions. Lehmkuhl and Haselein (2000) characterize it as warm period with the initiation of glacier retreat of Qaidam lake,

China and called it the early stage of the so called “Kataglacial” (24-15 ka cf. Hövermann and Süßenberger, 1986, quoted from Lehmkuhl and Haselein, 2000). This is also consistent with the findings of Chen and Bowler (1986) that reported the warm and dry period between 24 and 21 ka and called this as stage of evaporation. The slight difference in age period might be due to the regional differences in humidity for the dry lands in western China and Mongolia (Yang et al., 2004).

The warm and dry conditions were followed by semi humid and cool conditions between 22.7-18.9 K cal B.P. Wang et al. (1990) reported high water levels between 22 to 18.5 ka due to high precipitation from different lakes of western Tibet. Fang (1991) suggested the existence of high water level around 18 ka is a subject of special discussion (Lehmkuhl and Haselein, 2000).

In general, dry and cold climate prevailed after 18.9 ka cal B.P. (Fig. 4). The conditions remained arid and cold during the late Pleistocene (18.9-11.0 ka cal BP), becoming hyperarid after 11.0 ka cal B.P in our findings. Similar dry and cold (Chen et al., 1997; Johnsen et al., 2001; Yang et al., 2004) conditions were reported from different parts of monsoonal central Asia. This corresponds to Heinrich 1 event recorded from North Atlantic region (Bond et al., 1992). This interval is supported by the results of Quaternary palaeoenvironmental changes on the Tibetan plateau and adjacent areas (western China and Mongolia by Lehmkuhl and Haselein (2000) while Kramer et al. (2010) inferred similar dry interval between 17.7- 11.5 ka cal B.P. from Naleng lake, Tibetan plateau, China. They reconstructed hyperarid climatic conditions of the evaporate stage between 15 to 9 ka. . Based on multi proxy study of sediments, Shen et al. (2005) attest arid and cold climate from 18.2 and 14.1 ka cal B.P from Qinghai lake area, China whereas Hövermann and Süßenberger (1986) reported a dry and cold interval between 14 to 10 ka.

It is generally accepted that the Marine Oxygen Isotope Stage 2 (MIS 2) including the last glacial maximum (LGM) was dry and cold in unglaciated areas of Siberia and central China (Komatsu et al., 2001).

The most dry and severe cold interval was recorded between 11.0 to 3.0.ka cal BP. in our lake archive. The palaeoenvironmental reconstruction derived from the Juyanze palaeolake also suggest desert vegetation, low lake levels and dry conditions of the Alashan Plateau, China during early mid-Holocene (10,700-5400 cal yr BP, Herzschuh et al., 2006b). The pollen record from Lop Nuer in eastern Tarim Basin of western China suggests a desert environment for the entire Holocene (Yang et al., 2004).

7. Conclusion

The palynological study from the sediments of Orog Nuur reveals the first high resolution lake archive from the valley of lakes, southwestern Mongolia. The region is located on the margin of summer monsoon and westerlies. The results of this investigation show reconstructed vegetation and climate history during late Quaternary. We conclude that the Orog Nuur located at the Gobi-Altai transition, is highly sensitive to climate and landscape change.

Our findings emphasize the need of further detailed studies of well selected lake archives of the climatically sensitive area of Mongolia to reconstruct its complex spatial climatic pattern currently controlled by the combined influence of westerlies and the monsoon system (Yang et al., 2004).

Generally warm (interstadial) and semi humid conditions prevailed between 49.5 and 44.7 ka cal BP., correlating to Marine Oxygen Isotope stage 3 (Lehmkuhl and Haselein, 2000). It is followed by relatively dry and cool climate from 44.7 to 23.2 ka cal BP corresponding to Marine Oxygen Isotope stage 2. Increase in temperature with semi arid conditions was observed between 23.2 and 22.7 ka cal BP, indicating the initiation of glacier retreat during the late glacial times. The aridity of the climate becomes more arid from 22.7 ka cal BP till the late Holocene. Xeromorphic taxa increased in abundance at about 18.9 ka cal BP, indicating that the conditions became arid and cold. The further decrease in precipitation and changes in the vegetation towards desert are reflected by the increase in the frequency of Chenopodiaceae and *Ephedra* shrubs from about 11 ka cal BP to point hyperarid climatic conditions. More high resolution palaeovegetation and palaeoclimate data is needed to observe short lived events.

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Chapter 5

Supplementary Study (unpublished)

Vegetation and climate history of Olgoy Nuur, central Mongolia during late Glacial to Holocene based on pollen records

General comments

This chapter is written in the style of a manuscript but preliminary results are presented here due to the unavailability of optically stimulated luminescence (OSL) dating analyses. The samples of the core (Lake archive of Olgoy Nuur) are still under study for OSL dating by Alexandra Hilgers, Institute of Geography, University of Cologne. The abstract, discussion and conclusion about this manuscript will be written after the completion of dating analyses. The sediments of Olgoy Nuur are collected from three different sites rather than a single core. The lower two zones i.e. OLG U (Olgoy bottom) and OLG O (Olgoy top) in pollen diagram (Fig.5.1) indicate the results of two different sites and roughly covers late Glacial age. The difference in time duration between the samples of top and bottom sampling site is currently unknown. The upper two zones (OLG 1a and OLG 1b) are showing the analyses of sediment samples of a third site of Olgoy Nuur (OLG 1) and it roughly determine the transition stage from Pleistocene to early Holocene.

Introduction

High-resolution pollen records of the sediments are very essential from climatically sensitive regions like Mongolia to understand the vegetation history, climate changes and their controlling mechanisms. Few research studies have been carried out in different parts of Mongolia to reconstruct the climate changes during the transitional period from the late Glacial to Holocene and disputes still remain regarding the vegetation history and climatic stability (Tarasov et al., 1999, 2000; Feng et al., 2007). It is also to be mentioned here that most of the palaeoecological surveys conducted in Mongolia are restricted to the Holocene. Wang et al. (2009) proposed that a mid-Holocene optimum have prevailed in Ugi Nuur, central Mongolia. The same approach of mid Holocene optimum (wet and warm) is also revealed from the pollen, lacustrine and eolian records from Hoton Nuur (Tarasov et al., 2000) and Gun Nuur (Wang et al., 2004; Feng et al., 2005) northern Mongolia. Contrary to this approach, Peck et al. (2002) and Fowell et al. (2003) reported a dry mid-Holocene climate (7110 and 4390 cal a BP) shown by low lake level and high pollen based aridity index. A dry mid-Holocene climate is also reconstructed by Feng et al. (2005) from Mongolian plateau where as pollen and diatom records from lake Hovsgol documented a warm and dry climate between 6000 and 3500 cal a BP (Prokopenko et al., 2007). Wang et al. (2011) also suggested a prolonged mid-Holocene drought prevailing extensively in the central-east Asian arid and hyper-arid areas based on temperature and climate indices inferred

from pollen and diatom records of Lake Ugii Nuur, central Mongolia. It is worthy to note here that all these previous studies present asynchronous results. Therefore, more work is needed to assess the stability of Holocene and reconstruct the vegetation history and climate change during the transitional period from the late Glacial to Holocene.

To further improve our understanding of the transitional period from the late Glacial to Holocene, we present a high-resolution pollen record from the Olgoi Nuur (OLG) lake to retrieve the vegetation history variations and associated climate changes during the late Quaternary. The study site seem to be one of the most sensitive areas to climate changes due to its location at the transition zone of dry steppe and forest steppe vegetation. It is expected that the regional reconstruction will be very helpful in overall understanding of climate changes of central Mongolia. It should be noted that our archive would facilitate our understanding of the controlling mechanisms during the transition from the late glacial to the Holocene.

Regional setting

The Olgoi Nuur lies in the foothill piedmont at the southern flank of the Hangai Mountains in the valley of Gobi lakes. The valley is 500 km long, 150 km wide and has an average elevation of 1000-1400 m. The valley of Gobi lakes is characterized by an extreme continental climate with cold and dry winters. The summers are hot and arid. The mean annual temperature is 2 °C to 6 °C but can vary from -16 °C in January to 20 °C in July. The mean annual precipitation is about 250 mm (Tuvdendorzh and Myagmarzhav, 1985; Finch, 1996).

The modern zonal vegetation around the Olgoi Nuur is dominated by Poaceae (*Stipa* species, *Cleistogenes Squarrosa* steppes), *Artemisia frigida* and Chenopodiaceae. The Poaceae dominated steppe is divided in to dry steppes and humid meadows. The dry steppe includes *Stipa* species, *Kochia prostrate* and *Salsola ruthenica* on sunny and drier slopes. The meadow steppes contain *Stipa* species and *Carex* species (Cyperaceae) in lake shore wetlands (Tuvdendorzh and Myagmarzhav, 1985; Hilbig, 1995).

Materials and methods

Sediment samples of 1-2 cm³ were taken at every 10 cm interval from the sediment samples of the cores OLG 1 and OLG top where as at 20 cm interval from core OLG bottom. All the pollen samples were processed in the laboratory using KOH, HCl, HF and acetolysis with standard palynological procedure (Erdtman, 1960; Moore et al., 1999). Two tablets of *Lycopodium* spores were added to each sample for calculating pollen concentration (pollen grains/cm³), pollen influx (pollen grains/cm²/yr) and charcoal. The suspensions were sieved in an ultrasonic bath through a 1.5 um mesh and glycerin was used for storage and preparation of microscopic slides.

The preservation was not so good and the palynomorphs percentage was very low to count a total of 400 pollen grains in every sediment sample. In total 19 pollen taxa and 12 spore types were identified

in the 32 sediment samples. The pollen percentages were calculated on the bases of pollen sum in every sample. The sum of pollen counts was excluding the pollen of Cyperaceae and aquatics, algae and fungal spores. Pollen sum in few samples was high up to 350 pollen. The immature pollen grains sticking together, denoting pollen clumps, were also observed as palaeoecological parameter (Schlütz and Lehmkuhl, 2007). Pollen and spore types were identified with the help of available literature (Beug, 2004; Moore et al., 1999; Van Geel et al., 2003; Vanky, 1994) and on reference collection at the Department of Palynology and Climate Dynamics, Göttingen. The pollen and spores percentage diagram was plotted using the software C2 version 1.5.1 (Juggins, 2007). In diagram, all the taxa are arranged according to their ecology and chronological order.

Results and interpretation

Four stratigraphical zones are distinguished from bottom to the top based on the variations in percentage values of the palynomorph and associated fungal spores. These zones are labeled as OLG U, OLG O, OLG 1a and OLG 1b (Fig. 5.1). The brief description of the zones is summarized below:

Zone OLG U (5 samples): *Artemisia* steppe, semi humid and warm conditions

This zone contains high proportion of *Artemisia* (51%) followed by Chenopodiaceae (26%). The *Artemisia* / Chenopodiaceae ratios (A/C ratio) are >2. The pollen frequency of Poaceae (10%), *Thalictrum* (4%) and *Quercus* (5%) are found relatively high. The fungal spore of *Sporormiella*-type occur in high frequency (4%)

The high A/C ratio of >2 and the relative high values of Poaceae and *Thalictrum* represent the establishment of meadow steppe vegetation and attest better growing (warm and humid) climatic conditions which allow the *Quercus* trees to grow at some favorable habitats on the landscape. The occurrence of fungal spore such as *Sporormiella*-type at relative high values point to grazing impact during this zone.

Zone OLG O (5 samples): Forest steppe or meadow steppe, humid and cold conditions

Both *Artemisia* (16%) and Chenopodiaceae (10%) show a simultaneous decrease while Poaceae (42%), Cyperaceae (29%) increase sharply. The A/C ratio is ~1. *Thalictrum* pollen remains more or less same as in previous zone. The pollen proportion of *Ephedra distachya*- (12%), *Ephedra fragilis*-type (11%) and *Pinus* Haploxyton-type (8%) increase. Pollen concentrations decrease sharply. The concentration of green algae such as *Pediastrum* (60%) and *Botryococcus* (53%) and fungal spores like *Glomus*-type (108%) occur at relatively high values. Dung related fungal spores such as *Diporotheca*, *Podospora*- and *Sordaria*-type attain their highest values. The proportion of smut fungi such as the *Thecaphora*- and *Tilletia*-type is also high. The concentration of charcoal has maximal frequency.

