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The Tsakhiurtyn Hundi Lakeland – geological and geomorphological factors influencing the development of small lakes south of the Arts Bogd Massif (Gobi-Altai Range, Mongolia)

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This study analyses the geological and geomorphological conditions in which palaeolakes developed in the southern margin of the Arts Bogd Massif (Mongolia), identifying and documenting fifteen dry lakes in the Shereegiin Gashuun Basin, in the area called the Tsakhiurtyn Hundi Lakeland. The lake basins were formed by a combination of tectonic and aeolian processes. Their occurrence is closely related to regional fault structures and subsidence of the bedrock within a pull-apart basin. Aeolian processes, including deflation and sedimentation of silts, further influenced the palaeolakes' morphology and their evolution. Field study and remote data analysis have made it possible to determine the factors shaping the dynamics of the alluvial-pluvial processes involved, and the structural conditions determining the formation of the basins. Nowadays, the lakes are dry, and their bottoms are filled with clayey and clayey-sandy sediments with clearly marked palaeoshorelines. Analyses have shown that geomorphological processes such as aeolian erosion and the accumulation of alluvial fan deposits significantly influenced the geometry of the former reservoirs.

Key words: lacustrine environment, remote sensing, palaeolakes, morphological analysis, Mongolia.

INTRODUCTION

Among the key factors determining the development of lakes are the geological and geomorphological conditions. The lithological and facies record of lake deposits allows interpretation of these conditions (Cheng-Bang et al., 2008; Lee et al., 2013). Studies of lake deposits can provides information on changes in the local environment, and can also document global events (Sevastyanov et al., 1989; Sletten et al., 2003; Smith et al., 2004; Capra et al., 2023; Witze, 2023). Interpretations of the origin and development of lake basins can also provide a key to determining the dynamics of landscape development in the surrounding areas (Owen et al., 1997). Studies on the genesis of lakes and their dynamics and extents over time are of key importance for the economy and for functioning of human societies in regions characterized by a dry continental climate. There have been several such studies in Mongolia (Sevastyanov et al., 1989; Naumann and Walther, 2000; Komatsu et al., 2001; Stolz et al., 2012; Felauer et al., 2012; Szumińska, 2016; Walther et al., 2016; Yu et al., 2017; Orkhonselenge and Bulgan, 2021; Enkhbold et al., 2025). As a result of these studies, it turned out that many Mongolian lakes have a tectonic origin (Cunningham, 2005; Enkhbold et al., 2022a, b).

Southern Mongolia has the second highest number of documented lakes in the country, comprising 24.7% of them (Orkhonselenge et al., 2022). Previous publications have usu-

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ally focused on the study of large lakes in this region that still exist today, including Biger Nuur, Orog Nuur, Shargiin Tsagaan Nuur, Taatsiin Tsagaan Nuur and Ulaan Nuur (e.g., Tserensodnom, 2000; Komatsu et al., 2001; Kang et al., 2015; Orkhonselenge et al., 2018a, b), while small lakes have occasionally been studied (Grunert et al., 2009). The latest classification (Orkhonselenge et al., 2022) shows that, in Mongolia, 65.9% of lakes are prairie lakes, 74.6% are low-altitude lakes, and 85% are very small lakes. In addition, 56% of lakes are ephemeral, including playa lakes, of which 15.5% are found in southern Mongolia. Shallow lakes dominate (96.6%), and 70.3% are closed lakes, mainly in the south of the country (28.6%).

In this paper, we describe the results of geological and geomorphological mapping, structural and landform analyses, and the evolution of 15 palaeolakes south of the Arts Bogd Massif on the border of Övörkhangai and Ömnögovi provinces (Fig. 1). We term this area the Tsakhiurtyn Hundi Lakeland. The lakeland neighbours the Tsakhiurtyn Hundi (Flint Valley), which is one of the most extensive prehistoric sites of Central Asia, owing its name to the presence of abundant flint-bearing outcrops and the resulting innumerable flint artefacts (Derevianko et al., 2002; Masojć et al., 2017).

These lakes have not previously been the subject of geological research. We pay special attention to five of these: Talingaryn Shal (Lake 1), Chavgantsyn Shal (Lake 2), Zuun Khuree (Lake 3), Luulityn Toirom (Lake 4), and Baruun Khuree (Lake 5; we derived the names of the lakes from the local population), because there are archaeological sites located within them realting to early hunter-gatherer communities. Archaeological research at Talingaryn Shal Lake has documented 138 kyr-old deposits at a depth of 5.15 m b.g.l., ~10.640 kyr at 1.45 m b.g.l and ~3.69 kyr at 0.6 m b.g.l. (dated by optically stimulated luminescence – OSL; Masojć et al., 2024). In the Luulityn Toirom lake the oldest deposits were dated at 88.1 kyr at 5 m b.g.l, while some younger dates were also obtained: 86.6 kyr at 3 m b.g.l., 72.9 kyr at 4.9 m b.g.l. and 8.13 kyr at 0.9 m b.g.l. (OSL dates; Michalec et al., 2025). These results, together with geological analyses, may provide new data on the factors shaping the dynamics of alluvial-pluvial processes in the context of the geological structure and geomorphology of food-providing areas in the Quaternary period. Lake deposits are ideally suited for such research because they are an extremely sensitive record of environmental changes. Our results directly contribute to the understanding of the geomorphological setting, and emphasize the relationship of neotectonics to the occurrence of conditions favourable to the development of human settlements from the late Pleistocene to the present.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The study area is located within the Mongolian Plateau (Fig. 1). It is a foothill, and the extreme southern part of the Arts Bogd Massif in the eastern part of the Gobi-Altai Range (Fig. 1A). This area is drained by rivers flowing into two large endorheic basins: the Shereegiin Gashuun Basin (Shereegeen Gashoon, Shiregin Gashun) to the west and the Ulaan Nuur Basin (Ulan Nur) to the east.

Tectonically, the study area is located within the Central Asian Orogenic Belt (CAOB; Fig. 1B), which in Mongolia is divided into a northern and southern domain by the Main Mongolian Lineament (MML). The basement of the study area consists of rocks of the Paleozoic Gobi-Altai Terrane located in the southern domain, in close proximity to the Bogd Fault (part of the MML (Badarch et al., 2002; Guy et al., 2014). The area on which the study site is located extends from east to west and is known as the Mongol Altai Accretionary Wedge (MAAW; Guy et al., 2021). It is bounded to the north by the Bogd Fault and to the south by the Bulgan Fault (Fig. 1C), which are regional-scale intracontinental strike-slip faults (Florensov and Solonenko,1965; Cunningham et al., 1997; Valtr and Hanžl, 2008).

The modern relief of the study area is closely related to the Cenozoic (from Miocene time) tectonic activity of the bedrock resulting from the Indo-Eurasia collision, and the reactivation of older structures related to Triassic-Jurassic compression (closure of the Mongol-Ochotsk Ocean), Jurassic-Early Cretaceous extension and continental rifting, and middle Cretaceous compression and basin inversion (Molnar and Tapponier, 1975; Hendrix et al., 1996; Cunningham, 1998; Buriánek et al., 2008; Roberts and Cunningham, 2008; van Hinsberger et al., 2015). Arts Bogd is the eastern element of a complex structure, a restraining bend mountain range, developed along the WNW–ESE trending Bogd Fault System. It is observed along the entire Gobi-Altai Range over a distance of 250–300 km and is characterized by the presence of asymmetrical flower structures and NW thrusts that developed along sinistral strike-slip faults (Fig. 2; Florensov and Solonenko, 1965; Bayarsayhan et al., 1996; Cunningham, 2007). They are accompanied by deformation expressed as folds, thrusts and orographic fronts. Kinematic and geometrical relationships similar to the Bogd Fault System occur in the Gurvan Saikhan Ranges, located directly south of the study area, which are associated with the Gobi-Tien Shan Fault System (E–W; Cunningham, 2007, Rippington, 2008). These areas are separated by the E–W extending Shereegiin Gashuun Basin (Fig. 2).

The deformation results from Late Cenozoic regional tectonic transpression (Cunningham et al., 1996, 1997; Cunningham, 2010, 2013) and large-scale anticlockwise rotation of the crystalline basement (Bayasgalan et al., 1999). It has been responsible for numerous earthquakes, including the 1957 event of M 7.8–8.3, which caused ground deformation over a distance of 260 km and a width of 40 km (Florensov and Solonenko, 1965). Strike-slip displacements along the Bogd Fault Zone during the Late Pleistocene and Holocene are estimated to have been ~0.5 mm/yr (Ritz et al., 1995; Rizza et al., 2011). Displacements as a result of the 1958 Bogd earthquake were 3–5.2 m in its western part and 2–3.5 in its eastern part (Florensov and Solonenko, 1965; Kurtz et al., 2018). The Cenozoic deformation is thus part of the ongoing post-Triassic remodelling of the Mongolian CAOB in the Gobi-Altai range, which is classified as an intraplate, intracontinental transpressional orogen (Cunningham, 2010).

The influence of tectonic remodelling on the Cenozoic relief has resulted in the area possessing physiographic features characteristic of a basin-and-range province (Cunningham, 2013). Despite the dominant E–W orientated structures, the eastern end of the Arts Bogd Massif has a N–S orientation, which is due to the existence of an orogenic front there developed along an eastwards verging thrust (Figs. 2 and 3). The orogenic front on the northern side of the massif is associated with N–NW verging thrusts. The uplift rate there is estimated to have been 60 mm/yr during ~600 kyr (Lee et al., 2021), while the strike-slip component along the southern margin of the Arts Bogd reached ~5.8 mm/yr during the last 32 kyr (Lee et al., 2021).

