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Original Article

Geomorphological study of the origin of Mongolian Altai Mountains Lake depressions: implications for the relationships between tectonic and glacial processes

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ABSTRACT

The lake depressions in the Mongolian Altai Mountains, and the issues related to their formation have yet to be thoroughly examined in previous research. Previous studies primarily focused on the paleogeographical evolution and glaciation dynamics of the Altai Mountains. This study presents relationships between tectonic and glacial processes that have formed the lake depressions, such as Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern) in the Mongolian Altai Mountains. The depressions of Khoton, Khurgan, and Dayan lakes are situated along regional fault zones, extending in an nortwest -southeast direction, forming intermontane depressions directly connected to the Mongolian Altai Mountains. However, the depressions of Dayan, Khar (western), and Khar (eastern) lakes have been dammed by moraine deposits in the near portion of the depression. The compliance matrix of tectonic geomorphological criteria indicates that the Khoton, Khurgan, Dayan Lake, and Khar (western) Lake depressions are more than 50% compatible. Similarly, the compliance matrix for glacial geomorphological criteria indicates more than 60% compliance for all lake depressions. The Mongolian Altai intermontane depressions are thus of tectonic origin, whereas the lakes have a glacial origin, resulting from dammed moraine sediments. The significance of this work lies in demonstrating how geomorphological research can be employed to provide a detailed understanding of the pattern of lake depressions.

Keywords: Western Mongolia, glacial lakes, morphometric analysis, geomorphological criteria

INTRODUCTION

The origin of the lake depression is due to the combined influence of endogenous and exogenous factors of the Earth (Mats, 1993; Tserensodnom, 2000). Comprehensive research across various landscapes is crucial for developing a new classification of lake depressions. A lake depression is a negative form of water-accumulated relief with a size of 0.1 km² or more in the interior of a continent that developed as a result of internal and external earth processes (Hutchinson, 1957; Wetzel, 2001; Cohen, 2003; Enkhbold et al., 2022a,b,c). This effort aims to rectify shortcomings in previous classifications and establish a seamless transition between classifications regarding the origin of lake depressions. The study of the origin of lake depressions contributes to scientific values for researchers of scientific and practical significance (Hutchinson, 1957; Dearing and Foster, 1993; Wetzel, 2001; Cohen, 2003; Hakanson, 2012). Improvements in classifying lake depressions of terrestrial origin are imperative, considering factors such as geology, tectonics, geomorphology, and climate effects. To comprehend the evolution of a lake depression, a thorough analysis of basin morphology and area is necessary. This includes investigating regional rocks, their structural patterns, subsidence, and uplift processes, as well as the influences of climate on the system. Understanding the relationship between faults, glacial activity, and depressions is crucial for unraveling the origin of lakes.

The land surface of Mongolia consists of various forms such as the high, medium, and low mountains, valleys and ridges, vast steppes as well as the taiga, forest steppes, and desert mixed with the mountains and forests, with an average altitude of 1580 m.a.s.l which is also the features of its location (Tsegmid, 1969; Tserensodnom, 1971; Klinge, 2001). More than 80% of the land exists at an altitude of 1000 m.a.s.l, the western parts are located at an average altitude of 2500-3500 m.a.s.l with mountains Mongol Altai and Gobi Altai, and

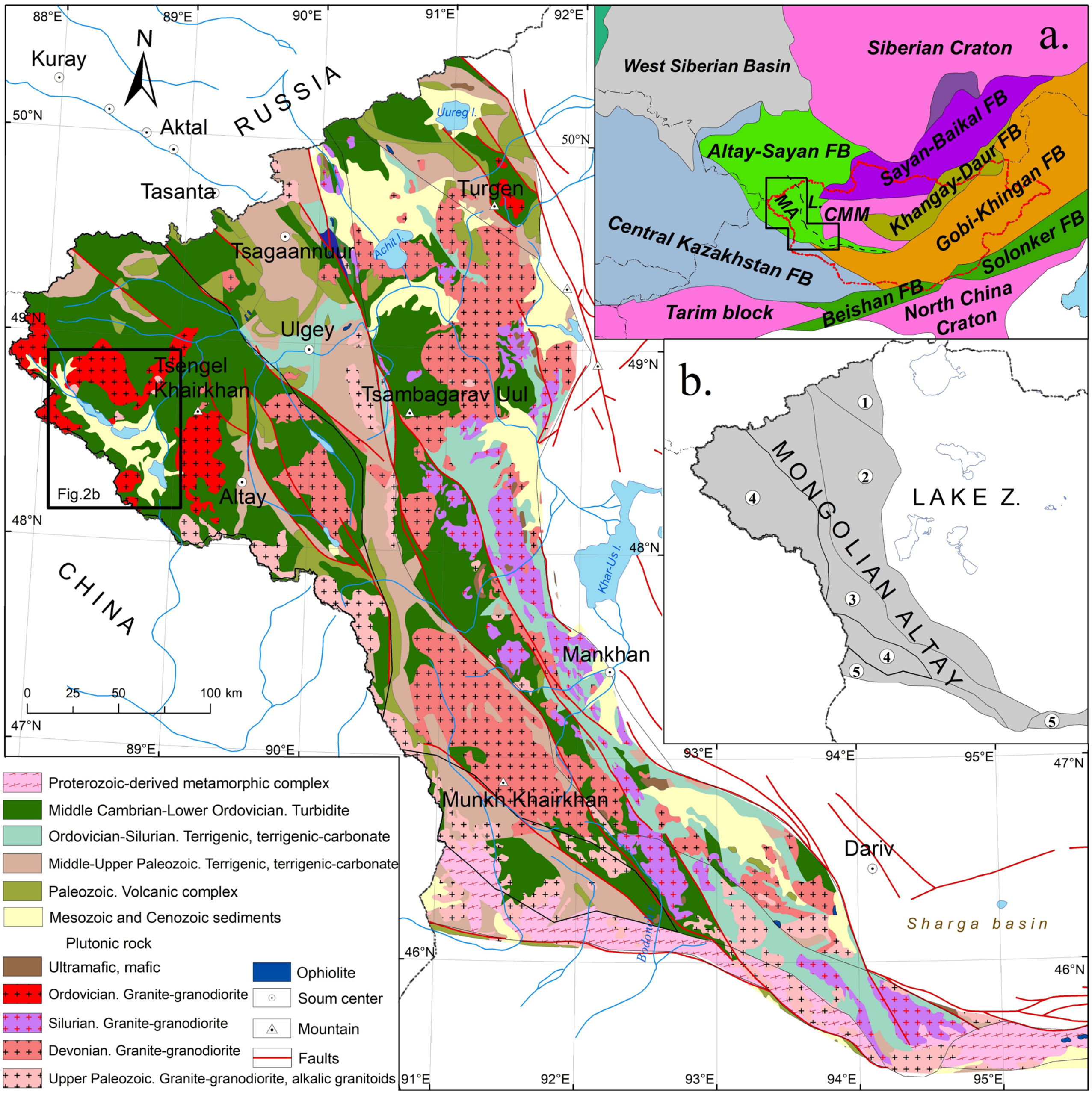

Fig. 1. Geological map of the Mongolian Altai (adapted from Khukhuudei et al., 2020). Inset a) shows the Mongolian Altai region in the Central Asian Orogenic Belt. The main zones of the Mongolian Altai are depicted in Inset b) 1- Tsagaanshuvuut, 2- Khovd, 3- Ulgii, 4- Altai, and 5- Bodonch-Tseel.

the northwestern parts are located at the average altitude of 2000-2500 m.a.s.l with the mountains of Khangai, Khentii, and Khuvsgul as well as the altitude of 600-1500 m.a.s.l in the steppes of Eastern Mongolia's steppes, low mountains, and desert (Lehmkuhl et al., 2011; Doljin and Yembuu, 2021). The Mongolian Altai Mountain range is approximately 2500-3500 m.a.s.l, and about 70% of the total surface area is occupied by high and medium-high mountains (Tsegmid, 1969; Doljin and Yembuu, 2021). This characteristic of the continental land surface directly influences the location of lakes and the form of depressions.

The natural conditions and resources of the lake in Mongolia are closely related to the primary morphology of the lake depression (Enkhbold et al., 2022a). The study of the formation of lake depressions is of great scientific and practical importance (Enkhbold et al., 2021). Detailed identification of the origin of lake depressions will establish the fundamental conditions for understanding how to utilize and protect the lake ecosystem.

Tserensodnom (1971) divided the lakes of Mongolia into the main classes of internal and external factors based on their origin and distinguished them according to several depression types. The type of origin of the depressions of the lakes in Mongolia is divided into tectonic, volcanic, glacial, karst, landslide-dammed, and aeolian depressions, and lakes formed in depressions caused by changes in the direction of river valleys (Tserensodnom, 1971 and 2000). However, the classification of lake depressions was not performed in detail but at the level of general description. When combining the materials of previous researchers, it was explained that the origin of the depressions of the above lakes was established only in depressions of glacial origin (Tserensodnom, 1971; Tsegmid and Vorobiev, 1990; Tserensodnom, 2000).

