

Syntheses in Limnogeology

Alexander Orkhonselenge
Munkhjargal Juganzaya
Tuyagerel Davaagatan

Lakes of Mongolia

Geomorphology, Geochemistry and
Paleoclimatology

 Springer

Syntheses in Limnogeology

Series Editors

Michael R. Rosen
United States Geological Survey
Carson City, NV, USA

Antje Schwalb
Institute of Geosystem and Bioindication
Technische Universität Braunschweig
Braunschweig, Germany

Blas L. Valero-Garcés
Instituto Pirenaico de Ecología
Consejo Superior de Investigaciones Científicas (CSIC)
Zaragoza, Spain

The aim of this book series is to focus on syntheses or summaries of modern and/or ancient lake systems worldwide. Individual books will present as much information as is available for a particular lake basin or system of basins to offer readers one distinct reference as a guide to conduct further work in these areas. The books will synthesize the tectonics, basin evolution, paleohydrology, and paleoclimate of these basins and provide unbiased new interpretations or provide information on both sides of controversial issues. In addition, some books in the series will synthesize special topics in limnogeology, such as historical records of pollution in lake sediments and global paleoclimate signatures from lake sediment records.

More information about this series at <https://link.springer.com/bookseries/10029>

Alexander Orkhonselenge
Munkhjargal Uuganzaya • Tuyagerel Davaagatan

Lakes of Mongolia

Geomorphology, Geochemistry
and Paleoclimatology

 Springer

Alexander Orkhonselenge
Laboratory of Geochemistry
and Geomorphology
School of Arts and Sciences
National University of Mongolia
Ulaanbaatar, Mongolia

Munkhjargal Uuganzaya
Laboratory of Geochemistry
and Geomorphology
School of Arts and Sciences
National University of Mongolia
Ulaanbaatar, Mongolia

Tuyagerel Davaagatan
Laboratory of Geochemistry and
Geomorphology
School of Arts and Sciences
National University of Mongolia
Ulaanbaatar, Mongolia

Division of Physical Geography
Institute of Geography and Geoecology
Mongolian Academy of Sciences
Ulaanbaatar, Mongolia

ISSN 2211-2731

ISSN 2211-274X (electronic)

Syntheses in Limnogeology

ISBN 978-3-030-99119-7

ISBN 978-3-030-99120-3 (eBook)

<https://doi.org/10.1007/978-3-030-99120-3>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2022

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*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 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.