In the study area, Paleozoic rocks are represented by the Silurian phyllites and marbles (crystalline limestones) of the Khanankharsny Formation (Togtokh et al., 1985). They are part

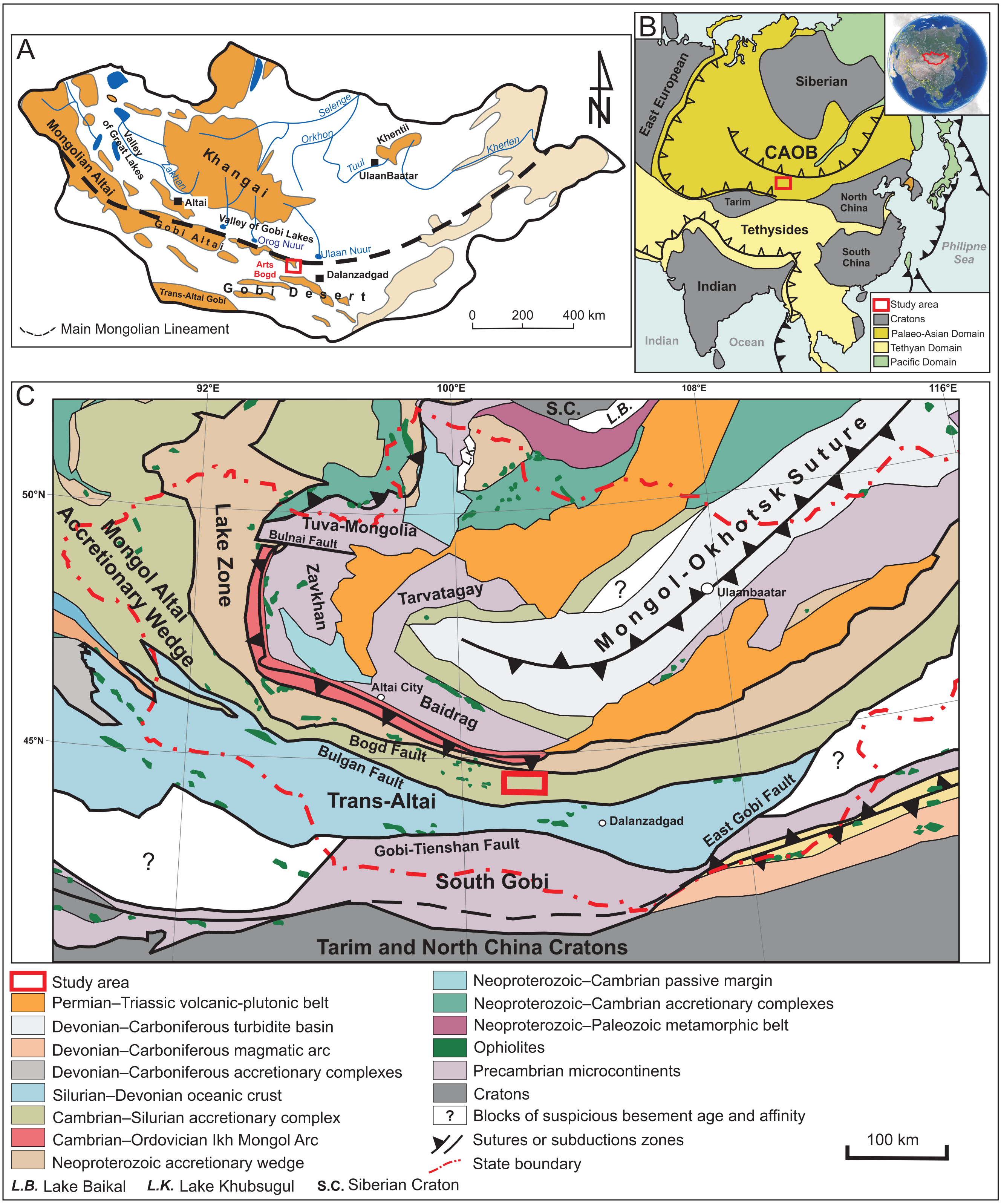

Fig. 1A – location of the study area on a general map of Mongolia; B – sketch tectonic map of Central Asia (after Liou et al., 2017); C – tectonic zonation of the Mongolian part of the Central Asian Orogenic Belt (CAOB; after Parfenov et al., 2003; Guy et al., 2021; Peřestý et al., 2025, modified)

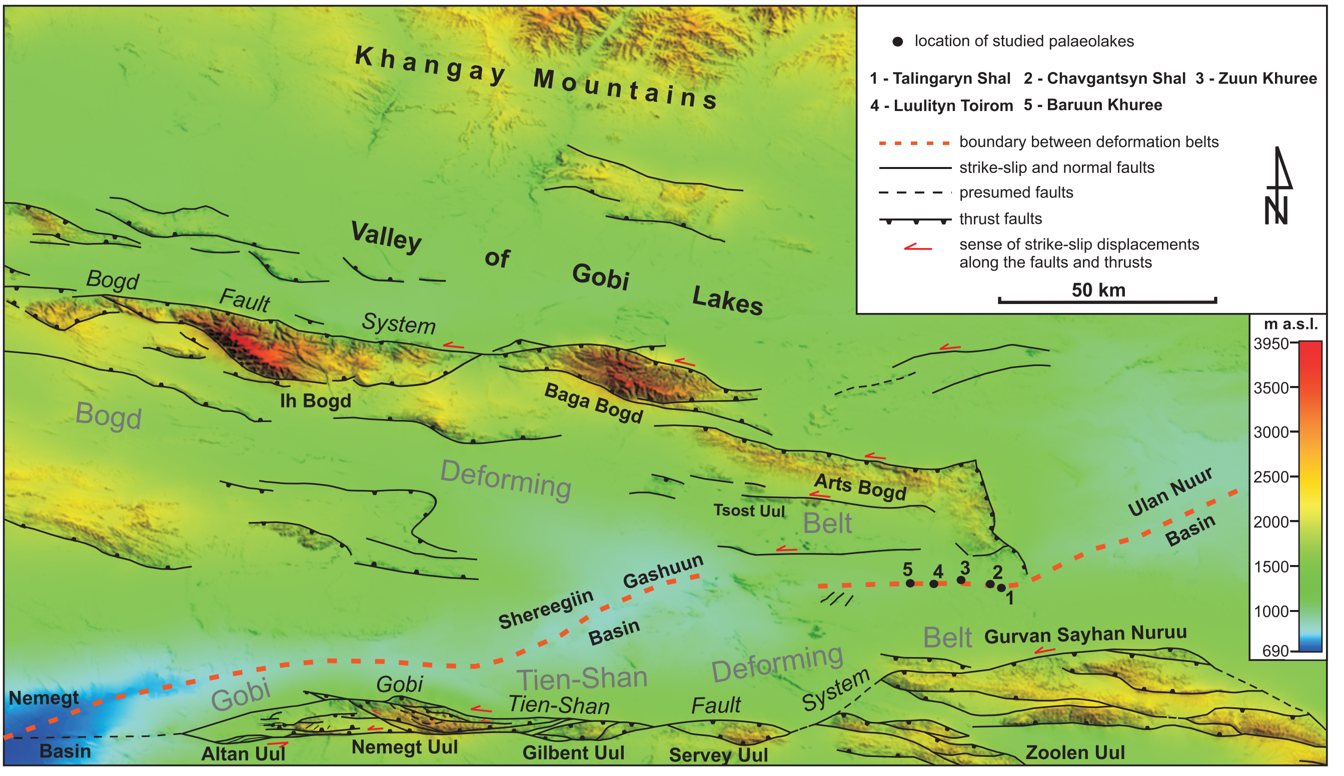

Fig. 2. Digital elevation model based on a STRM V3 digital elevation model with interpretation of subsidence axis (orange line) between the restraining bend mountain ranges of the Gobi-Altai orogen

Fault and thrust data after (Cunningham 2007, 2010, 2013; Cunningham et al., 2009, modified)

of the Upper Silurian-Devonian sedimentary succession (Guy et al., 2021) and are exposed from beneath the andesites and basalts (trachybasalts, Samoilov et al., 1998) belonging to the lower part of the Lower Cretaceous Malnai Formation (117.6–120.3 Ma, Sheldrick et al., 2018), of which the entire Arts Bogd Massif is predominantly composed (Figs. 3 and 4).

The Cretaceous stratal succession, which forms the southern edge of the mountain slopes, begins with the younger (upper) Malnai Formation, which is unconformably deposited on top of volcanic rock (Figs. 3 and 4). It consists of conglomerates, sandstones and red mudstones (Fig. 4). The subsequent subdivisions of the sedimentary Cretaceous rock sequence lie conformably, and the layers commonly dip monoclinally to the south (Fig. 5). Consequently, successively younger lithostratigraphic subdivisions are observed there. The Lower Cretaceous Khokhshir Formation (Figs. 3 and 4; Togtokh et al., 1985) consists of claystones, mudstones, polymictic sandstones, limestones and marls. The Upper Cretaceous Bombokhoi Formation and Baruungoyot Formation (Togtokh et al., 1985) are represented by conglomerates, sandstones, red siltstones and gypsum-bearing clays. The Baruungoyot Formation also contains marls and variegated clays (Figs. 3 and 4; Gradziński and Jerzykiewicz, 1974; Jerzykiewicz and Russel, 1991).