Nevertheless, the fundamental morphology of these lake depressions might have been shaped by the combined influence of tectonics and glacial effects. The exploration of lakes in the Mongolian Altai Mountains commenced in the late 19th century. Russian researchers were the first to study the water depth, water regime, composition, water plants, and animals of water

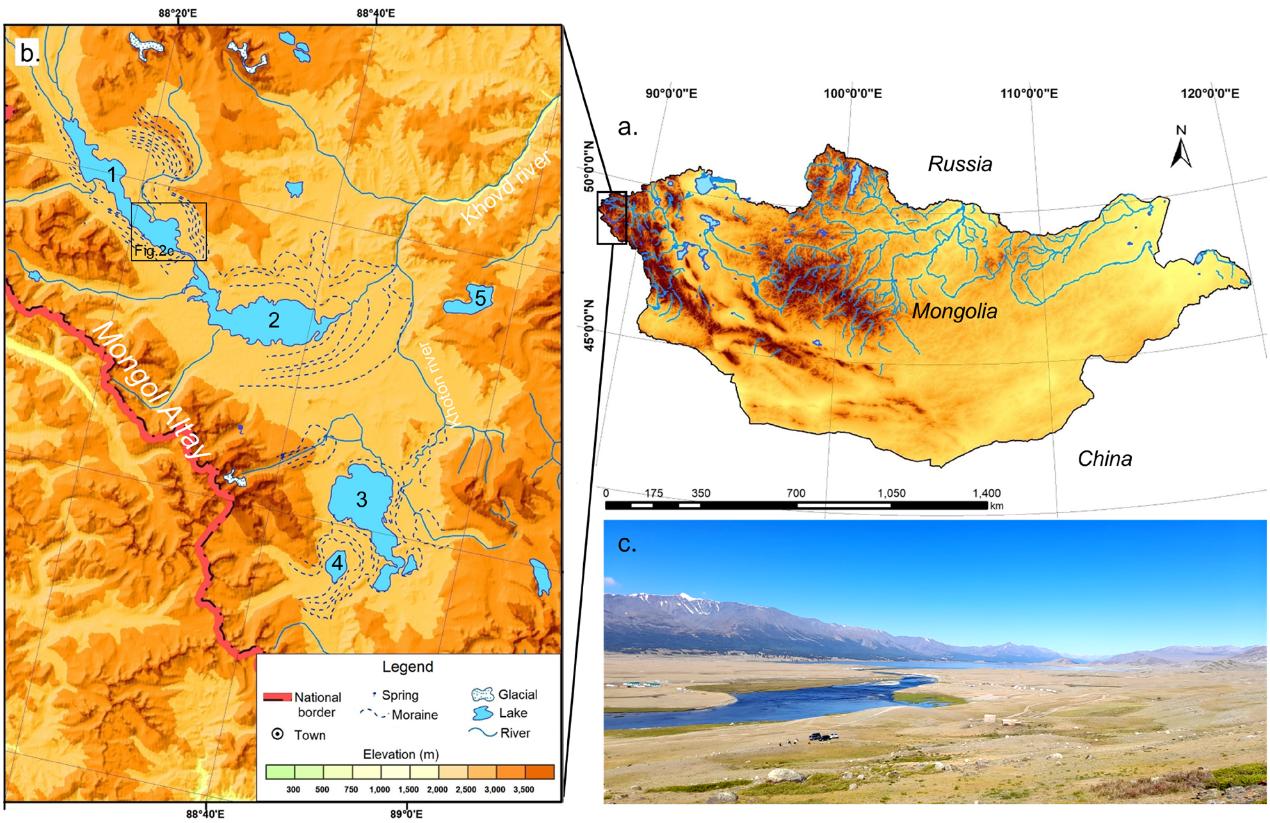

Fig. 2. Location of the study area. a) Inset map of Mongolia and the Altai Mountains, b) Location of lakes: 1. Khoton 2. Khurgan 3. Dayan 4. Khar (western) 5. Khar (eastern), c) Landscape view of the study area, photo by Altanbold Enkhbold, 2023.

in the Mongolian Altai lakes (Tserensodnom, 1971; Yembuu and Doljin, 2021). However, more needs to be studied about the origin of the depressions in the lakes.
Secondly, in the past 20 years, several research works have been conducted and published on the lakes situated in the depressions between the mountains of the Mongolian Altai Mountains. Specifically, they analyzed the paleogeographical evolution from the Pleistocene to the Holocene, the sediments accumulated in the lakes, and the remains of plant pollen and diatom contained therein (Tarasov et al., 2000; Rudaya et al., 2009, Rudaya and Li, 2013; Walther et al., 2017; Unkelbach et al., 2019; Bliedtner et al., 2021), establishing the paleogeographical conditions and transformations of the Mongolian Altai.
Thirdly, the relationship between glaciers and glacial sediments was investigated, revealing the impacts of glacial sediment patterns in the Mongolian Altai Mountains. The relationship between lake level fluctuations and climatic changes is extensively characterized, at least during the Last Glacial Maximum, based on OSL and 14C dating of sediments from several lake terraces (Lehmkuhl et al., 2016; Klinge and Sauer, 2019; Klinge et al., 2021; Walther et al., 2024). They found that Mongolia's climate became cooler and more humid at the beginning of the Holocene, and drier from the middle of the Holocene onwards. However, the results of the aforementioned studies needed to address the morphological origin of the lake depressions and the issues related to their formation.
In this study, we aimed to elucidate how tectonic and glacial factors influenced the pattern of the origin of depressions in lakes, such as Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern), in the Mongolian Altai Mountains.

STUDY AREA

Geologically, the Mongolian Altai is divided into four large stratigraphic complexes with an interval from the Late Neoproterozoic to Devonian have formed the geological basis of the Mongolian Altai (Dergunov et al., 1980; Tomurtogoo, 2014; Khukhuudei et al., 2020, 2022; Fig. 1).
The Altai Mountains began to grow at ~5 Ma (apatite fission-track analysis, De Grave et al., 2007; Jolivet et al., 2007) and became higher until the plateau summit reached more than 2000 m.. As a result of this neotectonic movement, block uplift and subsidence, bounded by major faults in the northwest-southeast direction, continue to occur intensively in the Mongolian Altai Mountains (Cunningham et al., 2003; Cunningham, 2005). This forms the fundamental condition for the formation of depressions between mountains. Between the branch mountains of the Mongolian Altai range, large depressions form a narrowing morphological pattern from northwest to southeast (Lehmkuhl et al., 2011).
A group of lakes situated in intermontane depressions in the Mongolian Altai was chosen as the study area, and an investigation into the updated classification of lake depressions was conducted. The Mongolian Altai, the largest mountain range in Mongolia, features five lakes that were selected for this study (Fig. 2).
The depressions of Khoton, Khurgan, Dayan, and Khar (western) Lakes in the Mongolian Altai Mountains are enclosed by high mountains on the west and southwest, moraine hills on the east, southeast, and south, and moderately high

Table 1. Morphometric volumes of lake depressions (Enkhbold et al., 2021)

Number in Fig. 2	Name of lake	Length, km	Width, km	Area, km^2	Height above sea level, m			Relief energy, m
					Low	Medium	High	
1	Khoton	31.26	22.02	364.20	2,028	2,363	2,837	809
2	Khurgan	31.84	26.63	458.75	2,043	2,194	2,852	809
3	Dayan	32.09	18.09	385.80	2,224	2,322	2,939	715
4	Khar (western)	5.52	3.77	14.8	2,326	2,662	2,999	673
5	Khar (eastern)	7.67	3.94	44.8	2,437	3,190	3,943	1506

Table 2. Morphometric parameters of lakes (Tserensodnom, 2000; Walther et al., 2017; Bliedtner et al., 2021)

№	Name of lake	Geographical location	Water level, above sea level., m	Area, km²	The longest, km	The widest, km	The deepest, m	The volume of water, km³
1	Khoton	48°39’ N, 88°16’ E	2,078	54.1	22	4	58	1.23
2	Khurgan	48°32’ N, 88°37’ E	2,071	67.8	23.3	6	28	0.44
3	Dayan	48°22’ N, 88°49’ E	2,226	67	18	9	4	0.16
4	Khar (western)	48°17’ N, 88°48’ E	2,344	7.8	4.4	2.8	18	0.04
5	Khar (eastern)	48°37’ N, 88°56’ E	2,486	13.9	7.1	3.9	49.4	0.24

mountains on the southeast. They exhibit an oval-shaped depression extending from northwest to southeast. In the case of Khar (eastern) Lake, it is enclosed by moraine sediments in the east and surrounded by moderately high mountains in other directions. The morphometric parameters of the studied lake depressions are presented in Table 1.

The morphometric parameters of the studied lakes are presented in Table 2.

MATERIALS AND METHODS

We have used those topographic (1:100 000 scale) and SRTM-30 m data maps, bathymetric maps of the lakes (data from Tserensodnom, 1971; Sevastyanov et al., 1994; Walther et al., 2017), Landsat OLI (30 m) satellite imagery, Google Earth Pro map (2.5 m) software were used. Field morphometric data was measured in August 2023.

