Syntheses in Limnogeology

Alexander Orkhonselenge
Munkhjargal Uuganzaya
Tuyagerel Davaagatan

Lakes of Mongolia

Geomorphology, Geochemistry and Paleoclimatology

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A. Orkhonselenge dedicates this book to the honorable memory of her mother, B. Lkhagvasuren (1954–2017), whom she owes everything, including enormous support for her education and spawn love for science.

This book is also dedicated to all the members of the Laboratory of Geochemistry and Geomorphology (LGG), National University of Mongolia (NUM) where Mongolian future geoscientists have been educating and growing with theoretical knowledge, analytical methods, and empirical skills in Earth Science fields since 2015.

Preface

New research data from lakes of Mongolia arise from time to time, which provide a fundamental clue in understanding of surface processes operating in lake basins of Mongolia. Such data in lake study of Mongolia continue to emerge giving with deeper insights into basic principles of the processes. In other words, over the past two decades, lake studies in Mongolia have profoundly challenged us for the need to synthesize valuable implications regarding the surface processes (e.g., lacustrine, fluvial, aeolian, glacial) within lake basins in the context of principles of geomorphology, sedimentology, and geochemistry and of the reconstruction of past and present climate changes.

The following aspects promote to publish this book *Lakes of Mongolia*: *Geomorphology*, *Geochemistry,* and *Paleoclimatology*:

1. Recent studies revealing significant vulnerability of Mongolian lakes and their rapid evolution due to climate change have raised wider concerns.
2. Comprehensive study in geomorphology, geochemistry, and paleoclimatology of Mongolian lakes has yet to be conducted with the exception of general descriptions of lakes by Tserensodnom (1971, 2000) who introduced a number of lakes and classified them based on their distributions according to each aimag (meaning province), administration unit of Mongolia.
3. The study of lakes in Mongolia in terms of interdisciplinary fields (e.g., limnogeology, hydrogeomorphology, hydrogeochemistry) needs more leaderships of Mongolian geoscientists, i.e., most of recent results about lakes in Mongolia have been provided or led by foreign scientists including those outside of the former Soviet bloc (e.g., Grunert et al., 2000; Fowell et al., 2003; Kashiwaya et al., 2010; Kang et al., 2015; Mischke et al., 2020).
4. There have emerged powerful advanced methodological progresses in the application of numerical techniques, conceptual models, and mapping tools in the field of lacustrine geomorphology, geochemistry, and paleoclimatology.
5. It is important to let foreigners know the correct physiographic names and their spellings not only of lakes but also of other geographical objects in Mongolia.

All these points demand a new edition in the book form in order to bring readers up to date on them.

In This New Book

- The opportunity to include some older Russian and Mongolian literature, which have never been written in English, is to present in the book in order to review the early stage of lake study in Mongolia.
- New, pertinent references to more recent research article, report, presentation, and book publications help keep this new book up to date for informing readers about the advancement in lake study of Mongolia during the last two decades.
- The book presents statistical data about the lake distribution in five physiographic regions of Mongolia. The regions are holistically determined based on landscape type and landform feature of Mongolia providing a representative categorization.
- The book describes data on expansion and reduction of lake area and change in lake level for representative lakes in each region of Mongolia controlled by the prevailing semiarid to arid climates.
- The book addresses the sedimentation dynamics and geochemical characteristics derived from stratigraphic features of lake sediments for selected lakes.
- The book reflects on the scientific background of modern lakes throughout the country and gives detailed information on their evolution over the geological time scales and paleoclimate changes in lake basins during the Pleistocene, Holocene, and Anthropocene.
- The paleoclimate changes inferred from high-resolution multi-proxy data recorded in lake sediments are newly synthesized. The chronologies are primarily revealed with the radiocarbon isotope (^{14}C) extending to the late Pleistocene and with some optically stimulated luminescence (OSL) records.
- The book introduces recent new data on modern academic, economic, and touristic prospects and concerns of lakes in Mongolia.
- New figures and photos illustrate the topics discussed in the related text and represent current research advances.
- The correct spelling from modern Mongolian Cyrillic alphabet for geographical place names is introduced by transliteration into English.

This book is meant to be not only a scientific summary of Mongolian lakes but also a reference source in the applied fields within Earth Science. We hope and intend that the book contents would be still valid for future multi-decades for lake studies in Mongolia and Eurasia.