Ulaanbaatar, Mongolia

Alexander Orkhonselenge
Munkhjargal Uuganzaya
Tuyagerel Davaagatan

References

- Fowell, S. J., Hansen, B. C., Peck, J. A., Khosbayar, P., & Ganbold, E. (2003). Mid to late Holocene climate evolution of the Lake Telmen basin, north central Mongolia, based on palynological data. *Quaternary Research*, 59(3), 353–363.
- Grunert, J., Lehmkuhl, F., & Walther, M. (2000). Paleoclimatic evolution of the Uvs Nuur basin and adjacent areas (Western Mongolia). *Quaternary International*, 65–66, 171–192.
- Kashiwaya, K., Ochiai, S., Sumino, G., Tsukamoto, T., Szyntyszewska, A., Yamamoto, M., Sakaguchi, A., Hasebe, N., Sakai, H., Watanabe, T., & Kawai, T. (2010). Climato-hydrological fluctuations printed in long lacustrine records in Lake Hövsgöl. *Mongolia Quaternary International*, 219(1–2), 178–187.
- Kang, S., Lee, G., Togtock, C., & Jang, K. (2015). Characterizing regional precipitation-driven lake area change in Mongolia. *Journal of Arid Land*, 7(2), 146–158.
- Komatsu, G., Brantingham, P. J., Olsen, J. W., & Baker, V. R. (2001). Paleoshoreline geomorphology of Boon Tsagaan Nuur, Tsagaan Nuur and Orog Nuur: The Valley of Lakes, Mongolia. *Geomorphology*, 39, 83–98.
- Krivonogov, S. K., Sheinkman, V. S., & Mistryukov, A. A. (2005). Stages in the development of the Darhad dammed lake (Northern Mongolia) during the Late Pleistocene and Holocene. *Quaternary International*, 136(1), 83–94.
- Lehmkuhl, F., Grunert, J., Hülle, D., Batkhishig, O., & Stauch, G. (2018). Paleolakes in the Gobi region of southern Mongolia. *Quaternary Science Reviews*, 179, 1–23.
- Mischke, S., Lee, M. K., & Lee, Y. I. (2020). Climate history of Southern Mongolia Since 17 ka: The Ostracod, Gastropod and Charophyte Record from Lake Ulaan. *Frontiers in Earth Science*, 8(221), 1–15.
- Orkhonselenge, A., Krivonogov, S. K., Mino, K., Kashiwaya, K., Safonova, I. Y., Yamamoto, M., Kashima, K., Nakamura, T., & Kim, J. Y. (2013). Holocene sedimentary records from Lake Borsog, eastern shore of Lake Khuvsgul, Mongolia, and their paleoenvironmental implications. *Quaternary International*, 290–291, 95–109.
- Peck, J. A., Khosbayar, P., Fowell, S. J., Pearce, R. B., Ariunbileg, S., Hansen, B. C. S., & Soninkhishig, N. (2002). Mid to Late Holocene climate change in north central Mongolia as recorded in the sediments of Lake Telmen. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 183, 135–153.
- Prokopenko, A. A., Khursevich, G. K., Bezrukova, E. V., Kuzmin, M. I., Boes, X., Williams, D. F., Fedenya, S. A., Kulagina, N. V., Letunova, P. P., & Abzaeva, A. A. (2007). Paleoenvironmental proxy records from Lake Hovsgol, Mongolia, and a synthesis of Holocene climate change in the Lake Baikal watershed. *Quaternary Research*, 68, 2–17.
- Tserensodnom, J. (1971). *Lakes of Mongolia*. State Publishing, Ulaanbaatar, 202 p. [In Mongolian].
- Tserensodnom, J. (2000). *A catalog of lakes in Mongolia*. Shuvuun Saaral Publishing, 141 p. [In Mongolian].
- Wang, W., Ma, Y., Feng, F., Narantsetseg, T., Liu, K., & Zhai, X. (2011). A prolonged dry mid-Holocene climate revealed by pollen and diatom records from Lake Uggii Nuur in central Mongolia. *Quaternary International*, 229, 74–83.
- Yu, K., Lehmkuhl, F., Schlütz, F., Diekmann, B., Mischke, S., Grunert, J., Murad, W., Nottebaum, V., Stauch, G., & Zeeden, C. (2019). Late quaternary environments in the Gobi Desert of Mongolia: Vegetation, hydrological, and palaeoclimate evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 514, 77–91.

Acknowledgments

This book *Lakes of Mongolia: Geomorphology, Geochemistry, and Paleoclimatology* is primarily based on the results, concerns, prospects, and insights gained from our own and others' research and also on discussions with our colleagues and graduate students at the Laboratory of Geochemistry and Geomorphology (LGG), National University of Mongolia (NUM). We thank all of them.

We would like to express many thanks to executive editor P.V. Steenbergen for receiving our wishes to publish this book and for making his kind acceptance. We are also very grateful to book editorial director, G.Z. Landolfo and vice president, D. Merkle for having agreement and permission to publish the book *Lakes of Mongolia: Geomorphology, Geochemistry, and Paleoclimatology*, the book project advisor Dr. A. Schiller and coordinators Mr. D.M. Manoharan, Henry Rodgers and P. N. Kala for their continuous technical support, and anonymous reviewers for improvement of the book and precious contribution to the enhancement of the quality of the book. Finally, we would also like to acknowledge the precious suggestions and constant availability of Springer senior publisher and the assistance by the Springer book project coordinators who took care of this book with remarkable dedication and patience, in particular the volume production and quality. It was a real pleasure to work on such an exceptional book describing Mongolian lakes, associated landforms, and paleoclimate change reconstruction of Mongolia.