Morphometric analysis: Faults are evident on the earth’s surface with distinct indications (Cunningham et al., 2003; Byamba, 2009; He et al., 2018; Enkhbold et al., 2022a,b,c). This feature is detected by morphometric analysis and the fault is visualized on a topographic map (Mark, 1975; Filosofov, 1967; Bold, 1987; Florinsky, 1996; Jacques et al., 2014; Hassen et al., 2014; Yang et al., 2015; He et al., 2018; Enkhbold et al., 2021; Enkhbold et al., 2022a,b,c).

The fault system is the main element representing the tectonic influence of the depressions of the lakes. If the distance between the relief contours indicates a close linear structure, it is a regularity that indicates faulting (Yang et al., 2015; Enkhbold et al., 2022b). In topographical maps, the distance between the contour lines is short, and the sharp slopes that form the linear structure are mainly formed along the faults (Bold, 1987; Florinsky, 1996; Jacques et al., 2014; Hassen et al., 2014; Enkhbold et al., 2021).

Faults can be detected using relief elements and abrupt changes and distortions in their shapes. Depending on the purpose of the research, they are systematically classified according to the direction and length of the faults, the sequence of formation, and the characteristics of the relief formation (Yang et al., 2015). As part of the research framework, we established criteria for identifying faults on the topographic map and analyzed the lake depression.

Geomorphological criteria analysis: This study elucidates and ranks the geomorphological elements that influence the formation of lake depressions. It becomes possible to define lake depressions by integrating multiple components, highlighting the primary and dominating factors. The researcher evaluates the characteristics of the morphological formations observed on the surface, utilizing specific criteria based on the factors influencing the origin of the lake depression (Enkhbold et al., 2022a,b).

The ten criteria were developed for various types of lake depressions. The typology of these depressions was established by analyzing both field and map materials using geomorphological

Table 3. Suitability matrix of geomorphological criteria

№	Compliance ratio	Conformity suitability	Percent, %
1	0>3	Not compliance	0-30
2	3>4	Less compliance	31-40
3	5>7	Compliance	51-70
4	7>9	Good compliance	71-90
5	9<10	Excellent compliance	91-100

criteria. The determination of the origin of lake depressions involves two main steps. Firstly, an analysis of geomorphological patterns, field measurements, and geological and geomorphological research documents is conducted. Secondly, the mapping method analysis identifies and confirms the factors influencing the formation of lake depressions. The typology of lake depressions is then assessed using a suitability matrix of geomorphological criteria (Table 3).

If more than five criteria are met in the lake depression, based on the suitability assessment, it is considered a major influencer. Through the evaluation of this matrix, it becomes possible to determine the relationship between various combined effects of endogenous and exogenous factors on the lake depression.

Geomorphological criteria are 1. Interpretation of endogenous surface forms 2. Interpretation of exogenous surface forms 3. Interpretation of quantitative morphometric dimensions. This study developed and used criteria for determining the morphology of tectonic and glacial lake depressions (Tables 5 and 6).

Spatial improvement method: Sobel filter analysis was done using digital data and satellite images of a certain part of the Earth's surface taken from satellites (Sobel 2014; Nixon and Aguado, 2019; Singh et al., 2023). A directional filter is an edge enhancer in satellite imagery and is applied by computing the first derivative of the image. For the detection of tectonic faults on the surface by Sobel filter analysis (Enkhbold et al., 2021; Enkhbold et al., 2022 a,b,c), the following equations are used to calculate the results of various satellite imagery. These include:

$$G_{jk}=/G_x/+/G_y/ \quad (1)$$

$$G_x=F_{j+1,k+1}+2F_{j+1,k}+F_{j+1,k-1}-(F_{j-1,k+1}+2F_{j-1,k}+F_{j-1,k-1}) \quad (2)$$

$$G_y=F_{j-1,k-1}+2F_{j,k-1}+F_{j+1,k-1}-(F_{j-1,k+1}+2F_{j,k+1}+F_{j+1,k+1}) \quad (3)$$

Here, *(j, k)* are the detailed values of F_{jk} for each pixel in the satellite image. G_{xy} stands for horizontal and vertical filters. It identifies faults or straight structures in satellite imagery by masking them using the following matrix values.

$$Y\ mask = \begin{matrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{matrix} \qquad X\ mask = \begin{matrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{matrix} \quad (4)$$

Sobel filter analysis, the radiometric value of each image pixel is changed to improve the spatial representation of the natural and artificial linear objects depicted in the image (Nixon and Aguado, 2019). Using satellite images from satellites, the faults of the lake depression were mapped using the Directional filter (X, Y axis) command of the Convolution and Morphology menu in ENVI 5.3 remote sensing software. Analysis based on spatial mapping material saves time and can fully meet the requirements of detailed clarification of research results.

Finally, the results calculated by topographical mapping analysis, geomorphological criteria analysis, and spatial improvement method of remote sensing research were mapped. The methods used in the research are those that can be used to interpret surface tectonic faults, glacial, and other forms of external force on the surface. Based on the morphometric and depressional morphology of this depression, geomorphological criteria were developed and analyzed in the study area.

RESULTS

Effect of Lake depression and Tectonics:

A morphometric analysis was employed to explore the impact of tectonics on the

Table 4. Morphometric analysis of the study area (modified after Filosofov, 1967; Bold, 1987; Florinsky, 1996; Jacques et al., 2014; Hassen et al., 2014; Yang et al., 2015; He et al., 2018; Enkhbold et al., 2021; Enkhbold et al., 2022a, b, c).

№	Criteria	Khoton	Khurgan	Dayan	Khar (western)	Khar (eastern)
		Definition (compliance+, non-compliance –)				
1	To be a close of contours spacing as linear in the topographic map.	+	+	+	+	+
2	To occur repeatedly abrupt change of high-altitude contours along linear view.	+	+	+	+	–
3	The sharp difference in height between the mountains and elevation numbers located around the lake depression in the topographical map	+	+	+	+	+
4	In the topographical map, whether the river channel flowing into the lake has been deformed due to sharp bends	+	+	+	+	–
5	Whether lake bathymetric isobaths form hierarchical linear structures	+	+	+	+	–
6	Creating distortions in isobaths in the lake bathymetry map, whether the distortions are repeated along the same line	–	–	+	–	–
7	Whether bathymetric isobaths of the lake form a linear structure parallel to the main contour line	+	–	–	–	–
8	Whether the surface area of the lake has a rectangular or straight shape in any part or a non-geometric shape	+	–	–	–	–
9	Create a rectangular or kind of linear shape on any part of the lakebed	+	+	+	–	–
10	Whether the lakes are located in a series along a straight line in the topographical map	+	+	+	+	–
	Compliance with topographic analysis	9	7	8	6	2

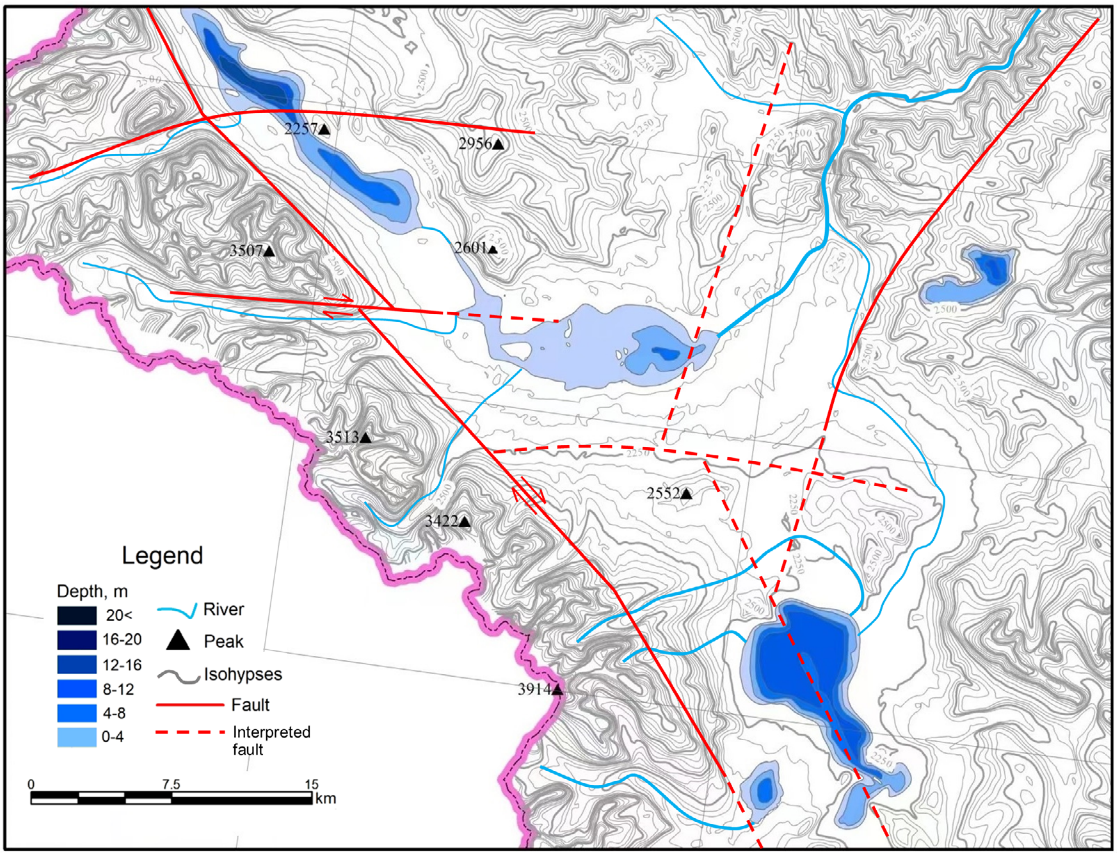

Fig. 3. Correlation between faults and lake depressions

Table 5. Geomorphological criteria for determining tectonic effect (compliance+, non-compliance –)