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Acknowledgments

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About the Book

The book *Lakes of Mongolia*: *Geomorphology*, *Geochemistry,* and *Paleoclimatology* aims to systematically provide an upgraded overview of the most spectacular lakes in Mongolia from scientific, economic, and scenic points of view, presenting lake area changes, associated outstanding landforms in lake basins, their sedimentological and geochemical characteristics, valuable economic and geoheritage resources, paleogeographical evolution and paleoclimate change reconstruction in a comprehensive manner.

Understanding geomorphic evolution of lacustrine landscape and investigating changes in lake areas in Mongolia are important because they contribute to obtain an overall view of histories of the paleo- and modern-day climate changes in Mongolia and Eurasia. However, despite some early works on paleoclimate and paleoenvironmental changes recorded in lakes of Mongolia intending to shed light on large-scale regional changes (e.g., Grunert et al., 2000; Komatsu et al., 2001; Peck et al., 2002; Krivonogov et al., 2005; Prokopenko et al., 2007; Wang et al., 2011; Orkhonselenge et al., 2013; Lehmkuhl et al., 2018; Yu et al., 2019), temporal and spatial analyses of modern lakes in Mongolia have not been conducted sufficiently.

This book covers lacustrine geomorphology, geochemistry, and paleoclimatology which best contribute to represent uniqueness and geodiversity of lakes in the country and past and present climate changes in Mongolia and Eurasia. It also introduces these lakes with scientifically essential lacustrine landscapes, economically useful resources, and recreationally fascinating geosites, which are of crucial importance to understanding the geomorphic evolution of lake basins in Mongolia.

In this book, a special attention is given to the lakes from where recent intensive investigations have brought new insights into the spatial and temporal reconstructions of paleoclimate and paleoenvironmental changes within Mongolia and Eurasia. The book not only emphasizes internationally well-known lakes of Mongolia, but it also tends to describe far less popular lakes which have been remained unrecognized of their scientific importance.

This book is the first effort to synthesize the geomorphological, geochemical, sedimentological, paleogeographical, and paleoclimatological implications with

present climate change obtained from the lakes of Mongolia. The book is divided into three parts.

Part I introduces an overview of past and present lake studies in Mongolia. Moreover, it is concerned with aspects of formation, evolution, origin, and classification of Mongolian lakes taking account of the great variety of the lakes existing in the country.

Part II introduces the geological, climatological, geomorphological, cryological, and hydrological characteristics of each region in the east, south, west, north, and center of Mongolia. In these regions, 10 lakes that are geomorphologically, sedimentologically, geochemically, and paleoclimatologically valuable are discussed in alphabetical order as Buir, Buun Tsagaan, Khargal, Khoton, Khuvsgul[1], Khukh, Terkhiin Tsagaan, Ugii, Ulaan, and Uvs. In addition, it deals with paleoclimatic and paleoenvironmental reconstructions in Mongolia and Eurasia inferred from the long-term geomorphological, sedimentological, and paleogeographical evolutionary histories of lake basins.

Part III provides readers essential core aspects of academic, economic, and geotouristic significance, especially those valuable lakes in Mongolia, and their implications on the lakes and landscapes. This part highlights an extension based on the scientific values of lake study to applicable fields of higher education, economy, and geopark.

All the chapters of the book begin with an overview clue abstract and ends with a review comprehensive summary. The overall goal of the book is to provide an accessible, highly illustrated, virtually attractive, and well-integrated publication suitable for pure and applied sciences and their interdisciplinary fields.

We hope that the book *Lakes of Mongolia*: *Geomorphology*, *Geochemistry,* and *Paleoclimatology* will be used as a primary source for scholars, researchers, experts, and professionals in the fields of Earth science, Quaternary science, and Environmental science. The observed surface processes in lake basins, resulting in geomorphological features and sedimentological and geochemical characteristics, have a fundamental bearing on our understanding not only of lake evolution over various geological time scales and paleo- and modern-day climate changes in lake basins but also of the present academic issues, future scientific development, and sustainability of economic and geoheritage resources.

This book is the culmination of years of experience in training undergraduate and graduate students in fields of introduction to Earth science, geomorphology, sedimentology, geochemistry, and paleogeography, and in working for research projects over the last two decades. It intends to provide a valuable source material useful for describing and analyzing lake sediments, related landforms and Earth surface processes in lake basins, and regional patterns of paleoclimate changes in large lake basins of Mongolia.