There is a stratigraphic gap in the profile between the Mesozoic strata and the Quaternary cover (Togtokh et al., 1985). The oldest Pleistocene deposits in the study area are found on the slopes in the form of alluvial, alluvial-proluvial clays and debris, and proluvial and alluvial sands and gravels. In the valleys and at the foot of the slopes, there are Pleistocene and Holocene alluvial and proluvial deposits: gravel, sand, clayey sand, silty sand, and clay, including lacustrine clay. Aeolian sands and silts are also present, forming continuous covers and small dunes (Figs. 3 and 4).

METHODS

REMOTE SENSING, GEOMORPHOLOGICAL ANALYSIS AND FIELD SURVEY

The field survey was preceded by an analysis of the 1:200,000 geological map (Togtokh et al., 1985) and satellite imagery. Remote analyses were carried out in a Geographic Information System (GIS) environment using *BlueMarble's Global Mapper* and *ESRI's ArcGIS* software. High-resolution images from *ESRI's* resources were used. These are images obtained by *Maxar* satellites (*Maxar Space Systems*). They were taken between 2015 and 2024. The images analysed have a resolution of 1.20 m and are displayed with a maximum accuracy of 5 m. During the analysis, image magnifications from 1:50,000 to 1:5,000 in true colour imaging were used. A STRM V3 (The Shuttle Radar Tomography Mission) digital elevation model with 1 arc-second (30 m) resolution from NASA JPL (Farr et al., 2007) was also analysed. Additionally, in order to illustrate and recognise the landforms around the lakes, photographs of the terrain surface taken with an unnamed aerial vehicle (UAV) were used. Satellite and UAV images and terrain models were analysed in terms of relief characteristics, recognition of geomorphological forms, determination of the type of

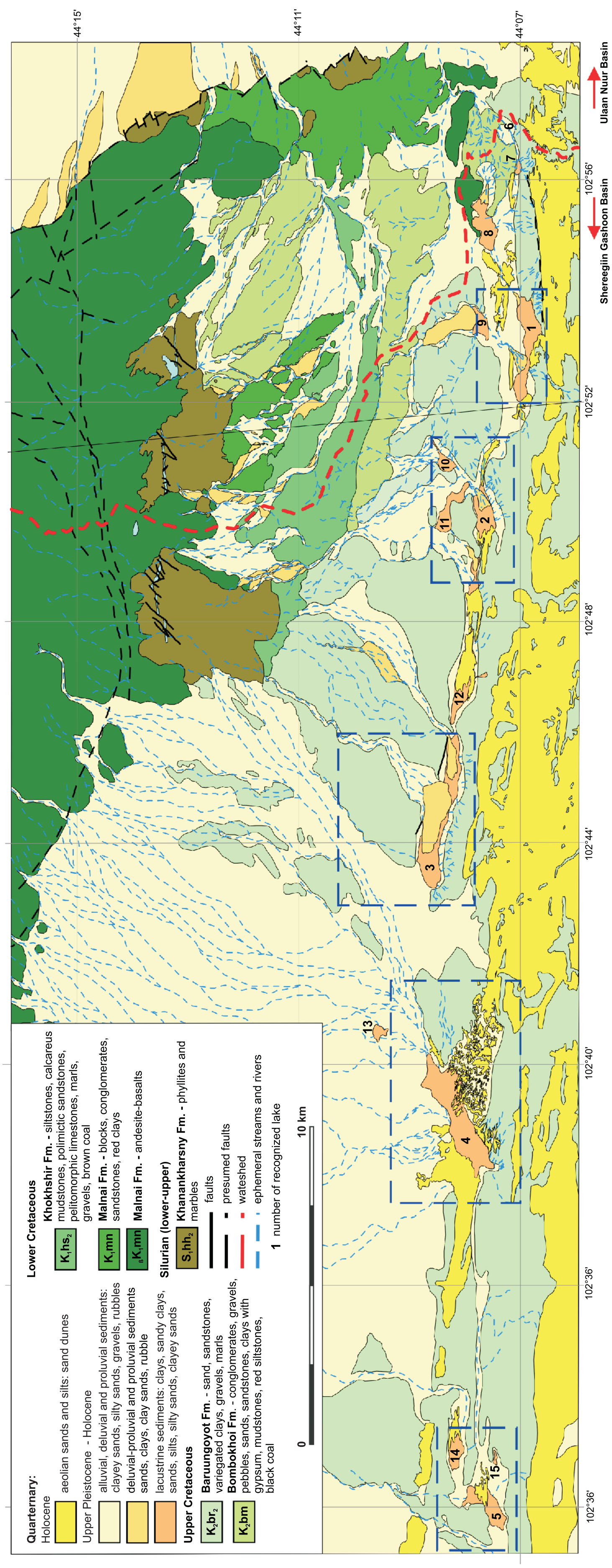

Fig. 3. Geological map of the study area (stratigraphy after Togtokh et al., 1985)

river network and interpretation of the occurrence and geometry of lakes or their remains (both geomorphological forms and lacustrine deposits). Attention was paid to the physiographic parameters of the palaeolakes identified and documented, allowing them to be classified in terms of their genesis, landscape type, area, stability, depth, salinity, and presence of outlet (after Orkhonselenge et al., 2022). Elements of the various landforms such as the interpretation of the palaeoshoreline, recent floodplain and sand cover, potential sediment source areas, and the existence of alluvial fans were also analysed and used to determine the relationship between the geology and tectonics of the bedrock and the relief.

An important element of the research was fieldwork consisting of geomorphological and geological mapping including the recognition of the relationship between landforms and the tectonic structure of the bedrock. The field research consisted of confirming the presence of the former lakes interpreted remotely on satellite images and determining their boundaries. Geomorphological mapping was carried out, in addition to identifying drainage patterns and other landforms such as mesas and cuestas. Attention was paid to the geometry of recognized forms such as topographic ridges, including their direction, asymmetry, tilt and orientation. During geological mapping, rock exposures and the type of deposits occurring around palaeolakes were also identified and documented, potential alimentary areas were indicated (based on petrographic analyses of sedimentary material), and the extent of bedrock subcrops beneath the Quaternary cover was recognized. Attention was paid to lithological contacts and the presence of tectonic structures. Faults and thrusts that could have influenced the development of the general terrain relief and individual landforms, or could help document the neotectonic activity of the study area or recent seismic events (earthquakes), were identified and documented.

The lakes surveyed were categorized according to the classifications of Orkhonselenge et al. (2022), Hutchinson (1957) and Tserensodnom (1971, 2000).

RESULTS

GEOMORPHOLOGY OF THE TSAKHIURTYN HUNDI LAKELAND AND ADJACENT AREAS

In the study area, three basic types of landscape were distinguished. The Arts Bogd mountain area represents a rocky desert (1); to the south and east of it, at the mouth of the river valleys, there is a bajada with alluvial cones (2); and the surface of the terrain in the southern part of the area is covered by the so-called Gobi pavement (3; Fig. 6A–C). The maximum altitudes of the mountainous part of the massif reach up to 1770 m a.s.l. The mountain peaks are flat, and slopes below them have debris covers and in

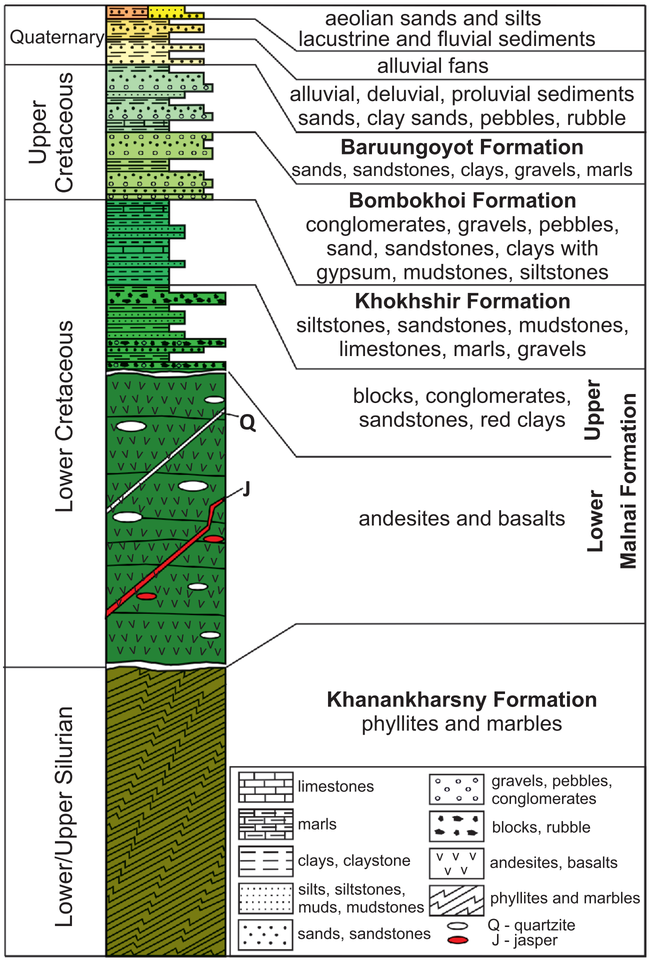

Fig. 4. Stratigraphical profile of the study area (stratigraphy after Togtokh et al., 1985)

places rock blocks (Fig. 6D). There are intramontane depressions within the massif, the main river valleys are wide, and their slopes are generally steep with a gradient of 25–50°. There are also vertical rock walls reaching a height of 300–350 m above the flat valley floors.