№	Indicators	Khoton	Khurgan	Dayan	Khar (western)	Khar (eastern)
1	Whether or not tectonic faults formed around the lake depression	+	+	+	+	–
2	Whether the depression is 2-4 times larger than the area of the lake	+	+	+	+	–
3	Whether the lake depression is located at an elevation (500 m or more above sea level)	+	+	+	+	+
4	The relative height difference between the lake depression and the surrounding mountains is 600 m or more than	+	+	+	+	+
5	Whether there are source rocks of volcanic origin around the lake depression	–	–	–	–	–
6	An island was formed in a row in the lake	–	–	–	–	–
7	Whether the lake has a steep bank and whether the bottom morphology of the lake depression has an uneven surface	+	+	–	–	–
8	Whether the area around the lake is hollow, oval, or has an uneven geometrical shape	+	+	+	–	–
9	Abrupt changes in lake depression and bathymetry have been observed	+	+	+	–	–
10	Whether the lake water is fresh, deep, and has a large volume of water	+	+	–	+	+
	Compliance with tectonic geomorphological analysis	8	8	6	5	3

formation of lake depressions. The signs of faults manifesting on the surface of the lake depression can be accurately determined using a topographical map. Fault analysis based on geomorphological morphometric analysis in the study area was conducted (Table 4).

According to the criteria of morphometric analysis, the signs of faulting are consistent with Khoton 9, Khurgan 7, Dayan 8, Khar (western) 6, and Khar (eastern) 2 lake depression. A criterion correlation of 5 more than indicates that the criterion matches. According to the results of the criteria, the influence of tectonics was directly reflected in the origin of the depressions of the Mongolian Altai lakes. However, the tectonic influence on the morphology of the Khar (eastern) lake depression is slight. The topographical map of the study area was assessed by criteria, and the faults were mapped (Fig. 3).

At the next stage of research, the surface forms of depressions in Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern) lakes were analyzed using geomorphological criteria to determine the origin and tectonic morphological pattern of lake depressions (Table 5).

According to the compliance of the tectonic geomorphological criteria for determining the origin and morphological pattern of the lake depression, there are eight consistent indicators for the Khoton, eight for the Khurgan, six for the Dayan, five for the Khar (western), and three for the Khar (eastern) lakes. When evaluated by morphometric and tectonic geomorphological criteria, the depressions of Khoton, Khurgan, Dayan, and Khar (western) lakes belong to the graben type. It is found that these are depressions with characteristic graben patterns of tectonic origin. A field survey mapped the Khoton Fault (Fig. 4).

The influence of tectonic activity in the Mongolian Altai Mountains is closely linked to the formation of lake depressions. Active tectonic processes resulted in the elevation of parts of the surface, forming mountains. At the same time, extensive depressions developed parallel to this uplift, contributing to the creation of the present lake system. Large graben depressions, formed by faults, emerged during the uplift of the Mongolian Altai Mountains.

Despite significant changes in the lakes' locations in the past, notably during the Last

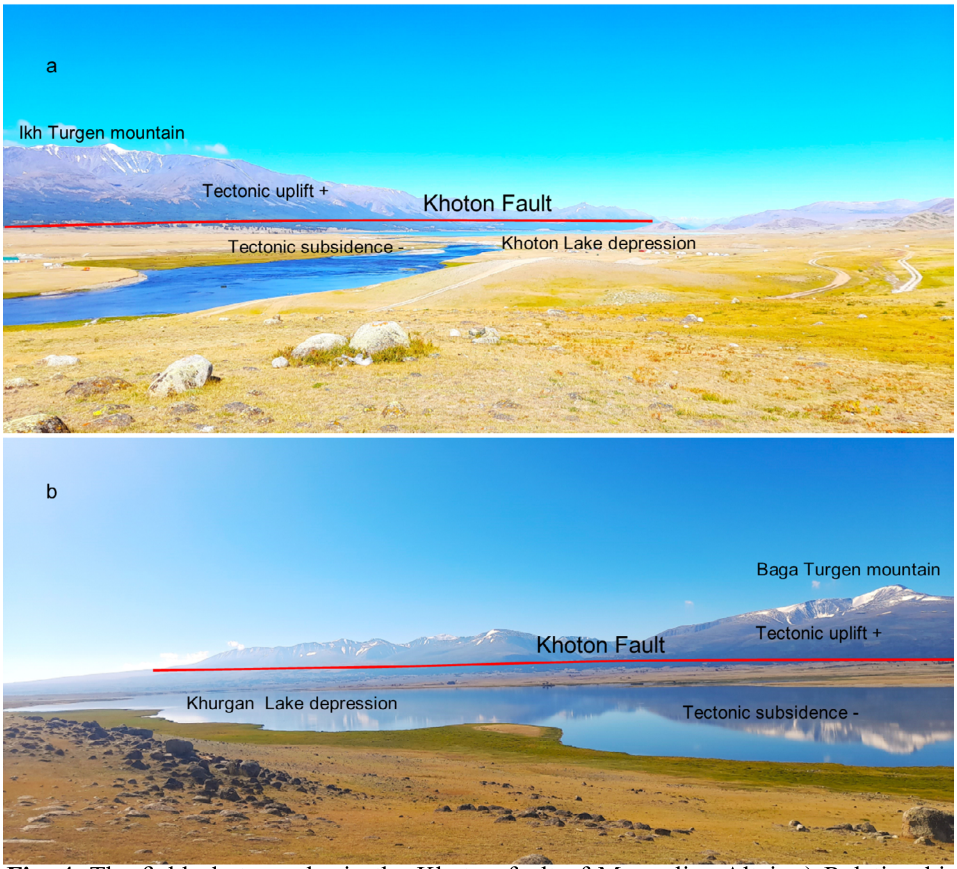

Fig. 4. The field photography in the Khoton fault of Mongolian Altai. a) Relationship between Khoton Lake depression and faulting b) Relationship between Khurgan Lake depression and faulting, Photo by Altanbold Enkhbold

Table 6. Geomorphological criteria for determining glacial effect (compliance+, non-compliance –)

№	Indicators	Khoton	Khurgan	Dayan	Khar (western)	Khar (eastern)
1	Whether the lake depression is relatively glacial Trough or U-shaped	+	+	–	+	+
2	Whether the lake depression is surrounded by high mountains	+	+	+	+	+
3	Is there a distribution of glacial sediments (Rigel, esker, moraine, Kam) around the lake depression	+	+	+	+	+
4	Whether glacial landforms (circus, drumlin, crag-tail, nunatic,) were formed in the vicinity of the lake depression.	+	+	+	+	+
5	The shape of the depression around the lake is oval and straight, and whether the topography of the lake is suitable according to that shape	+	+	+	+	+
6	Whether the bottom of the lake depression is relatively flat	–	–	+	+	+
7	Whether the mountains surrounding the lake form a flat tabletop	+	+	+	+	+
8	Whether the erosion of the shore of the lake is relatively small and the bathymetry parameters are less distorted	–	–	–	–	–
9	Whether the lake has inlets and outlets of the river in a certain direction	+	–	–	–	+
10	Whether the lake area forms a relative circle in topography	–	–	+	+	+
	Compatibility of geomorphological analysis	7	6	7	8	9

Fig. 5. The glacial morphology of the study area. a, b) Glacial striations are the evidence of glacial abrasion in the Khoton Lake depression, c) Glacial moraine sediments in the Khurgan Lake depression, d) Glacial drumlin, moraine sediments in the Khar (eastern) Lake depression, photo by Altanbold Enkhbold, e) Glacial moraine dam in the Dayan Lake depression, f) Glacial moraine sediments in the Khar (western) Lake depression, photo by Sergey Grinevich

Glacial and Holocene periods, the shape of the large-scale geomorphological features known as depressions, wherein these lakes are situated, has likely remained more stable over time due to their control by tectonic forces.

