IT ISSN 0391 - 9838

GEOGRAFIA FISICA e DINAMICA QUATERNARIA

An international Journal published under the auspices of the
Rivista internazionale pubblicata sotto gli auspici di

Associazione Italiana di Geografia Fisica e Geomorfologia
and (e) Consiglio Nazionale delle Ricerche (CNR)

recognized by the (*riconosciuta da*)

International Association of Geomorphologists (IAG)

volume 44 (1)
2021

COMITATO GLACIOLOGICO ITALIANO - TORINO
2021

Bollettino del Comitato Glaciologico Italiano - ser. 3

GEOGRAFIA FISICA E DINAMICA QUATERNARIA

A journal published by the Comitato Glaciologico Italiano, under the auspices of the Associazione Italiana di Geografia Fisica e Geomorfologia and the Consiglio Nazionale delle Ricerche of Italy. Founded in 1978, it is the continuation of the «Bollettino del Comitato Glaciologico Italiano». It publishes original papers, short communications, news and book reviews of Physical Geography, Glaciology, Geomorphology and Quaternary Geology. The journal furthermore publishes the annual reports on italian glaciers, the official transactions of the Comitato Glaciologico Italiano and the Newsletters of the Intemational Association of Geomorphologists. Special issues, named «Geografia Fisica e Dinamica Quaternaria - Supplementi», collecting papers on specific themes, proceedings of meetings or symposia, regional studies, are also published, starting from 1988. The language of the journal is English, but papers can be written in other main scientific languages.

Rivista edita dal Comitato Glaciologico Italiano, sotto gli auspici dell'Associazione Italiana di Geografia Fisica e Geomorfologia e del Consiglio Nazionale delle Ricerche. Fondata nel 1978, è la continuazione del «Bollettino del Comitato Glaciologico Italiano». La rivista pubblica memorie e note originali, recensioni, corrispondenze e notiziari di Geografia Fisica, Glaciologia, Geomorfologia e Geologia del Quaternario, oltre agli Atti ufficiali del C.G.I., le Newsletters della I.A.G. e le relazioni delle campagne glaciologiche annuali. Dal 1988 vengono pubblicati anche volumi tematici, che raccolgono lavori su argomenti specifici, atti di congressi e simposi, monografie regionali sotto la denominazione «Geografia Fisica e Dinamica Quaternaria - Supplementi». La lingua usata dalla rivista è l'Inglese, ma gli articoli possono essere scritti anche nelle altre principali lingue scientifiche.

Editor Emeritus (*Direttore Emerito*)
P.R. Federici
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel. 0502215700

Editor in Chief (*Direttore*)
C. Baroni
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel 0502215731

Vice Editor (*Vice Direttore*)
A. Ribolini
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel 0502215769

Editorial Board (*Comitato di Redazione*) **2021**

F. Andrè (Clermont Ferrand), D. Capolongo (Bari), L. Carturan (Padova), A. Cendrero (Santander), M. Frezzotti (Roma), E. Fuache (Paris/Abu Dabi), E. Jaque (Concepcion), H. Kershner (Innsbruck), E. Lupia Palmieri (Roma), G. Mastronuzzi (Bari), B. Rea (Aberdeen), M. Schiattarella (Potenza), M. Soldati (Modena e Reggio Emilia).

Indexed/Abstracted in: Bibliography & Index of Geology (GeoRef); GeoArchive (Geosystem); GEOBASE (Elsevier); *Geographical Abstract*: *Physical Geography* (Elsevier); GeoRef; Geotitles (Geosystem); Hydrotitles and Hydrology Infobase (Geosystem); Referativnyi Zhurnal.
Geografia Fisica e Dinamica Quaternaria has been included in the Thomson ISI database beginning with volume 30 (1) 2007 and now appears in the Web of Science, including the Science Citation Index Expanded (SCIE), as well as the ISI Alerting Services.

HOME PAGE: http://gfdq.glaciologia.it/ - CONTACT: gfdq@dst.unipi.it

Printed with the financial support from (pubblicazione realizzata con il contributo finanziario di):

- Comitato Glaciologico Italiano
- Associazione Italiana di Geografia Fisica e Geomorfologia
- Ministero dell'Istruzione, Università e Ricerca
- Consiglio Nazionale delle Ricerche
- Club Alpino Italiano

Comitato Glaciologico Italiano
President (*Presidente*) M. Frezzotti

Geogr. Fis. Dinam. Quat.
44 (2021). 69-82, 8 figg., 3 tabb.

DOI 10.4461/ GFDQ.2021.44.5

Altanbold ENKHBOLD [1], Batsuren DORJSUREN [2*], Ulambadrakh KHUKHUUDEI [3], Gansukh YADAMSUREN [4], Daariimaa BADARCH [3], Sanchir DORJGOCHOO [5], Yumchmaa GONCHIGJAV [1], Odkhuu NYAMSUREN [1], Gantulga RAGCHAA [1] & Mohammed GEDEFAW [6]

IMPACT OF FAULTS ON THE ORIGIN OF LAKE DEPRESSIONS: A CASE STUDY OF BAYAN NUUR DEPRESSION, NORTH-WEST MONGOLIA, CENTRAL ASIA

Abstract: Enkhbold A., Dorjsuren B., Khukhuudei U., Yadamsuren G., Badarch D., Dorjgochoo S., Gonchigjav Y., Nyamsuren O., Ragchaa G. & Gedefaw M., *Impact of faults on the origin of lake depressions: a case study of Bayan Nuur Depression, North-West Mongolia, Central Asia.* (IT ISSN 0391-9839, 2021).

This study focuses on the impact of faults on the origin and depression morphology of Bayan Nuur in North-West Mongolia. The relationships of Nuur and faults have been studied using morphometric analysis, spatially-improved remote sensing and magnetic survey. According to the results, the main fault formed in the western part of the Bayan Nuur depression influenced the origin of the lake depression SW -NE oriented. The length of the Bayan Nuur main fault is 147.1 km; 4 lakes have been formed along this fault, of which, the Bayan Nuur is the largest one. This study suggests that the Bayan Nuur origin is different from that suggested by previous studies and we conclude that the depressions hosting lakes in Mongolia need to be further investigated. This study represents a new contribution to better understand both the origin of the depressions hosting the Mongolian lakes and the impact of neotectonic activity, through morphometric analysis integrated with remote sensing analysis and geophysical surveys.

Key words: Mongolia, Morphometric Analysis, Lake Depression, Faults, Remote Sensing, Bayan Nuur.

Riassunto: Enkhbold A., Dorjsuren B., Khukhuudei U., Yadamsuren G., Badarch D., Dorjgochoo S., Gonchigjav Y., Nyamsuren O., Ragchaa G. & Gedefaw M., *Impatto delle faglie sull'origine delle depressioni lacustri: un caso di studio della depressione di Bayan Nuur, Mongolia nord-occidentale, Asia centrale.* (IT ISSN 0391-9839, 2021).

Questo studio ha per oggetto l'impatto delle faglie sull'origine e la morfologia della depressione di Bayan Nuur nella Mongolia nord-occidentale. Le relazioni tra il Nuur e le faglie presenti sono state studiate utilizzando l'analisi morfometrica, il telerilevamento e rilevamenti geo-magnetici. Secondo i risultati da noi ottenuti, la faglia principale della depressione si è formata nella parte occidentale della depressione di Bayan Nuur e ha influenzato l'origine della depressione del lago con orientamento SW-NE. La lunghezza della faglia principale di Bayan Nuur è di 147,1 km; 4 laghi si sono formati lungo questa faglia e, tra questi, il Bayan Nuur è il più esteso. Questo studio suggerisce una origine del Bayan Nuur diversa rispetto a quella proposta dagli studi precedenti e conclude che le depressioni dei laghi in Mongolia necessitino di ulteriori indagini geologiche e geomorfologiche. Questo studio rappresenta un nuovo contributo per ottenere una migliore comprensione dell'origine delle depressioni che ospitano i laghi mongoli e dell'impatto dell'attività neotettonica attraverso l'analisi morfometrica integrata dal telerilevamento e da rilievi geofisici.

Termini chiave: Mongolia, Analisi morfometrica, Depressione lacustre, Faglie, Telerilevamento, Bayan Nuur.

INTRODUCTION

According to Tserensodnom (1971, 2000), genetically, Mongolian lakes were classified based on 7 types of depressions, including tectonic, volcanic, glacial, sinkholes, fluvial, gravity and eolian.

Faults may relate to lake depression (Mats, 1993, Shamir, 2006). Faults in Mongolia have been well studied (Bayasgalan & *alii*, 1999; Lamb & *alii*, 1999; Carretier & *alii*, 2002; Cunningham & *alii*, 2003a; Cunningham & *alii*, 2003b; Cunningham, 2005; Walker & *alii*, 2007; Cunningham, 2013; Rizza & *alii*, 2015) but, to our knowledge, lake depressions along tectonic faults have not been studied.

---

[1] *Department of Geography, School of Art and Sciences, National University of Mongolia, Ulaanbaatar 210646, Mongolia.*

[2] *Department of Environment and Forest Engineering, School of Engineering and Applied Sciences, National University of Mongolia, Ulaanbaatar 210646, Mongolia.*

[3] *Department of Geology and Geophysics, School of Arts and Sciences, National University of Mongolia, Ulaanbaatar 210646, Mongolia.*

[4] *Department of Soil Science, School of Agroecology, Mongolian University of Life Sciences, Ulaanbaatar 17024, Mongolia.*

[5] *Department of Magmatism and Metallogeny, Institute of Geology, Mongolian Academy of Sciences, Ulaanbaatar 15160, Mongolia.*

[6] *Department of Natural Resource Management, University of Gondar, Gondar 196, Ethiopia.*

* *Corresponding author: B. Dorjsuren (batsuren@seas.num.edu.mn)*

This research was funded by the National University of Mongolia Under (Grant agreement P2019-3745) and from the National University of Mongolia (Grant agreement P2021-4163).We thank the Department of Geography, National University of Mongolia, and all who provided data for this research.