Based on the analysis of satellite images, a watershed line was drawn for the Shereegiin Gashuun Basin and the Ulaan Nuur Basin, which generally runs in an arc from north to south-east (Fig. 3). The northeastern part of the area drains towards the Ulaan Noor Basin, while the western and southern parts drain towards the Shereegiin Gashuun Basin.

In this part of the study area, land with a bedrock composed of horizontally or approximately horizontally layered volcanic rocks forms a plateau-like landscape (Fig. 6D, E). Edge relief occurs in the part made of folded metamorphic rocks, which are characterized by a steeply inclined (up to 30°) foliation surface towards the south. Vertical ridges can be found in the northern part of their outcrop, where the inclination of the metamorphic foliation exceeds 30° (Fig. 6F). Vertical relief is also evident close to the faults and thrust zones, where the Mesozoic volcanic rocks are tilted at various angles.

The southern outskirts of the Arst Bogd Massif in the study area are characterized by hilly terrain with heights between 1180 and 1400 m a.s.l., and local peaks reaching up to 1480 m a.s.l. (Fig. 6E). The geological and geomorphological analysis of the foothills of the study area, where the lakes are located, showed that the horizontal and monoclinal arrangement of Mesozoic sedimentary rocks dipping at low angles (up to 5°) towards the south determines the development of a mixed relief, of plateaus and its edges (Fig. 6E). The E–W direction of the cuestas' ridges corresponds to the strike of the Cretaceous strata, and the height of their steep slopes decreases towards the south. The mesas and cuestas are at a mature stage of development. Their ridges and slopes are cut by transverse valleys of intermittent streams (Fig. 6G). For this reason, in many cases, these ridges have become fragmented and commonly form isolated plateau-like surfaces. Between the cuestas' ridges, depressions have been formed into which water from the nearby hills flows. The valleys, which run along and perpendicular to the cuestas' ridges, cut deep into the bedrock, locally by >20 metres. To the north, these form long valleys draining the Arts Bogd Massif. In the foothills, their bottoms are flat and wide with many shallow channels, which is typical of intermittent rivers in a dry climate. Intermittent water inflow into the depressions also takes place from the south through valleys located on steep, but low and poorly topographically defined, cuesta ridges. These valleys are much shorter and do not cause extensive and deep erosion cuts. Some depressions are reached by the drainage valleys of the

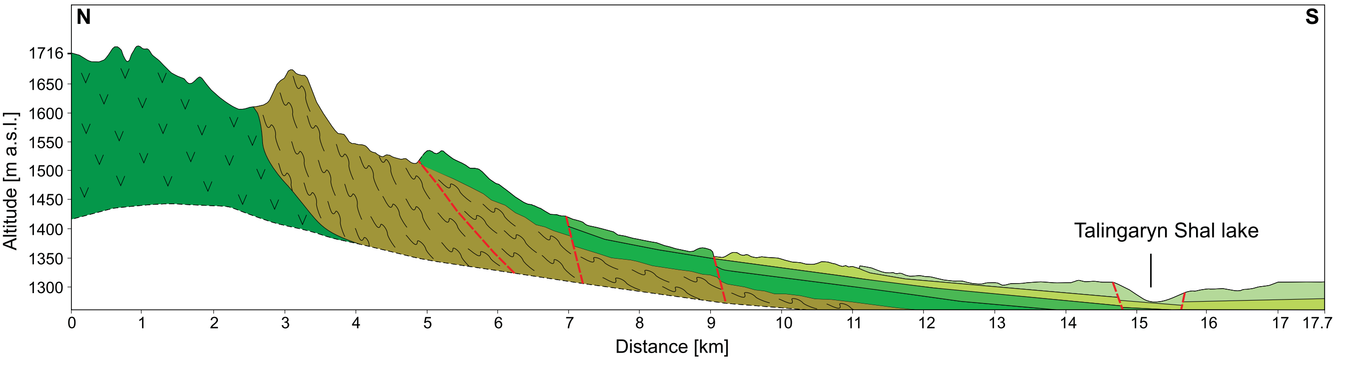

Fig. 5. Schematic geological cross-section of the study area (for explanation see Fig. 3)

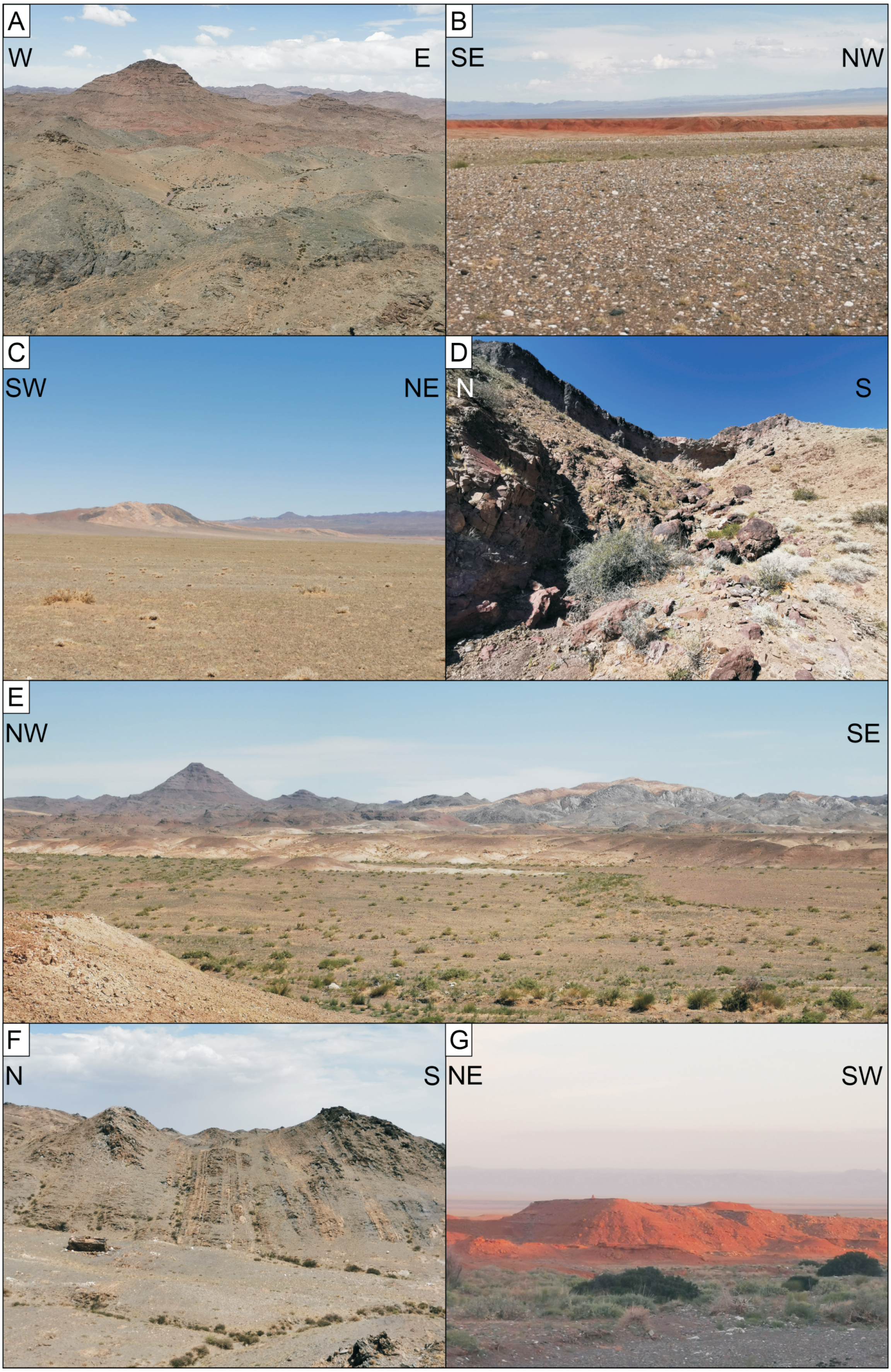

Fig. 6. Landscapes of the study area

A – hamada landscape of the Arts Bogd Massif; **B** – bajada landscape on the southern edge of the Arts Bogd; **C** – Gobi pavement to the south of study area; **D** – boulders at the foot of a flat mountain peak; **E** – panoramic view of the Arts Bogd Massif and its foothills; **F** – edge type of terrain relief on an area of Paleozoic metamorphic rocks; **G** – mature stage of isolated mesa built by Cretaceous sedimentary rocks in the southern foothills of the Arts Bogd northern slope of the Gurvan Saikhan Range. The drainage system observed in the study area carries a variable structure. It is predominantly dendritic in the mountainous area, parallel and sub-parallel in the foothills, and centripetal araound the lakes.