Effect of Lake Depression and Glaciation:

Glaciers spread several times in the Mongolian Altai mountains in the western part of Mongolia (Klinge, 2001; Lehmkuhl et al., 2011; Lehmkuhl et al., 2016; Klinge et al., 2021). The Pleistocene glaciated area in the Mongolian Altai is calculated to be about 21,000-29,000 km² (Devjatkin, 1981; Klinge, 2001). The present glaciated area in the Mongolian Altai is around 850 km² (Klinge, 2001).

In the Mongolian Altai, the forms of glacial surface are flat-top and trough-valley glaciation (Tsegmid, 1969; Lehmkuhl et al., 2016; Walther et al., 2017). Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern) Lake depressions are the main areas of distribution of glacial sediments in the Mongolian Altai.

In this study, we evaluated the effects of glaciation on the depressions of lakes in the Mongolian Altai Mountains using the criteria outlined in Table 6. A geomorphological criteria analysis was conducted to elucidate the potential glacial pattern of Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern) lake depressions.

The compatibility of the geomorphological criteria for determining the origin and morphological type of the lake depression by seven criteria in Khoton, six for Khurgan seven for Dayan, eight for Khar (western), and nine for Khar (eastern) lake depression. Surface forms of glacial origin are illustrated and confirmed by field studies (Fig. 5).

The Middle Pleistocene glacial was the most extensive, with younger moraines dating from the Late Pleistocene (Lehmkuhl et al., 2011).

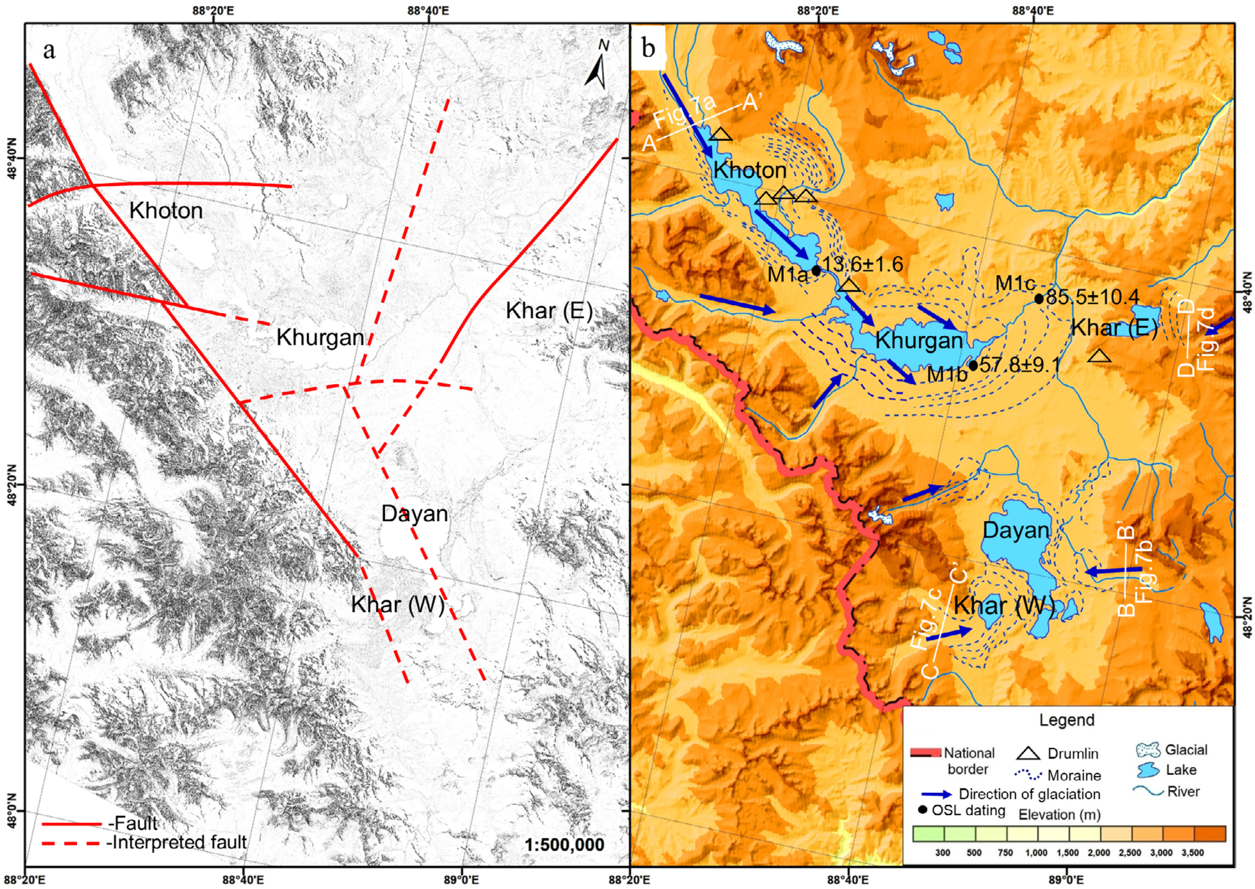

Fig. 6. a) Directional filtering on the surface by spatial improvement method of faults b) Descriptive mapping of glacial surface morphological forms

The characteristic Late Pleistocene terminal moraines were formed by massive valley glaciers (Lehmkuhl et al., 2016). Surface forms created at the glacier's edge encompass ridges, U-shaped valleys, and moraines. These lakes are situated at various elevations, separated by moraine dams and hills. Almost all types of depressions of ancient glacial origin in Khoton, Khurgan, Dayan, Khar (western), and Khar (eastern) lakes are distributed (Tserensodnom, 2000; Dashtseren, 2006). For example, the moraine hills extending 45 km from the northwest to southeast direction of Khoton and Khurgan Lakes and about 10 km from the southwest of Khurgan Lake are curved in several parallel semi-circles, and 10-15 km wide terraced terraces were formed due to glacial retreat (Lehmkuhl et al., 2016). In these moraine terraces, pseudo-karsts with a depth of about 2 m have formed, and some small-sized multi-lakes have been established (Tserensodnom, 2000). Melting permafrost and glacier meltwater created these pseudo-karst.

Almost all forms of glacial relief, including marginal moraines, drumlins, abrasion surfaces, and moraine dams, were observed in the depressions of the lakes studied in the Mongolian Altai.

Among the surface forms of glacial water origin, the most prevalent in the depressions of these lakes is the kame, which forms in groups in the west and northwest. The melting water from the glacier transfers sand and stones, accumulating at the bottom of the river valley and forming kame (Lehmkuhl et al., 2011). Its surface is composed of sandy and clayey material, featuring steep sides, flat tops, and an oval shape. It also indicates that after the last ice age, there were severe floods in this region.

A 1.5 km long esker (Tarasov et al., 2000; Dashtseren, 2006) has been formed on the western shore of Khoton, Khurgan, and Dayan Lake.

Faults and glacial morphological forms within the lake depressions were validated through topographical analysis using the directional

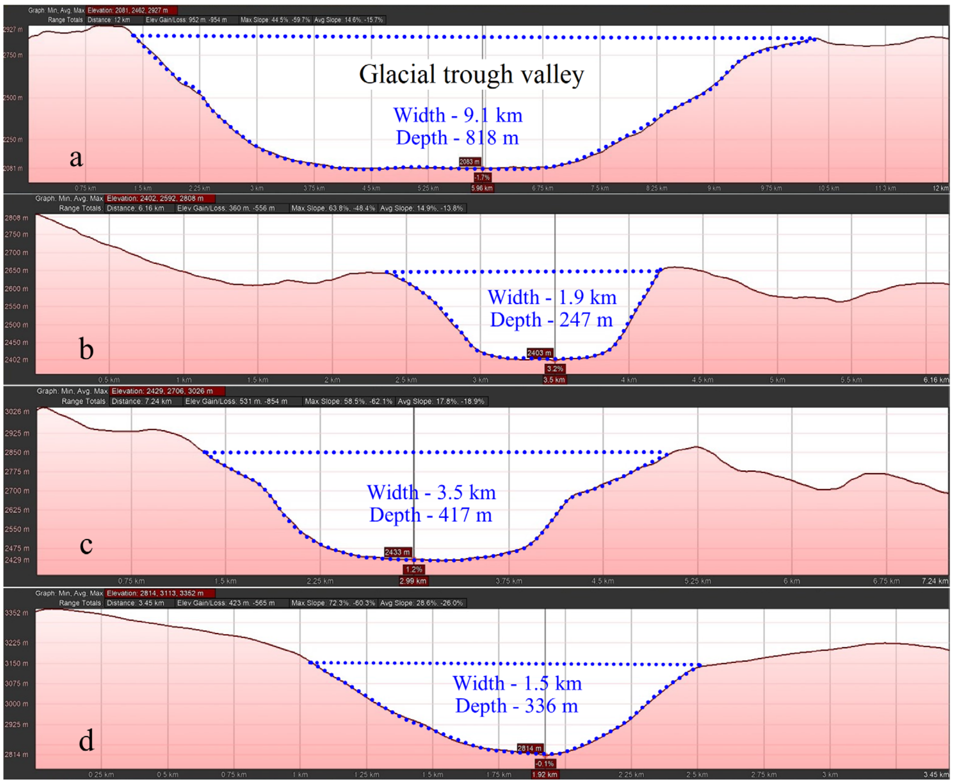

Fig. 7. Glacial depressions of Mongolian Altai lakes. a) Around Khoton, Khurgan Lake b) Around Dayan Lake c) around Khar (western) Lake d) Khar (eastern) Lake

filter of Remote Sensing Research and the high-frequency Sobel filter method (Fig. 6).