A. Orkhonselenge expresses her sincere gratitude, in particular, to loving mother B. Lkhagvasuren (1954–2017) and families. She acknowledges the important influence of her supervisors, co-workers, and co-authors Prof. Ch. Gonchigsumlaa (1963–2008), Dr. G. Undral, Prof. K. Kashiwaya, Prof. J. Harbor, Prof. M. Wagreich, Prof. F. Lehmkuhl, Prof. G. Nanson, Prof. F. Zucca, Prof. S. Fowell, and Dr. S. Ariunbileg. She thanks her students N. Amgalan-Erdene, T. Davaagatan, M. Uuganzaya, Ts. Davaakhuu, N. Altansukh, B. Myadagbadam, N. Khishigsuren, D. Gerelsaikhan, O. Bulgan, D. Batzorig, P. Bolor-Erdene, G. Tserendorj, Ts. Bulgantamir, and G. Narmandakh at the LGG, NUM for their enormous assistance in fieldworks, analyses, and maps. She also thanks Dr. G. Komatsu for reading the book manuscript and contributing to its advancement.

M. Uganzaya expresses her gratitude to all colleagues at the LGG, NUM, especially to her supervisor A. Orkhonselenge, who taught and introduced glacial geomorphology during her graduate school and gave advice during compiling maps for her contribution to this book. She also thanks her families.

T. Davaagatan acknowledges the influence of her supervisor and families. She thanks all colleagues at the LGG, NUM, and Division of Physical Geography, Institute of Geography and Geoecology, Mongolian Academy of Sciences. She expresses her gratitude to her supervisor A. Orkhonselenge, who led her with analytic methods in lacustrine geomorphology and paleoclimatology and gave advice on research publication and opportunity to deliver her contribution to this book.

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, Khuvs gul¹, 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 *Khuvs gul* has been misspelled as *Hovsgol* and *Khubsugul* in publications. *Khuvs gul* is the right English transliteration from Mongolian *Хөвсгөл*.

Contents

1	Introduction	1
1.1	Overview of Mongolian Physiography	1
1.2	Overview of Mongolian Lakes.....	5
1.3	Scope and Structure of the Book	8
1.4	Importance of the Book	12
	References.....	13
 Part I Lake Studies and Types of Lakes in Mongolia		
2	Lake Studies in Mongolia: An Overview	17
2.1	Introduction	18
2.2	Lake Studies in the Nineteenth Century	20
2.3	Lake Studies in the Twentieth Century	21
2.3.1	1900–1950	21
2.3.2	1950–2000	23
2.4	Lake Studies in the Twenty-First Century	25
2.4.1	Changes in Lake Level	25
2.4.2	Changes in Lake Area	26
2.4.3	Geomorphological Processes in Lake Basins	27
2.4.4	Geochemistry of Lake Water and Sediments.....	28
2.4.5	Lake Studies on Paleoclimate and Paleoenvironmental Changes	30
2.5	Summary	33
	References.....	33
3	Formation and Evolution of Lakes in Mongolia	39
3.1	Introduction	39
3.2	Formation of Lakes	45
3.3	Evolution of Lakes.....	47
3.3.1	Tectonics-Induced Evolution	48
3.3.2	Climate-Induced Evolution	48