[1] *Khuvsgul* has been misspelled as *Hovsgol* and *Khubsugul* in publications. Khuvsgul is the right English transliteration from Mongolian *Хөвсгөл*.

Contents

About the Authors

Alexander Orkhonselenge's research interests focus on glacial, lacustrine, fluvial, and aeolian sedimentological, geochemical, and geomorphological processes, paleoclimate changes, and Quaternary science. Her interest in the galactic formation, evolution, and processes in the Solar System and the Earth was inspired by a fascinating lecture on geochemistry at her freshman. Later on, her continuous learning from eminent professors and researchers expanded in the fields of geomorphology, sedimentology, and paleoclimatology.

Her research has largely focused on lake sedimentations and alpine glaciations in Mongolia and on reconstruction of paleoclimate changes based on their deposits. She also has studied peatland formation and evolution in northeastern Mongolia and how paleoclimate changes have influenced peatlands. She has been studying stratigraphic sequences of outcrops in the Govi[1] region, southern Mongolia. Over the last two decades, she worked in the Mongolian-Russian-Japanese-Korean joint research projects in Lake Khuvsgul[2] (HDP) and paleolake Darkhad (DDP), and the Swedish-American-Chinese-Mongolian joint research project (CAPP) in the Mongolian Altai Mountain Range.

She established the Laboratory of Geochemistry and Geomorphology (LGG) at the National University of Mongolia (NUM) on September 28, 2015 for training undergraduate and graduate students in Earth science and for developing fields in Earth science, especially geomorphology, sedimentology, and geochemistry, in Mongolia. The first LGG's research project was to reconstruct paleoclimate change in southern Mongolia based on lakes in the Valley of Lakes of the Govi region. The research has led her, together with her students, to work in eastern, northern, and central Mongolia. She is an author and a coauthor of about 20 scientific articles published internationally. Laboratory of Geochemistry and Geomorphology,

[1] *Govi* has been often spelled as *Gobi* in the international literature. Govi is the correct English transliteration from Mongolian *Говь*.

[2] *Khuvsgul* has been misspelled as *Hovsgol* and *Khubsugul* in many publications. The Khuvsgul is the right English transliteration from Mongolian *Хөвсгөл*

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Munkhjargal Uuganzaya graduated from the National University of Mongolia (NUM) with BSc in Geography in 2011 and MSc in Environmental Science in 2015. Since her graduate school, she has been deeply interested in glacier changes of Mongolia and joined the colleagues at the Laboratory of Geochemistry and Geomorphology (LGG). Her master thesis under the supervisor A. Orkhonselenge entitled *Estimating modern glacier changes of Mongolia using remote sensing*: *the case of Mt. Ikh Turgen* contributed and upgraded her research in advanced level professionally.

Her research focuses on alpine glaciations and lake area changes in Mongolia. She has specialized in GIS and remote sensing techniques. She participated in research projects at the LGG and published over ten scientific articles related to paleo- and modern glaciers in the Mongolian Altai, Khangai and Khentii. Mountain Ranges and lake sedimentations in Lake Ulaan at national and international peer-reviewed journals. Laboratory of Geochemistry and Geomorphology, School of Arts and Sciences, National University of Mongolia, Ulaanbaatar, Mongolia

Tuyagerel Davaagatan graduated from Mongolian State University of Education with BSc in Geography in 2011 and National University of Mongolia (NUM) with MSc in Geography in 2014. After her graduate school, she joined her colleague at Laboratory of Geochemistry and Geomorphology (LGG), NUM.

Her research focuses on lake sedimentations and past and present climate changes in Mongolia. She participated in the fieldwork for lake sedimentations in the Mongolian-Russian-Japanese-Korean joint international research project in paleolake Darkhad (DDP) with her supervisor A. Orkhonselenge from NUM and professors and graduate students from Kanazawa University, Japan, in 2011 and the national research project *Landscape Structure, Change, Planning and Proper Zonation in eastern Mongolia* led by the Division of Physical Geography, Institute of Geography and Geoecology in 2016. She has specialized in analytic methods to determine physical and chemical properties of lake sediments since her training at Kanazawa University in 2012.