The characterization of faults involves a combination of topographical map analysis and satellite image spatial improvement methods. Faults are discernible through a notable color difference on the ground surface after applying a Sobel filter to the satellite image (Fig. 6a).

A trapezoidal surface extending downward from Khoton and Khurgan Lakes toward Ice Mountain was filled with drumlins and moraine sediments, resulting in a slightly undulating moraine sediment side.

The age of the OSL dating from moraine (M) sediments was determined as M1c- 85.5±10.4 ka, while the age of the moraine formed in the same direction as the sediments of the moraine was M1b- 57.8±9.1 ka, while the age of the moraine surrounding Khoton Lake was M1a- 13.6±1.6 ka ago (Lehmkuhl et al., 2016), affected the origin of the current lake (Fig. 6b). The study of the age of the lake sediments indicates that the forms of moraine closures and trough valleys confirm that the last ice age receded 12-10 ka ago (Tserensodnom, 2000).

While the study of the age of the moraine formed in the depressions of Dayan, Khar (western), and Khar (eastern) lakes has not been determined in detail, there is a likelihood that, in terms of space and time, the temporal pattern aligns with the moraine sediments formed in the vicinity of Khoton and Khurgan lakes (Fig. 6b).

According to the analysis of pollen in Holocene sediments, it was estimated that the ages of the same generation of the sediments of 3.2-3.5 deep glacial origin of lakes such as Khoton and Dayan are pretty close to each other, 3 270±90 a BP (Tserensodnom, 2000). On the other hand, the sample taken from the southern part of Dayan Lake was determined to be 4 375±150 years old by radiocarbon dating (Unkelbach et al., 2019), while the chronology of 9 070±150 years was recorded in the sediments of Khoton Lake (Tarasov et al., 2000).

Estimates of the age of lake sediments have limited relevance to the origin of the lake depression. However, the characteristics of sediment layers accumulated in the lake depression serve as a crucial archive, illustrating the history of paleogeographic development in both the lake and the surrounding region.

One of the critical pieces of evidence for

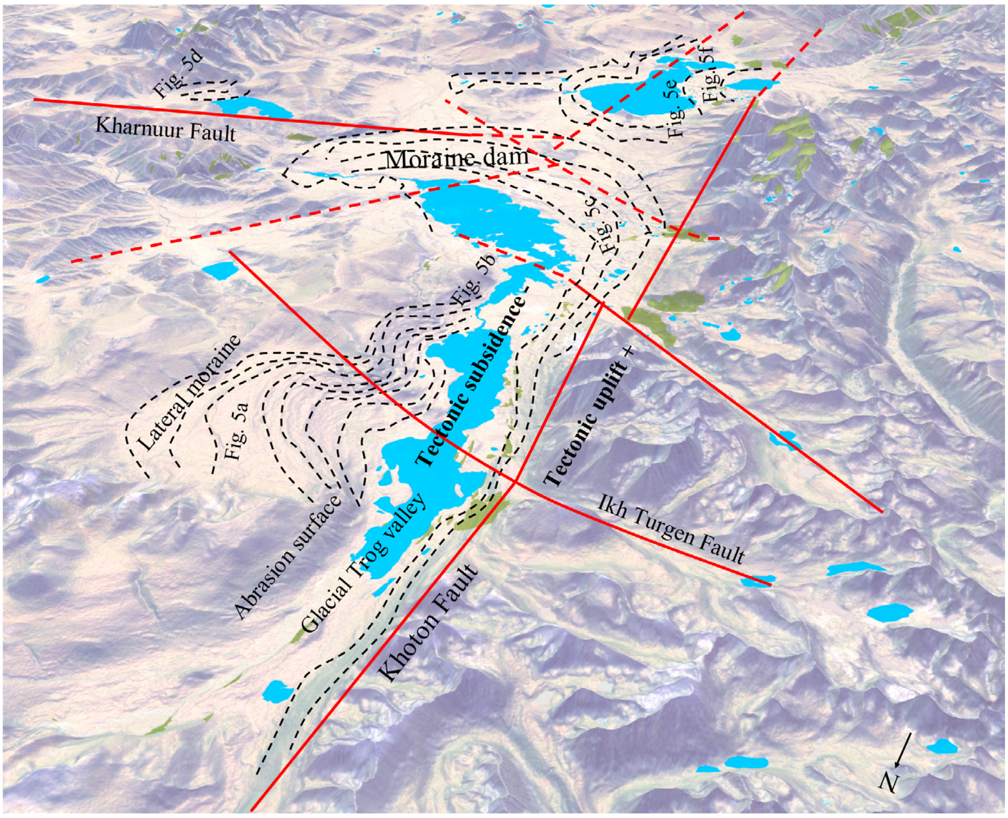

Fig. 8. Interpretation of the relationship between tectonic and glacial activity in the origin of the lake depression

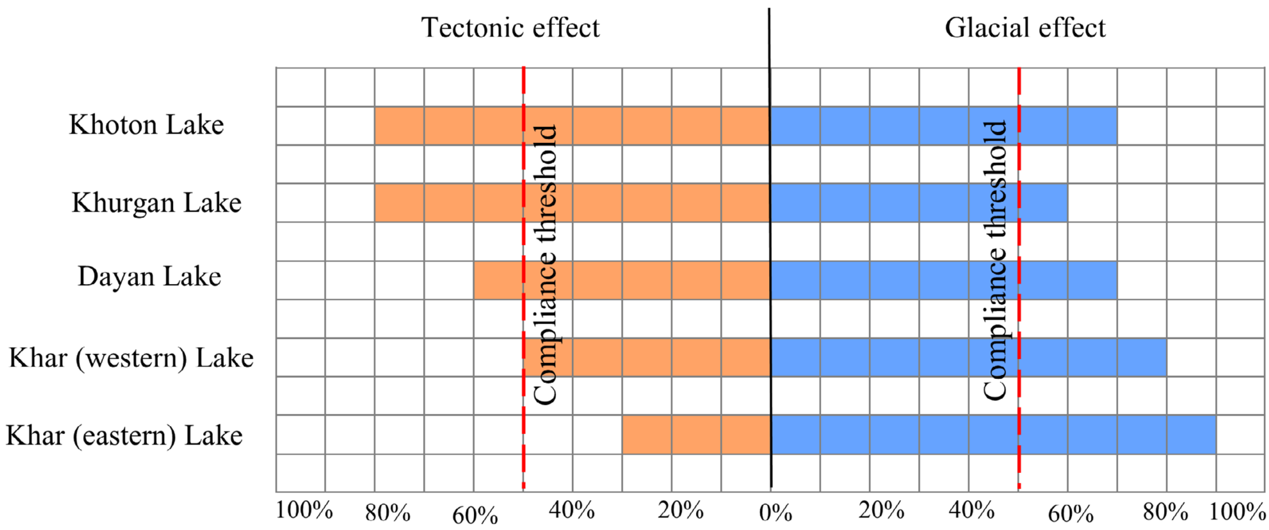

Fig. 9. Diagram of the relationship between tectonic and glacial activity in the origin of the lake depression

glaciation in the depressions of the lakes is the morphology of the glacial trough valley. The glacial effects on lake depressions were determined, and hypsometric sections were created (Fig. 7).

In the mountains surrounding the lake depression, the morphology of the glacial trough valley is well-developed due to the influence of Alpine glaciation, as confirmed by hypsometric sections. The glacial trough valley has an average width of 4 km and a maximum width of around 9 km, with an average depth of approximately 450 m and a maximum depth of almost 800 m.

At the end of the glacial trough valley, lateral and end moraine sediments accumulated in various sizes, directly impacting the origin of today's lakes. Moraine dykes formed in the northwest to southeast direction of Khoton and Khurgan lakes, moraine dams developed on almost all sides of the depression of Dayan Lake, and moraine formed in the eastern part of the depression of Khar (western) and Khar (eastern) Lakes

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DISCUSSION AND CONLUSIONS

In addition to tectonic influences, the climatic and geomorphological processes of the glacial and post-glacial periods have had a major impact on the location, appearance, and type of Central Asian lakes (Enkhbold et al., 2022d). The Alpine glaciation has influenced the pattern, location, and area of the depressions in the lakes. These large depressions, situated between the mountains of Mongolia, predominantly exist in the western half of the country, with their direction extending from northwest to southeast. Following this system of mountains and depressions, an extensive lake system of Mongolia was formed (Tsegmid, 1969; Tserensodnom, 1971; Shinneman et al., 2009; Enkhbold et al., 2022d).