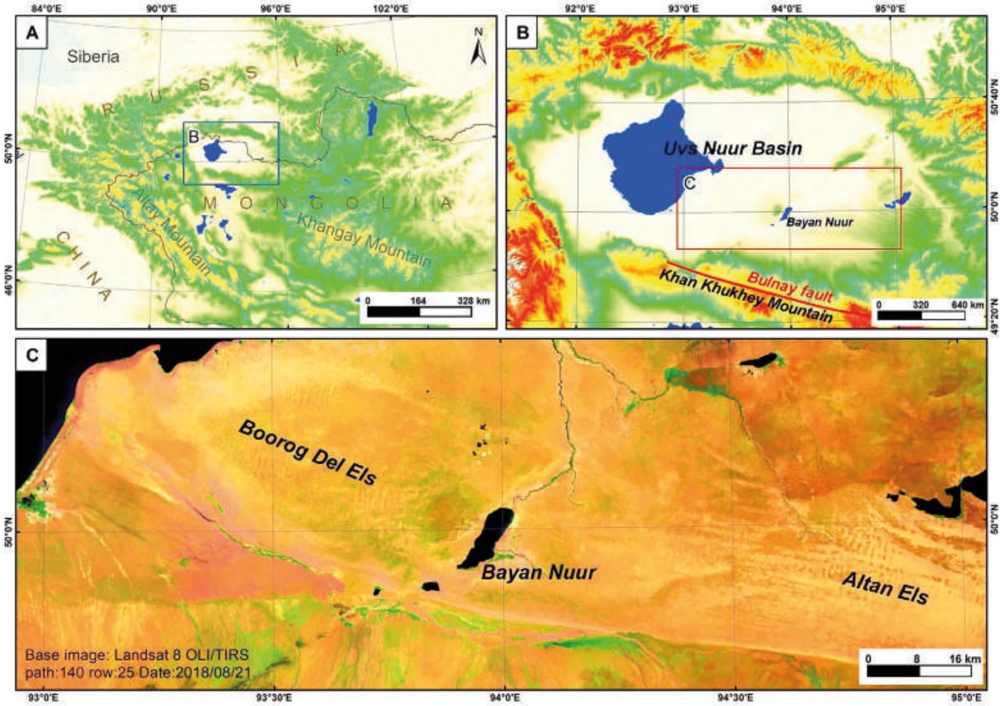

FIG. 1 - Location of the Bayan Nuur, Uvs Nuur Basin, North-West Mongolia.

According to research on lakes in Mongolia, palaeogeographic reconstruction, paleoclimate inferences, hydrologic regime and water properties were the dominant topics (Enkhbold & *alii*, 2021a), whereas investigations about the origin of lakes depression account for 2% (Enkhbold & *alii*, 2020b). Only a few of these latter concerns the morphological patterns of the lake depressions caused by the tectonic effect.

Some paleogeographical and geomorphological studies have been undertaken on the Uvs Nuur basin (Grunert & *alii*, 1999; Naumann & Walther, 2000; Grunert & *alii*, 2000; Grunert & Lehmkuhl, 2004; Walther, 2010; Rudaya & *alii*, 2021). The relationships of Bayan Nuur and faults have not been studied in detail, and previous studies proposed that its depression was formed by a dune barrier (Tudev, 2003; Tserensodnom, 1971).

In this paper, we focused on the interpretation of a fault crossing the Bayan Nuur depression in the formation of the lake depression.

GEOLOGY AND TECTONICS

Bayan Nuur (Nuur = lake in English) is located in Uvs Province, Mongolia. The study was conducted in the Uvs Nuur Basin area which is part of the North-West Mongolian arid zone in the Great Lake depression. Bayan Nuur is surrounded by arid desert steppe environment. The Bayan Nuur (between 93° 56' E and 93° 59' E, and between 49° 56' N and 50° 01' N) is located in the Uvs Nuur basin, at 929 m above sea level (Tserensodnom, 1971; Naumann & Walther, 2000; fig. 1).

The lake covers 31.6 km^2 with a length of 11.9 km, a width of 3.9 km, and a shoreline length of 28.7 km. The deepest part of the lake reaches 29.2 m and the total volume is 0.36 km^3 (Tserensodnom, 2000; Naumann & Walther, 2000; Walther, 2010).

Pollen contents in lake sediments have provided radiocarbon ages ranging from 13.2 and 15.6 ka BP (Dorofeyuk & Tarasov, 1998; Grunert & *alii*, 2000; Naumann & Walther, 2000; Walther, 2010; Rudaya & *alii*, 2021).

The study area is located in the Agardag backarc/forearc basin, which is located east of Uvs Nuur and extends into Tuva, Russia (Pfaènder & *alii*, 2000). It consists of Neoproterozoic ophiolite units, Lower Cambrian conglomerate, sandstone and limestone overlain by Silurian and Devonian shallow-marine sedimentary rocks. The northeastern continuation of the bedrock in Tuva is characterized by southeast-directed thrust sheets composed of serpentinite melange (Badarch & *alii*, 2002). These sequences are covered by lacustrine sediments, eolian sand dunes and alluvial fans (fig. 2). Furthermore, to the south-east along Khan Khukhiin mountainthe E-W strike-slip Bulnay fault is evident (Choi & *alii*, 2018).

The Bulnay fault (Rizza & *alii*, 2015) is often considered as a deep-seated ancient fault system that bounds Proterozoic continental crustal fragments (Badarch & *alii*, 2002), and is interpreted to have formed via north-south shortening of western Mongolia where central Mongolia moves eastward concerning Siberia (Walker & *alii*, 2008).

Fault system in combination with fissure eruptions has been activated in the Late Mesozoic. The formation of fault-related troughs occurred in the western zones of the Central Asian belt (Delvaux & *alii*, 1995; Dobretsov & *alii*, 1996). On the other hand, the Cenozoic north-south compression and shear movements along pre-existing northwest-trending faults led to the separation of the Altai and Kuznetsk-Sayan uplifts. The movement of these blocks

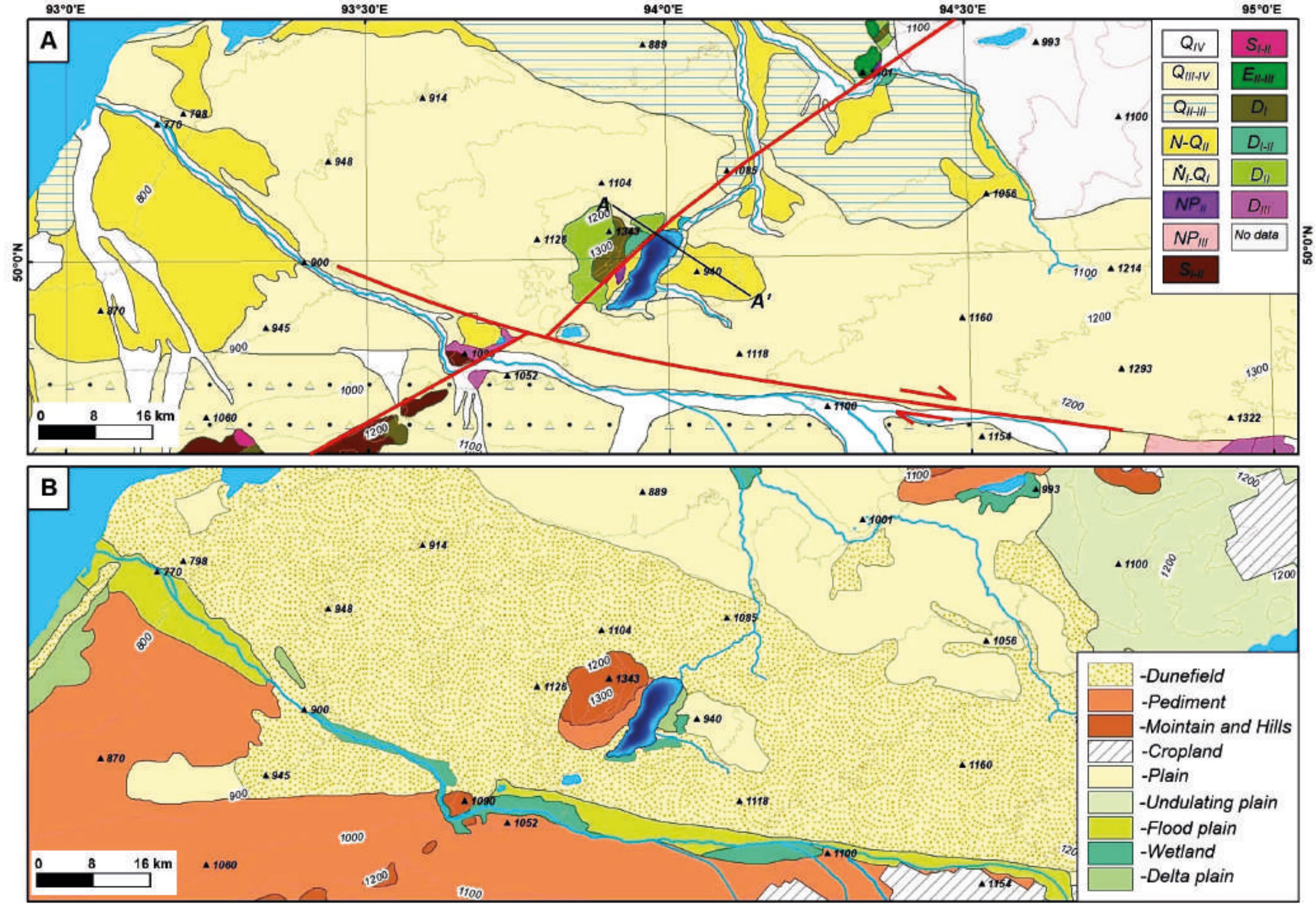

FIG. 2 - Geological map of Bayan Nuur depression (See for explanation of cross-section A–A' in text) B. Geomorphological map of Bayan Nuur depression (Modified after Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019).

northward and northwestward was impeded by structures of the southern folded margin of West Siberia. The development of the Cenozoic structure of the Altai resulted in the variable morphology of the troughs and their separating ridges (Delvaux & *alii*, 1995; Dobretsov & *alii*, 1996).

The general subsidence trend of the Uvs Nuur Basin has evolved since the Mesozoic (Khukhuudei & *alii*, 2020).

The long period of tectonic inactiveness, which favoured denudation processes, was replaced by a phase of active tectonic movements from the mid-late Pliocene (Khukhuudei, 2015). Neotectonic movement led to the pain to be subdivision into blocks that in some places, raised hundreds or thousands of meters (in Khan Khukhiin Mountain and other mountainous systems). The fingerprint on the relief of neotectonic movements corresponds to fault-aligned lakes and springs and surface ruptures. Moreover, these neotectonic movement played a significant role in the formation of the depression of lakes in the modern Uvs Nuur Basin (Delvaux & *alii*, 1995, Dobretsov & *alii*, 1996), with a relevant contribute bylarge meltwater flooding coming from mountain glaciers (Grunert & Lehmkuhl, 2004, An & *alii*, 2008, Walther, 2010, Huang & *alii*, 2018, Zhang & Feng, 2018, Klinge & Sauer, 2019).