She also participated in some research projects at the LGG and published more than ten scientific articles at national and international peer-reviewed journals. Recently, she published the coauthored books in Mongolian entitled *Landscape Ecological Potential of Mongolia* in 2020 and *Geographical Uniqueness of Mongolia* in 2021. Laboratory of Geochemistry and Geomorphology, School of Arts and Sciences, National University of Mongolia, Ulaanbaatar, Mongolia

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Abbreviations

AD	Anno Domini meaning a calendar year, the start of the era
Al	Aluminum
Al_2O_3	Aluminum oxide
&	And
~	Approximately, nearly, about
Ar	Argon
As	Arsenic
a.s.l.	Above sea level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
B	Boron
BA	Bølling–Allerød
BP	Before Present
Br	Bromine
BRZ	Baikal Rift Zone
Ca	Calcium
$CaCO_3$	Calcium carbonate
cal.	Calibrated
CaO	Calcium oxide
CAOB	Central Asian Orogenic Belt
carb	Carbonic
^{14}C	Radiocarbon-14
$\delta^{13}C$	Ratio of stable isotopes carbon-13 (^{13}C) : carbon-12 (^{12}C)
CHs	Carbohydrates
^{o}C	Celsius degrees
CRU	Climatic Research Unit
Cl	Chlorine
C/N	Carbon to nitrogen ratio
DDP	Darkhad Drilling Project
DEM	Digital Elevation Map
dm	Decimeter
EASM	East Asian Summer Monsoon

EAWM	East Asian Winter Monsoon
EC	Electrical conductivity
e.g.	For example
et al.	And others
etc.	And so on
Fe	Iron
Fe_2O_3	Hematite
FeOOH	Goethite
Fig.	Figure
GC	Gas chromatography
g/l	Gram per liter
GPa	Gigapascal
HCO_3	Bicarbonate
HDP	Hovsgol (or Khuvsgul) Drilling Project
H_2S	Hydrogen sulfide
i.e.	In other words
IR	Infrared
IRSL	Infrared optically stimulated luminescence
ITM	International Travel Mart
K	Potassium
ka	Kilo annum meaning thousands of years ago
KDP	Khuvsgul Drilling Project
km	Kilometer
km^2	Square kilometer
km^3	Cubic kilometer
K_2O	Potassium oxide
LGG	Laboratory of Geochemistry and Geomorphology
LGM	Last Glacial Maximum
Li	Lithium
LLGM	Local Last Glacial Maximum
LOI	Loss on ignition
l/s	Liter per second
m	Meter
m^2	Square meter
m^3	Cubic meter
Ma	Mega annum meaning millions of years ago
MAS	Mongolian Academy of Sciences
mg/l	Milligram per liter
MgO	Magnesium oxide
MIS	Marine Isotope Stage
MHPS	Mongolian High-Pressure System
MnO	Manganese oxide
mm	Millimeter
MODIS	Moderate Resolution Imaging Spectroradiometer
MPI	Max Planck Institute

m/s	Meters per second
MS	Magnetic susceptibility
Mt	Mountain
N	North
Na	Sodium
NAO	North Atlantic Oscillations
Na_2O	Sodium oxide
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NGO	Non-governmental organizations
NH_4	Ammonium
NMR	Nuclear Magnetic Resonance
NOAA	National Oceanic and Atmospheric Administration
NO_3	Nitrate
NUM	National University of Mongolia
$\delta^{18}O$	Ratio of stable isotopes oxygen-18 (^{18}O)/oxygen-16 (^{16}O)
org	Organic
OSL	Optically stimulated luminescence
PAHs	Polycyclic aromatic hydrocarbons
PCA	Principal Component Analysis
%	Percentage
±	Plus or minus
pH	Potential of hydrogen
ppm	Part per million
P_2O_5	Phosphorus oxide
RAS	Russian Academy of Sciences
S	South
SAR	Synthetic Aperture Radar
SDSN	Sustainable Development Solutions Network
Si	Silicon
SiO_2	Silicon dioxide
SIRM	Saturation Isothermal Remnant Magnetization
SO_4	Sulfate or Sulphate
Sr	Strontium
TC	Total carbon
TDS	Total dissolved solids
Th	Thorium
Ti	Titanium
TIC	Total inorganic carbon
TiO_2	Titanium dioxide
TL	Thermoluminescence
TOC	Total organic carbon
TM	Thematic Mapper
TN	Total nitrogen
TS	Total sulfur

U	Uranium
USSR	Union of Soviet Socialist Republics
vs.	Versus
YD	Younger Dryas
yr	Year