Many lakes in Mongolia were formed by the influence of tectonic movements between mountains, valleys, and faults (Tserensodnom, 2000; Enkhbold et al., 2021; Enkhbold et al., 2022a,b,c). Also, the movement of mountains during the plays an important role in finding the modern appearance of the lake depressions (Cunningham, 2005; Byamba, 2009; Khukhuudei et al., 2020).

Lakes of glacial origin in Mongolia are closed mainly by moraine sediments, and later due to water erosion, their basins burst and lose water, so their area and depth have decreased significantly (Tsegmid, 1969; Tserensodnom, 2000; Lehmkuhl et al., 2016). Mongolia exhibits numerous lakes of glacial origin, including Khoton, Khurgan, Tolbo, Dayan, Khar (western), and Khar (eastern) lakes in the Mongolian Altai Mountains, which stand as a focal point of ancient glaciation. Our current research has provided evidence regarding the origin and types of depressions in certain lakes within the Mongolian Altai Mountains. The logical relationship between tectonic and glacial activity in the formation of lake basins is illustrated in Figs. 8 and 9.

The depressions of Khoton, Khurgan, and Dayan Lakes extend in a northwest to southeast direction, formed along regional fault zones. This is prominently visible on their southwest side, directly connected with the Mongolian Altai Mountain range and confined by faults, resulting in a graben depression. The relief of these depressions was further influenced by glaciation.

Moraine sediments encircle Dayan Lake on nearly all sides, and the depression of the lake was elevated due to the impact of regional faults in the west and southwest, forming under the combined influence of tectonics and glaciation. In the case of Khar (western) and Khar (eastern) Lakes, moraine sediments have blocked the water in the eastern part of the depression (Fig. 8).

According to the matrix criteria results, the direct influence of both glacial and tectonic factors is evident in the origin of the depressions in the Mongolian Altai lakes. The compliance matrix of tectonic geomorphological criteria indicates more than a 50% concordance for the depressions of Khoton, Khurgan, Dayan Lake, and Khar (western) Lake. Similarly, the compliance matrix of glacial geomorphological criteria shows more than a 60% concordance for all lake depressions. The research results suggest that various factors have influenced the origin of the intermontane lake depressions in the Mongolian Altai. They are of tectonic origin, while the lakes have a post-glacial origin and were formed by dams built from moraine sediments.

In summary, it is evident from the research findings that the lake depressions and the origins of the lakes are not solely controlled by a single factor but by multiple coupled exogenic and endogenic forces.

The critical significance of this study lies in demonstrating that it is possible to determine the detailed pattern of lake depressions through geomorphological research. Particularly, the development of topographical and geomorphological indicators and the use of spatial and topographical mapping materials has introduced an innovative approach to determining the typology of lake depressions and their characteristics.

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REFERENCES

Bliedtner, M., Struck, J., Strobel, P., Salazar, G., Szidat, S., Bazarradnaa, E., Lloren, R., Dubois, N., Zech, R. 2021. Late Holocene climate changes in the Altai Region based on the first high-resolution biomarker isotope record from Lake Khar Nuur. Geophysical Research Letters, v. 48(20), p. 1-11. https://doi.org/10.1029/2021GL094299

Bold, Ya. 1987. Fundamentals of Geomorphological research. Ulaanbaatar, Mongolia, p. 94-98 (in Mongolian).

Byamba, J. 2009. Lithospheric Plate Tectonics, Geology and Mineral Resources of Mongolia. v. IV, Ulaanbaatar, p. 126-128 (in Mongolian).

Cohen, A.S. 2003. Paleolimnology: The History and Evolution of Lake Systems. Oxford University Press. p. 21-66. https://doi.org/10.1093/oso/9780195133530.001.0001

Cunningham, D. 2005. Active intracontinental transpressional mountain building in the Mongolian Altai: Defining a new class of orogen. Earth and Planetary Science Letters, v. 240(2), p. 436-444. https://doi.org/10.1016/j.epsl.2005.09.013

Cunningham, D., Dijkstra, A., Howard, J., Quarles, A., Badarch, G. 2003. Active intraplate strike-slip faulting and transpressional uplift in the Mongolian Altai. Geological Society, London, Special Publications, 210(1), p. 65-87. https://doi.org/10.1144/GSL.SP.2003.210.01.05

Cunningham, W.D. 1998. Lithospheric controls on late Cenozoic construction of the Mongolian Altai. Tectonics, v. 17(6), p. 891-902. https://doi.org/10.1029/1998TC900001

Dashtseren, Ts. 2006. Glacial surface features of Khoton and Khurgan Lake regions, Natural conditions, resources, and biodiversity of the Mongolian Altay region, No. 2. Ulaanbaatar. p. 44-46

De Grave, J., Buslov, M.M., Van den Haute, P. 2007. Distant effects of India–Eurasia convergence and Mesozoic intracontinental deformation in Central Asia: Constraints from apatite fission-track thermochronology. Journal of Asian Earth Science, v. 29 (2-3), p. 188-204. https://doi.org/10.1016/j.jseaes.2006.03.001

Dearing, J.A., Foster, D.L. 1993. Lake sediments and geomorphological processes: Some Thoughts. In McManuc, J., Duck R.W. (Eds) Geomorphology and Sedimentology of Lakes and Reservoirs, p. 5-14.

Dergunov, A.B., Luvsandanzan, B., Pavlenko, V.S. 1980. Geology of West Mongolia, Transactions, v. 31, 195 p. Moscow, Nauka (in Russian)

Devjatkin, E.V. 1981. Cenozoic of Inner Asia. Nauka, Moscow, p. 196-198 (in Russian).

Doljin, D., Yembuu, B. 2021. The Relief and Geomorphological Characteristics of Mongolia. In The Physical Geography of Mongolia. Cham: Springer International Publishing. p. 23-50. https://doi.org/10.1007/978-3-030-61434-8_3

Enkhbold, A., Dorjsuren, B., Khukhuudei, U., Yadamsuren, G., Badarch, A., Dorjgochoo, S., Gonchigjav, Y., Nyamsuren, O., Ragchaa, G., Gedefaw, M. 2022b. Impact of faults on the origin of lake depressions: a case study of Bayan Nuur depression, North-west Mongolia, Central Asia. Geografia Fisica e Dinamica Quaternaria, v. 44(1), p. 53-66. https://doi.org/10.4461/GFDQ.2021.44.5

Enkhbold, A., Khukhuudei, U., Doljin, D. 2022d. A review of modern trends and historical stages of development of lake research in Mongolia. Proceedings of the Mongolian Academy of Sciences, v. 62(01) p. 25-37. https://doi.org/10.5564/pmas.v62i01.2085

Enkhbold, A., Khukhuudei, U., Doljin, D. 2021. Morphological classification and origin of lake depressions in Mongolia. Proceedings of the Mongolian Academy of Sciences, v. 61(02), p. 35-43. https://doi.org/10.5564/pmas.v61i02.1758

Enkhbold, A., Khukhuudei, U., Kusky, T., Chun, X., Yadamsuren, G., Ganbold, B., Gerelmaa, T. 2022c. Morphodynamic development of the Terkhiin Tsagaan Lake Depression, Central Mongolia: Implications for the relationships of Faulting, Volcanic Activity, and Lake Depression Formation. Journal of Mountain Science, v. 19(9), p. 2451-2468. https://doi.org/10.1007/s11629-021-7144-1

Enkhbold, A., Khukhuudei, U., Kusky, T., Tsermaa, B., Doljin, D. 2022a. Depression morphology of Bayan Lake, Zavkhan province, Western Mongolia: implications for the origin of lake depression in Mongolia. Physical Geography, v. 43(6), p. 727-752. https://doi.org/10.1080/02723646.2021.1899477

Filosofov, V.P. 1967. The value of the map of potential relief energy for geomorphological and Neotectonic studies. Methods geomorphological. Novosibirsk: Science. Siberian Department. p. 193-198.

Florinsky, I.V. 1996. Quantitative topographic method of fault morphology recognition. Geomorphology, 16(2), p. 103-119. https://doi.org/10.1016/0169-555X(95)00136-S

Hakanson, L. 2012. A manual of lake morphometry. Springer Science & Business Media. p. 56-78. https://doi.org/10.1007/978-3-642-81563-8

Hassen, M.B., Deffontaines, B., Turki, M.M. 2014. Recent tectonic activity of the Gafsa fault through morphometric analysis: Southern Atlas of Tunisia. Quaternary International, v. 338, p. 99-112. https://doi.org/10.1016/j.quaint.2014.05.009

He, C., Cheng, Y., Rao, G., Chen, P., Hu, J., Yu, Y., Yao, Q. 2018. Geomorphological signatures of the evolution of active normal faults along the Langshan Mountains, North China. Geodinamica Acta, v. 30(1), p. 163-182. https://doi.org/10.1080/09853111.2018.1458935

Hutchinson, G.E. 1957. A Treatise on Limnology. Vol. 1, Geography, Physics, and Chemistry. Geological Magazine, v. 95(1), p. 1-57.