In addition to the clearly developing fluvial-denudational relief, aeolian processes also affect the surface of the terrain. Winds blow across the elevations, so the mesa surfaces and the gentle slopes of the cuestas are covered with a deflation pavement (Fig. 7A). The pavement pebbles comprise phyllite, volcanic rock and crystalline limestone. In depressions, there are also accumulations of silts and aeolian sands. These form small dunes with characteristic ripples and phytogenic hills, so-called nebkha (coppice dunes) around sparse shrub vegetation (Fig. 7B). On the surface of the dried-out bottoms of ephemeral lakes there are thin sandy-silty covers. These feature low (up to 10 cm), asymmetrical aeolian ripple marks with sinusoidal crests. The distances between the crests of the ripples marks range from ~10 to ~40 cm (Fig. 7C). Trenches within the lake areas revealed varied sedimentary facies, showing a typical arid zone facies association that includes lacustrine, fluvial and aeolian deposits (Fig. 7D).

The analysis of the depressions on the digital terrain model in the southern part of the study area revealed the existence of a latitudinally oriented zone where there is a regional (in the sense of the study area) change in the orientation of the slopes (Fig. 8). To the north of this zone, slopes that dip towards the south dominate, while to the south, slopes oriented towards the north are more common.

TECTONICS

The area has structures associated with disjunctive tectonics. Within the Paleozoic rocks, faults have been identified and documented based on satellite images showing shifts in rock outcrops, mainly in a NE–SW direction (Fig. 9A). In the Cretaceous sedimentary rock outcrops, normal and reverse faults with N–S and NW–SE orientations were recognized (Figs. 9B–F and 10). These are dislocations with small displacements (from several tens of centimetres to several metres) and extents (commonly several tens of metres), so they are not of regional significance.

GENERAL PALAEOLAKE CHARACTERISTICS

Fifteen lakes were identified and documented (Fig. 3) belonging to the Shereegiin Gashuun Basin catchment area. Lake sedimentation occurred in depressions in front of the cuestas' escarpments, where the waters of seasonal streams flowed. Thes accumulated in wide, drainless deflation basins formed as a result of intensive aeolian processes. The basins were formed in the clastic Upper Cretaceous strata of the Baruungoyot Formation and, less frequently, the Bombokhoi Formation (Fig. 3). Currently, the lakes are dry, and their palaeoshorelines (Fig. 11A–G) are visible around beds of clay and clayey sand. The palaeolake slopes are covered by sands and gravels.

Within the clayey deposits, open polygonal desiccation fractures have been observed. In places, these surfaces are over-

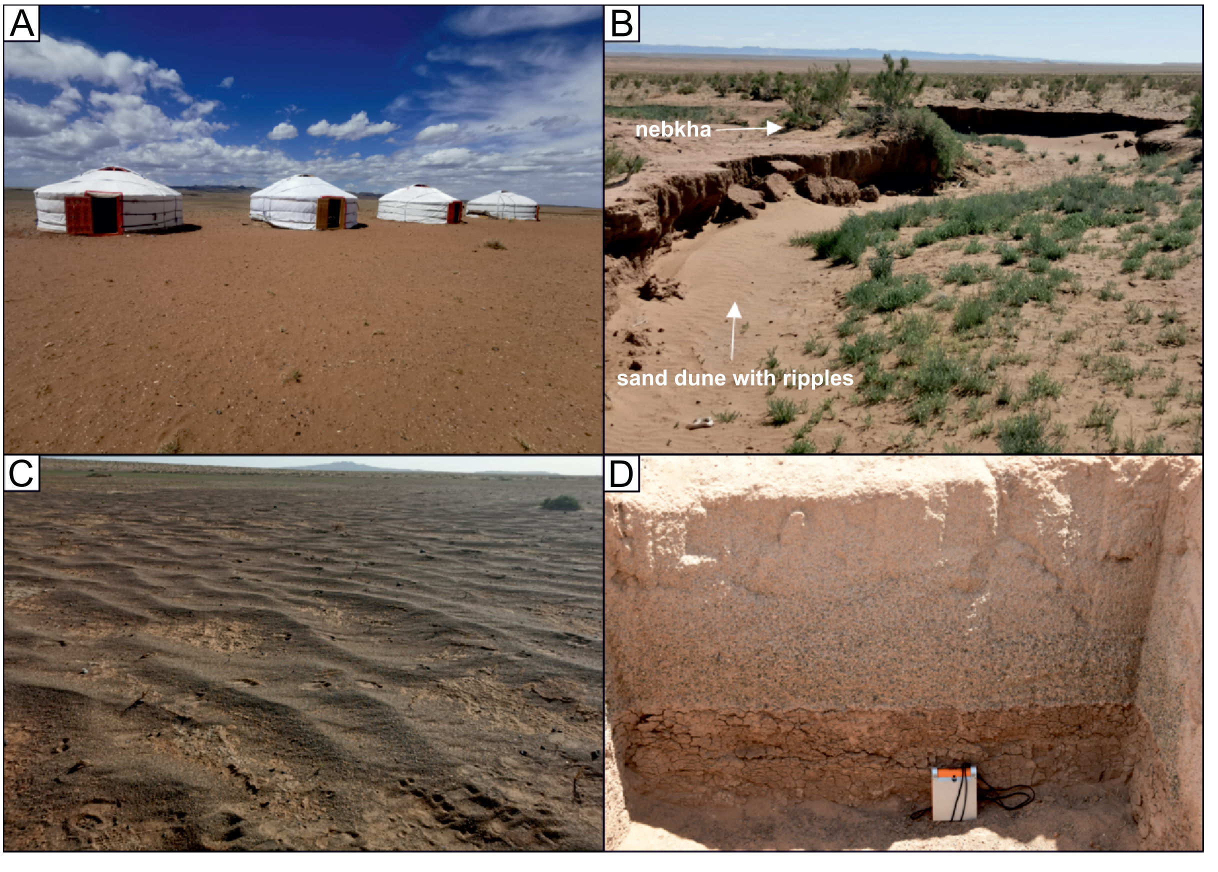

Fig. 7A – Cretaceous surface planation on the top of a mesa; B – aeolian sediments within an ephemeral stream channel; C – asymmetrical aeolian ripples on the surface of a dried lake; D – sequence of playa lake deposits (lacustrine, fluvial and aeolian facies) in an archaeological trench

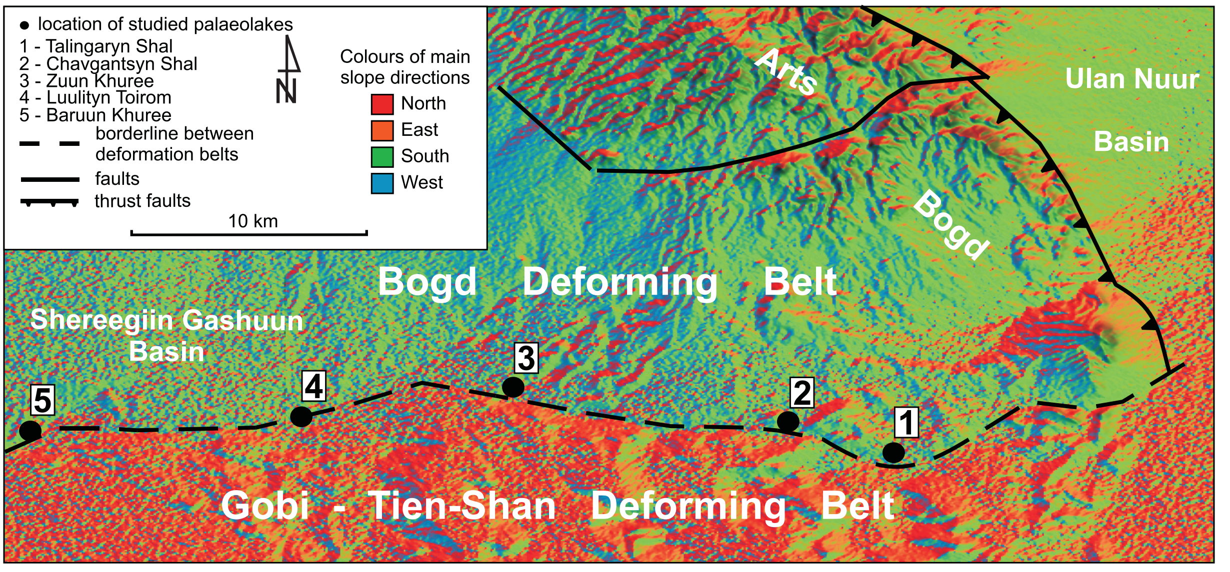

Fig. 8. Location of the palaeolakes studied on a slope aspect map of the study area based on a STRM V3 digital elevation model

grown by sparse vegetation, which suggests that the surface sediments are more humid than the surrounding area, due to periodic flooding during rainfall (Fig. 11A–F). Despite continuous deflation, the dry parts of the lake floors are covered by aeolian sands and silts (Fig. 11B, C). Remote sensing and field surveys have confirmed the existence of alluvial fans that transported sediments to the palaeolakes. The most extensive fans are associated with streams flowing in from the north or north-east, which in several cases partially filled the lake basins (Figs. 3 and 11A,C).