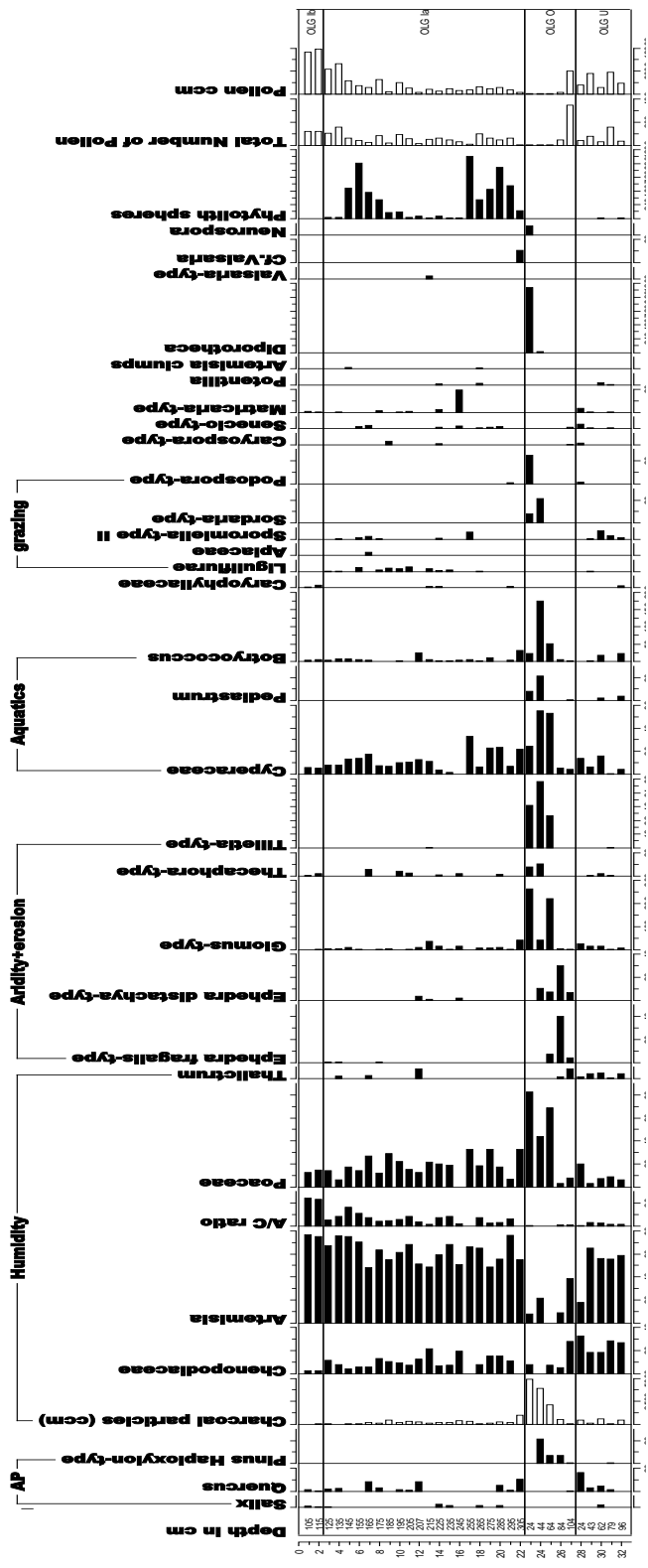


Fig. 5.1: Pollen and non pollen palynomorphs percentage diagram from Olgoi Nuur, central Mongolia. A/C ratios and the concentration of charcoal particles are also shown.

The simultaneous decrease of Chenopodiaceae and *Artemisia* indicate cold but humid conditions (Jiang et al., 2007). This is consistent to the notable increase in Poaceae, Cyperaceae and the relatively high mean values of *Thalictrum*, documenting humid forest steppe or meadow steppe around the lake. The highest percentages of *Ephedra* and *Pinus* Haploxylon-type imply cold conditions around the study site. The increase of *Ephedra* shrubs might be due to a strong seasonality of precipitation in response to winter and summer insulation contrast (Zhao et al., 2007). The increase of *Pediastrum* also shows a humid phase (Zhao et al., 2007; Kramer et al., 2010) whereas *Botryococcus* is known to tolerate cold conditions (Rull et al., 2008). Owing to winter and summer insulation contrast, extreme cold and high precipitation the pollen production is decreased. The mycorrhizal fungus (*Glomus*-type) is erosion indicator. Due to soil erosion the minerogen input is expected into the lake due to uneven high precipitation in very cold conditions. The view of soil erosion is also supported by the high input of smut fungi such as *Thecaphora*- and *Tilletia*-type (Kramer et al., 2010). The relative increase of *Diporotheca*, *Podospora*- and *Sordaria*-type at the end of the zone indicate grazing activities. The contrasting humid and cold conditions led to thin vegetation cover, further affected by severe fires (charcoal).

Zone OLG 1a (20 samples): *Artemisia* steppe, semi desert and dry conditions

A significant spike is noted in the frequency of *Artemisia* (62%) while Chenopodiaceae (10%) is as same as in earlier zone, leading to high A/C ratio of >6. There is a gradual decrease in Poaceae (19%) relative to previous zone. Tree pollen such as *Quercus* (3%) and *Salix* (1%) occurs in low proportion. The frequency of grazing weeds and spores such as Liguliflorae and the fungal spores such as the *Sporormiella*- and *Thecaphora*-type may reach up to 2%. The concentration of phytoliths achieves highest values.

The high A/C ratio reflects the establishment of *Artemisia* steppe and attests relative dry conditions. *Quercus* and *Salix* have grown at some favourable sites at water banks under semi desert conditions. Liguliflorae (2%) and the fungal spores such as *Sporormiella*-type and *Thecaphora*-type point to grazing impact.

Zone OLG 1b (2 samples): *Artemisia* steppe, humid but warm conditions

Artemisia (77%) pollen attains maximum frequency while Chenopodiaceae (3%) drops to its minimum percentage, leading to very high A/C values of 24. Caryophyllaceae, Cyperaceae and Poaceae occur at relative high values. Pollen concentration is very high. The very high A/C ratios and the gradual increase in herbaceous pollen document steppe vegetation established during humid and warm conditions.

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Chapter 6

Supplementary Studies (Unpublished)

MASTER KEY FOR POLLEN GRAINS IDENTIFIED FROM BAYAN TOHOMIIN NUUR, OROG NUUR AND OLGROY NUUR, MONGOLIA

LIST OF TABLES

1	+ Grains with air sacs.....	Table I	
	- Grains without air sacs.....		2
2	+ Pollen grains with no distinct porus or colpus, some having colpi like grooves (<i>Ephedra</i>).....	Table II	
	- Pollen grains either with porus or colpus or with both.....		3
3	+ Porate (sulcate) or colporate pollen grains.....		4
	- Colporate pollen grains.....	Table III	
4	+ Colporate pollen grains.....	Table IV	
	- Porate pollen grains.....		5
5	+ Monoporate and monosulcate pollen grains.....	Table V	
	- Tri to hexazonoporate and periporate pollen grain.....	Table VI	

Table I saccate (vesiculate)

1	+ Pollen bisaccate, large and more than 80 um, angular transition between body and bladder, the wall opposite the bladder is very thick and uneven, proximal part of the exine (crest) more than 5 um in thickness.....		<i>Abies</i>
	- Pollen bisaccate, less than 80 um in size, proximal part of the exine less than 5 um in thickness.....		2
2	+ Smooth transition between Bladder and body wall, more than 75 um in size, no clear constriction between air sac and body of the grain.....		<i>Picea</i>
	- Pollen less than 75 um, there is distinct constriction Between air sac and body of the grain.....		3
3	+ Abrupt transition between structure of air sacs and that of the wall of the body, colpus membrane dotted.....	<i>Pinus</i>	Haploxylon-type

- Smooth transition between structure of air sac and that of the wall of the body, colpus membrane smooth..... *Pinus* Diploxylon-type

Table II polylicate and inaperturate

1	+ Grain with meridional groves (Longitudinal ridges) and polylicate.....	2
	- Grain without meridional groves (Longitudinal ridges).....	3
2	+ Groves few (usually 3-8) and branched.....	<i>Ephedra distachya</i> -type
	- Groves many (usually more than 10) with straight edges and un branched.....	<i>Ephedra fragilis</i> -type
3	+ Grain reticulate, sculpturing elements arranged in a reticulate pattern of muri, lumina variable in size and shape.....	<i>Potamogeton pictinatus</i> -type
	- Grain psilate, Gemmate or scabrate.....	4
4	+ Grain gemmate, microgemmate or with minute granules or having mixture of all these but not clavate or baculate.....	5
	- Grain pear shaped, heteropolar with thin areas (Lacunae), one of the lacunae usually forms a rudimentary pore at broad end.....	Cyperaceae
5	+ Gemmae scattered, deciduous, grains commonly two slits, smaller than 50 um in size.....	<i>Juniperus</i>
	- Grain circular but mostly crumpled or split in the manner of <i>Juniperus</i> , larger than 50 um in size.....	<i>Larix</i>

Table III colpate (tricolpate and polycolpate)

1	+ Tricolpate pollen grain.....	2
	- Stephanocolpate (polyzonocolpate) grain.....	<i>Mentha</i>
2	+ Grains rugulate-striate or reticulate-rugulate.....	3
	- Grains other than above type.....	4
3	+ Distinctly striate grain, striae meridional.....	<i>Acer</i> - type
	- Reticulate-rugulate or eurenticulate grains.....	Brassicaceae
4	+ Grain clavate (Intectate), clavae free and variable.....	<i>Ilex</i>

	- Grains having no clavae.....	5	
5	+ Columellae dimorphic, sparse thick columellae Irregularly arranged among numerous fine columellae.....		<i>Ranunculus acris-</i> type
	- Columellae monomorphic.....	6	
6	+ Columellae branched, tectum is perforated and Grains psilate.....		<i>Convolvulus</i>
	- Columellae unbranched, grains reticulate, echinate, verrucate or aerolate.....	7	
7	+ Grains aerolate, colpus long sunkun with acute ends.....		<i>Myricaria germanica</i>
	- Grains reticulate, echinate or verrucate.....	8	
8	+ Tectum reticulate with smooth muri, furrows are straight and narrow, some time hexacolpate.....		Lamiaceae
	- Tectum verrucate or echinate.....	9	
9	+ Tectum verrucate.....	10	
	- Tectum echinate, columellae of same length all over the surface and infra reticulate.....		<i>Papaver rhoeas</i> -type
10	+ Verrucae rounded, columellae appear as white dots in high focus.....		<i>Anemone</i> -type
	- Verrucae elongated and unequally distributed.....		<i>Quercus</i>

Table IV colporate pollen grain

1	+ Grain fenestrate.....	Liguliflorae
	- Grains non fenestrate.....	2
2	+ Pollen grain hexazonocolporate or polycolporate.....	3
	- Pollen grain tricolporate.....	4
3	+ Grain hexazonocolporate, psilate-scabrate-echinate, one porus per colpus, operculum as broad as the intercolpium.....	<i>Sanguisorba officinalis</i>
	- Grain polycolporate, ectocolpus long narrow with acute ends.....	<i>Nitraria</i>
4	+ Pollen grain psilate, scabrate, echinate or verrucate.....	5
	- Pollen grain micro reticulate, striate, striate reticulate,	

	striate regulate.....	10
5	+ Columellae branched, tectum echinate.....	<i>Senecio</i> -type
	- Columellae unbranched, tectum may be echinate, psilate to scabrate-verrucate	6
6	+ Tectum echinate or verrucate, membrane rough, true columellae visible under tectum.....	<i>Matricaria</i> -type
	- Psilate or scabrate grain.....	7
7	+ Mesocolpium convex, colpi long curving round the margin.....	<i>Hippophae</i> -type
	- Mesocolpium without such characteristics.....	8
8	+ Endoaperture is 8 shaped, colpi sunken or enrolled.....	<i>Solanum nigrum</i> -type
	- Having no such colpi and endoaperture.....	9
9	+ Tectum densely punctuate, finely scabrate, sexine as thick as nexine.....	<i>Rheum</i> -type
	- Psilate or scabrate, rarely rugulate, exine has out thick and inner thin layer, pori oblong, colpus wider in middle and narrow at both ends, the margins of pori are irregular.....	<i>Artemisia</i>
10	+ Grain elliptic, oblate-spheroidal, prolate, sub prolate with costae.....	11
	- Grain pea nut shaped with internal thickening (costae) surrounding a porus.....	Apiaceae
11	+ Striate-rugulate.....	12
	- Micro reticulate or striate reticulate	14
12	+ Striate-rugulate exine pattern, branched striae.....	<i>Sorbus</i> -type
	- Striate-rugulate, striae without branching.....	13
13	+ Operculate colpi.....	<i>Potentilla</i> -type
	- Non operculate colpi.....	<i>Gentiana pneumonenthe</i> -type
14	+ Micro reticulate grain, pori lolongate, sometimes tetra colporate.....	<i>Rumex</i> -type
	- Striate reticulate grain.....	15
15	+ Colpi with acute ends, membrane granular, exine tectate.....	<i>Haplophyllum</i>

- Outline margin micro wavy, having pronounced margo, reticulation (both muri and lumina) decrease in size near the furrow..... *Salix*

Table V monoporate and monocolpate

1	+ Grain bilaterally symmetrical, monosulcate (Monocolpate).....	<i>Allium</i> -type
	- Grain radially symmetrical, porate	2
2	+ Porus indistinct, without operculum and annulus.....	3
	- Circular porus with a distinct annulus, grain tectate, scabrate, psilate.....	<i>Poaceae</i>
3	+ Grain often crumpled, spinulate-punctate or echinate, porus more or less circular and very small.....	<i>Lemna</i>
	- Grain surface micro reticulate, tectate perforate.....	<i>Sparganium</i> -type

Table VI tri-hexaporate and polyporate

1	+ Pollen grain tri-hexa zonoporate.....	2
	- Pollen grain periporate.....	6
2	+ Trizonoporate, vestibulate pori, vestibular conical with slanting sides than cylindrical.....	<i>Betula</i>
	- Tetra-hexazonoporate, echinate or scabrate to rugulate.....	3
3	+ Tetra-pentazonoporate, psilate, scabrate to rugulate.....	4
	- Tetra-hexazonoporate, echinate, pori slightly protruding and shallow.....	<i>Ulmus</i>
4	+ Scabrate to rugulate pollen, pori with distinctive Lines of thickening (acri) joining the pori in both hemispheres.....	<i>Alnus</i>
	- Psilate pollen, pori without distinctive lines of thickening (acri).....	5
5	+ Annulus protruding, more thick and distinct.....	<i>Myriophyllum spicatum</i> -type
	- Annulus flattened and indistinct.....	<i>Myriophyllum verticellatum</i> -type
6	+ Distinct annulus always present.....	7

	- Distinct annulus or operculum may or may not be present.....	9
7	+ Grain with differentiated annulus around porus.....	8
	- Pori appear sunken and surrounded by fine, short, regularly arranged columellae forming a diffuse annulus.....	<i>Allisma</i> -type
8	+ Tectum perforate, reticulate or reticulate scabrate.....	Caryophyllaceae
	- Tectum non perforate, microechinate.....	Chenopodiaceae
9	+ Tectum coarsely reticulate (almost having no tectum).....	<i>Tribulus terrestris</i>
	- Tectum micro-echinate, scabrate or verrucate.....	10
10	+ Porus margins flattend, porus membrane with cavities (warts), pori may be in slightly sunken areas giving the grain a dimpled appearance.....	<i>Thalictrum</i>
	- Porus margins clearly defined, more or less rounded in shape, pore not sunken.....	<i>Plantago</i> -type

Chapter 7

Synthesis

The southern Mongolia is situated in the triangle of the Mongolian High Pressure System (MHPS), the North Atlantic Oscillation (NAO) associated westerlies and Asian summer monsoon. Its geographical location is of interest for palaeo-vegetation and palaeo-climate studies and is considered to be very important to vegetation and climate changes. In order to know more about the late Quaternary vegetation and climate history, two lake archives (Bayan Tohomiin Nuur and Orog Nuur) were investigated. The BTN and ONW lake sediments provide records to improve the understanding of the palaeo-vegetation history and palaeo-climate development of the region during the last 50 ka cal BP.