Jacques, P.D., Salvador, E.D., Machado, R., Grohmann, C.H., Nummer, A.R. 2014. Application of morphometry in neotectonic studies at the eastern edge of the Paraná Basin, Santa Catarina State, Brazil. Geomorphology, v. 213(1/2), p. 13-23. https://doi.org/10.1016/j.geomorph.2013.12.037

Jolivet, M., Ritz, J.-F., Vassallo, R., Larroque, C., Braucher, R., Todbileg, M., Chauvet, A., Sue, C., Arnaud, N., De Vicente, R., Arzhanikova, A., Arzhanikov, S. 2007. Mongolian summits: an uplifted, flat, old but still preserved erosion surface. Geology, v. 35(10), p. 871-874. https://doi.org/10.1130/G23758A.1

Khukhuudei, U., Kusky, T., Otgonbayar, O., Wang, L. 2020. The early Paleozoic mega-thrusting of the Gondwana-derived Altay–Lake zone in Western Mongolia: Implications for the development of the Central Asian Orogenic Belt and Paleo-Asian Ocean Evolution. Geological Journal, v. 55(3), p. 2129-2149. https://doi.org/10.1002/gj.3753

Khukhuudei, U., Kusky, T., Windley, B., Otgonbayar, O., Wang, L. 2022. Ophiolites and ocean plate stratigraphy (OPS) preserved across the Central Mongolian Microcontinent: A new mega-archive of data for the tectonic evolution of the Paleo-Asian Ocean. Gondwana Research, v. 105, 51-83. https://doi.org/10.1016/j.gr.2021.12.008

Klinge, M. 2001. Glazial geomorphologische Untersuchungen im Mongolischen Altai als Beitrag zur jungquartären Landschafts- und Klimageschichte der Westmongolei. Geographisches Institut der RWTH. p. 24-46.

Klinge, M., Sauer, D. 2019. Spatial pattern of Late Glacial and Holocene climatic and environmental development in Western Mongolia-A critical review and synthesis. Quaternary Science Reviews, v. 210, 26-50. https://doi.org/10.1016/j.quascirev.2019.02.020

Klinge, M., Schluetz, F., Zander, A., Huelle, D., Batkhishig, O., Lehmkuhl, F. 2021. Late Pleistocene Lake level, glaciation, and climate change in the Mongolian Altai deduced from sedimentological and palynological archives. Quaternary Research, v. 99, p. 168-189. https://doi.org/10.1017/qua.2020.67

Lehmkuhl, F., Klinge, M., Rother, H., Hülle, D. 2016. Distribution and timing of Holocene and late Pleistocene glacier fluctuations in western Mongolia. Annals of Glaciology, v. 57(71), p. 169-178. https://doi.org/10.3189/2016AoG71A030

Lehmkuhl, F., Klinge, M., Stauch, G. 2011. The extent and timing of Late Pleistocene Glaciations in the Altai and neighboring mountain systems. In Ehlers, J., Gibbards, P.L. (Eds) Quaternary Glaciations - Extent ad Chronology: A Closer Look, v. 15, p. 967-979.

Mark, D.M. 1975. Computer Analysis of Topography: A Comparison of Terrain Storage Methods. Geografiska Annaler: Series A, Physical Geography, v. 57(3-4), p. 179-188. https://doi.org/10.1080/04353676.1975.11879914

Mats, V.D. 1993. The structure and development of the Baikal rift depression. Earth-Science Reviews, v. 34(2), p. 81-118. https://doi.org/10.1016/0012-8252(93)90028-6

Nixon, M.S., Aguado, A.S. 2019. Feature Extraction and Image Processing. Newnes. p. 263-282. https://doi.org/10.1016/C2011-0-06935-1

Rudaya, N., Li, H.C. 2013. A new approach for reconstruction of the Holocene climate in the Mongolian Altai: The high-resolution δ13C records of TOC and pollen complexes in Hoton-Nur Lake sediments. Journal of Asian Earth Sciences, v. 69(2), p. 185-195. https://doi.org/10.1016/j.jseaes.2012.12.002

Rudaya, N., Tarasov, P., Dorofeyuk, N., Solovieva, N., Kalugin, I., Andreev, A., Daryin, A., Diekmann, B., Riedel, F., Tserendash, N., Wagner, M. 2009. Holocene environments and climate in the Mongolian Altai reconstructed from the Hoton-Nur pollen and diatom records: a step towards better-understanding climate dynamics in Central Asia. Quaternary Science Reviews, v. 28(5-6), p. 540-554. https://doi.org/10.1016/j.quascirev.2008.10.013

Sevastyanov, D.V., Shuvalov, V.F., Neustrueva, I.Y. 1994. Limnology and Paleolimnology of Mongolia. St. Petersburg, p. 59-94 (in Russian)

Shinneman, A.L., Almendinger, J.E., Umbanhowar, C.E., Edlund, M.B., Nergui, S., 2009. Paleolimnologic Evidence for Recent Eutrophication in the Valley of the Great Lakes (Mongolia). Ecosystems, v. 12, p. 944-960. https://doi.org/10.1007/s10021-009-9269-x

Singh, A.K., Mitra, S., Chaudhuri, D., Chaudhuri, B.B., Singh, M.P. 2023. Optimization of Multi-Class Non-Linear SVM Image Classifier Using A Sobel Operator Based Feature Map and PCA. 2023 3rd International Conference on Range Technology (ICORT) p. 1-6. IEEE. https://doi.org/10.1109/ICORT56052.2023.10249196

Sobel, I. 2014. An Isotropic 3x3 image gadient operator. Presentation at Stanford Project 1968.

Tapponnier, P., Molnar, P. 1979. Active faulting and Cenozoic tectonics of the Tien Shan, Mongolia, and Baykal Regions. Journal of Geophysical Research: Solid Earth, v. 84(B7), p. 3425-3459. https://doi.org/10.1029/JB084iB07p03425

Tarasov, P., Dorofeyuk, N., Tseva, E.M. 2000. Holocene vegetation and climate changes in Hoton-Nur basin, northwest Mongolia. Boreas, v. 29(2), p. 117-126. https://doi.org/10.1111/j.1502-3885.2000.tb01205.x

Tomurtogoo, O. 2014. Tectonics of Mongolia. In: Tectonics of Northern, Central and Eastern Asia, explanatory note to the Tectonic map of Northern Central Eastern Asia and adjacent areas at scale 1:2500000, p. 110-126.

Tsegmid, S. 1969. Physical geography of Mongolia. Mongolian Academy of Sciences, Institute of Geography and Permafrost. Ulaanbaatar, Mongolia. p. 23-67 (in Mongolian)

Tsegmid, S., Vorobiev, B.B. 1990. National Atlas of the People's Republic of Mongolia. Academy of Sciences of the People's Republic of Mongolia: Ulaanbaatar. p. 118-127

Tserensodnom, J. 1971. Lakes of Mongolia. Mongolian Academy of Sciences, Institute of Geography and Permafrost. Ulaanbaatar, Mongolia, p. 44-56 (in Mongolian)

Tserensodnom, J. 2000. Catalog of lakes of Mongolia. Mongolian Academy of Sciences, Institute of Geography and Permafrost. Ulaanbaatar, Mongolia p. 67-76. (in Mongolian)

Unkelbach, J., Kashima, K., Enters, D., Dulamsuren, C., Punsalpaamuu, G., Behling, H. 2019. Late Holocene (Meghalaya) palaeoenvironmental evolution inferred from multi-proxy studies of lacustrine sediments from the Dayan Nuur region of Mongolia. Paleogeography, Palaeoclimatology, Palaeoecology, v. 530, p. 1-14. https://doi.org/10.1016/j.palaeo.2019.05.021

USGS. 2023. Available online: https://earthexplorer.usgs.gov (accessed on March 2023).

Walther M., Dashtseren, A., Kamp, U., Temujin, K., Meixner, F., Pan, C.G., Gansukh, Y. 2017. Glaciers, Permafrost, and Lake Levels at the Tsengel Khairkhan Massif, Mongolian Altai, During the Late Pleistocene and Holocene. Geosciences, v. 7(3), p. 1-20. https://doi.org/10.3390/geosciences7030073

Walther, M., Kamp, U., Nandintsetseg, N-O., Dashtseren, A., Temujin, K. 2024. Glacial Lakes of Mongolia. Geographies, v. 4(1), p. 21-39. https://doi.org/10.3390/geographies4010002

Wetzel, R.G. 2001. Rivers and Lakes-Their Distribution, Origins, and Forms. Limnology: Lake and River Ecosystems. Gulf Professional Publishing. p. 15-42 https://doi.org/10.1016/B978-0-08-057439-4.50007-1

Yang, X., Li, W., Qin, Z. 2015. Calculation of reverse-fault-related parameters using topographic profiles and fault bedding. Geodesy and Geodynamics, v. 6(2), p. 106-112. https://doi.org/10.1016/j.geog.2014.09.002

Yembuu, B., Doljin, D. 2021. Historical Geography: Administrative Division and Research in Physical Geography of Mongolia. The Physical Geography of Mongolia. Springer International Publishing. p. 9-22. https://doi.org/10.1007/978-3-030-61434-8_2