Intense neotectonic activities have caused a significant change in the fluvial drainage system during the the late middle Pleistocene (Delvaux & *alii*, 1995, Dobretsov & *alii*, 1996). As a result of the uplift of the Khan Khukhii mountains, the Uvs Nuur depression became separated from the southern Khyargas Lake depression (Sevastianov & *alii*, 1993). The process of uplift of these mountains is directly related to the Bulnay fault. The rate of fault transition was determined by GPS data from the Upper Pleistocene to the Holocene at an average annual rate of 3.1 ± 1.7 mm and a maximum of 5.0 mm (Rizza & *alii*, 2015), (Choi & *alii*, 2018). During this time, relevant faults have formed in the Uvs Nuur Basin (Sevastianov & *alii*, 1993).

The geomorphological observations highlighted the presence of plains near around lake depression, residual hills, low to medium mountains (1000-1143 m a.s.l) in the western part of the lake, and transverse dune (Khukhuudei & *alii*, 2020). The Bayan Nuur depression is surrounded by Boorog Del Els dunes. These dunes were deposited by northwest winds during the Lateglacial period, i.e. 20-13 ka (Klein, 2001).

Table 1 - Morphometric parameters of Bayan Nuur depression.

N°	Morphometric parameters	Unit	Measurement value	Comment
1	Depression width	km	15,95	Parameters were created by the polygon and line tools of the Ruler menu of the Google Earth Pro software.
2	Depression length	km	21,67	
3	Depression area	km²	231,1	
4	Depression perimeter	km	60,4	
	Maximum elevation	m	1343	Depression maximum point
5	Minimum elevation	m	900	Depression minimum point
6	Energy of Relief	m	443	Depression minimum and maximum point high difference.
7	West coastline slope	Degree	19,7	Slope parameters were created by the patch tools of the Ruler menu of the Google Earth Pro software.
8	East coastline slope	Degree	2,1	
9	North coastline slope	Degree	5,2	
10	South coastline slope	Degree	1,9	

Table 2 - Criteria for determination of lake depressions in the Topography and Geomorphological criteria (Modified after Filosofov, 1967; Bold, 1987; Ben Hassen & *alii*, 2014; Jacques & *alii*, 2014; Enkhbold & *alii*, 2021b).

N°	Topographical map criteria	Description
1	To be a close of contours spacing as linear in the topographic map.	The determination of lake depressions of the study area identifies the 10 main criteria for the identification of faults, indicating their compliance or non-compliance.
	To occur the repeatedly abrupt change of high-altitude contours along linear view.	
3	To form linear view bathymetric isobaths of the lake depression	
4	The lake bathymetric isobaths form a straight line structure parallel to the main contours.	
5	The presence of abrupt changes in the contour lines.	
6	A series of hills lifted in a straight line on the steppe surface	
7	The course of a river, flowing on a steppe surface, has changed dramatically	
8	The origin of a series of freshwater lakes on the steppe surface	
9	The origin of springs in a straight line on the steppe surface	
10	A rectangular or linear shape on any part of the lake bed.	

MATERIALS AND METHODS

Data Source

The geomorphological features were individuated and mapped on topographic map (1: 100 000), Satellite imagines (Landsat OLI 30 m resolution, Aster GDEM 30 m resolution mps), SRTM 90 m elevation model grid and imagines coming from a geomagnetic survey (1: 500 000). To put all the data together, ArcGIS 10.3 and ENVI 5.3 software has been used.

Methods

To investigate the relationships between fault and the Bayan Nuur depression we employed a Morphometric analysis (Topographical analysis, Hypsometric Integral (HI) and Relief Slope (RSl) and Relief Energy (RE) analysis), along whit Spatial improvement of Remote Sensing and a geomagnetic survey.

Based on the morphometric parameters of Bayan Nuur in Uvs Province, it is determined whether the fault has impacted the shape of the lake depression. Morphometric parameters were checked and confirmed through fieldwork (table 1).

TOPOGRAPHICAL ANALYSIS - The Topographical Analysis has been performed using the topography map together with the geomorphological evidence detected in the field. Faults can be identified on the topographic map because they form abrupt changes in elements visible on the surface (Filosofov, 1967; Ozdemir & Bird, 2009; Abdullah & *alii*, 2010; Ben Hassen & *alii*, 2014; table 2).

HYPSOMETRIC INTEGRAL (HI), RELIEF SLOPE (RSL) AND RELIEF ENERGY (RE) ANALYSIS - Hypsometric Integral (HI) is one of the most widely used geomorphological analysis to to infer a possible tectonic influence in shaping a basins (Keller & Pinter, 2002). The formula for determining the hypsometric Integral (Eq. 1) is as follows (Mayer, 1990; Keller & Pinter, 2002).

$$HI\ (\%) = (Hmean-Hmin)/(Hmax-Hmin) \qquad (1)$$

Where Hmax, Hmean and Hmin expresses the maximum, the mean, and the minimum elevation. The higher value of the HI, surface area the more likely it is that faults have affected the basin development.

With the value of the HI, the indexes for determining faults are now considered. HI (%) indicates the probability that there may be a fracture, as follows: If

HI < 0.35, there is a low probability of fault presence, and if 0.35 < HI < 0.6, there is a probability of fault presence, and HI > 0.6, the probability of fault presence is high (Hassen & *alii*, 2014).

Signs of faults can be identified by the sharp gap in relative height and steep side slopes (Ezati & *alii*, 2021). From the analysis performed in the Bayan Nuur depression area, we can see the sharp gap between depression and convexity on the surface of the western coast of the lake depression is represented.

Relief Slope (RSl) analysis can be made to define a fault in a lake depression. Traces of a fault can be identified by the sharp gap in relative height and steep side slopes caused by the hypsometric cross-section profile (Jordan, 2003). RSl analysis can be used to define fault in lake depression (Onorato & *alii*, 2017; Korzhenkov & *alii*, 2020). A hypsometric cross-section can be identified on a topographic map or satellite map (DEM), defining the value of RSl (Hooper & *alii*, 2003; Hall, 1996).

The presence of faults can be determined by the following indications based on the surface slope in the lake depression. These include RSl < 5^0 low probability of faulting, 5^0 < RSl < 10^0, there can be a fault, RSl >10^0 high probability of fault presence (Bucknam & Anderson, 1979; Ganas & *alii*, 2005; Gürbüz & Gürer, 2008; Onorato & *alii*, 2017; Korzhenkov & *alii*, 2020; Hooper & *alii*, 2003). The appearance of a straight shape along the sloping surface indicates that it coincides with a fault. The more visible its length is, the more likely it is that there are faults.

We used spatial resolution imagery in Aster GDEM 30 m to calculate RSl values. It is possible to identify a fault in the steppe surface by morphological analysis based on the Relief Energy (RE) indications (Kot, 2018). RE is the difference in the relative height of the surface (Di Crescenzo & Santo, 2005). The fault can be identified by abrupt changes in the slope size in the steppe surface where the gap of the (RE) occurs (Kot, 2018; Di Crescenzo & Santo, 2005). The RE differences are calculated by the given formula below (Eq. 2):

$$RE = h_{max} - h_{min} \tag{2}$$

Where *RE* is the value of Relief Energy (in m), h_{max} – the maximum height of the surface (in m), h_{min} – the minimum height of the surface (in m).

Using the 3D elevation model grid map and hypsometric curve, the upper, lower and middle dimensions of the relative height of the surface can be determined. As the value of the RE (m) sharp increases, the steppe surface is more likely to be associated with the fault.

SPATIAL IMPROVEMENT OF REMOTE SENSING - The method of clarifying with all possible criterion that can be disclosed and integrating all their results based on the surface shape described on the aerial photo, which is taken from the Spatial improvement method of remote sensing (Nixon & Aguado, 2019).

The Bayan Nuur faults were defined on Landsat OLI Satellite map t(30-m resolution) by adopting a remote sensing directional filter matrix and high-frequency Sobel filter (Aqrawi, 2014).

The Sobel function backing an approximation to the Sobel edge improvement operator for satellite images (Eq. 3-4),

$$G_{jk} = /G_x / + / G_y / \tag{3}$$

$$\begin{aligned} G_x &= F_{j+1,\ k+1} + 2F_{j+1,\ k} + F_{j+1,\ k-1} - \left(F_{j-1,\ k+1} + 2F_{j-1,\ k} + F_{j-1,\ k-1}\right) \\ G_y &= F_{j-1,\ k-1} + 2F_{j,\ k-1} + F_{j+1,\ k-1} - \left(F_{j-1,\ k+1} + 2F_{j,\ k+1} + F_{j+1,\ k+1}\right) \end{aligned} \tag{4}$$

Where G_x and G_y are two images which at each point contain the horizontal and vertical derivative approximations, and also (*j*, *k*) are the coordinates of each pixel F_{jk} in the satellite images. This is equivalent to a convolution using the following masks (Eq. 5):

$$Ymask = \begin{matrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{matrix} \qquad Xmask = \begin{matrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{matrix} \tag{5}$$

All of the edge points in the result are set to zero. We have used horizontal and vertical Sobel filter using an Image Analysis toolbox of the ArcMap 10.3 version. To determine 2 directional line objects of satellite images, we have calculated a summary of both images (x and y directional images) which indicate line edges with the highest value as white.

Bayan Nuur fault was mapped by the directional filter command of the Convolution and Morphology menu at ENVI 5.3 remote sensing software (Canty, 2014) using the Landsat OLI satellite's resolution (30 m) satellite image.

AEROMAGNETIC SURVEY - To delineate geological boundaries and buried faults in the study area, spectral analysis and directional derivatives were applied to an aeromagnetic data set. The spectral analysis is a powerful tool to be used for separating regional and local geomagnetic anomalies. It must be used to follow 2-D forward and inverse Fourier transforms because anomaly separation is easily achieved in the wavenumber domain (Eq. 6-7):

$$g\left(k_x, k_y\right) = F\left[f\left(x, y\right)\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f\left(x, y\right) e^{-i\left(k_x x + k_y y\right)} dx\ dy \tag{6}$$

$$f\left(x, y\right) = F^{-1}\left[g\left(x, y\right)\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g\left(k_x, k_y\right)\ e^{i\left(k_x x + k_y y\right)} dk_x\ dk_y \tag{7}$$

Where, $f(x,y)$ is a geomagnetic field, $g(k_x,k_y)$ is the Fourier spectrum in the wave number domain, $g(k_x,k_y)$ are *x*, *y* components of wave number vector, *F*[] is forward Fourier transform and F^{-1}[] is inverse Fourier transform (Salem & *alii*, 2008).