The lake BTN is situated at about 1280 m elevation in the semiarid to arid Gobi Altai in southern Mongolia. This lake occupies a small catchment area of 1750 km² with a flat surface and ephemeral streams. It is mostly dry during the year due to low precipitation and high evaporation. However, it has a remaining swamp area in the center which is fed by ground water from the surrounding alluvial fans. The studied site is located at the transition zone between the Gobi desert and the desert-steppes of southern Mongolia. Therefore, it is an archive very sensitive to vegetation and climate changes. Due to its unique geographical location and small catchment area, the lake sediments provide a peculiar record of the past local and regional developments of vegetation and climate (chapter 1 and 2).

The sediments of BTN were analysed for pollen, non-pollen palynomorphs, geochemistry and ostracod studies. These multidisciplinary high resolution analyses of the BTN revealed a detailed history of continental vegetation, climate dynamics and environmental change in high continental Asia during the last 15 ka cal BP (chapter 2 and 3). The interdisciplinary analyses presented the first high resolution lake archive of Gobi desert.

Four semi-arid phases (*Artemisia* steppe) were interceded by short arid spells (Chenopodiaceae desert). The high values of the *Glomus*-type (10 - 20%), high concentrations of titanium and high rubidium/strontium ratios in arid phases indicate a stronger terrigenous input into the lake due to sparse vegetation in the catchment area of the lake. This is coincident to the expansion of *Ephedra* shrubs which can be related to barren grounds. The first reconstructed phase at about 15.3 to 12.3 ka cal BP is characterized by a relatively dry *Artemisia* desert-steppe with Chenopodiaceae desert and correlates to the late glacial stadials known from Northern Europe and north-east China as phases of forest re-establishment and increased delta ¹⁸O values in ice cores from Greenland. This late glacial warm period lasted in NE-China until 12.5 ka cal BP. It is followed by a pronounced climatic deterioration (12.3 -11.1 ka cal BP) of about 1200 years. This first arid phase indicates that the climate during the late glacial changed from wet towards more dry conditions equivalent to the Younger Dryas which is represented by a forest decline in north-east China and is considered a dry phase in many regions of Central Asia lasting from about 12.8 to 11.5 ka cal BP. The delay of the Younger Dryas period of

about 400 years might be attributed to uncertainties in the age-depth model. An early short and slight climatic deterioration at around 13.5 ka cal BP may reflect the Oldest Dryas period (13.9-13.8 ka cal BP) in north-east China. The first arid phase is followed by the rise in temperature and precipitation, marking the onset of the Holocene with prevailing relatively humid conditions. The humid period of the Holocene lasted until about 3.8 ka cal BP, interrupted by arid oscillations at 8.6 – 7.6 ka cal BP and 4.9 – 4.5 ka cal BP. The relatively humid conditions during the Holocene may coincide with the onset of higher effective moisture in continental Asia at around 11.5 ka cal BP due to an abrupt intensification of the westerlies and summer monsoon system. The phase of climate amelioration during the early Holocene is replaced by a short arid spell between 8.6 – 7.6 cal BP. This phase shows a climate shift from cold and dry conditions to warm and dry conditions as reflected by a gradual vegetation succession from *Ephedra* shrubs to Chenopodiaceae desert and can be correlated to the 8.2 ka event. The dry early Holocene is superseded by a wet middle Holocene. The climate amelioration at about 7.6 ka cal BP marks the onset of middle Holocene. This abrupt change to moister conditions existed till 4.9 ka cal BP. The most stable and relatively moist conditions (*Artemisia* steppe) occurred in the middle Holocene from 6.3 to 4.9 ka cal BP which represents Holocene climate optimum in the Gobi Altai, Mongolia. These correlations point to a climatic synchronicity with the northern hemisphere and most probably a stronger moisture input by the westerlies caused the mentioned Holocene climate optimum. Nevertheless, a combined influence of westerlies and the summer monsoon caused a quite humid phase just before the Holocene optimum, while bordering areas in the north and south were dry. The Holocene climate optimum in the Gobi Altai was suddenly replaced by an arid and cold spell at about 4.9 ka cal BP might be due to the weakening of monsoonal influence in Central Asia since 7 ka cal BP. The abrupt shift from semi-arid and moist to arid and cold climate is in consonance with a recorded minimum summer rainfall and the regional moisture deficit at about 4.9 ka cal BP in NE-China. The geochemical record infers that the aridity in southern Mongolia increased after 3.8 ka cal BP accompanied by the strengthening of aeolian processes, dune remobilization and lake desiccation. Pollen of trees, shrubs, grazed weeds and spores of coprophilous and plant infecting fungi are present only in low quantities. Fossil eggs of the intestinal parasite *Trichuris* are reported for the first time from Mongolia.

The results of this investigation show a general consistence with palaeoclimatic data from surrounding regions of Central Asia. Due to a different initiation and characteristic of climatic events as well as different regional influences within central Asia, a comparison to short term climatic changes in Mongolia and China is not always possible. The overall high correlation with superregional climate dynamics seems to be a peculiarity of the BTN record, while most of the Mongolian archives stress small-scale differences obscuring overarching commonalities to some extent. We can conclude that the small catchment area of the BTN, its location at the transition from desert to semi-desert and the shallow character of the lake led the sediments of the BTN to become a highly sensitive and representative archive for climate and landscape change.

The lake Orog Nuur (ONW) covers an area of approximately 129 km² in a region on the margin of summer monsoon and westerlies in southwestern Mongolia. Lake ONW is located in the semiarid Gobi-Altai transition zone in the valley of lakes at about 1280 m elevation (chapter 4). The geochemical, granulometric, palynological and ostracod analyses from lake sediments of ONW have proved to serve as good archives for the reconstruction of vegetation and climate history. Such multiproxy studies are essential to reconstruct the vegetation and climate change and possibly the human impact during the past. However, we presented here the palynological results only. The research work on the geochemical and ostracod data is still in process and will be compiled soon.

High resolution pollen and non pollen palynomorph records from the sediments of lake ONW was used to reconstruct vegetation and climate history during the last 50 ka cal BP. Our findings provide the first pollen and spores evidences of the late Quaternary period for this semiarid region under the control of combined influence of westerlies and Asian summer monsoon. The palynological results show seven major phases of climate change in response to the palaeovegetation analyses. *Artemisia* steppe desert prevailed between 49.5 and 44.7 ka cal BP, indicating warm (interstadial) and semihumid conditions correlating to marine Oxygen Isotope stage 3. It was followed by a short semiarid and probably cool spell at about 44.7 ka cal BP. The successive climate change from semiarid and cool climate to relatively humid and cold climate between 41.3 to 23.2 ka cal BP corresponds to marine Oxygen Isotope stage 2. This is consistent with the findings from palaeoenvironmental records of lake Baikal, western China and northwestern Mongolia. Generally a humid and cold climate is recorded on the basis of palaeoshore-lines, geochemistry of Ostracoda in lacustrine sediments and on observation of alluvial fans in Inner Mongolia and Mongolia. Increase in temperature was observed at 23.2 and 22.7 ka cal BP, marking the initiation of glacier retreat during the late glacial times. The warm and relatively dry period between 24 and 21 ka was recorded from western China and called this as stage of evaporation. The slight difference in age period might be due to the regional differences in humidity for the dry lands in western China and Mongolia. It was followed by relatively humid and cool conditions from 22.7 to 18.9 ka cal BP, ratifying high precipitation and high lake levels at about 18 ka from western Tibet. The high lake level at about 18 ka is a subject of special discussion for palaeoecologists. It was followed by arid period of the climate lasted until late Holocene. Arid and cold indicating pollen (*Chenopodiaceae* and *Ephedra* shrubs) increases in abundance at about 18.9 ka cal BP till about 11 ka cal BP and point to hyperarid climatic conditions.

When we compare our results of both lake archives (BTN and ONW), they present complementary approaches to palaeo-climate knowledge. The multiproxy study of the BTN represents regular alterations of arid and semiarid conditions from late Glacial to late Holocene. The first arid phase correlates with the Younger Dryas and the second one with the 8.2 ka event. Relatively dry early Holocene is followed by a mid-Holocene climatic optimum. Such a high consistency of different climate data indicate superregional climate pattern of Central Asia. The palynological results of ONW

indicate relatively arid and cold conditions during late Pleistocene to late Holocene rather than regular alterations of different climate pattern. The overall arid condition is the peculiarity of the ONW. Keeping in mind the difference in the locations of the both lake archives (BTN and ONW) to the summer monsoon, our findings emphasize to investigate the landscape development in detail to explore the contradictory results of climate change. Further studies about the vegetation and climate dynamics of continental Mongolia are needed to see the combined influence of westerlies and the monsoon system. The future research projects should concentrate on Gobi desert because it represents a transitional zone between the circulation systems of westerlies associated North Atlantic oscillation (NAO), Asian summer monsoon and the Mongolian High Pressure System (MHPS). Moreover, the available palaeo-climate data is not sufficient to understand the contradictory insight of palaeoenvironmental changes in the desert and semi desert region of continental Mongolia.

Continuation of further palaeoclimate studies would enhance the understanding of the past environmental changes and to get a projected view for future environmental change. The study would be helpful to observe short lived events and detect the complex spatial pattern climate history of Central Asia.

APPENDIX I

LIST OF IDENTIFIED POLLEN, FUNGAL SPORES, FERN SPORES, ALGAE AND ZOOLOGICAL REMAINS FROM LAKE SEDIMENTS OF BAYAN TOHOMIIN NUUR, OROG NUUR AND OLGROY NUUR, MONGOLIA

- Morphological characteristics of pollen, fern spores, fungal spores, algae and zoological remains are described with the help of published literature (Faegri, K. and Iversen, J., 1989; Moore et al., 1999; Beug, 2004; Smith, 1986; Vanky, 1994; Van Geel et al., 2003, Van Gell presentation in international palynological congress, 2008; Bell, 2005)
- Photographs were sketched from the prepared slides of sediment samples by using Axiostar Plus (Zeiss) microscope (40x/0.65 resolution) and Moticam 2300 digital camera (3.0 M Pixel)
- All photographs are without scale
- All pictures are taken from fossil material, therefore, type slides and relevant literature should be studied for a careful identification
- It was not possible to sketch photograph of every pollen, fungal spore, fern spore, algae and zoological remains. Photographs of most common types are presented here

Table A: List of identified pollen and fern spores

Pollen type	General Morphology	Photo No.
Chenopodiaceae	Polyantoporate (periporate), psilate- scabrate, tectate, tectum without perforations, microechinate, each porus with differentiated annulus, usually with >40 pori	1a/b/c
<i>Artemisia</i>	Globular, 3 lobed circular from polar view, tricolporate, psilate, regulate (having spinules) or scabrate, exine has inner and outer layers, outer thicker than inner, pores oblong, calpus wider in middle and narrow at both ends, pori margins ruminant or irregular	2a/b/c
<i>Matricaria</i> -type	Echinate to verrucate, tricolporate, membrane rough, columellae visible under tectum	3a/ b/c/d
Poaceae	Spheriodal to suboblata, monoporate, pore surrounded by annulus and operculum, psilate, scabrate, tectate	4a/ b/c
<i>Betula</i>	Psilate or scabrate , trizonoporate (pori in equatorial zone), vestibulate pori, vestibulae conical with slanting sides	5a/b
<i>Thalictrum</i>	Polyantoporate (periporate), spheriodal, apolar, microechinate, pori margins flattend, pores membranes with cavities, no annulus, pori in slightly sunken areas giving the grain a dimpled appearance	6a/b
<i>Haloxylon</i> -type	Pantoporate (periporate), pori usually 6-12, spheriodal, pore plate and tectum scabrate	....
<i>Plantago</i>	Round with a thin cobbly wall, with network of irregular verrucae, pantoporate (periporate), apolar, tectum aerolate or scabrate, operculate or non operculate annulus	7
Caryophyllaceae	Polyantoporate (periporate), apolar or isopolar, spheriodal to prolate spheriodal, reticulate or reticulate scabrate, grain with clear annulus, tectate, radially symmetrical	8a/b/c
Brassicaceae	Tricolporate, reticulate, trilobate	9
<i>Pinus</i> Diploxylon-type	Vesiculate (saccate), inaperturate, abrupt transition between structure of air sac and that of the wall of the grain body, colpus membrane dotted	10a/b
<i>Pinus</i> Haploxylon-type	Vesiculate (saccate), inaperturate, colpus membrane smooth	11a/b
<i>Picea</i>	Bisaccate (vesiculate), inaperturate, usually 75 um, smooth transition between bladder and body	12a/b
<i>Abies</i>	Bisaccate, inaperturate, usually >80 um, angular transition between bladder and body, wall opposite the bladder is uneven and thin	....
<i>Ulmus</i>	Tetra-penta-hexazonoporate,echinate, pori slightly protruding, suprareticulate reticulum or softly regulate	13a/b
<i>Ephedra distachya</i> -type	Oval shape, polyplicate, inaperturate, longitudinal ridges (groves or colpi) few (3-8) and branched	14a/b
<i>Ephedra fragilis</i> -type	Oval shape, polyplicate, inaperturate, longitudinal ridges (groves or colpi) many (more than 10) and unbranched	15a/b
<i>Rheum</i>	Isopolar, radially symmetrical, tricolporate, tectum densely punctuate, finely scabrate, sexine as thick as nexine	16a/b/c
<i>Nitraria</i>	Prolate (circular), polycolporate, striate, ectocolpus long, narrow with acute ends, sexine thinner than nexine	17a/b/c
<i>Salix</i>	Spheriodal to subspheriodal or prolate, tricolporate, finely reticulate or striate reticulate, outline margin microwavy having clear margo with SEM, reticulation of both muri and lumina decreases in size near the furrows	18a/b
<i>Convolvulus</i>	Suboblata or oblate-spheriodal, tectum perforated, psilate, trizonocolpate, columellae branched, nexine thinner than sexine	19a/b