Chapter 1
Introduction

Abstract Mongolia consists of the highly elevated Mongolian Plateau between the Siberian and Chinese Cratons on the Central Asian Orogenic Belt (CAOB) and occupies a transitional region between the Siberian taiga forest in the north and the Govi desert in the south. Mongolia is situated at the region characterized by the highest degree of continentality within Eurasia developing under the interaction of three large-scale climatic systems (the Siberian high- and the Asian low-pressure cells and the westerlies). Because of its unique physiographic condition, landscape of Mongolia is diverse and very peculiar and extraordinary with glaciated high mountains, large freshwater and saline lakes, spacious plains, spectacular Govi deserts, and large rivers. Landscape and lakes of Mongolia represent the natural museum of the northeastern, eastern and southeastern Eurasian continent because of its untouched, wild, and less anthropogenic nature. In this chapter, the whole of Mongolian landscape and lakes and their evolution and feature are introduced in detail, and the scope and worth of the book are highlighted.

Keywords Physical Geography · Geomorphology · Landscapes · Landforms · Lakes · Mongolia

1.1 Overview of Mongolian Physiography

Mongolia, a highly uplifted country in Eurasia, is located in the region characterized by the highest degree of continentality with extreme diurnal, seasonal, and annual air temperature amplitudes. Mongolia lies at the southern limit of both the Siberian taiga forest and permafrost, and the northern limit of both the Govi (or Gobi)[1] desert area and steppe grassland. Because of its unique physiographic condition, landscape of Mongolia is diverse and very peculiar within Eurasia.

[1] *Govi* has been often spelled as *Gobi* in the international literature. Govi is the correct English transliteration from Mongolian *Говь*.

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Lakes of Mongolia, situating in the eastern part of a great lake zone extending from the Mediterranean Sea to the Lake Baikal[2] (Murzaev, 1952; Tsegmid, 1969), constitute a spectacular scenery among numerous extraordinary attractive landscapes of the country (e.g., glaciated high mountains such as the Altai, Khangai,[3] and Khentii[4] Mountain Ranges; large freshwater and saline lakes such as Lakes Buir, Khuvsgul,[5] and Khyargas; open wide plains such as Dornod, Menen, and Sulin Kheer plains; Govi Desert regions such as Borzon, Uush, and Galba and large rivers such as Orkhon, Kherlen, and Selenge[6] Rivers). An outstanding overview regarding physical geography of Mongolia was published in a book by Russian physical geographer E.M. Murzaev in 1952 (see Chap. 2) with remarkable observations and a series of valuable topographic maps, and this book was translated and published from Russian to Mongolian language by Tsegmid (1969). Landscape diversity in each region of Mongolia is deeply connected with the long-term geological evolution and climate changes over the geological time scale. The Mongolian landscape is diverse and distinctive owing to the country's highly elevated intercontinental location in the Central Asian Orogenic Belt (CAOB), the deep interior of the Eurasian continent occupying a transitional area between the Siberian taiga forest in the north and the Govi Desert in the south.

Landscapes and landforms of Mongolia reflect interactive imprints of the major Central Asian geotectonic setting consisting of the Siberian Craton in the north and the Tarim and Sino-Korean Cratons in the south. The landscapes and landforms also are under the influence of an extremely arid extra-continental climate developing under the interaction of three large-scale climatic systems (the Siberian high- and the Asian low-pressure cells and the westerlies) (Hilbig, 1995; Gong & Ho, 2002; Panagiotopoulos et al., 2005), which are modulated by the North Atlantic Oscillations (NAO) (Visbeck, 2002). The extreme continental climate of Mongolia is reflected in the annual air temperature amplitude of approximately 45 °C and the low annual precipitation with dominant supplies from June to August (Academy of Sciences of Mongolia and Academy of Sciences of USSR, 1990), decreasing from more than 400 mm/year in the north to less than 50 mm/year in the south affecting the latitudinal trends in distributions of soil and vegetation covers from the north to the south. This considerable variation in the climatic condition makes Mongolia sensitive to climate change (Sugita et al., 2007). Data on paleoclimate change help us to understand the responses of various sensitive landscapes, especially lake basins in

[2] *Baigali* meaning *nature* has been misspelled as *Baikal* based on the Russian pronunciation. Baigali is the right English transliteration from Mongolian *Байгаль*.