3.4 Summary 49

References..... 50

4 Genesis of Lakes in Mongolia 51

4.1 Introduction 51

4.2 Genesis of Lakes 54

 4.2.1 Tectonic Lakes 54

 4.2.2 Volcanic Lakes 55

 4.2.3 Landslide Lakes 56

 4.2.4 Glacial Lakes 56

 4.2.5 Karst (and Thermokarst) Lakes 57

 4.2.6 Fluvial Lakes 59

 4.2.7 Aeolian Lakes 59

4.3 Summary 60

References..... 60

5 Classification of Lakes in Mongolia 63

5.1 Introduction 63

5.2 Altitude 65

 5.2.1 High-Altitude Lakes..... 65

 5.2.2 Low-Altitude Lakes 67

5.3 Area 67

 5.3.1 Large-Sized Lakes 68

 5.3.2 Small-Sized Lakes 68

5.4 Stability 70

 5.4.1 Perennial Lakes 70

 5.4.2 Ephemeral Lakes 70

5.5 Depth 71

 5.5.1 Deep Lakes..... 72

 5.5.2 Shallow Lakes 72

5.6 Salinity 72

 5.6.1 Freshwater Lakes 73

 5.6.2 Saline Lake..... 73

5.7 Presence of Outlet 74

 5.7.1 Open Lakes 74

 5.7.2 Closed Lakes 74

5.8 Summary 75

References..... 75

**Part II Landscape Evolution of Large Lakes in Mongolia
and Their Paleoclimate Records**

**6 Landscape, Lake Distribution, and Evolution in Eastern
Mongolia 79**

Introduction..... 80

Landscape 84

 Geology..... 84

Climate	84
Landform	86
Glaciers and Permafrost	88
Groundwater	89
Surface Water	91
Lakes	93
Lake Evolution	96
Lake Yakhi	96
Lake Ganga	97
Lake Toson	98
Lake Burd	98
Summary	100
References	100
7 Lake Buir	103
7.1 Introduction	103
7.2 Physiographic Condition	105
7.3 Geological and Geomorphological Settings	106
7.4 Climate Condition	107
7.5 Hydrological Condition	109
7.6 Changes in Area	111
7.7 Summary	113
References	113
8 Lake Khukh	115
8.1 Introduction	115
8.2 Physiographic Condition	116
8.3 Geological and Geomorphological Settings	119
8.4 Climate Condition	119
8.5 Hydrological Condition	121
8.6 Changes in Area	122
8.7 Summary	125
References	125
9 Landscape, Lake Distribution, and Evolution in Southern Mongolia	127
9.1 Introduction	127
9.2 Landscape	130
9.2.1 Geology	130
9.2.2 Climate	131
9.2.3 Landform	132
9.2.4 Glaciers and Permafrost	134
9.2.5 Groundwater	135
9.2.6 Surface Water	137
9.3 Govi Lakes	138
9.3.1 Paleolakes	139
9.3.2 Modern Lakes	139

- 9.4 Lake Evolution 141
 - 9.4.1 Lake Taatsiin Tsagaan 144
 - 9.4.2 Lake Orog 144
 - 9.4.3 Lake Biger 146
 - 9.4.4 Lake Shargiin Tsagaan 146
- 9.5 Summary 147
- References 147
- 10 Lake Buun Tsagaan 151**
 - 10.1 Introduction 151
 - 10.2 Physiographic Condition 153
 - 10.3 Geological and Geomorphological Settings 154
 - 10.4 Climate Condition 154
 - 10.5 Hydrological Condition 155
 - 10.6 Changes in Area 158
 - 10.7 Summary 160
 - References 160
- 11 Lake Ulaan 163**
 - 11.1 Introduction 164
 - 11.2 Physiographic Condition 165
 - 11.3 Geological and Geomorphological Settings 166
 - 11.4 Climate Condition 167
 - 11.5 Hydrological Condition 169
 - 11.6 Changes in Area 170
 - 11.7 Geochemical Review 173
 - 11.8 Summary 176
 - References 176
- 12 Landscape, Lake Distribution, and Evolution in Western Mongolia 179**
 - 12.1 Introduction 179
 - 12.2 Landscape 182
 - 12.2.1 Geology 182
 - 12.2.2 Climate 183
 - 12.2.3 Landform 183
 - 12.2.4 Glaciers and Permafrost 184
 - 12.2.5 Groundwater 187
 - 12.2.6 Surface Water 188
 - 12.3 Lakes 189
 - 12.3.1 Lakes in the Mongolian Altai Mountain Range 191
 - 12.3.2 Lakes in the Depression of Great Lakes 192
 - 12.4 Lake Evolution 193
 - 12.4.1 Lake Khyargas 194
 - 12.4.2 Lake Khar Us 195
 - 12.4.3 Lake Khar 196