CHARACTERISTIC OF SELECTED PALAEOLAKES

TALINGARYN SHAL LAKE (LAKE 1)

Talingaryn Shal Lake is the most easterly of all the palaeolakes studied (Fig. 12). The surface of its bed is elongated E–W, is at an altitude of ~1280 m a.s.l. (Table 1), and the boundaries of the basin, filled with lacustrine deposits, are irregular. The relief around the basin indicates that the lake was a closed water body. A distinct narrowing in the middle part of the lake is visible, caused by the presence of an alluvial fan, the sediments of which filled the reservoir from the north-east (Fig. 12). Geomorphological analysis shows that the main source of sediment filling the reservoir was located ~5 km to the north. This was a ridge made of sedimentary rocks of the Khokhshir Formation and Bombokhoi Formation. The intermediate source area for the sediments was the more closely located outcrops of the Baruungoyot Formation. Before the water reached the lake, it accumulated in a smaller water body (Lake 9) located ~1 km to the north between outcrops of the Baruungoyot Formation (Figs. 3 and 12). Flowing water also supplied sedimentary material to the reservoir from the east and south. In the former case, these first accumulated in an intermediate basin (Lake 8) fed by waters flowing down from the ridge present there, made up of volcanic rocks of the Lower Malnai Formation and the Bombokhoi Formation. The northwestern palaeoshoreline is marked in the relief, and the southern one coincides with the modern boundary limit of the range of periodic rain-fed floods (Fig. 11A, B). Aeolian silts and sands migrate from the south onto the deflation surface of the lake bed.

CHAVGANTSYN SHAL LAKE (LAKE 2)

Chavgantsyn Shal Lake was also a closed water body. It is elongated ENE–WSW and is the smallest in terms of area of the lakes analysed (Table 1). Its western part is covered by aeolian sands (Fig. 13). The present-day dry lake floor is at an altitude of ~1300 m a.s.l. (Table 1). It was fed from the north-east, where alluvial fan deposits can be found today. As in the case of Talingaryn Shal Lake, the water flowed into the lake indirectly, through two other lakes (Lake 10 and Lake 11) located to the north and north-east. The sedimentary source areas were the previously described hill ridges made of the Cretaceous Khokhshir and Bombokhoi formations. In addition, the lake to the north was also fed from the mountainous part of Arst Bogd, from outcrops of the volcanic rocks of the Malnai Formation and metamorphic rocks of the Khanankharsny Formation (Fig. 3). The palaeoshoreline is subtly marked in the terrain relief. Its northern and southern parts coincide with the modern boundary of periodic flooding by rainwater (Fig. 11C, D).

ZUUN KHUREE LAKE (LAKE 3)

Zuun Khuree Lake is located on the western edge of the southern foothills of the Arts Bogd and is the second largest of the lakes analysed (Table 1). The present-day dry lake bottom is located at an elevation of ~1270 m a.s.l. It originally had a strongly elongated shape in a WNW–ESE direction, but its central and eastern parts are largely buried by alluvial fan deposits (Fig. 14). It was a closed water body supplied directly by river water flowing from the upland part of the Arts Bogd and the

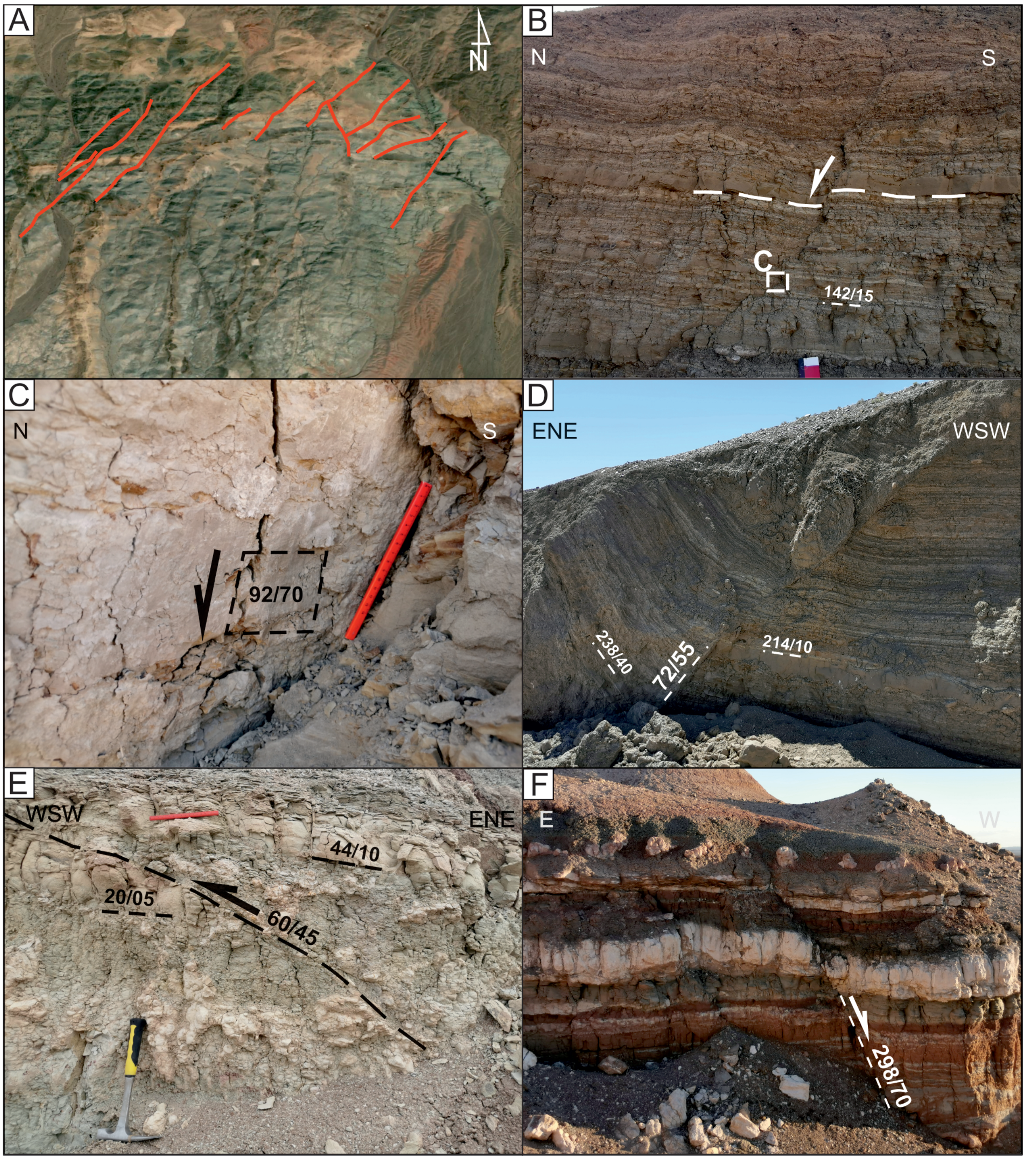

Fig. 9. Faults recognized in the study area

A – faults within Paleozoic metamorphic rocks interpreted on satellite images (plane view); **B** – normal fault within sedimentary rocks of the Khokhshir Formation; **C** – slickensides on the normal fault surface from picture B; **D** – reverse fault within sedimentary rocks of the Khokhshir Formation; **E** – reverse fault within sedimentary rocks of the Baruungoyot Formation; **F** – normal fault within the upper part of the Khokhshir Formation on the Flint Valley mesa slope

ridges of nearby cuestas. The alimentary areas for the lake sediments included the Khanankharsny, Khokhshir and Baruungoyot formations outcrops. On the northern side of the reservoir, the palaeoshoreline is clearly marked, coinciding with the boundary of periodic rainwater flooding in the southern part (Fig. 11E, F).

LUULITYN TOIROM LAKE (LAKE 4)

Luulityn Toirom Lake is located outside the elevated area, within the Shereegiin Gashuun Basin (Fig. 3). In this area, the relief is smoother with small height differences. This lake was the largest of those surveyed (Table 1). Its longer axis runs