<i>Rumex</i> -type	Oblate-spheriodal to prolate, micro reticulate, tri-tetracolporate, pores lolongate	20
<i>Senecio</i> -type	Subprolate, tricolporate, echinate, columellae branched, spines with conical base	21a/b
Liguliflorae	Fenestrate, echinate, lophate, tricolporate	22a/b
<i>Limonium</i>	Oblate-spheriodal, reticulate tectum with regular pattern of muri, tricalpate	23a/b
<i>Alnus</i>	Oblate, scabrate to rugulate, stephanoporate, usually 4-5 pori in equatorial plane with distinctive lines of thickening (acri) joining the pori in both hemispheres	24
<i>Hippophae</i>	Trizonocolporate, mesocolpium convex, colpi long, curving round the margin, circular-elliptic endopori, each porus has a constriction to the colpus, festigia prominent, psilate to scabrate-verrucate	25a/b
<i>Tribulus terrestris</i>	Spheriodal, or oblate spheriodal, pantoporate, coarsely reticulate, porus circular with or without annulus	26a/b
<i>Calligonum</i> -type	Grain symmetric, isopolar, tricolpate, reticulate-faveolate	27a/b
<i>Myriophyllum spicatum</i>	Psilate, grain oblate, stephanoporate, usually 4 or 5 pores sometimes 3, pores meridionally elongated with endexinous annuli, equatorial limb regular, pores equidistant, annulus distant and protruding	28a/b
<i>Myriophyllum verticellatum</i>	Psilate, grain oblate, stephanoporate, usually 4 pores sometimes 3 or 5, pores meridionally elongated with endexinous annuli, equatorial limb regular, pores equidistant, annulus externally flat and not protruding	29
<i>Polygonum aviculare</i> -type	Grain elliptic or rectangular-obtuse, columellae unbranched, tricolporate, psilate - scabrate	....
<i>Sparganium</i> -type	Grain reticulate, heterobrochate, monoporate, pore small and distinct, no annulus, diameter less than half that of the margin	30a/b
<i>Allium</i> -type	Grain more or less circular, monad, monosulcate (monocolpate) or monosulcate-operculate, sulcus narrow at the equator and widens at the poles, sulcus ends blunt, broad and rounded, heteropolar, bilaterally symmetrical	31a/b
<i>Gentiana pneumonantha</i> -type	Grain elliptic and slightly pointed at the poles, about 30 um, trizonocolporate, pori distinct, striate- regulate, striae short and meridional	....
Apiaceae	Pea nut shaped, tricolporate, costae (internal thickenings) surround a porus, striate, rugulate or psilate	....
<i>Potamogeton pectinatus</i> -type	Spheriodal, inaperturate, apolar, radially symmetrical, tectum coarsely reticulate with irregular pattern of muri, lumina variable in size and shape	32
<i>Anemone</i> -type	Trizonocolpate, tectum processes more or less irregular in distribution, verrucate, verrucae rounded, columellae monomorphic and appear as white dots in high focus, tectum is smooth, densely perforate	....
Cyperaceae	Pear shaped, inaperturate, psilate, appear as infolded spheres with double edges of the folds thickened, heteropolar having thin areas (lacunae)	33
<i>Genista</i> group	Tricolporoidatae, circular to rhomboic-obtuse, suprareticulate or faveolate, porus indistinct with a ruptured area at the equator	....
<i>Haplophyllum</i>	Isopolar, monad, radially symmetrical, tricolporate, colpi with acute ends, membrane granular, striate, or striate-reticulate	....
<i>cf. Ilex</i>	Spheriodal to prolate, trizonocolpate, clavate, clavae free, small clavae scattered beneath the large ones	34
<i>Juniperus</i>	Inaperturate, gemmate sculpture, apolar, surface unevenly granular, grain commonly split	....
Lamiaceae	Prolate or sub-spheriodal, tricolpate or hexacolpate, stephanocolpate, reticulate, furrows straight and narrow, muri smooth, 35-50 um	....

<i>Larix</i>	Spheriodal, inaperturate, psilate	....
<i>Lemna</i>	Spheriodal, apolar, monoporate, tectum spinulate-punctate or scabrate, pores circular and small	....
<i>Mentha</i> -type	Spheriodal to prolate, Staphanocolpate, usually 6 colpi, reticulate, columellae restricted to muri, muri not beaded	35a/b
<i>Myricaria germanica</i>	Sub-prolate, tricolpate, colpus long and sunken with acute ends, aerolate, trilobed in polar view	....
<i>Papaver rhoeas</i> -type	Trizonocolpate, echinate, columellae of the same length all over the surface, infrareticulate	....
<i>Potentilla</i> -type	Tricolporiadatae, striate	36
<i>Quercus</i>	Prolate, trizonocolpate, scabrate to verrucate with elements of various size, verrucae elongated and unevenly distributed, tectum without perforations	....
<i>Ranunculus acris</i> -type	Trizonocolpate, microechinate, colpi usually wide and granulate, columellae dimorphic; sparse thick columellae irregularly arranged among numerous fine columellae	....
<i>Sanguisorba officinalis</i>	Oblate-globular, hexazonocolporate, one porus per colpus, tectae operculum, operculum as broad as the intercolpium, psilate-scabrate-echinate	....
<i>Solanum nigrum</i> -type	Tricolporoidatae, triate, vallae fine and without dense structure, perforations distinct,	....
<i>Sorbus</i> -type	Subprolate - suboblate, regulate-striate, striae branched, trizonocolporate	....
<i>Acer</i> -type	Tricolpate, striate or striate rugulate, striae meridional, exine perforated	....
<i>Alisma</i> -type	Polyantoporate, tectum perforate, intrareticulate, pori appear sunken (exine thinner at the porus edge compared to the mesopodium), sunken porus is surrounded by fine and short columellae forming a diffuse annulus, porus membrane granulate	....
<i>Monolete</i> spore	Grain bean shaped, psilate, monocolpate	37
<i>Polypodium</i>	Grain bean shaped, verruculose, monocolpate	38
<i>Pteridium</i> (trilete spore)	Spore psilate, triangular-obtuse with concave sides, trilete scar with short arms	39

Table B: List of identified fungal spores, algae and zoological remains

Fungus/Alga type	General Morphology	Photo No.
<i>Alternaria</i> -type	Psilate to scabrate, spores 2-10 born on a stalk with abeaked apical cell	40a/b/c
<i>Glomus</i> -type	spore globose, occur isolated or in clusters, variable in size	41a/b
<i>Cercophora</i> -type	Ascospores 13-27 × 6-14 um, truncated at the basal side and tapering at the apical end, sub-apical pore is ~0.7 um in diameter	42a/b
<i>Thecaphora</i> -type	Basidiospores, occur in groups of cells, pore is ~3 um, surface has a protuberance	43a/b
<i>Gelasinospora</i> -type	Ascospores ellipsoid, spore surface black ornamented with evenly hyaline pits, spore walls thick	44a/b
<i>Leptosphaeria</i>	Ascospores ellipsoidal, septate, usually 4-5 celled, subapical cell large in size	45a/b
<i>Drechslera</i> -type	Spores may be straight, slightly curved, club-shaped, cylindrical, or elliptical, smooth or warty, occur individually, thick walled, the septa between cells appear to be incomplete (pseudosepta)	....
<i>Chetomium</i>	Ascospores one celled, lemon shaped, light brown, 6-12 × 4-9 um, somewhat flattened in one plane	....
<i>Cladosporium</i> -type	Spores smooth or minutely rough, sometime with warty wall, occur in long branching chains, spherical, barrel-like or lemon-shaped	46a/b

<i>Caryospora</i> -type	Ascospores usually two celled, sometime with additional septa, ellipsoid, cells rounded at apices, smooth	47a/b
<i>Caryospora callicarpa</i> -type	Ascospores usually two celled, sometime with additional septa, ellipsoid, cells rounded at apices, striate	48a/b
<i>Tilletia</i> -type	Spores globose, sculpture has anastomosing grooves	49a/b
<i>Podospora</i> -type	Ascospores one celled, ellipsoidal, smooth brown, 39-48 × 16-23 um, pore is protruding directly below the apex and ~2 um in diameter, pore is surrounded by annulus, basal end is bluntly conical	50
<i>Sporomiella</i> -type	Ascospores three to many septate, septa transverse to oblique, smooth, brown, every cell has elongated germ slit extending the entire length of the cell, 14-21 × 11-17 um,	51a/b
<i>Diporothea</i>	Ascospores bisepate, fusiform, brackish brown or light brown, both ends truncate having a germ pore	52a/b
<i>Coniochaeta ligniaria</i>	Ascospores one celled, ellipsoid, brown, bilaterally flattened, with long germ slit	53
<i>Valsaria</i> -type	Uniseptate ascospores, 42 × 22 um inclusive of the velum which forms longitudinal ribs and an equatorial ring around the septum	54a/b
<i>Entorrhiza</i>	Globose or subglobose teliospore, smooth to finely or coarsely verrucate	55
<i>Pleospora</i> -type	Ascospores ellipsoid or oblong, brown, muriform, 7 × 2-3-septate, ascoma wall cells ~ 10 um in diameter	56
Xylariaceae	Ascospores ellipsoidal, one celled with longitudinal germ slit, perithecia embedded in stroma	57
<i>Curvularia</i>	Sopre crescent shape, psilate having mostly five cells	58a/b
<i>Pithomyces chartarum</i>	Spores brown, barrel shaped, somewhat roughened, several celled with cell divisions running both horizontally and vertically, colourless	59
<i>Hypocopra</i> -type	Ascospores flattened on one side, ellipsoidal in other view, surrounded by a gelatinous sheath	....
<i>Delitschia</i> -type	Ascospores dark, ellipsoidal, mainly two celled with longitudinal straight or sinuous germ slit	60a/b
<i>Sordaria</i> -type	Ascospores one celled, ellipsoidal, 16-31 × 10-17 um, apical pore 1.5 um, wall around apical pore is thick and dark, basal pore of the pore is flattened	61
<i>Trichodelitschia</i> -type	Ascospores two celled, dark, each cell having a polar germ pore	....
<i>Arnim</i> -type	Ascospores one celled, ellipsoidal, 86 × 30-36 um with ~ 1.5 um wide pore at both ends	62
<i>Munkovalsaria/Montagnula</i>	Ascospores fusiform, reddish brown, 1-septate, both ends pointed	....
<i>Neurospora</i> -type	Ascospores ellipsoidal, non septate, brown with two protruding apical pores, contains longitudinal grooves	63
<i>Urocystis</i>	Ustilospore subglobose, ellipsoid, ovoid or angular, verruculose	....
<i>Pediastrum</i>	Coenobium circular in outline, cells irregular or polygonal, cell wall granular, marginal cells have two lobes, ending by long narrow hyaline abrupt processes	64
<i>Volvocaceae</i>	Each cell round with S-like-split-opening, colourless, having rough surface	65
<i>Botryococcus</i>	Yellow brown to yellow colonies, cells elongated, obovate or cylindrical, enclosed by a mucilage, sometimes apical ends of cells emerged from the mucilaginous cups	66
<i>Chironomids</i>	Mandibles of invertebrates	67a/b
<i>Trichuris</i>	Egg cuticle of parasitic Nematodes	68
<i>Foraminefera</i>	Rhizopod cells composed of a series of increasing size chambers. there are 6-8 chambers in one convolution	69

Table C: List of unknown pollen, fungal spores, algae and zoological remains. Most of them occur very rarely (one to two times) and not included in the diagrams. The supposed names of fungal spores start with letter T are based on matching with the spores type reported by Van Gell, 2008 (slide presentation in international palynological congress, Bonn). ONW is a supposed name stand for Orog Nuur

Supposed Name	Photo No.	Supposed Name	Photo No.
T 1032	70	Unknown 2	98
T 1042	71a/b	Unknown 3	99
T 1045	72	Unknown 4	100
T 1051	73	Unknown 5	101a/b
T 1058 A1	74	Unknown 6	102
T 1061 A	75	Unknown 7	103
T 1061 D	76	Unknown 8	104
ONW-II-ab	77	Unknown 9	105
ONW-II-abc (cf. <i>Spirogyra</i>)	78	Unknown 10	106
ONW-II-type 1	79a/b	Unknown 11	107
ONW-II-type 2 (cf. <i>Rotatoria</i> egg)	80	Unknown 12	108
ONW-II-type 3(cf. <i>Rotatoria</i> egg)	81a/b	Unknown 13	109
ONW-II-type 4(cf. <i>Rotatoria</i> egg)	82a/b	Unknown 14	110
ONW-II-type 5	83a/b	Unknown 15	111
ONW-II-type 6	84	Unknown 16	112
cf. <i>Taniola rudis</i>	85	Unknown 17	113
cf. <i>Lembosina</i>	86	Unknown 18	114
cf. <i>Phoma glomerata</i>	87	Unknown 19	115
cf. <i>Ascobolus</i>	88	Unknown 20	116
cf. <i>Geoglossum</i>	89	Unknown 21	117
cf. <i>Microsporium</i>	90	Unknown 22	118
cf. <i>Fusicladum</i>	91	Unknown 23	119a/b
cf. <i>Puccinia</i> teletospore	92a/b	Unknown 24	120
cf. <i>Tetraporina</i>	93	Unknown 25	121
cf. <i>Meliola</i>	94a/b	Unknown 26	122
cf. <i>Cerebella/ Stemphyllum</i>	95	Unknown 27	123
cf. <i>Acrodictys globulosa</i>	96	Unknown 28	124
Unknown 1	97a/b	Unknown 29	125
		Unknown 30	126
		Unknown 31	127a/b
		Unknown 32	128a/b
		Unknown 33	129