The horizontal derivative of the geomagnetic field in a given direction enhances lateral changes in the magnetic field and attenuates its regional trend along that direction (Blakely & *alii*, 2005; Golynsky & *alii*, 2018). The gradient is a maximum or minimum where the magnetic susceptibility contrast is higher thus discontinuities perpendicular to the direction of derivation and defining more clearly the faults and the edges of structures (Moghaddam & *alii*,

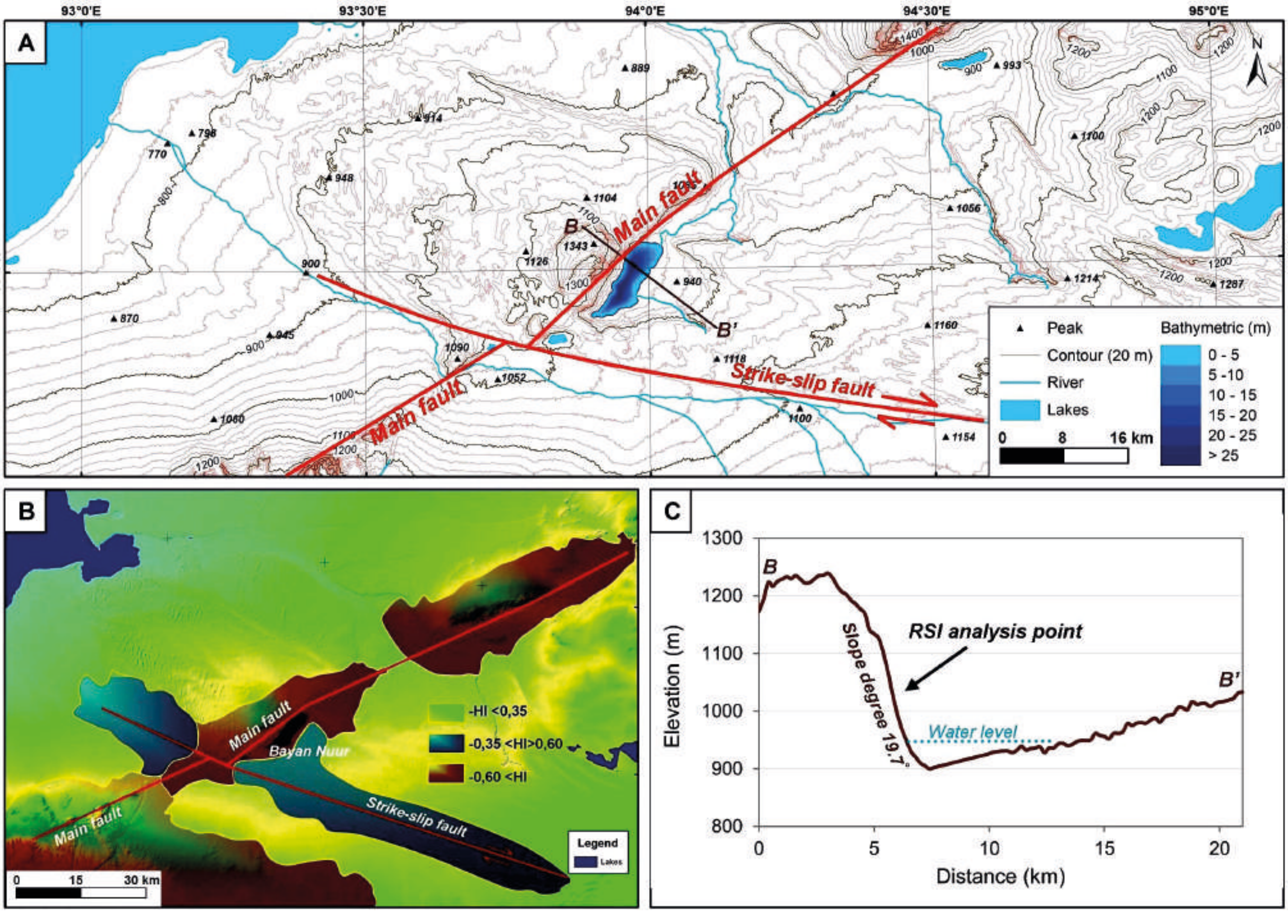

FIG. 3 - Morphometric analysis of Bayan Nuur depression A) Topographic analysis. B) HI analysis. C; RSI analysis.

2015). The horizontal gradient method is one of the most efficient approaches to estimate parameters of geological boundaries and buried fault. If $f(x,y)$ is the geomagnetic field then the horizontal gradient magnitude (*HGM*) can be calculated by:

$$HGM = \sqrt{\left(\frac{\partial f(x,y)}{\partial x}\right)^2 + \left(\frac{\partial f(x,y)}{\partial y}\right)^2} \qquad (8)$$

The interpretation of peak anomalies in the *HGM* field is somewhat complicated (Phillips, 2000). One need to take into account the following: regional magnetic field direction, the magnetization of rocks and geometrical parameters of faults (Eq. 8).

RESULTS

Interpretation of Morphometric Analysis

Lakes depression morphometric analysis of tectonics represents the main tools to evaluate and investigate neotectonic fault activities. The morphometric integrated analysis is reported in fig. 3.

The direction of the fault is SW-NE and influenced the origin of the lake depression. Fault tracks f on the surface around Bayan Nuur are related to detailed topographic elements: i) a linear close contour spacing in the topographic map in the Bayan Nuur, ii) an abrupt change of the Guramsan river channel, iii) an abrupt changes in the contour lines in the Bayan Nuur depression, iv) linear bathymetric isobaths in the Bayan Nuur, v) a linear structure created by bathymetric isobaths and a parallel structure of the contour lines in the western part of the Bayan Nuur. It is obvious that the fault caused a certain impact on the origin of the lake depression according to the topographic map analysis. The topographic analysis shows that the main fault on the west side of the Bayan Nuur depression is blocked by a bordering lateral fault.

An additional evidence of the fault of Bayan Nuur is the rapid direction change of the river channel. (Raoult & Meilliez, 1987; Replumaz & *alii*, 2001; Cowgill, 2007; Gasparini & *alii*, 2016; Racano & *alii*, 2020; Miccadei & *alii*, 2021; Bold, 1987; Thorndycraft & *alii*, 2008; Zhang & *alii*, 2004).

The marked deviation evident in the Guramsan river channel direction, west-south of Bayan Nuur, can be related to the presence of the fault of Bayan Nuur. The part where Guramsan river channel is bent coincides with the fault line of Bayan Nuur.

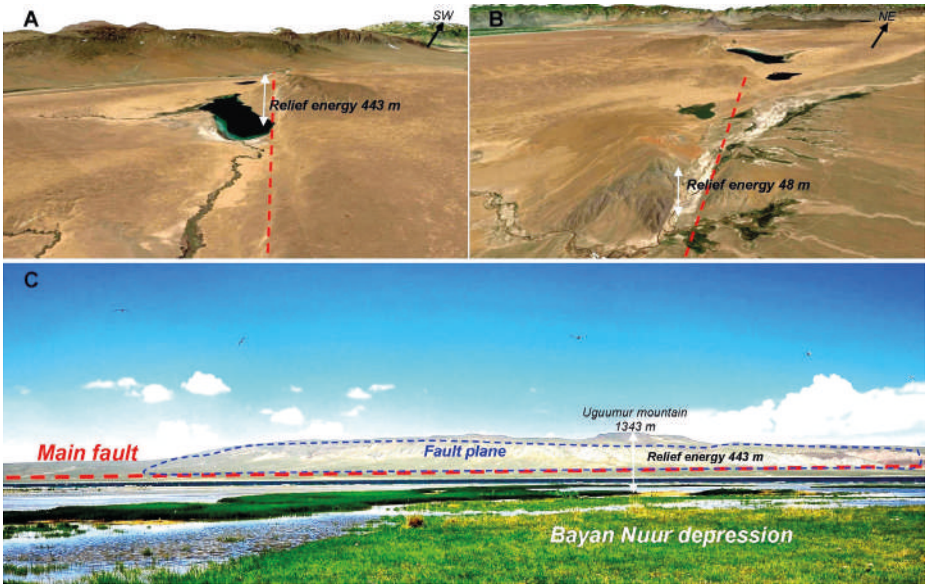

FIG. 4 - RE analysis. A. South west-facing view of the main fault B. North east-facing view of the main fault. C. East-facing view of the main fault, field photography of Bayan Nuur depression, Photo by Altanbold Enkhbold, 2018.

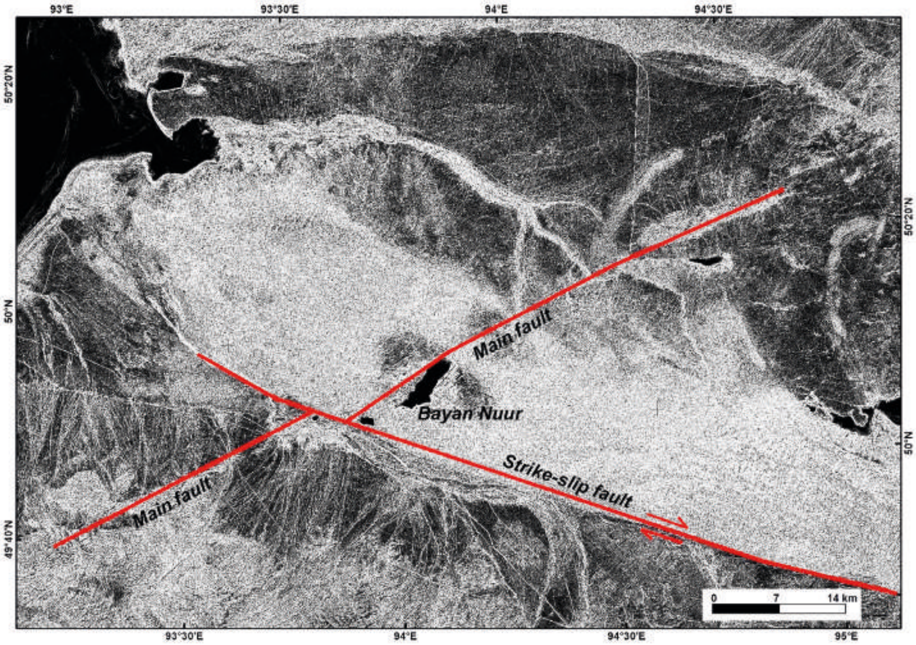

FIG. 5 - Landsat OLI Satellite (30m) image which processed by spatial improvement method has shown faults.

The water feeding the four lakes along the Bayan Nuur fault line, which is adry and cool climate region, is coming from the fault lines. The largest of these four lakes is Bayan Nuur.

The lake region has formed from more than 10 springs along the fault line in the south, east, and north of the Bayan Nuur depression. This geographical distribution is due to the fault geometry that has formed the Bayan Nuur depression. In terms of volume, the shape of Bayan Nuur is characterized by a deep depression in the western part of the lake and a relatively shallow depth in the eastern part. This depression shape is because Uguumur mountain lifted as the lake depression fell along the fault (fig. 3A).