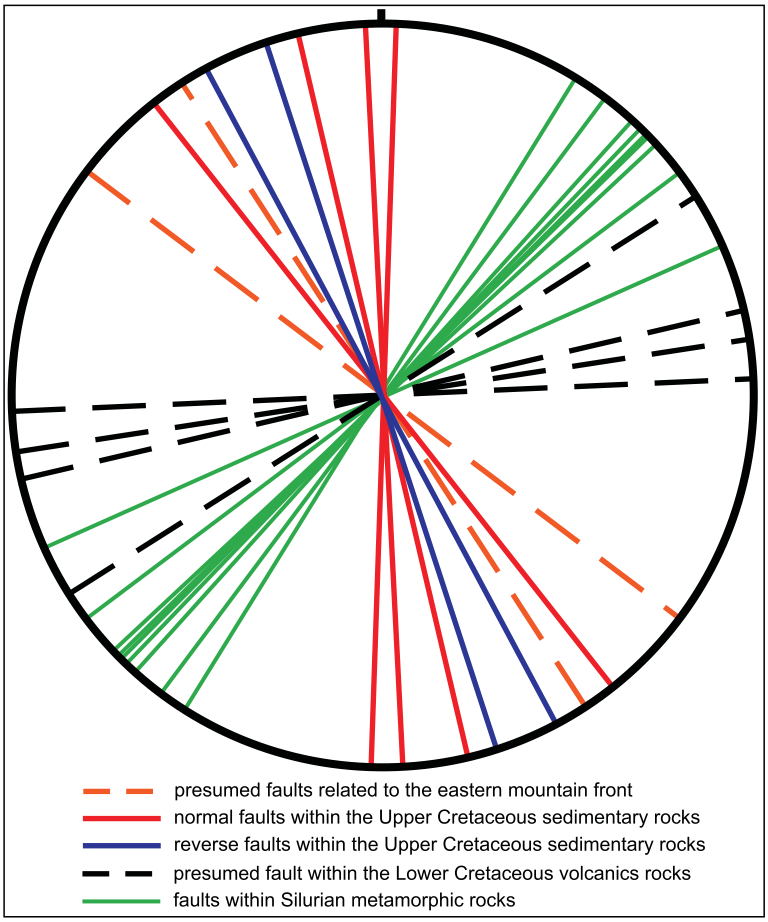

Fig. 10. Rose diagram of faults recognized within the study area

NE–SW (Fig. 15) and the present-day bottom surface is at an altitude of 1260 m a.s.l. It has been exposed by deflation (Fig. 11G). This surface is covered in its western and partly in its eastern part by aeolian sands, which form distinct dunes in the eastern part. On the satellite image, river channels cutting the present bottom of the lake are clearly visible. The lake was of closed type and similar to Zuun Khuree Lake, supplied mainly by waters draining the Malnai and Baruungoyot formations outcrops, which are located to the north-east. In addition, alimentary areas for sediment to the lake were also located in the central part of the Arts Bogd Massif, set back to the north of the study area, and on the escarpment of a poorly preserved cuesta ridge on the southern side of the lake (Fig. 3). The palaeoshoreline is well marked in the terrain relief, being well away from the present-day floodplain in the southern part and overlying it in the northern part. In the western part of the reservoir, the palaeoshoreline is covered by aeolian sediments.

BARUUN KHUREE LAKE (LAKE 5)

It is the most westerly lake and is approximately aligned with the Shereegiin Gashuun Basin (Fig. 3). A smaller lake (Lake 14) was identified to the north-east of it, which was an intermediate reservoir for water supplied from the north. Baruun Khuree Lake was of closed type, elongated NE–SW, and may have formed a single water body with Lake 15 in the past (Figs. 11H and 16). The present-day bottom in the southwestern part of the lake is at an elevation of ~1240 m a.s.l. (Table 1). Its central part is covered by aeolian sand dunes.

DISCUSSION OF THE RESULTS

GEOMORPHOLOGICAL AND TECTONIC DETERMINANTS OF LAKE BASIN FORMATION

Latitudinally oriented elements of the edge and plateau-cuesta landforms relate to fault zones and the course of lithological boundaries. The southwards tilt of the Cretaceous formations (including the Mesozoic planation surface) is caused by the tectonic, asymmetrical uplift of the Arts Bogd Massif (Cunningham, 2013). The lithological composition of the pavement on the cuestas and mesas suggests that these surfaces are older, Mesozoic, planation surfaces. Along the cuesta escarpments, which are parallel to the regional trend of longitudi-

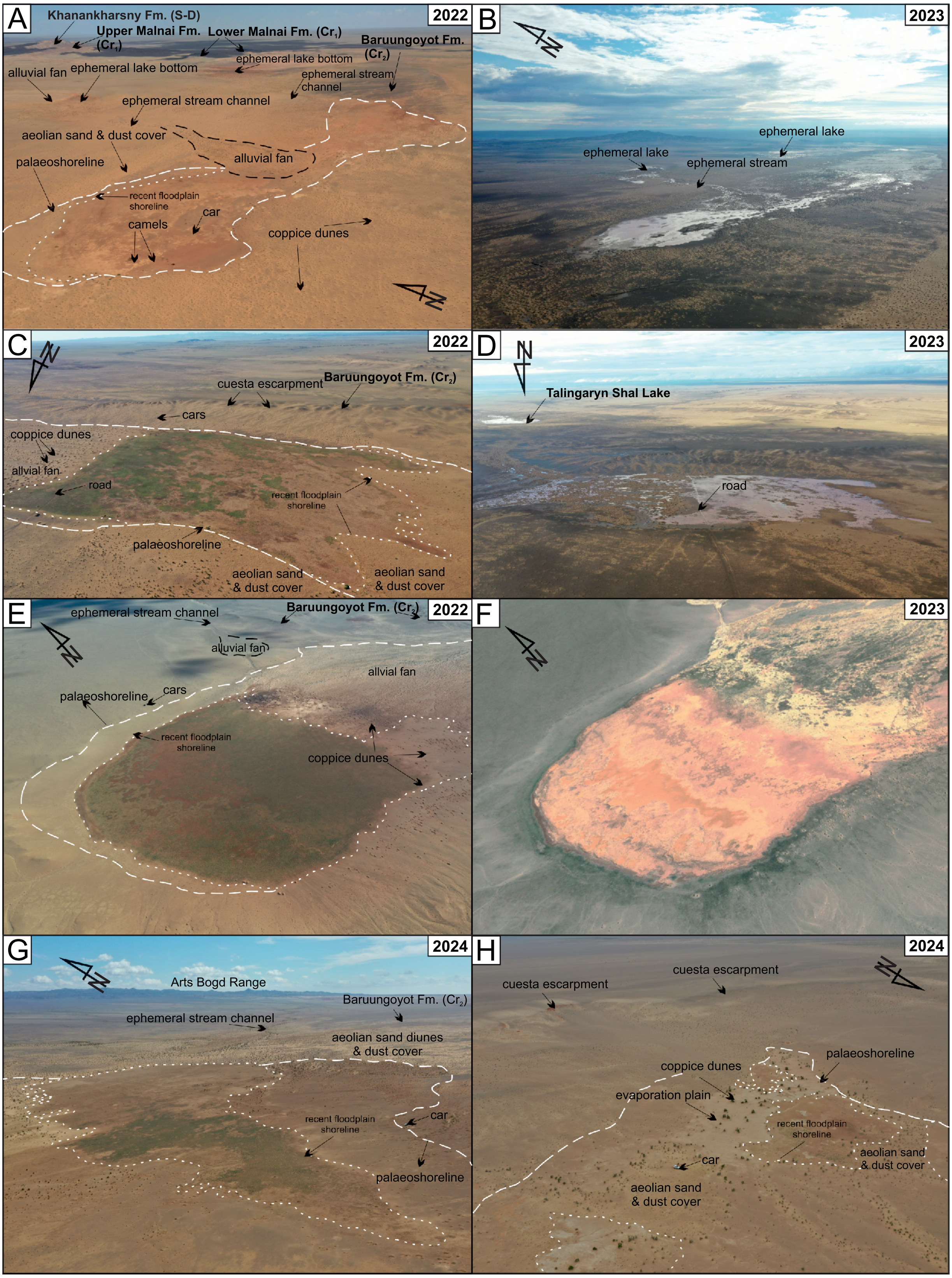

Fig. 11A – interpreted landforms of Talingaryn Shal Lake (photo taken in June 2022 with UAV); B – view of the Talingaryn Shal Lake area after a rainfall event (photo taken in June of 2023 with UAV); C – view and interpretation of landforms around Chavgantsyn Shal Lake (photo taken in June 2022 with UAV); D – Chavgantsyn Shall Lake area after rainfall event (photo taken in June 2022 with UAV); E – interpreted landforms of the Zuun Khuree Lake area (photo taken in June 2022 with UAV); F – Zuun Khuree Lake area after a rainfall event (in June 2023 on satellite images from Google Earth); G – interpreted landforms of the dried Luulityn Toirom Lake (photo taken in June 2024 with UAV); H – similar view on Baruun Khuree Lake (photo taken in June 2024 with UAV)