Plate 1: Showing pollen from 1a to 10b

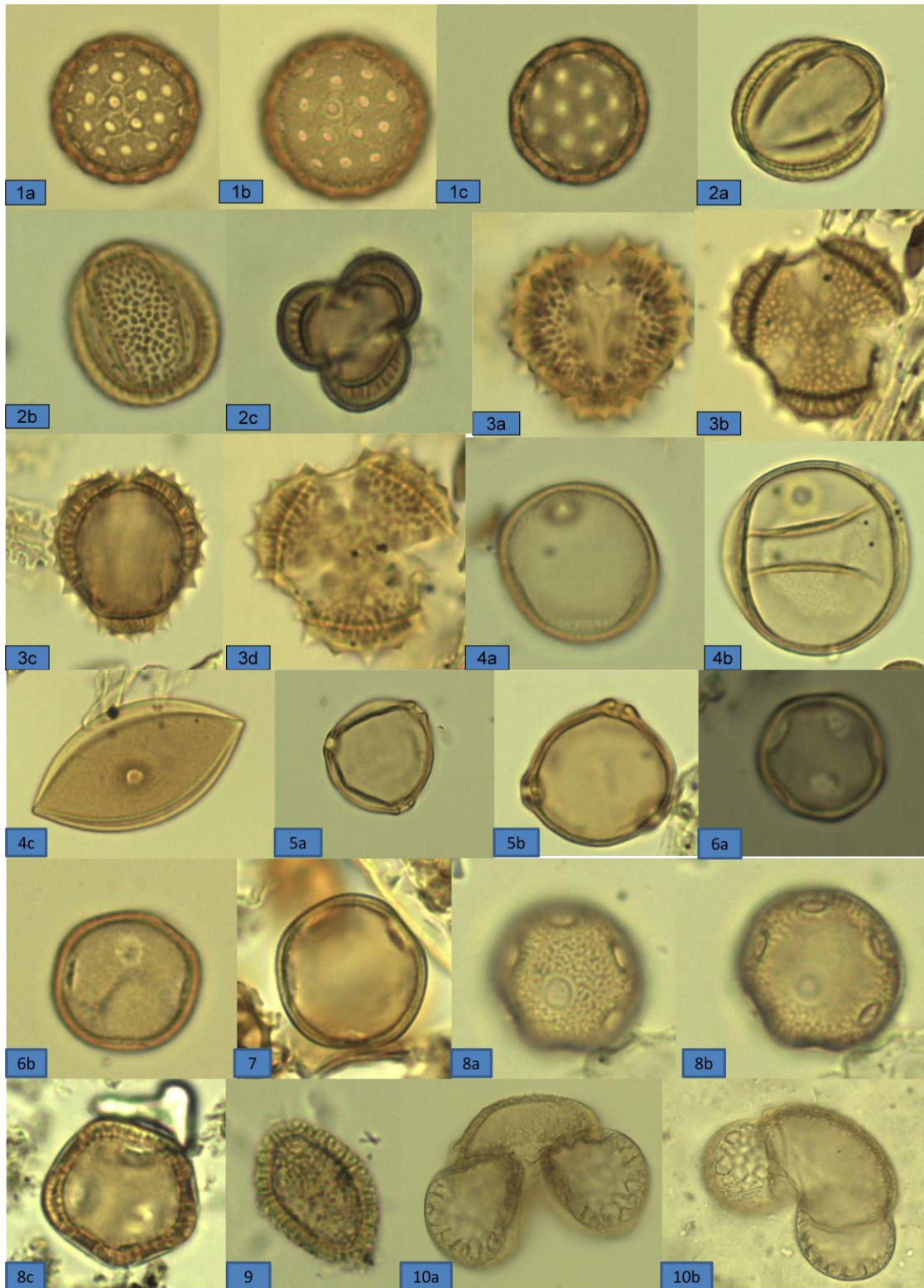


Plate 2: Showing pollen from 11a to 25a

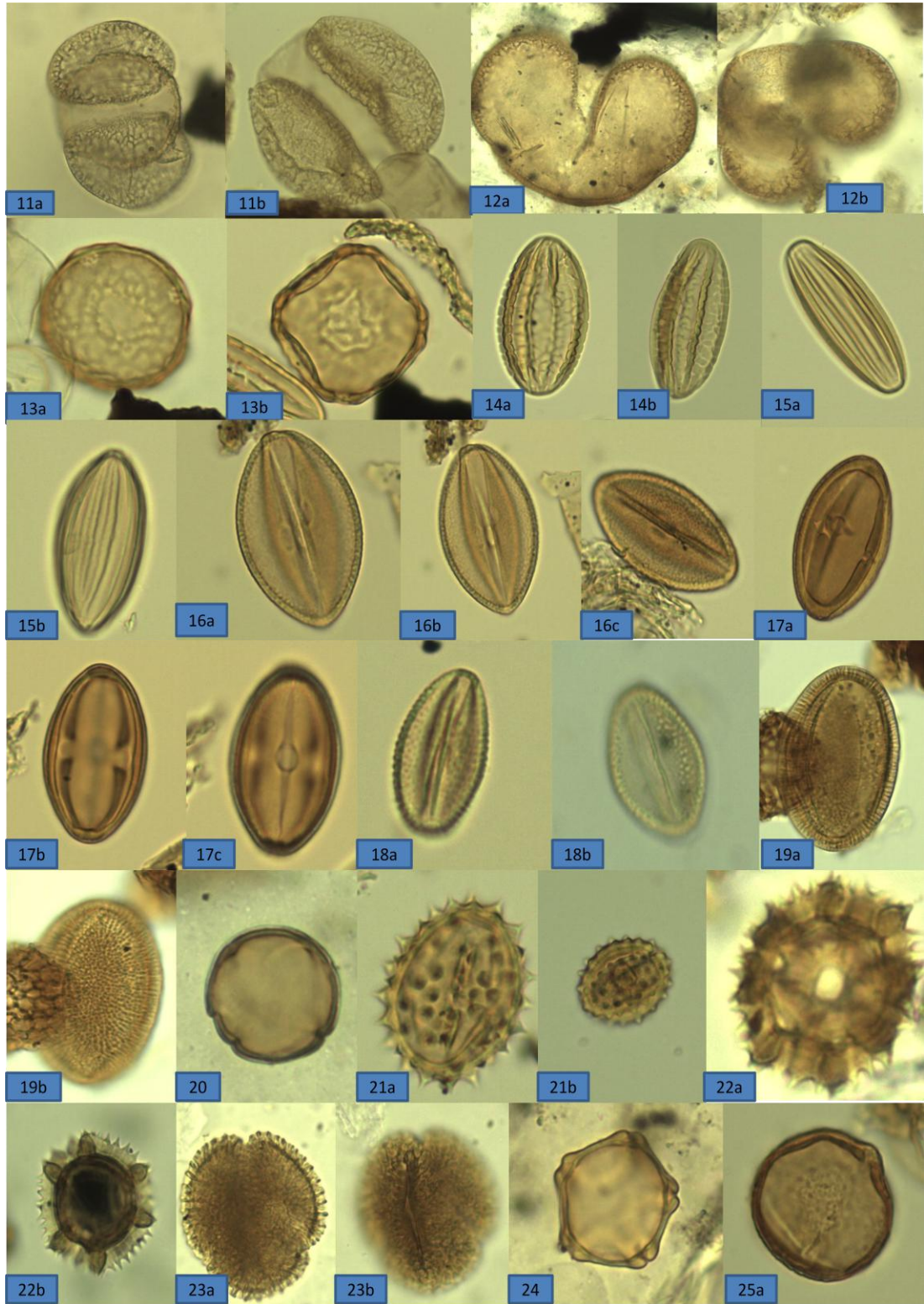


Plate 3: Showing pollen, fern spores and fungal spores from 25b to 42a

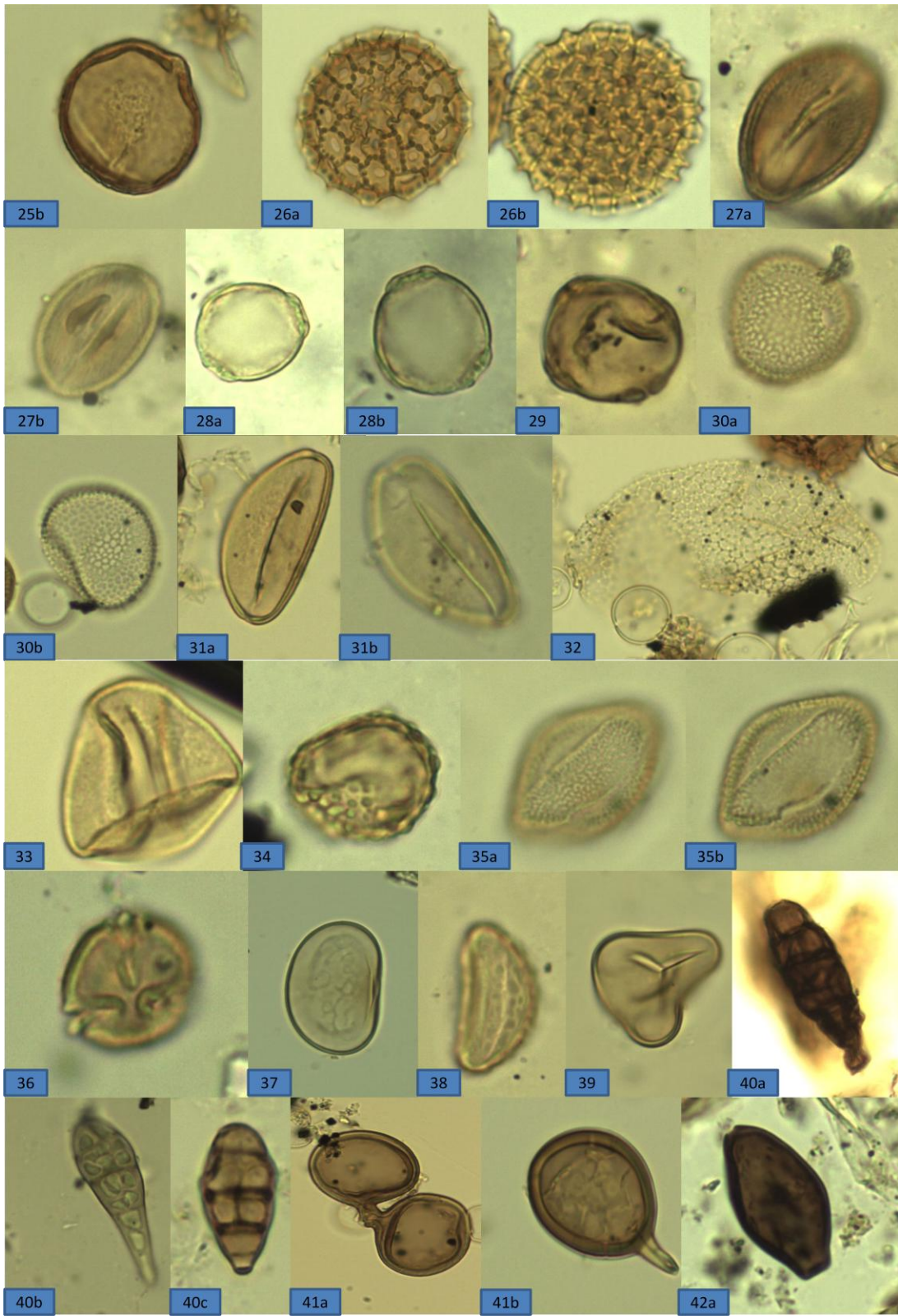


Plate 4: Showing Pollen fungal spores from 42b to 60b

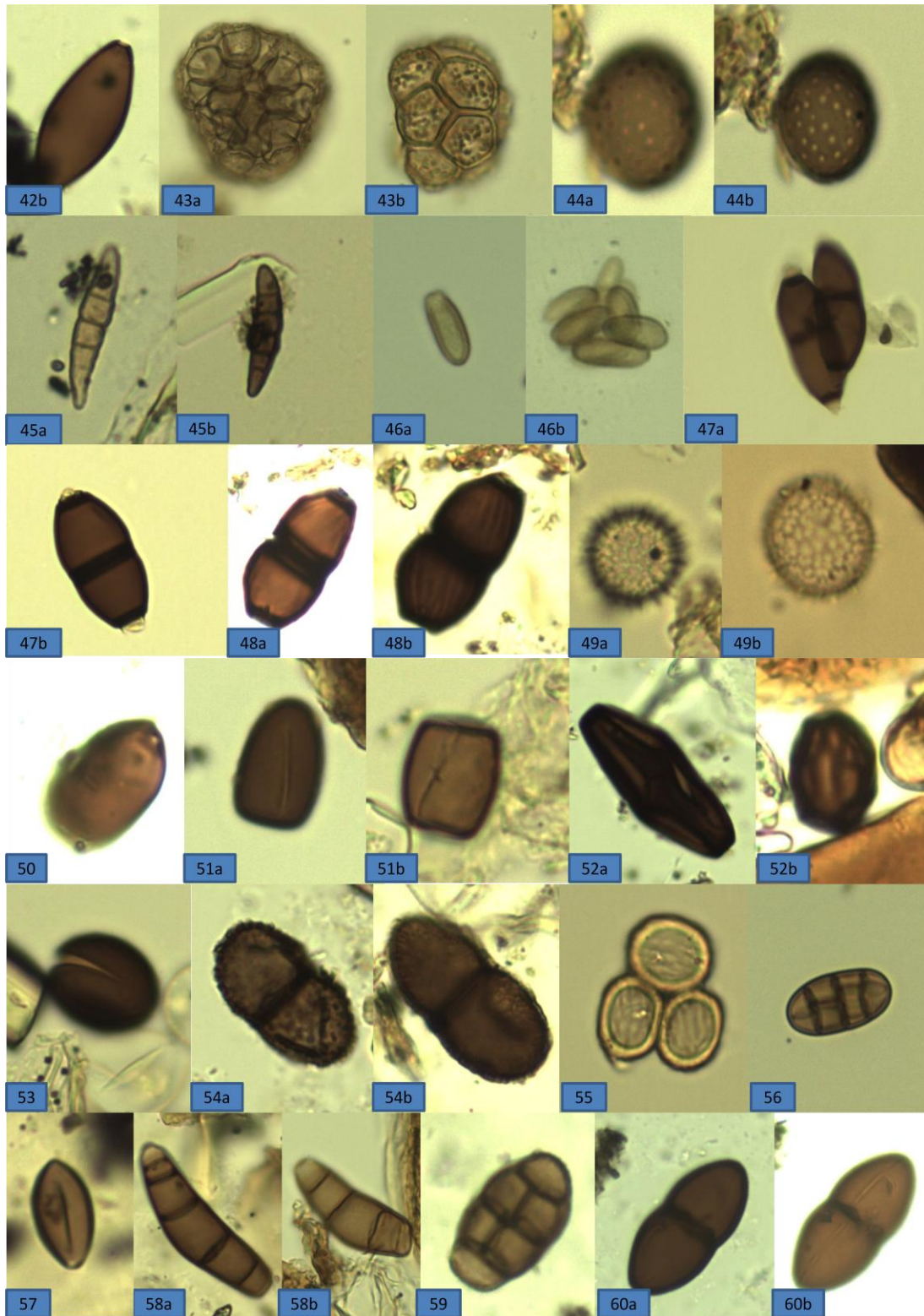


Plate 5: Showing fungal spores, algae, zoological remains and some unknown taxa from 61 to 85