The relationship between the changes in morphometric parameters proved the robust relationship that exists between the basin morphology and tectonic structures. When making HI calculation along the lake depression area, there is a high probability of having fault resulting the HI (%) equal to 0.673. The HI value was higher on the west side of the lake depression, indicating a high probability of faulting, consistently with the presence of the main fault that contributed to the morphology of the lake depression. In addition tom the HI data, results from other methods were put together for mapping the faults (fig. 3B).

Bayan Nuur depression is created by the elevation of the surface along the fault on the right side of the lake, but the surface is inclined in the opposite direction. This is more pronounced than a hypsometric curve. A value of 19.7 resulted from the RSl relatively to the Bayan Nuur depression. This indicates that the probability of fault is

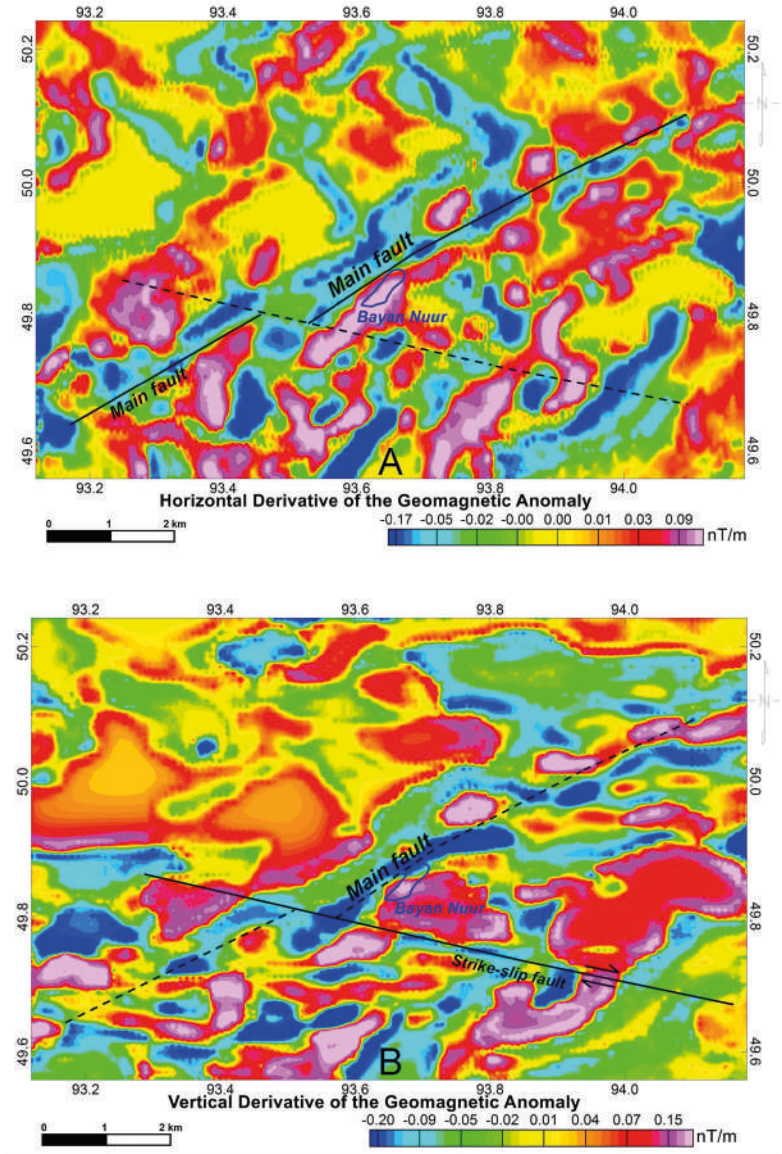

FIG. 6 - Geomagnetic anomaly in the vicinity of the faults. A. Relation between horizontal derivative map and main fault B. Relation between vertical derivative map and strike-slip fault.

high. The hypsometric curve of this lake shows that the hills are created by the uplift of the surface on the right side of Bayan Nuur, while the current Bayan Nuur depression is affected by slump triggered by thefault presence on the left side of the lake (fig. 3C).

This is clear from the relief energy (RE) patterns. The appearance of a straight structure on the surface resulted from the differences of this RE which emerged in the lake depression. The RE of the Bayan Nuur depression is 443 m. Due to the sharp difference of RE, a reverse fault may have formed in the Bayan Nuur depression. The sharp deflection of the Guramsan River is a major sign of strike-slip fault. According to the fault identified by the remote sensing and topographic analysis, there is a difference of 1090 m on the west side and 1052 m or 48 m on the east side of the Guramsan River. The Ikh Daagan (1299 m), Baga Daagan (1154 m), Uguumur (1343 m), and Ovoot (1085 m) hills were uplifted according to a straight line of movement from southwest to northeast of the Bayan Nuur depression. These hills were uplifted along the fault, while the Bayan Nuur depression is seated down (fig. 4).

Validation of Satellite and Geophysical mapping

The fault line, which was identified by the topographic map, was marked out by highlighting the linear spectrum on the satellite map with spatial improvement method. The fault line is located on the right side of the lake and it is consistent with the morphometric and topographic data (fig. 5).

The satellite map around Bayan Nuur shows that several lakes were created along this fault and there are elevated hills parallel to it. Calculated from the satellite imaging, the main fault length is 147.1 km. However, the length of the Strike-slip fault is 148.6 km.

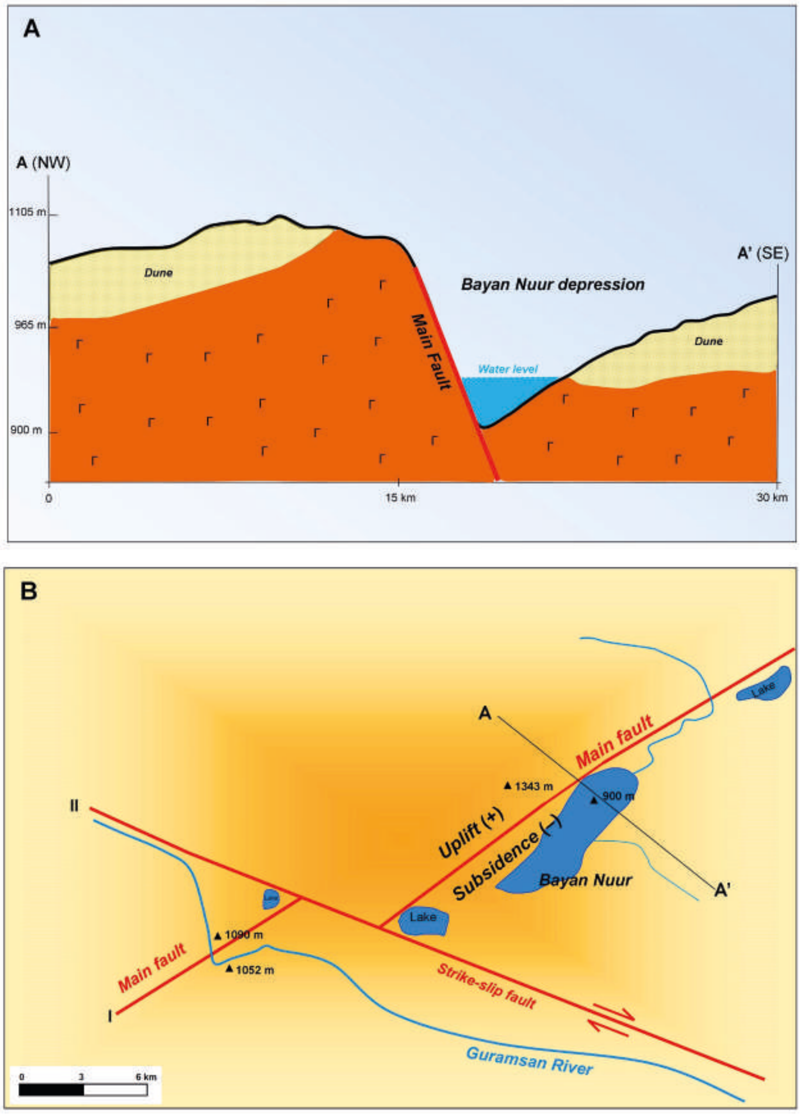

FIG. 7 - Bayan Nuur depression A. The cross-section of depression morphology of the Bayan Nuur B. Fault simplified model of the Bayan Nuur depression

A magnetic field anomaly effectively used for delineating tectonic fault (Agrawal & *alii*, 2004; Salem & *alii*, 2008). Directional derivatives of potential field data are the most common techniques to evaluate the spatial parameters of geologic bodies and tectonic elements. To understand the local tectonic settings of the Bayan Nuur, we have used regional scale (1:500 000) aeromagnetic anomaly data and its horizontal and vertical derivative maps (fig. 6).

The fault was identified based on the sharp difference in magnetic field anomaly. In the western part of the Bayan Nuur, a southwest-northeast striking fault can be identified. The horizontal map of the geomagnetic anomaly clearly shows the main fault. The vertical derivative maps of the geomagnetic anomaly highlight the strike-slip fault. Strike directions of these faults from magnetic anomaly maps were highly consistent with the results of the morphometric and remote sensing analysis

Relations between the depression cross-section and fault impact

Based on the cross-section and geological feature of the lake depression, we have defined the relations between the simplified model of the lake depression (fig. 7).

The western part of the lake depression uplifted along the main fault and the eastern part underwent to a subsidence, shaping in this way the Bayan Nuur depression. The lake depression model motivates underground water feeding along the fault line, the, so this could be the main reason for having freshwater in this lake An important spring is present at the foot of a dune slope near the eastern shore of Bayan Nuur, fed by groundwater that infiltrates from a lake 3.6 km to the west at 55 m higher altitude. According to hydrogeological estimates, the groundwater yield increases to 4.8-10.0 l/s (Paul, 2012). It is noted that the underground water through the fault alimented also many springs that drain into the Nariin River (Grunert & *alii*, 2000; Grunert & Lehmkuhl, 2004). The Bayan Nuur and lake depression origin is not connected with wind activity, but to local tectonics.

DISCUSSION

Uvs Nuur Basin water level change and Pleistocene environmental effect

The present location, water volume, and other patterns of the Central Asian lakes are quite different from that of the Pleistocene (Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019).

Early Pleistocene sediments were found in the pediment of the Togtokhiin Shil mountian as at the southern edge of the Uvs Nuur Basin (Walther & *alii*, 2020). According to Devjatkin & Murzaev (1989), during the early Pleistocene the water level in the Uvs Nuur basin reached an altitude of 1190 m above sea level.