12.4.4	Lake Achit	196
12.4.5	Lake Uureg	197
12.5	Summary	198
	References	198
13	Lake Uvs	203
13.1	Introduction	203
13.2	Physiographic Condition	204
13.3	Geological and Geomorphological Settings	206
13.4	Climate Condition	206
13.5	Hydrological Condition	208
13.6	Changes in Area	211
13.7	Summary	213
	References	213
14	Lake Khoton	215
14.1	Introduction	215
14.2	Physiographic Condition	217
14.3	Geological and Geomorphological Settings	217
14.4	Climate Condition	221
14.5	Hydrological Condition	222
14.6	Changes in Area	222
14.7	Summary	226
	References	226
15	Landscape, Lake Distribution, and Evolution in Northern Mongolia	229
15.1	Introduction	229
15.2	Landscape	235
15.2.1	Geology	235
15.2.2	Climate	236
15.2.3	Landform	238
15.2.4	Glaciers and Permafrost	240
15.2.5	Groundwater	243
15.2.6	Surface Water	243
15.3	Lakes	245
15.4	Lake Evolution	248
15.4.1	Lake Dood	250
15.4.2	Lake Dood Tsagaan	250
15.4.3	Lake Targan	251
15.5	Summary	252
	References	252
16	Lake Khuvsgul	257
16.1	Introduction	257
16.2	Physiographic Condition	260
16.3	Geological and Geomorphological Settings	261

16.4	Climate Condition	263
16.5	Hydrological Condition	264
16.6	Changes in Area	268
16.7	Summary	269
	References	271
17	Lake Khargal	275
17.1	Introduction	276
17.2	Physiographic Condition	277
17.3	Geological and Geomorphological Settings	278
17.4	Climate Condition	279
17.5	Hydrological Condition	281
17.6	Changes in Area	282
17.7	Geochemical Review	285
17.8	Summary	288
	References	288
18	Landscape, Lake Distribution, and Evolution in Central Mongolia	291
18.1	Introduction	291
18.2	Landscape	295
18.2.1	Geology	295
18.2.2	Climate	295
18.2.3	Landform	296
18.2.4	Glaciers and Permafrost	297
18.2.5	Groundwater	300
18.2.6	Surface Water	301
18.3	Lakes	302
18.4	Lake Evolution	305
18.4.1	Lake Lun	306
18.4.2	Lake Tsaidam	306
18.4.3	Lake Khar	306
18.4.4	Lake Shariin Tsagaan	307
18.4.5	Lake Telmen	307
18.5	Summary	309
	References	310
19	Lake Terkhiin Tsagaan	313
19.1	Introduction	314
19.2	Physiographic Condition	315
19.3	Geological and Geomorphological Settings	317
19.4	Climate Condition	318
19.5	Hydrological Condition	319
19.6	Changes in Area	319
19.7	Sedimentological Review	321
19.8	Summary	325
	References	326

20	Lake Ugi	329
20.1	Introduction	330
20.2	Physiographic Condition	331
20.3	Geological and Geomorphological Settings	332
20.4	Climate Condition	334
20.5	Hydrological Condition	335
20.6	Changes in Area	337
20.7	Sedimentological Review	340
20.8	Summary	342
	References	343
21	Paleoclimatic Patterns Recorded in the Lakes of Mongolia	345
21.1	Introduction	346
21.2	Local Spatial Pattern of Paleoclimate	363
21.2.1	Eastern Mongolia	363
21.2.2	Southern Mongolia	364
21.2.3	Western Mongolia	365
21.2.4	Northern Mongolia	366
21.2.5	Central Mongolia	367
21.3	Local Temporal Pattern of Paleoclimate	368
21.3.1	Late Pleistocene	368
21.3.2	Early Holocene	371
21.3.3	Middle Holocene	373
21.3.4	Late Holocene	374
21.4	Regional Pattern of Paleoclimate	377
21.4.1	Southern Russia	377
21.4.2	Northern China	379
21.5	Summary	381
	References	382
 Part III Scientific, Economic and Touristic Significances of Lakes in Mongolia		
22	Future Directions of Lake Study in Mongolia	393
22.1	Introduction	393
22.2	Scientific Significance of Lake Study	395
22.3	Environment of Lake Study	401
22.4	Challenges Facing Lake Study	402
22.5	Summary	403
	References	404
23	Economic Values of Lake Study in Mongolia	407
23.1	Introduction	407
23.2	Economic Significance of Lake Study	409
23.3	Study of Brines in Lakes	413
23.4	Study of Minerals in Lakes	416
23.5	Summary	418
	References	419