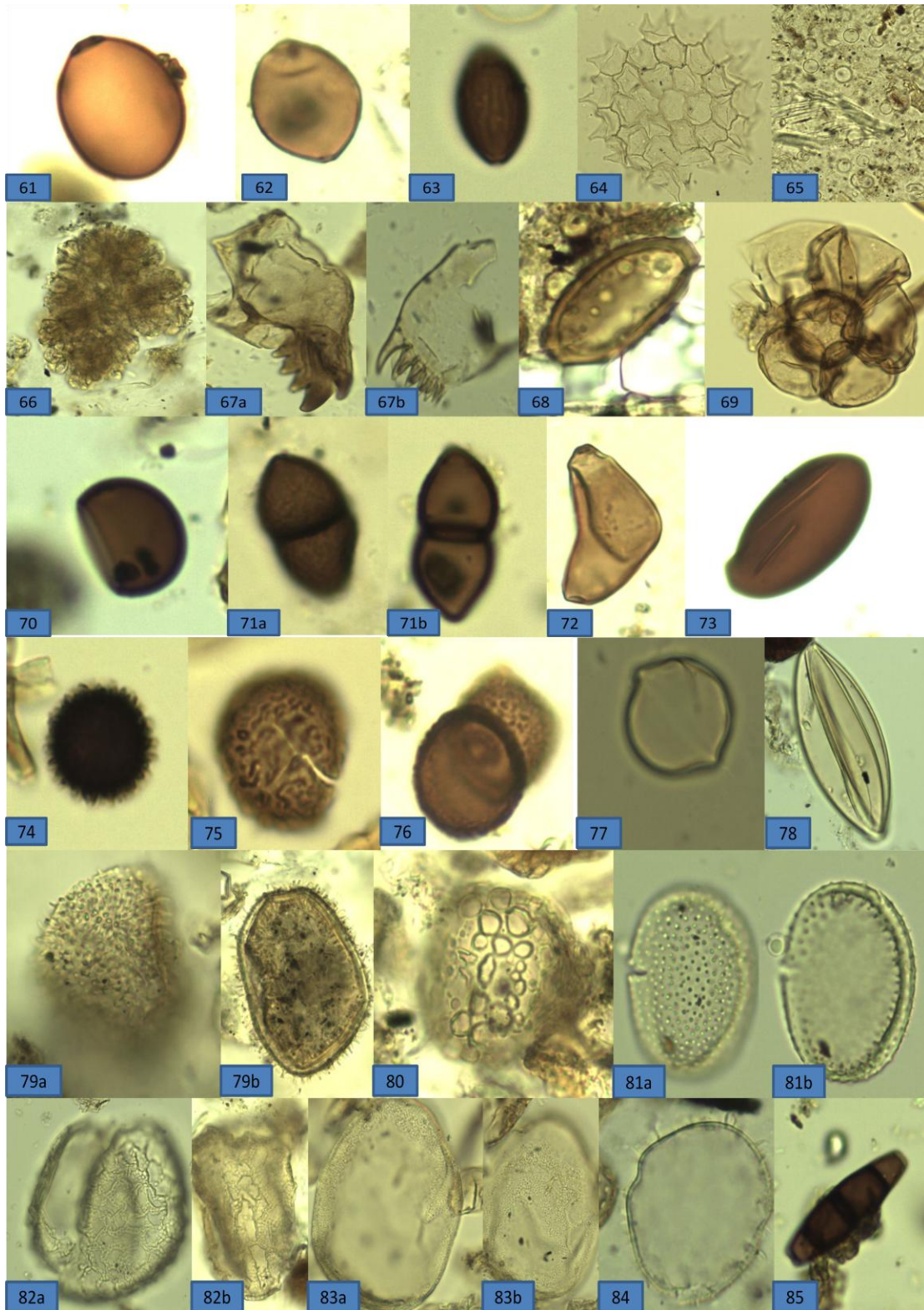
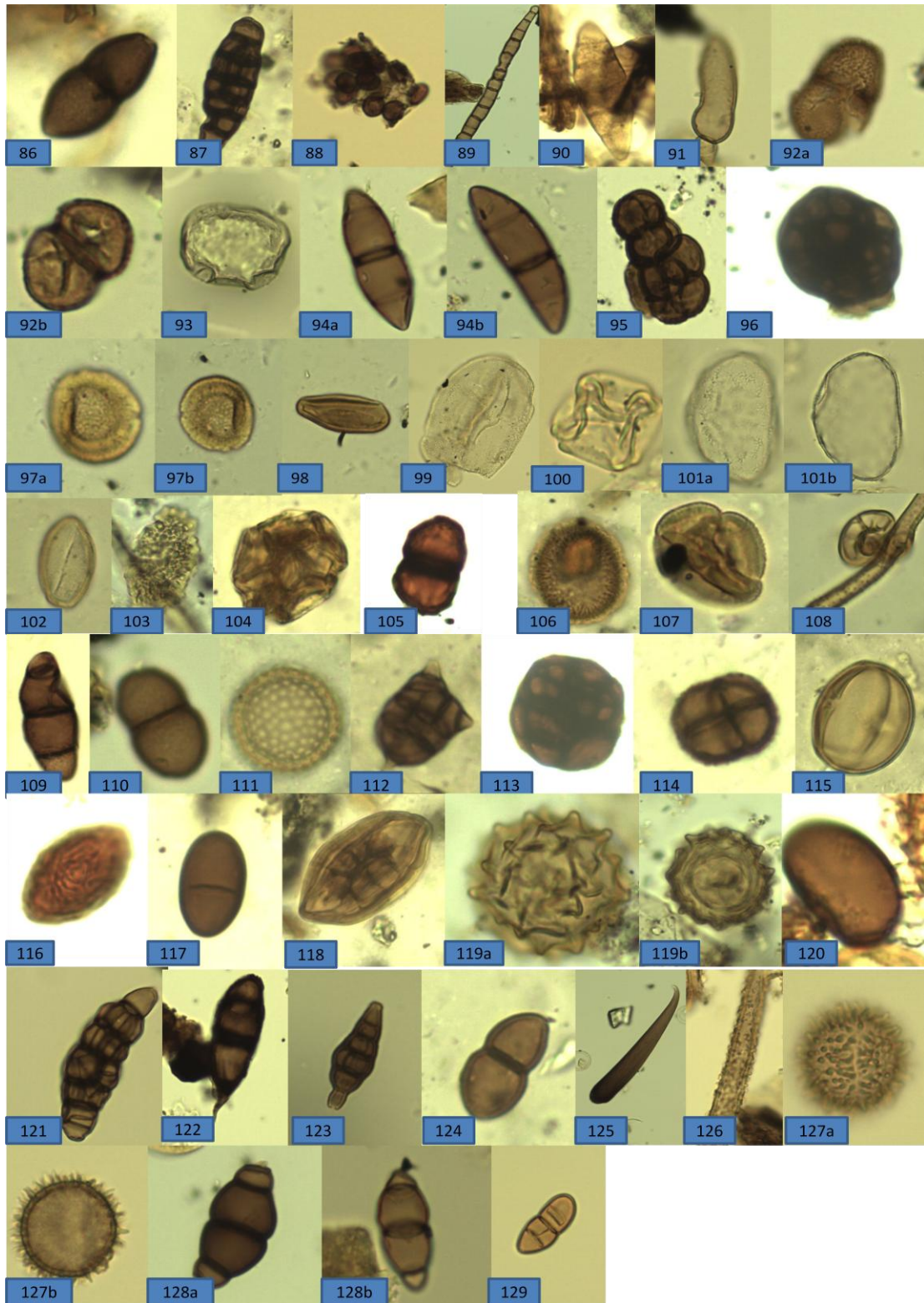


Plate 6: Showing unknown pollen, fungal spores, algae and zoological remains from 86 to 129