During the Middle Pleistocene, the surrounding mountains were covered by large glaciers (Grunert & Lehmkuhl, 2004, An & *alii*, 2008, Walther, 2010, Huang & *alii*, 2018, Zhang & Feng, 2018, Klinge & Sauer, 2019). An huge amount of melting water from these glaciers inundated the Uvs Nuur Basin. The amount of water in the Uvs Nuur basin increased from the current water level to 40-240 m (Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019). The current water level in Uvs Nuur is 759 m a.s.l. The Bayan Nuur is 929 m a.s.l. During floods from glaciers, the level of Uvs Lake has risen to 999 m, which testifies a connection between these lakes (fig. 8).

Palaeoclimate reconstructions reports of a relatively dry early Holocene, a wet mid-Holocene and a dry late Holocene (Tian & *alii*, 2014, Rudaya & *alii*, 2021). According to Huang & *alii* (2018), Zhang & Feng (2018), Klinge & Sauer (2019), aridity occurred in western Mongolia and the surrounding areas during the Holocene, as suggested by spatial and temporal variations of lake sediments. Enhanced aridity occurred in the rain shadow of western Mongolia through the increasing influence of the westerly. In the Great Lakes Depression, lakes levels were decreased from the early Holocene until the beginning of the mid-Holocene. Periods of increased eolian transport and deposition occurred from the Late Glacial until the early Holocene, and again during the late Holocene. In between, during the early Holocene, erosion by eolian and fluvial processes took place over large areas. This changes in the environment is reflected in the evolution of the Bayan Nuur depression. Dunes were recorded up to an elevation of 30–35 m above the present Bayan Nuur level (Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019). The Boorog Deliin Els dune is distributed along the south and north coastline of Bayan Nuur. It is still unclear the fluctuation of the water level of the Bayan Nuur during this period because lake terraces on the shoreline of the Bayan Nuur were not found.

Modern lake water Level, characteristics and climatic effects

Lakes in large, closed tectonic depressions tend to be salt lakes in an arid climate (Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019). The high alkalinity is a general property of the surface waters in the Uvs Nuur Basin. The water pH of Uvs Lake is 9.5 (Grunert & Lehmkuhl, 2004; An & *alii*, 2008; Walther, 2010; Huang & *alii*, 2018; Zhang & Feng, 2018; Klinge & Sauer, 2019). The pH of the water of Bayan Nuur instead is 7.7 (Klein, 2001). In the case of the Bayan Nuur the salinity is 0.5-3 ‰, while that of Uvs Nuur is 5-20 ‰ (Klein, 2001). These properties of lake water are explained by a groundwater feeding along tectonic faults for the Bayan Nuur, and a minor and inconstant (subaerial) alimentation for the Bayan Nuur, where phenomena of drying up could also occur.

We have defined fluctuation of surface water level of the present Bayan Nuur, based on calculated the Normalized Difference Water Index (NDWI), using satellite imagery (Landsat TM and OLI). The Bayan Nuur has not lost water in surface area over the last 30 years (table 3). We consider that it confirms a groundwater support along the fault.

TABLE 3 - Modern area changes of the Bayan Nuur.

N°	Date	Surface area, km^2
1	1990.07.07	31,57
2	1994.09.04	31,61
3	1998.08.13	31,53
4	2002.08.09	31,61
5	2006.08.04	31,57
6	2010.08.31	31,69
7	2014.08.26	31,59
8	2018.08.21	31,54
9	2020.08.29	31,58
10	Average	31,59

The surface areas of some lakes in Central Asia, even in Mongolia, have been declined and dry up in recent years (An & *alii*, 2008; Szumińska, 2016; Chun & *alii*, 2020). A lake that was close to the area of Bayan Nuur was shrunk and dries up due to modern global warming. In recent years, Shargyn Tsagaan, Biger Lakes of Western Mongolia, Orog, Ulaan Lakes of Southern Mongolia, and Avarga Toson, Yakhi Lakes of Eastern Mongolia have completely dried up (Szumińska, 2016; Yang & *alii*, 2012; Kang & *alii*, 2015; Davaa, 2018; Mandakh & *alii*, 2020), while Central Mongolia's Ugii Nuur Lake has shrunk by more than 10 per cent (Sumiya & *alii*, 2020). Despite these dramatic changes in lake hydrology, Bayan Nuur surface area has remained stable in recent years due to the underground water supply, which formed in depression by fault.

The impact of fault on the origin of the North-West Mongolian lakes depression is important because it opens to a future updating of Mongolian lake classifications, providing more details about the factors influencing changes in lake water regimes, volumes, and areas. Determining the origin of the lake depression has also a relevant practical importance for the sustainable use of the lake as as a resource for local economy, and this study provides a modern starting point for future use and protection of the Bayan Nuur. This results of this work show that there is the need

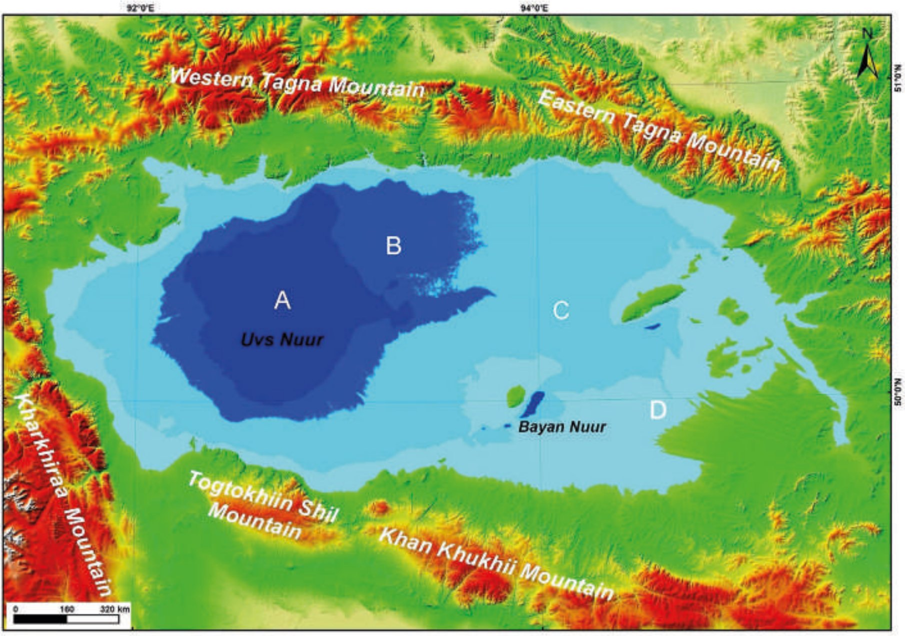

Fig. 8 - Uvs Nuur Basin water level change A. Recent level B. Late Pleistocene C. Middle Pleistocene D. Early Pleistocene (Modified after Deviatkin & Murzaev, 1989; Walther, 2010; Klinge & Sauer, 2019; Walther & *alii*, 2020)

to deeply understand the feeding sources of this lake water, calculating the relative percent and, on the basis of these analyses, to implement the future methods for water balance calculation.

Relations between tectonic fault and lake depression in Mongolia

The depressions of most Mongolian lakes are thought to berelated to tectonics (Tserensodnom, 1971). Even though faults have been extensively studied in Mongolia, no studies have been undertaken to investigate the relationship between lake depressions and faults. As a result, it is necessary to plan an extensive research throughout Mongolia, in order to provide a modern and updated classification of depressions, correcting the errors and flaws in the previous analyses.

According to geomorphological evidence of Mongolian large lake depressions, graben and rift in the framework of major tectonic features are considered in the formation of mountain lakes. However, also lakes formed in the steppe areas can be connected to faults presence. Bayan Nuur is one such example.

CONCLUSION

Bayan Nuur depression corresponds to a wide semi-graben structured according to a SW-NE fault system. Morphometric and remote sensing analyses have been used to locate the local tectonics elements, and this hypothesis has been confirmed by the interpretation of an aeromagnetic survey data. The results of this work now provides an explanation of the lake water regime and its physio-chemical characteristics, different for those of other lake in the region. The presence of a stable lake in this dry region of northwest Mongolia is granted by the groundwater fed along the fault line. The length of the Bayan Nuur main fault is 147.1 km and 4 lakes have been formed along the fault, of which the Bayan Nuur is the largest one. Bayan Nuur water surface area has remained stable in recent years due to the underground water supply.

This study represents an example of how the Mongolian lakes formation can be updated in the light of a clearer understanding of the regional morphotectonics supported by geomorphological and remote sensing analyses. A new lake classification, based on a modern approach, can open to better models of lake regimes and water resources exploitation, but even to a more robust forecasting of future evolution also in the light of ongoing global warming.

REFERENCES

Abdullah A., Akhir J.M. & Abdullah I. (2010) - *Automatic mapping of lineaments using shaded relief images derived from digital elevation model (DEMs) in the Maran–Sungi Lembing area, Malaysia.* Electronic Journal of Geotechnical Engineering, 15, 949-958.

Agrawal P., Pandey O. & Chetty T. (2004) - *Aeromagnetic anomalies, lineaments and seismicity in Koyna-Warna region.* Journal of Indian Geophysical Union, 8, 229-242.

An C.B., Chen F.H. & Barton L. (2008) - *Holocene environmental changes in Mongolia: A review.* Global and Planetary Change, 63, 283-289.

Aqrawi A.A. (2014) - *Adaptive Sobel based edge detection for enhaced fault segmentation.* IPTC 2014: International Petroleum Technology Conference. European Association of Geoscientists & Engineers, 1-6.

Badarch G., Cunningham W.D. & Windley B.F. (2002) - *A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia.* Journal of Asian Earth Sciences, 21, 87-110.

Batchuluun E. (2020) - *The Physical Geography of Mongolia.* Ulaanbaatar, Munkhiin Useg printing, 240 pp.

Bayasgalan A., Jackson J., Ritz J.F. & Carretier S. (1999) - *'Forebergs', flower structures, and the development of large intra-continental strike-slip faults: the Gurvan Bogd fault system in Mongolia*. Journal of Structural Geology, 21, 1285-1302.

Ben Hassen M., Deffontaines B. & Turki M.M. (2014) - *Recent tectonic activity of the Gafsa fault through morphometric analysis: Southern Atlas of Tunisia*. Quaternary International, 338, 99-112.

Blakely R.J., Brocher T.M. & Wells R.E. (2005) - *Subduction-zone magnetic anomalies and implications for hydrated forearc mantle*. Geology, 33, 445-448.

Bold Y. (1987) - *Research of Geomorphology and Concept*, Ulaanbaatar, State Press, 23-29.

Bucknam R. & Anderson R. (1979) - *Estimation of fault-scarp ages from a scarp-height–slope-angle relationship*. Geology, 7, 11-14.