- 24 Touristic Prospects of Lakes in Mongolia** 423
 - 24.1 Introduction 423
 - 24.2 Impact of Lake Study on Tourism 426
 - 24.3 Present Status of Tourism in Mongolia 431
 - 24.4 Lake Tourism in Mongolia..... 434
 - 24.4.1 Eastern Mongolia..... 434
 - 24.4.2 Southern Mongolia..... 436
 - 24.4.3 Western Mongolia 437
 - 24.4.4 Northern Mongolia..... 438
 - 24.4.5 Central Mongolia..... 439
 - 24.5 Summary 440
 - References..... 440

- Index**..... 443

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 Govi¹ region, southern Mongolia. Over the last two decades, she worked in the Mongolian-Russian-Japanese-Korean joint research projects in Lake Khuvsgul² (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*

School of Arts and Sciences, National University of Mongolia, Ulaanbaatar, Mongolia

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 Geocology 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
Division of Physical Geography, Institute of Geography and Geocology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia

Abbreviations

AD	Anno Domini meaning a calendar year, the start of the era
Al	Aluminum
Al ₂ O 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
δ ¹³ C	Ratio of stable isotopes carbon-13 (¹³ C) : carbon-12 (¹² C)
CHs	Carbohydrates
°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 ₂ O 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 ₂ S	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 ₂ O	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 ₂ O	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
δ 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 ₂ O 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
<i>vs.</i>	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 Gobi 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 Gobi 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 Gobi (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*.

Lakes of Mongolia, situating in the eastern part of a great lake zone extending from the Mediterranean Sea to the Lake Baikal² (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 Khentii⁴ 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 Selenge⁶ 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*.

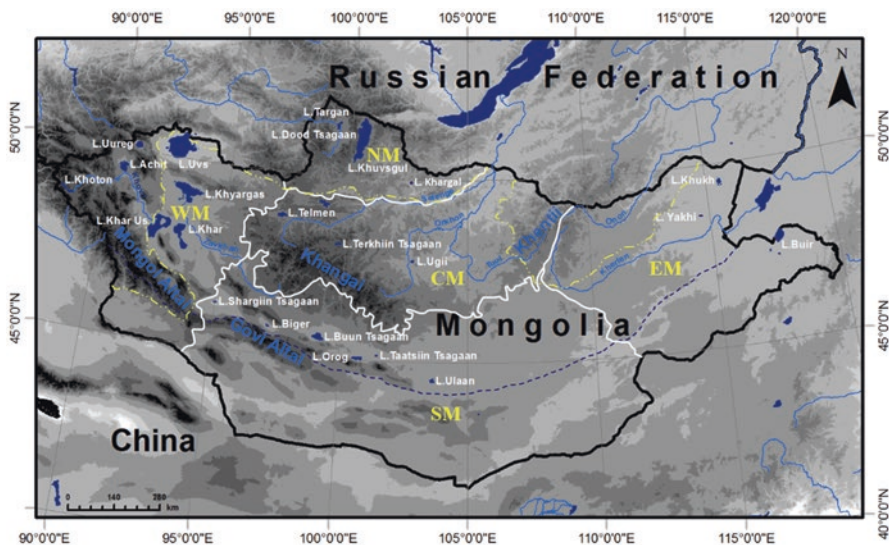


Fig. 1.1 Major lakes representing each region of Mongolia (*EM* eastern Mongolia (Chap. 6); *SM* southern Mongolia (Chap. 9); *WM* western Mongolia (Chap. 12); *NM* northern Mongolia (Chap. 15); and *CM* central Mongolia (Chap. 18), including the ten lakes described in Part II) with the Main Mongolian 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 volcanoclastic 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 volcanoclastic rocks with ophiolites and serpentinite mélanges and subdominant Silurian and Devonian fossil-rich reef limestones associated with terrigenous and volcanoclastic rocks in the north and of the