APPENDIX II

COMPLETE LIST OF POLLEN AND SPORES DIAGRAMS

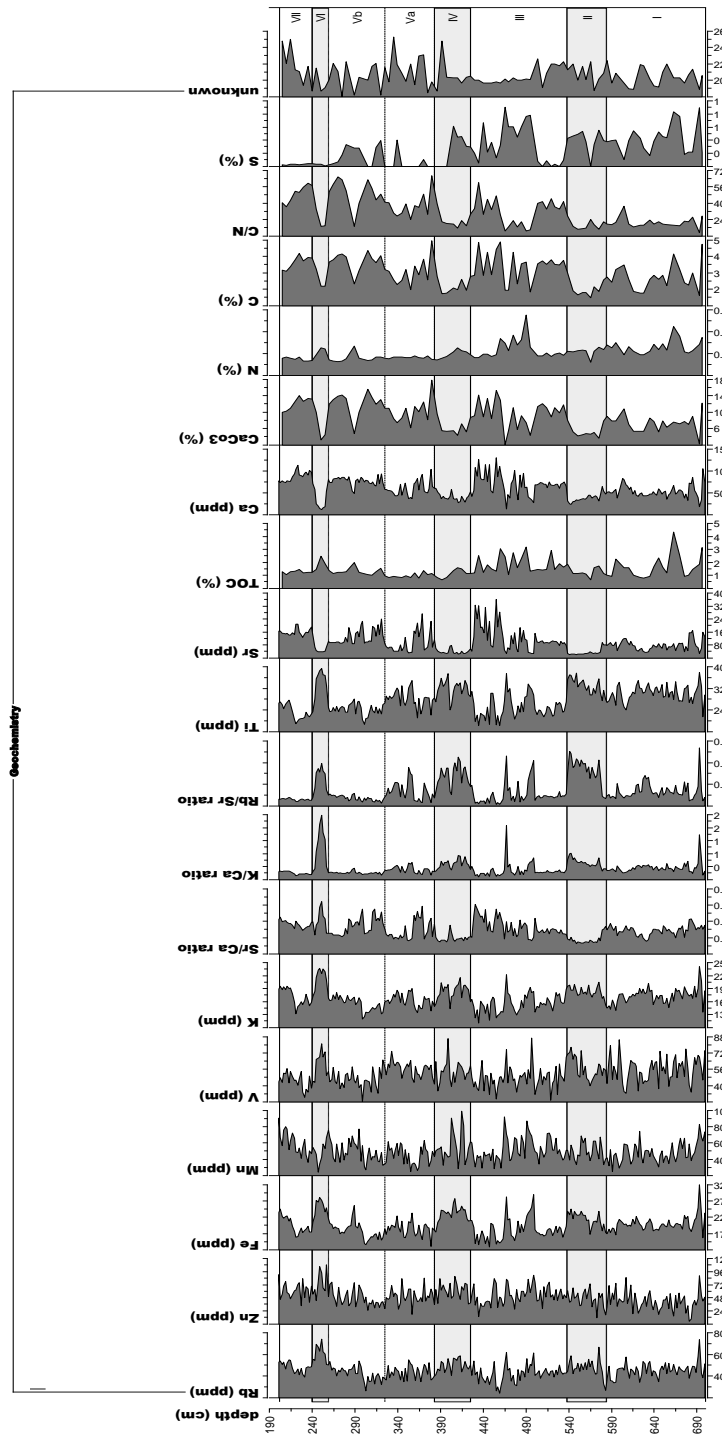
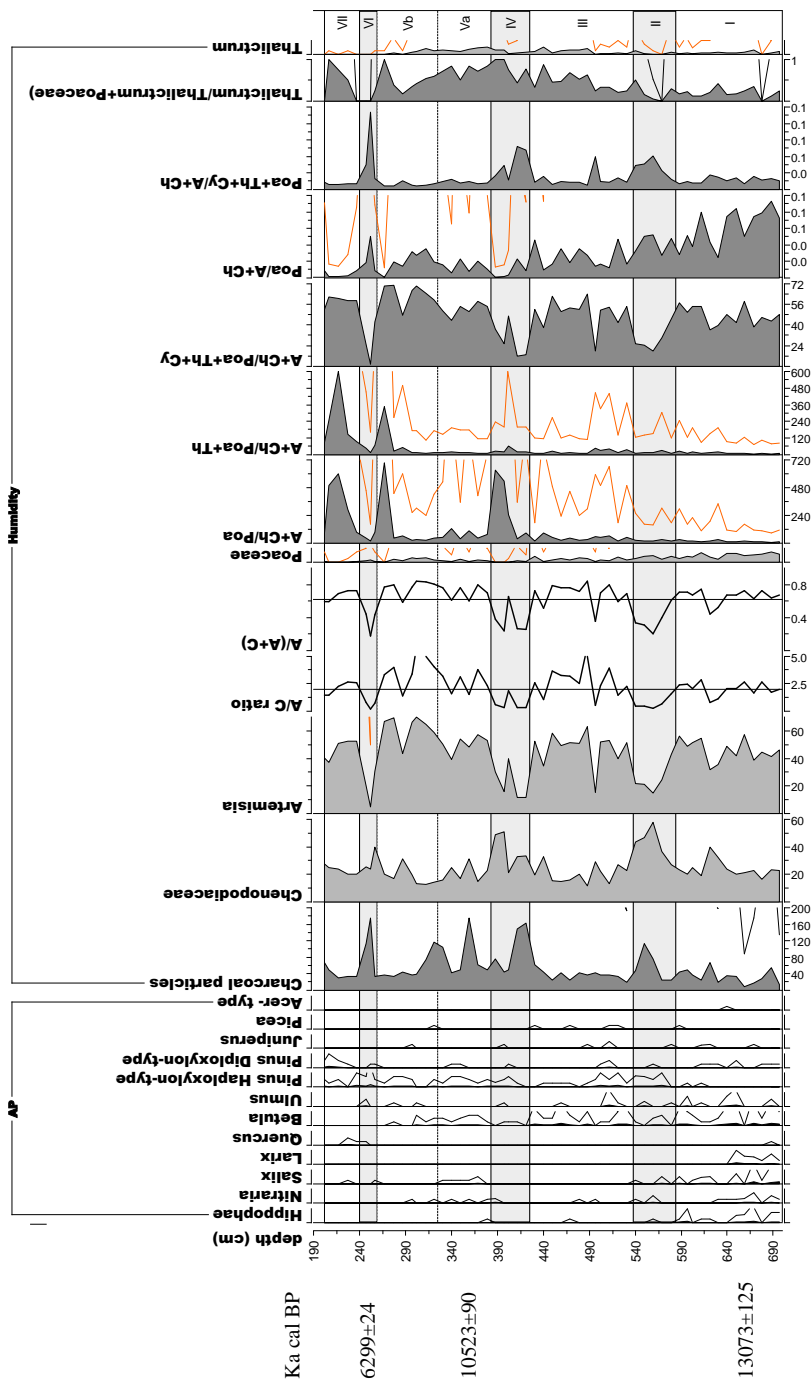
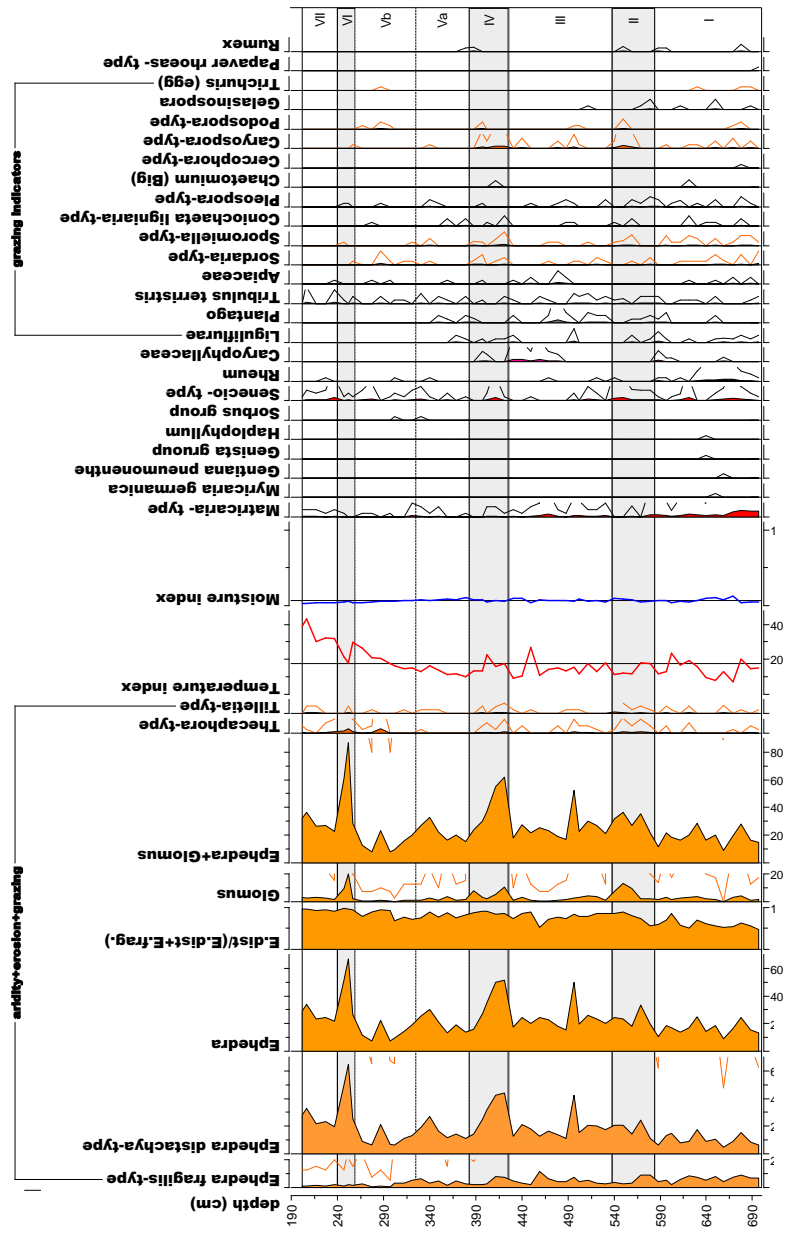


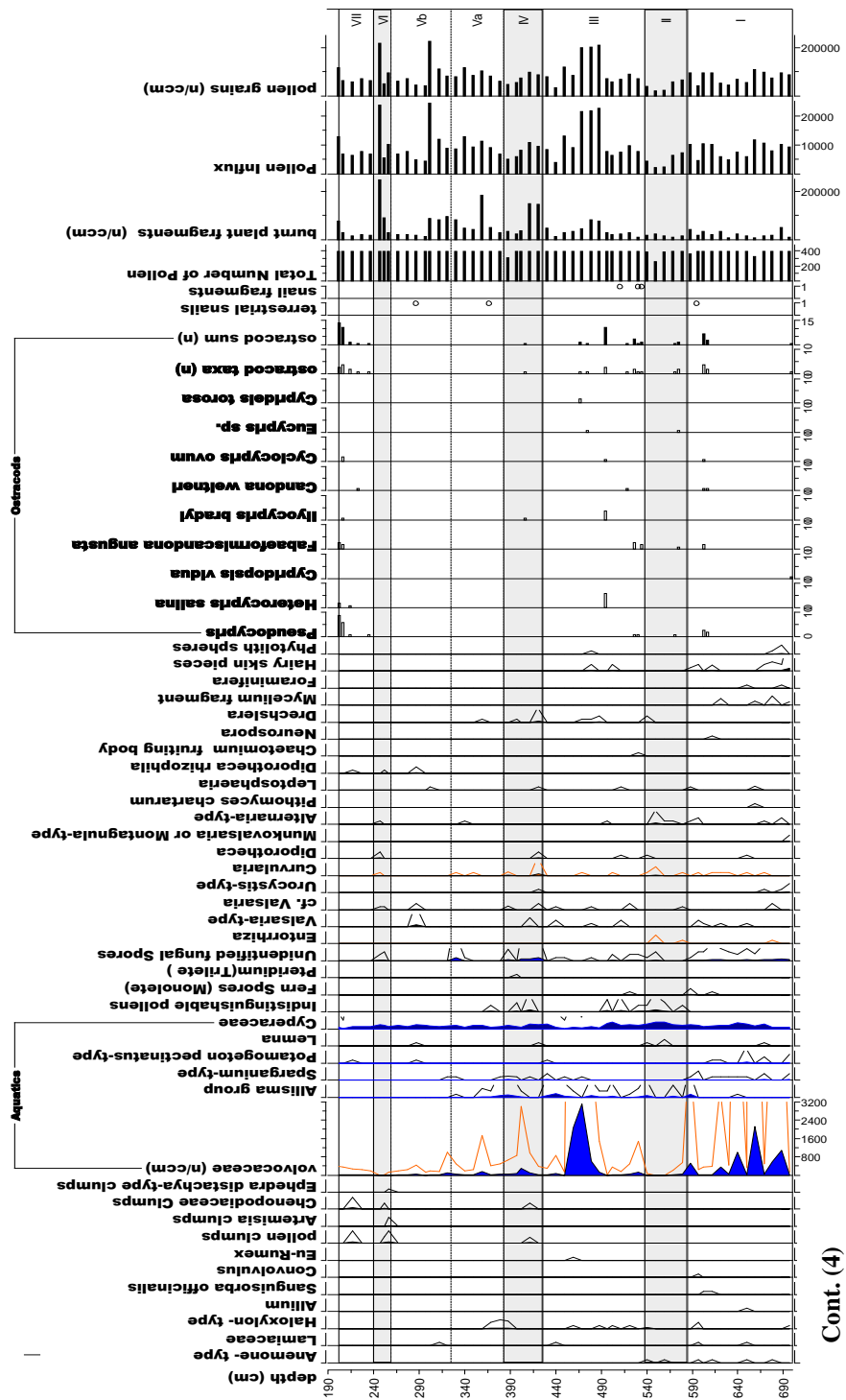
Diagram showing geochemical data, pollen, spores, algae and zoological remains from sediments of Bayan Tohomim Nuur (1)



Cont. (2)



Cont. (3)



Cont. (4)