Canty M.J. (2014) - *Image analysis, classification and change detection in remote sensing: with algorithms for ENVI/IDL and Python*. New York, Crc Press, 532 pp.

Carretier S., Ritz J.F., Jackson J. & Bayasgalan A. (2002) - *Morphological dating of cumulative reverse fault scarps: examples from the Gurvan Bogd fault system, Mongolia*. Geophysical Journal International, 148, 256-277.

Choi J.H., Klinger Y., Ferry M., Ritz J.f., Kurtz R., Rizza M., Bollinger L., Davaasambuu B., Tsend-Ayush N. & Demberel S. (2018) - *Geologic inheritance and earthquake rupture processes: The 1905 M≥ 8 Tsetserleg-Bulnay strike-slip earthquake sequence, Mongolia*. Journal of Geophysical Research: Solid Earth, 123, 1925-1953.

Chun X., Qin F.y., Zhou H.J., Dan D., Xia Y.Y. & Ulambadrakh K. (2020) - *Effects of climate variability and land use/land cover change on the Daihai wetland of central Inner Mongolia over the past decades*. Journal of Mountain Science, 17, 3070-3084.

Cohen A.S. (2003) - *Paleolimnology: the history and evolution of lake systems*. Oxford, Oxford University Press, 416 pp.

Cowgill E. (2007) - *Impact of riser reconstructions on estimation of secular variation in rates of strike-slip faulting: Revisiting the Cherchen River site along the Altyn Tagh Fault, NW China*. Earth and Planetary Science Letters, 254, 239-255.

Cunningham D. (2005) - *Active intracontinental transpressional mountain building in the Mongolian Altai: Defining a new class of orogen*. Earth and Planetary Science Letters, 240, 436-444.

Cunningham D. (2013) - *Mountain building processes in intracontinental oblique deformation belts: Lessons from the Gobi Corridor, Central Asia*. Journal of Structural Geology, 46, 255-282.

Cunningham D., Davies S. & Badarch G. (2003a) - *Crustal architecture and active growth of the Sutai Range, western Mongolia: a major intracontinental, intraplate restraining bend*. Journal of Geodynamics, 36, 169-191.

Cunningham D., Dijkstra A., Howard J., Quarles A. & Badarch G. (2003b) - *Active intraplate strike-slip faulting and transpressional uplift in the Mongolian Altai*. Geological Society, London, Special Publications, 210, 65-87.

Davaa G. (2018) - *Assessment of Water Resources of Lakes in Mongolia Based on Land and Satellite Data Information*. Ulaanbaatar, Information and Research Institute of Meteorology Hydrology and Environment of Mongolia. Project report.

Delvaux D., Theunissen K., Van Der Meer R. & Berzin N. (1995) - *Dynamics and paleostress of the Cenozoic Kurai-Chuya depression of Gorny Altai (South Siberia): tectonic and climatic control*. Russian Geology and Geophysics C/C of Geologiia I Geofizika, 36, 26-45.

Devjatkin E. & Murzaev E. (1989) - *The late Cenozoic of Mongolia. The Mongolian Altai*. Nauka, 42-47.

Di Crescenzo G. & Santo A. (2005) - *Debris slides–rapid earth flows in the carbonate massifs of the Campania region (Southern Italy): morphological and morphometric data for evaluating triggering susceptibility*. Geomorphology, 66, 255-276.

Dobretsov N.L., Buslov M.M., Delvaux D., Berzin N.A. & Ermikov V.D. (1996) - *Meso- and Cenozoic Tectonics of the Central Asian Mountain Belt: Effects of Lithospheric Plate Interaction and Mantle Plumes*. International Geology Review, 38, 430-466.

Dorofeyuk N. & Tarasov P. (1998) - *Vegetation and lake levels in Northern Mongolia in the last 12 500 years as indicated by data of pollen and diatom analyses*. Stratigraphy and Geological Correlation, 6, 70-83.

Enkhbold A., Khukhuudei U. & Doljin D. (2021a) - *Morphological classification and origin of lake depressions in Mongolia*. Proceedings of the Mongolian Academy of Sciences, 62 (02), 35-43.

Enkhbold A., Khukhuudei U., Kusky T., Tsermaa B. & Doljin D. (2021b) - *Depression morphology of Bayan Lake, Zavkhan province, Western Mongolia: implications for the origin of lake depression in Mongolia*. Physical Geography, 1-26.

Ezati M., Gholami E. & Mousavi S.M. (2021) - *Tectonic activity level evaluation using geomorphic indices in the Shekarab Mountains, Eastern Iran*. Arabian Journal of Geosciences, 14, 1-16.

Faghih A., Samani B., Kusky T., Khabazi S. & Roshanak R. (2012) - *Geomorphologic assessment of relative tectonic activity in the Maharlou Lake Basin, Zagros Mountains of Iran*. Geological Journal, 47, 30-40.

Filosofov V.P. (1967) - *The value of the map of potential relief energy for geomorphological and neotectonic studies*. Methods geomorphological research Novosibirsk, Science. Sib. Department, 193-198.

Florinsky I.V. (1996) - *Quantitative topographic method of fault morphology recognition*. Geomorphology, 16, 103-119.

Ganas A., Pavlides S. & Karastathis V. (2005) - *DEM-based morphometry of range-front escarpments in Attica, central Greece, and its relation to fault slip rates*. Geomorphology, 65, 301-319.

Gasparini N.M., Fischer G.C., Adams J.M., Dawers N.H. & Janoff A.M. (2016) - *Morphological signatures of normal faulting in low-gradient alluvial rivers in south-eastern Louisiana, USA*. Earth Surface Processes and Landforms, 41, 642-657.

Golynsky A.V., Ferraccioli F., Hong J.K., Golynsky D.A., Von Frese R.R.B., Young D.A., Blankenship D.D., Holt J.W., Ivanov S.V., Kiselev A.V., Masolov V.N., Eagles G., Gohl K., Jokat W., Damaske D., Finn C., Aitken A., Bell R.E., Armadillo E., Jordan T.A., Greenbaum J.S., Bozzo E., Caneva G., Forsberg R., Ghidella M., Galindo-Zaldivar J., Bohoyo F., Martos Y.M., Nogi Y., Quartini E., Kim H.R. & Roberts J.L. (2018) - *New Magnetic Anomaly Map of the Antarctic*. Geophysical Research Letters, 45, 6437-6449.

Grunert J., Klein M., Stumböck M. & Dasch M. (1999) - *Bodenentwicklung auf Altdünen im Uvs Nuur Becken*. Erde, 130, 97-115.

Grunert J. & Lehmkuhl F. (2004) - *Aeolian sedimentation in arid and semi-arid environments of Western Mongolia*. In: Smykatz-Kloss W. & Felix-Henningsen P. (Eds.), Paleoecology of Quaternary Drylands, Lecture Notes in Earth Sciences, 102. Berlin-Heidelberg, Springer, 195-218.

Grunert J., Lehmkuh F. & Walther M. (2000) - *Paleoclimatic evolution of the Uvs Nuur basin and adjacent areas (Western Mongolia)*. Quaternary International, 65-66, 171-192.

Gürbüz A. & Gürer Ö.F. (2008) - *Tectonic Geomorphology of the North Anatolian Fault Zone in the Lake Sapanca Basin (eastern Marmara Region, Turkey)*. Geosciences Journal, 12, 215-225.

Hall J.K. 1996. *Digital topography and bathymetry of the area of the Dead Sea Depression*. Tectonophysics, 266, 177-185.

Hooper D.M., Bursik M.I. & Webb F.H. (2003) - *Application of high-resolution, interferometric DEMs to geomorphic studies of fault scarps, Fish Lake Valley, Nevada–California, USA.* Remote Sensing of Environment, 84, 255-267.

Hu S., Qiu H., Pei Y., Cui Y., Xie W., Wang X., Yang D., Tu X., Zou Q., Cao P. & Cao M. (2019) - *Digital terrain analysis of a landslide on the loess tableland using high-resolution topography data.* Landslides, 16, 617-632.

Hu Y.N., Peng J., Liu Y. & Tian L. (2018) - *Integrating ecosystem services trade-offs with paddy land-to-dry land decisions: A scenario approach in Erhai Lake Basin, southwest China.* Science of The Total Environment, 625, 849-860.

Huang X., Peng W., Rudaya N., Grimm E.C., Chen X., Cao X., Zhang J., Pan X., Liu S., Chen C. & Chen F. (2018) - *Holocene Vegetation and Climate Dynamics in the Altai Mountains and Surrounding Areas.* Geophysical Research Letters, 45, 6628-6636.

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, 213, 13-23.

Jordan G. (2003) - *Morphometric analysis and tectonic interpretation of digital terrain data: a case study.* Earth Surface Processes and Landforms, 28, 807-822.

Kang S., Lee G., Togtokh C. & Jang K. (2015) - *Characterizing regional precipitation-driven lake area change in Mongolia.* Journal of Arid Land, 7, 146-158.

Keller E. & Pinter N. (2002) - *Active Tectonics: Upper Saddle River.* New Jersey, Prentice Hall, 362 pp.

Khukhuudei U. (2015) - *The origin of the Great Lakes Basin, Western Mongolia: not the super flooding, but glaciated super valley.* Geography and tourism, 3(1), 39-47.

Khukhuudei U., Kusky T., Otgonbayar O. & Wang L. (2020) - *The Early Palaeozoic 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, 55, 2129-2149.

Klein M. (2001) - *Binnendünen im nördlichen Zentralasien. Uws Nuur Becken, nordwestliche Mongolei.* Mainzer geographische Studien 47, Mainz, 182 pp.

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, 210, 26-50.

Korzhenkov A.M., Strelnikov A.A., Deev E.V., Korzhenkova L.A., Liu J., Mazeika J.V., Rogozhin E.A., Rodina S.N., Turova I.V., Usmanova M.T. & Fortuna A.B. (2020) - *Adyr Faults: Generators of Strong Earthquakes in the Lake Issyk-Kul Depression (a Case Study of the Kultor Fault Zone).* Seismic Instruments, 56, 599-619.

Kot R. (2018) - *A comparison of results from geomorphological diversity evaluation methods in the Polish Lowland (Toruń Basin and Chełmno Lakeland).* Geografisk Tidsskrift-Danish Journal of Geography, 118, 17-35.

Lamb M.A., Hanson A.D., Graham S.A., Badarch G. & Webb L.E. (1999) - *Left-lateral sense offset of Upper Proterozoic to Paleozoic features across the Gobi Onon, Tost, and Zuunbayan faults in southern Mongolia and implications for other central Asian faults.* Earth and Planetary Science Letters, 173, 183-194.