[3] *Khangai* has been misspelled as *Khangay* (or *Hangay*) and *Hangai* in many publications. Khangai is the right English transliteration from Mongolian *Хангай*.

[4] *Khentii* has been misspelled as *Khentey* (or *Hentey*) and *Khentei* (or *Hentei*) in many publications. Khentii is the right English transliteration from Mongolian *Хэнтий*.

[5] *Khuvsgul* has been misspelled as *Hovsgol* and *Khubsugul* in publications. Khuvsgul is the right English transliteration from Mongolian *Хөвсгөл*.

[6] *Selenge* has been often incorrectly written as *Selenga* internationally by the Russian pronunciation. Selenge is the correct English transliteration from Mongolian *Сэлэнгэ*.

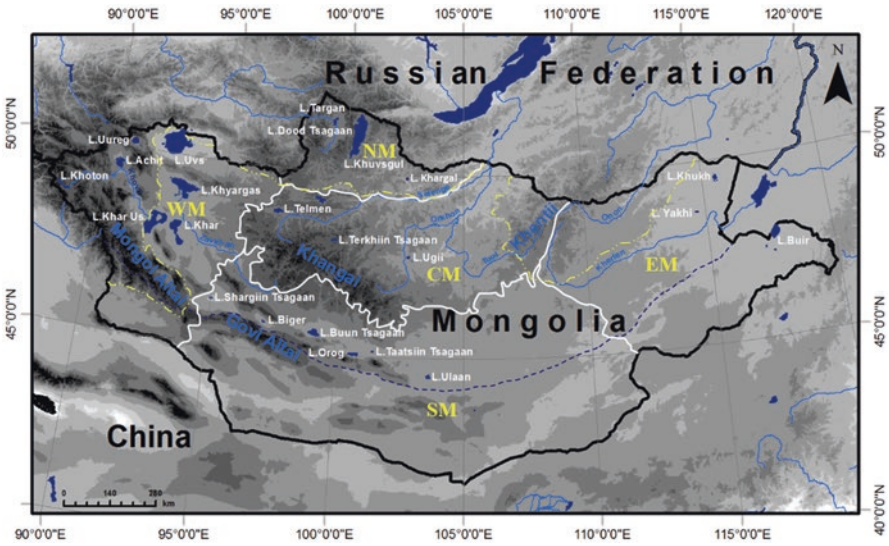

Fig. 1.1 Major lakes representing each region of Mongolia (*EM* eastern Mongolia (Chap. 6); *SM* southern Mongolia (Chap. 9); *WM* western Mongolia (Chap. 12); *NM* northern Mongolia (Chap. 15); and *CM* central Mongolia (Chap. 18), including the ten lakes described in Part II) with the Main Mongolian Lineament (blue dotted line) and a delineation of the Siberian and Central Asian geomorphological regions (yellow dotted line)

Mongolia (Davaagatan et al., 2015), to present and future climate changes (Orkhonselenge et al., 2019a). In addition, the geological structure of Mongolia is considerably manifested in the lake feature and evolution regarding their origin, diversity, and distribution.

The territory of Mongolia is divided by an approximate regional topographic and structural boundary, the Main Mongolian Lineament (Fig. 1.1), into the northern domain consisting of the Precambrian and early Paleozoic rocks and the southern domain of the early to late Paleozoic rocks (Badarch et al., 2002). In the northern domain, the Precambrian and early Paleozoic metamorphic rocks occur with the Neoproterozoic ophiolites, early Paleozoic island arc volcanic and volcaniclastic sediments, the Devonian to Carboniferous sediments, and the Permian volcanic-plutonic belts with marine and nonmarine sediments (Badarch et al., 2002). These geological elements of the basement are overlain by the postglacial landscapes in the Mongolian Altai Mountain Range, periglacial phenomena in the Khangai, Khuvsgul and Khentii Mountain Ranges, vast intermontane valleys and depressions between these ranges, large lakes in the Depression of Great Lakes and the Valley of Lakes, and the dominant river network of the Pacific Ocean and North Arctic Ocean drainage basins. In the southern domain, there is a complex of predominant early to late Paleozoic arc-related volcanic and volcaniclastic rocks with ophiolites and serpentinite mélanges and subdominant Silurian and Devonian fossil-rich reef limestones associated with terrigenous and volcaniclastic rocks in the north and of the