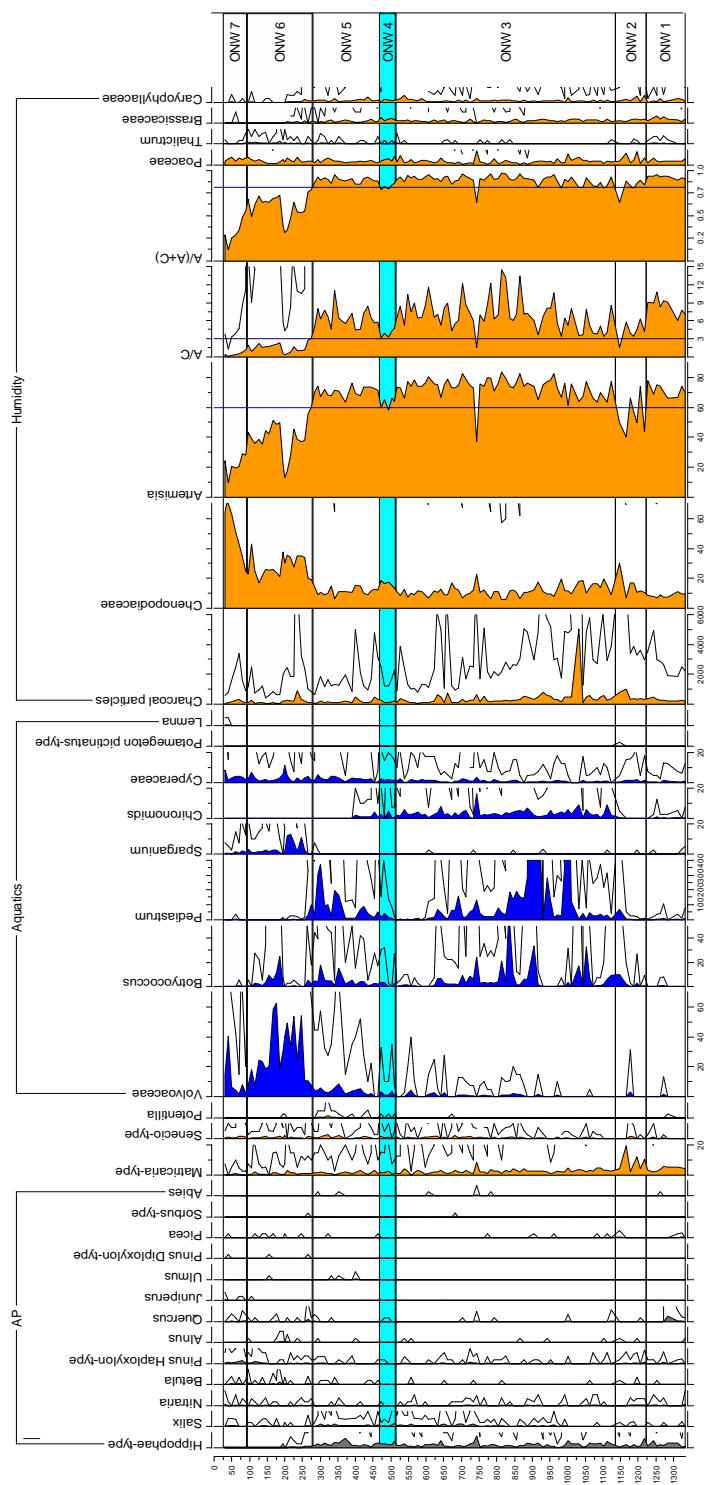
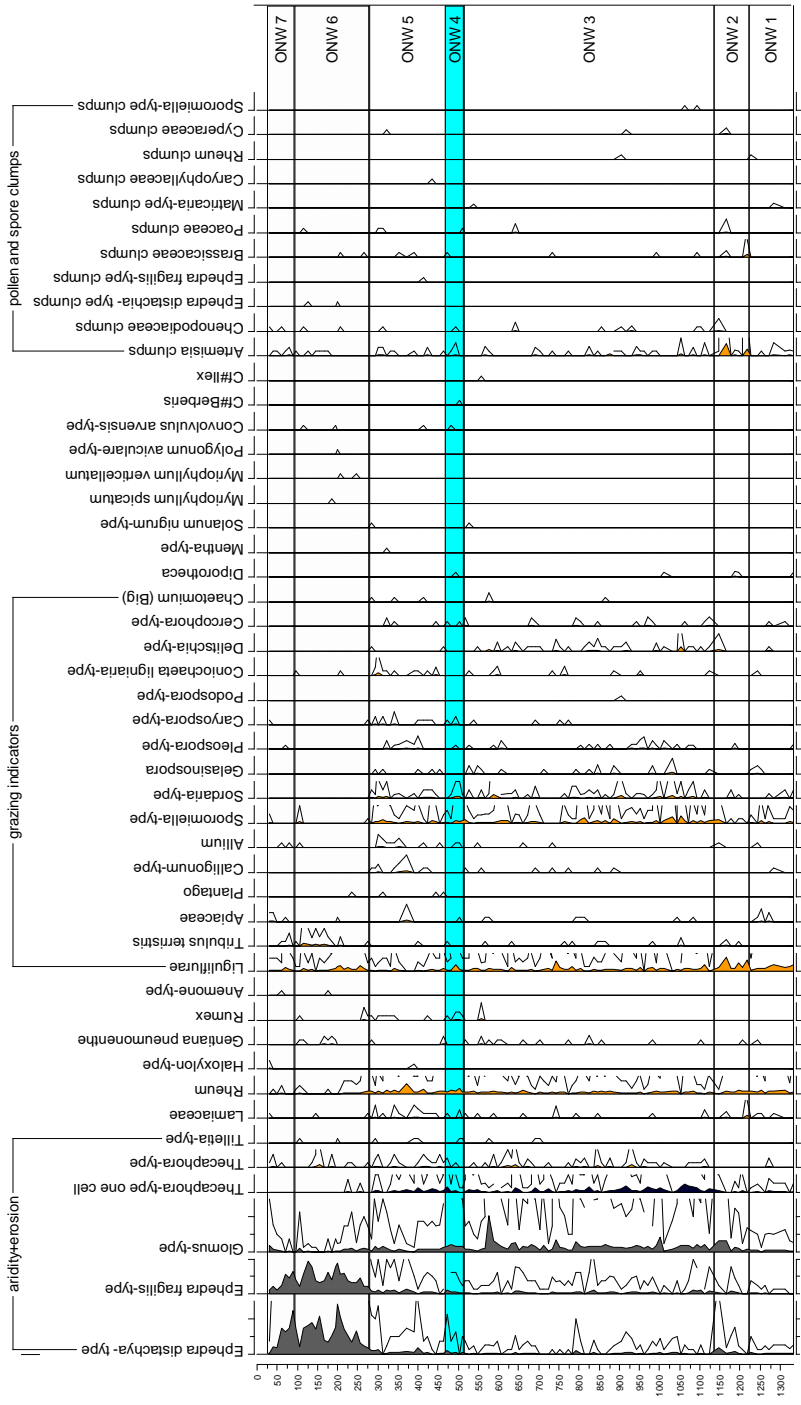
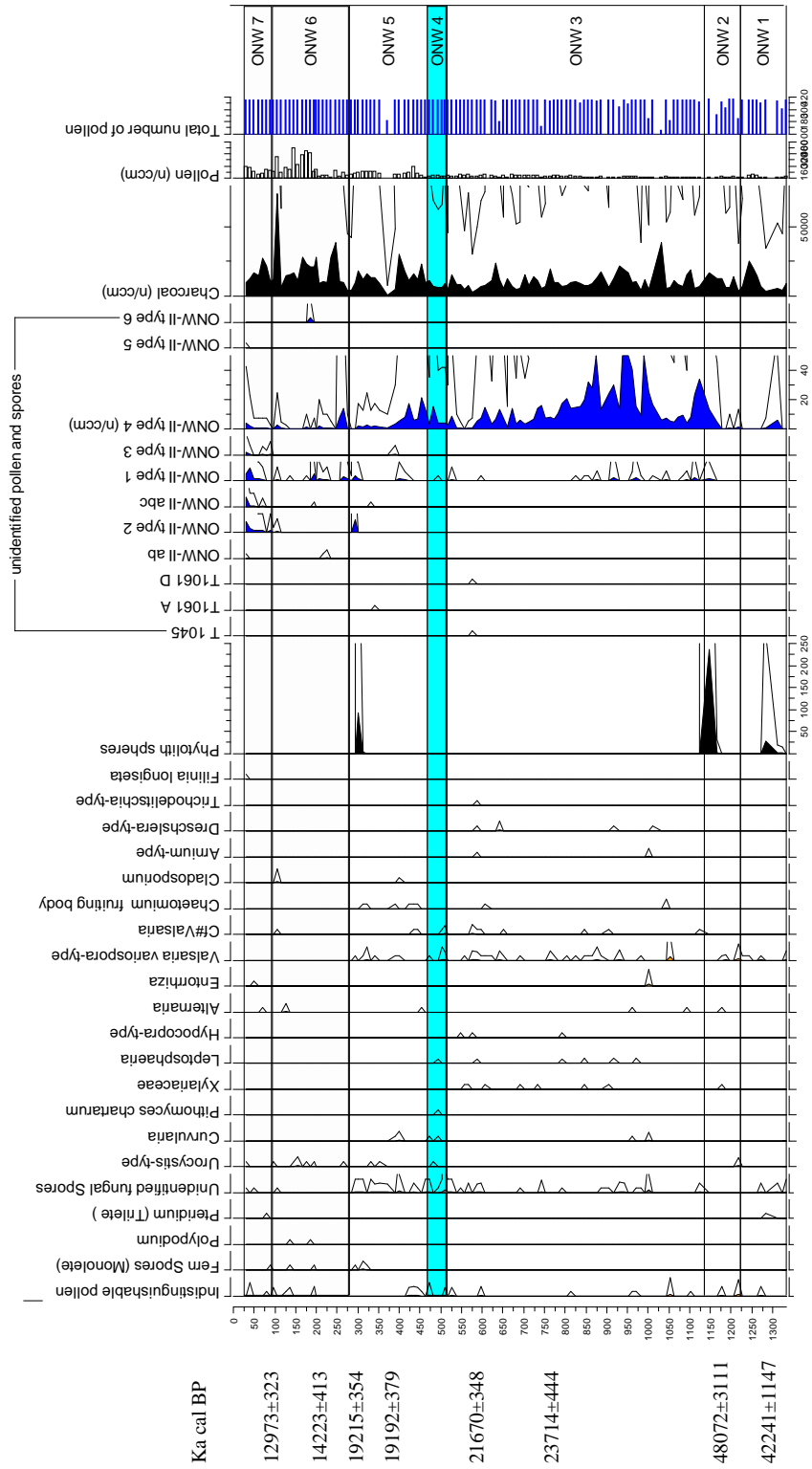


Diagram showing pollen, spores, algae and zoological remains from sediments of Orog Nuur (1)



Cont. (2)



Cont. (3)

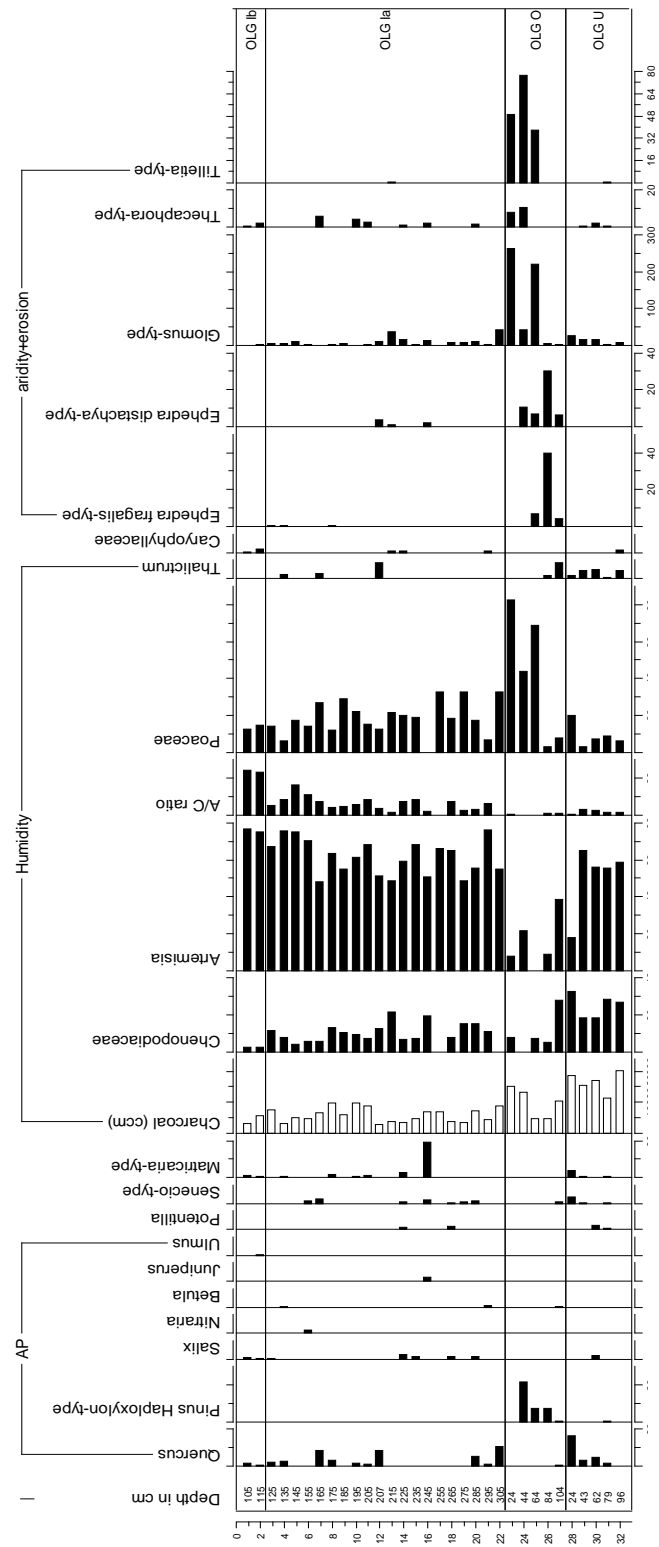
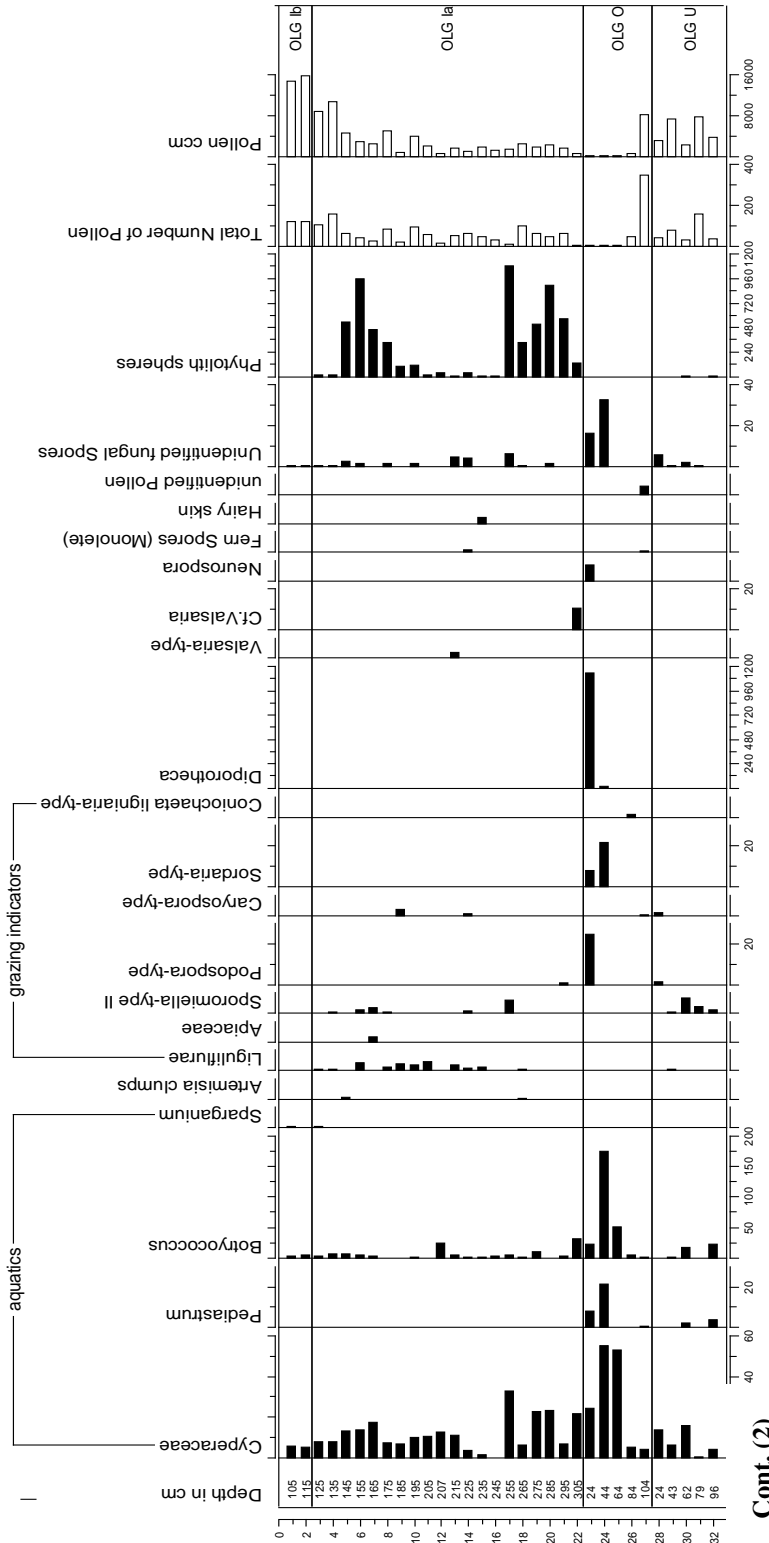


Diagram showing pollen, spores and algae from sediments of Olgyo Nuur (1)



Cont. (2)