Mandakh U., Ganbat D., Batsaikhan B., Dalantai S., Adiya Z., Bayasgalan N., Bayarsaikhan S., Borjigidai A. & LonG C. (2020) - *Impacts of Rapid Changes of Land Cover and Intensive Human Activities on Avarga Toson Lake Area, Mongolia.* Sustainability, 12, 6070.

Mathew M.J., Menier D., Siddiqui N., Kumar S.G. & Authemayou C. (2016) - *Active tectonic deformation along rejuvenated faults in tropical Borneo: Inferences obtained from tectono-geomorphic evaluation.* Geomorphology, 267, 1-15.

Mat V.D. (1993) - *The structure and development of the Baikal rift depression.* Earth-Science Reviews, 34, 81-118.

Mayer L. (1990) - *Introduction to quantitative geomorphology: an exercise manual,* Prentice-Hall International, 380 pp.

Miccadei E., Carabella C. & Paglia G. (2021) - *Morphoneotectonics of the Abruzzo Periadriatic Area (Central Italy): Morphometric Analysis and Morphological Evidence of Tectonics Features.* Geosciences, 11, 397.

Moghaddam M., Sabseparvar M., Mirzaei S. & Heydarian N. (2015) - *Interpretation of aeromagnetic data to locate buried faults in North of Zanjan Province. Iran.* Journal of Geophysics and Remote Sensing, 4, 2.

Naumann S. & Walther M. (2000) - *Mid-Holocene lake-level fluctuations of Bayan Nuur (North-west Mongolia).* Marburger Geographische Schriften, 135, 15-27.

Nixon M. & Aguado A. (2019) - *Feature extraction and image processing for computer vision.* London, Academic Press, 621 pp.

Onorato M.R., Coronato A., Perucca L.P., Rabassa J. & López R. (2017) - *Morpho-bathymetry and surficial morphology of Udaeta Lake, along the Magallanes-Fagnano fault system, Tierra del Fuego, Argentina.* Journal of South American Earth Sciences, 76, 1-10.

Osterkamp W.R. & Wood W.W. (1987) - *Playa-lake basins on the Southern High Plains of Texas and New Mexico: Part I. Hydrologic, geomorphic, and geologic evidence for their development.* GSA Bulletin, 99, 215-223.

Ozdemir H. & Bird D. (2009) - *Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point of floods.* Environmental geology, 56, 1405-1415.

Paul M. (2012) - *Limnological aspects of the Uvs Nuur Basin in northwest Mongolia.* Saechsische Landesbibliothek-Staats-und Universitaetsbibliothek Dresden, PhD Thesis, 186 pp.

Pfaènder J., Kroèner A., Jochum K., Kozakov I. & Oidup C. (2000) - *Ocean crust formation and crustal accretion in south-central Asia: Neoproterozoic to Early Palaeozoic ophiolite and island arc systems in Tuva.* IGCP-420, Continental growth in the Phanerozoic: Evidence from Central Asia. Abstracts and Excursion Guidebook Geosciences, Rennes, 63-64.

Phillips J. (2000) - *Locating magnetic contacts: a comparison of the horizontal gradient, analytic signal, and local wavenumber methods.* SEG Technical Program Expanded Abstracts 2000. Society of Exploration Geophysicists.

Pike R.J. & Wilson S.E. (1971) - *Elevation-Relief Ratio, Hypsometric Integral, and Geomorphic Area-Altitude Analysis.* Geological Society of America Bulletin, 82, 1079-1084.

Racano S., Fubelli G., Centamore E., Bonasera M. & Dramis F. (2020) - *Geomorphological detection of surface effects induced by active blind thrusts in the southern Abruzzi peri-Adriatic belt (Central Italy).* Geografia Fisica e Dinamica Quaternaria, 43, 3-13.

Raoult J.F. & Meillie F. (1987) - *The variscan front and the midi fault between the channel and the meuse river.* Journal of Structural Geology, 9, 473-479.

Replumaz A., Lacassin R., Tapponnier P. & Leloup P.H. (2001) - *Large river offsets and Plio-Quaternary dextral slip rate on the Red River fault (Yunnan, China).* Journal of Geophysical Research: Solid Earth, 106, 819-836.

Rizza M., Ritz J.F., Prentice C., Vassallo R., Braucher R., Larroque C., Arzhannikova A., Arzhannikov S., Mahan S. & Massault M. (2015) - *Earthquake geology of the Bulnay fault (Mongolia).* Bulletin of the Seismological Society of America, 105, 72-93.

Rudaya N., Nazarova L., Frolova L., Palagushkina O., Soenov V., Cao X., Syrykh L., Grekov I., Otgonbayar D. & Bayarkhuu B. (2021) - *The link between climate change and biodiversity of lacustrine inhabitants and terrestrial plant communities of the Uvs Nuur Basin (Mongolia) during the last three millennia.* The Holocene, 09596836211019093.

Salem A., Williams S., Fairhead D., Smith R. & Ravat D. (2008) - *Interpretation of magnetic data using tilt-angle derivatives.* GEOPHYSICS, 73, L1-L10.

Schallenberg M., De Winton M.D., Verburg P., Kelly D.J., Hamill K.D. & Hamilton D.P. (2013) - *Ecosystem services of lakes. Ecosystem services in New Zealand: conditions and trends.* Manaaki Whenua Press, Lincoln, 203-225.

Sevastianov D., Seliverstov J. & CernovA G. (1993) - *Landscape development in the Uvs Nuur basin.* Vestnik SPbGU Ser, 7, 71-81.

Sevastyanov D.V., & Dorofeyuk N.I. (1992) - *The history of the water ecosystem of Mongolia.* Izvestiâ Vsesoûznogo Geograficeskogo Obsestva, 124, 123-138.

SHAMIR G. (2006) - *The active structure of the Dead Sea Depression.* Special Papers, Geological Society of America, 401, 15.

Síkhegyi F. (2002) - *Active structural evolution of the western and central parts of the Pannonian basin: a geomorphological approach.* EGU Stephan Mueller Special Publication Series, 3, 203-216.

Singh O., Sarangi A. & Sharma M.C. (2008) - *Hypsometric integral estimation methods and its relevance on erosion status of north-western lesser Himalayan watersheds.* Water Resources Management, 22, 1545-1560.

Sizykh A., Voronin V., Azovsky M. & Sizykh S. (2012) - *Paragenese of the vegetation in ecosystems contact zones (in Lake Baikal basin).* Natural Science, 4, 271-275.

Souza-Filho P.W.M., Pinheiro R.V.L., Costa F.R., Guimarães J.T.F., Sahoo P.K., Silva M.S. & Silva C.G. (2020) - *The role of fault reactivation in the development of tropical montane lakes.* Earth Surface Processes and Landforms, 45, 3732-3746.

Sumiya E., Dorjsuren B., Yan D., Dorligjav S., Wang H., Enkhbold A., Weng B., Qin T., Wang K., Gerelmaa T., Dambaravjaa O., Bi W., Yang Y., Ganbold B., Gedefaw M., Abiyu A. & Girma A. (2020) - *Changes in Water Surface Area of the Lake in the Steppe Region of Mongolia: A Case Study of Ugii Nuur Lake, Central Mongolia.* Water, 12, 1470.

Szumińska D. (2016*) - Changes in surface area of the Böön Tsagaan and Orog lakes (Mongolia, Valley of the Lakes, 1974–2013) compared to climate and permafrost changes.* Sedimentary Geology, 340, 62-73.

Theilen-Willige B., Aher S.P., Gawali P.B. & venkata L.B. (2016) - *Seismic Hazard Analysis along Koyna Dam Area, Western Maharashtra, India: A Contribution of Remote Sensing and GIS.* Geosciences, 6, 20.

Thorndycraft V.R., Benito G. & Gregory K.J. (2008) - *Fluvial geomorphology: A perspective on current status and methods.* Geomorphology, 98, 2-12.

Tian F., Herzschuh U., Telford R.j., Mischke S., Van Der Meeren T. & Krengel M. (2014) - *A modern pollen-climate calibration set from central-western Mongolia and its application to a late glacial-Holocene record.* Journal of Biogeography, 41, 1909-1922.

Tsegmid S. (1969) - *Physical Geography of Mongolia.* The Institute of Geography & Permafrost, Mongolian Academy of Sciences. Ulaanbaatar, State Press, 56-59.

Tserensodnom J. (1971) - *Lakes of Mongolia. Ulaanbaatar,* Academy of Science, MPR (in Mongolian), 405 pp.

Tserensodnom J. (2000) - *Catalog of lakes of Mongolia.* The Institute of Geography, Mongolian Academy of Sciences. Ulaanbaatar, Shuvuun Saaral Publishing, 192 pp.

Walker R., Molor E., Fox M. & Bayasgalan A. (2008) - *Active tectonics of an apparently aseismic region: distributed active strike-slip faulting in the Hangay Mountains of central Mongolia.* Geophysical Journal International, 174, 1121-1137.

Walker R.T., Nissen E., Molor E. & Bayasgalan A. (2007) - *Reinterpretation of the active faulting in central Mongolia.* Geology, 35, 759-762.

Walther M. (2010) - *Paleo-Environmental Changes in the Uvs Nuur Basin (Northwest-Mongolia).* Exploration of Biological Resources of Mongolia, 11, 267-279.

Walther M., Horn W. & Dashtseren A. (2020) - *Uvs Nuur: A Sentinel for Climate Change in Eastern Central Asia.* Large Asian Lakes in a Changing World. Cham, Springer, 237-241.

Wang A., Wang G., Li D., Xie D. & Liu D. (2009) - *Tectonic Landform of Quaternary Lakes and Its Implications for Deformation in the Northern Qinghai-Tibet Plateau.* Acta Geologica Sinica - English Edition, 83, 121-129.

Wetzel R.G. (2001) - *Limnology Lake and River Ecosystems*, Third Edition. London, Academic Press, 1006 pp.

Yang H., Lee E., Do N., Ko D. & Kang S. (2012) - *Seasonal and inter-annual variations of lake surface area of Orog Lake in Gobi, Mongolia during 2000–2010.* Korean Journal of Remote Sensing, 28, 267-276.

Zhang D. & Feng Z. (2018) - *Holocene climate variations in the Altai Mountains and the surrounding areas: A synthesis of pollen records.* Earth-Science Reviews, 185, 847-869.

Zhang J., Li C., Zhang M. & Liu G. (2011) - *Geomorphologic analysis of the Golmud River drainage basin based on hypsometric integral value.* Journal of Mountain Science, 29, 257-268.

Zhang K., Liu K. & Yang J. (2004) - *Asymmetrical valleys created by the geomorphic response of rivers to strike-slip fault.* Quaternary Research, 62, 310-315.

(Ms. received 25 January 2021, accepted 05 December 2021)