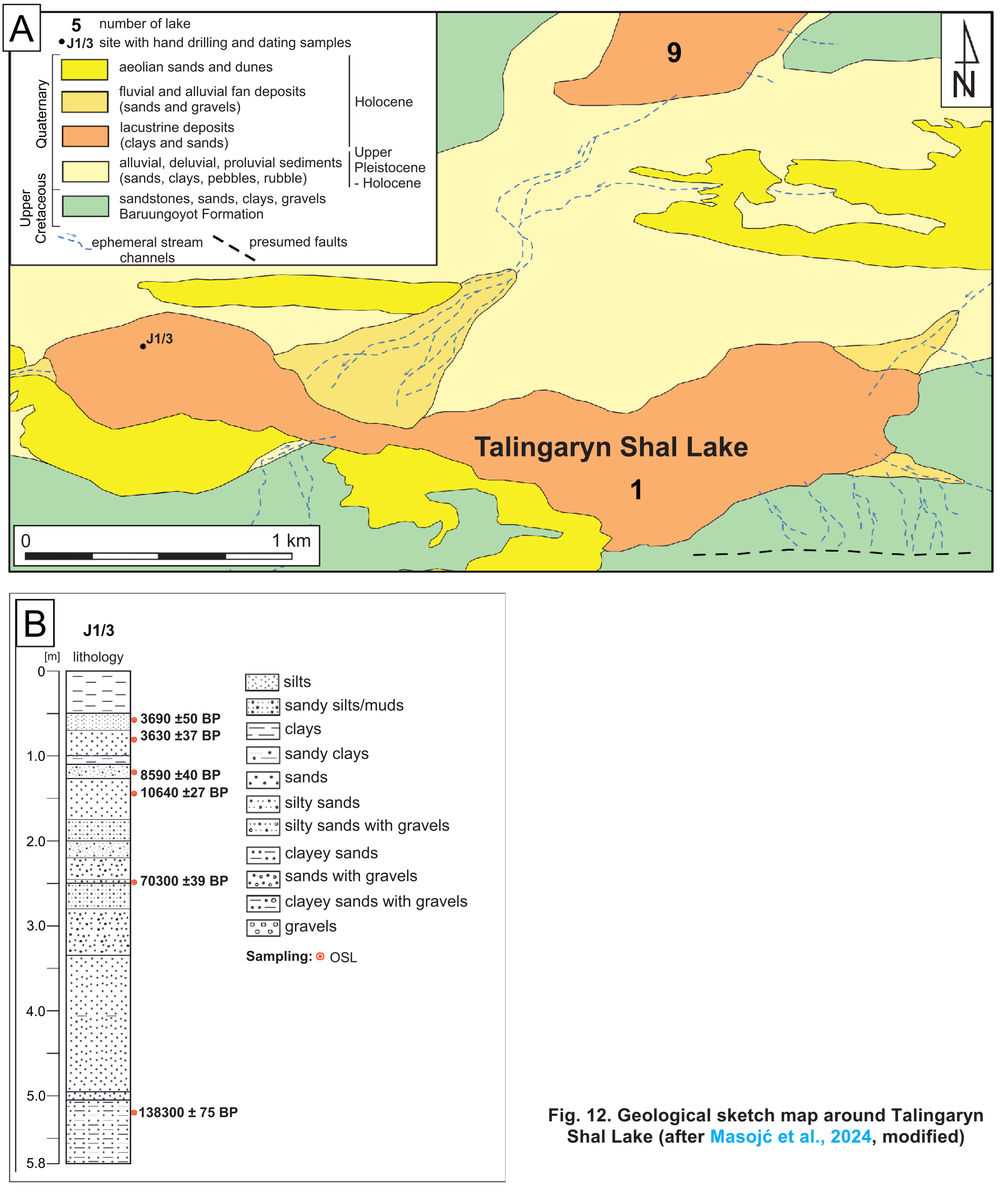

Fig. 12. Geological sketch map around Talingaryn Shal Lake (after Masojć et al., 2024, modified)

Table 1

Morphometric components of the lakes studied

no	Name of the lake	Geographical coordinates	Elevation [m a.s.l.]	Max. length [km]	Max. width [km]	Area [km^2]	Elongation	Bedrock
1	Talingaryn Shal (Lake1)	44°07‘23” N 102°53‘18” E	1280	2.37	0.58	0.84	E–W	Cr2 – Baruungoyot Fm.
2	Chavgantsyn Shal (Lake 2)	44°08‘08” N 102°50‘42” E	1300	0.56	0.44	0.22	ENE–WSW	Cr2 – Baruungoyot Fm.
3	Zuun Khuree (Lake 3)	44°08;59” N 102°44;28” E	1270	3.50	0.68	1.77	WNW–ESE	Cr2 – Baruungoyot Fm.
4	Luulityn Toirom (Lake 4)	44°08‘11” N 102°39‘47” E	1260	3.40	0.93	1.83	NE–SW	Cr2 – Baruungoyot Fm.
5	Baruun Khuree (Lake 5)	44°08‘02” N 102°33‘51” E	1240	0,15	0.44	0.57	NE–SW	Cr2 – Baruungoyot Fm.

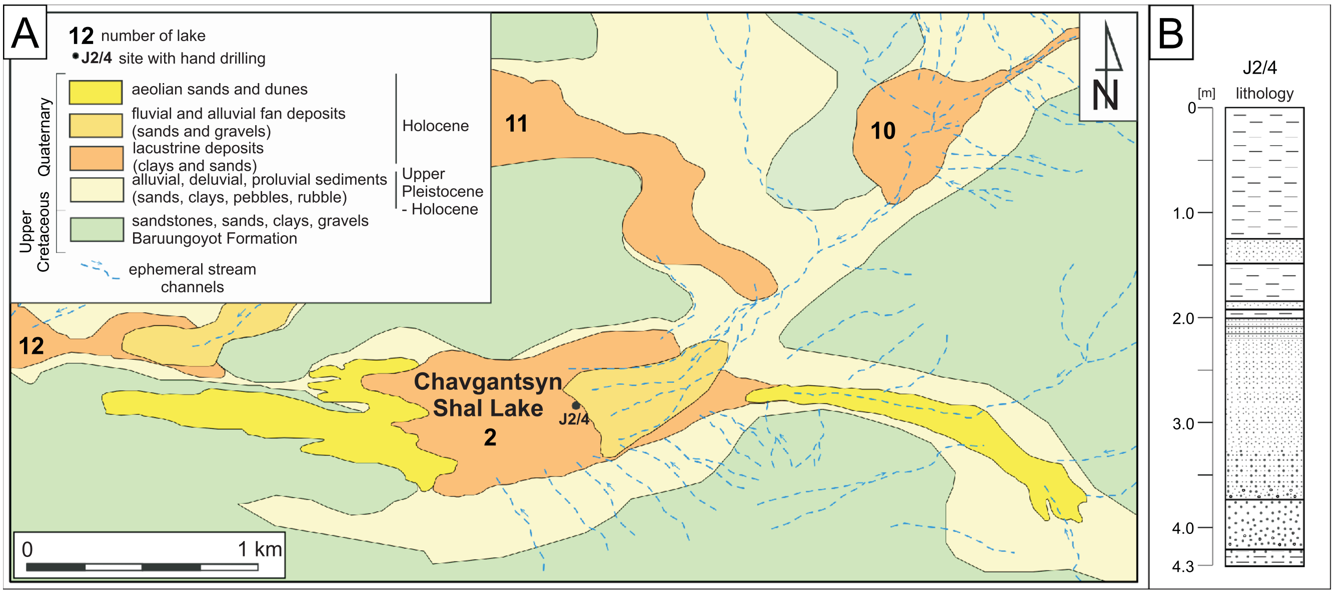

Fig. 13. Geological sketch map around Chavgantsyn Shal Lake

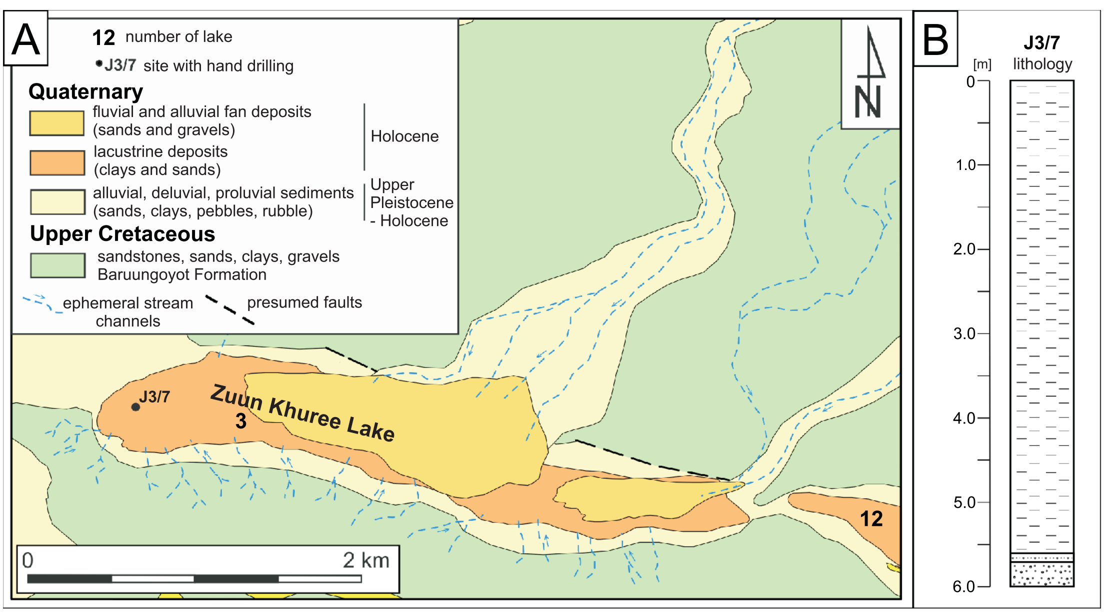

Fig. 14. Geological sketch map around Zuun Khuree Lake

nal faults, the main valleys of the periodic rivers flow, changing the direction of the water flow from the south to the west or east, or form depressions that were filled with lake sediments. The normal and reverse faults recognized, which are oriented diagonally or transversely (in a NW–SE direction) to the regional structures, have a local extent, but can affect the location of transverse incisions of the cuestas by valleys, which has been shown in several places. In terms of their origin, faults with NW–SE orientation are related to the NE-vergent thrust present on the eastern margin of the Arts Bogd Massif. They also record and provide evidence of post-Cretaceous neotectonic events and may be related to the present-day seismic activity of the area. The study area is located in the 1st seismic zone in Mongolia which is characterized by high seismic activity. Earthquake magnitudes in Arts Bogd do not exceed M 6 (Rizza et al., 2011) and the relationship between recognized faults and contemporary tectonic activity of the Gobi-Altai and Khangai basement requires further analysis. Identification of the regional slope reorientation zone in which the palaeolakes are located shows that it represents an axis with an approximate WSW–ENE course that connects intramontane basins. From west to east, these are the Nemegt, Shereegiin Gashuun and Ulan Nuur basins. This zone is parallel to the regional strike-slip faults, and it separates the Bogd Deforming Belt from the

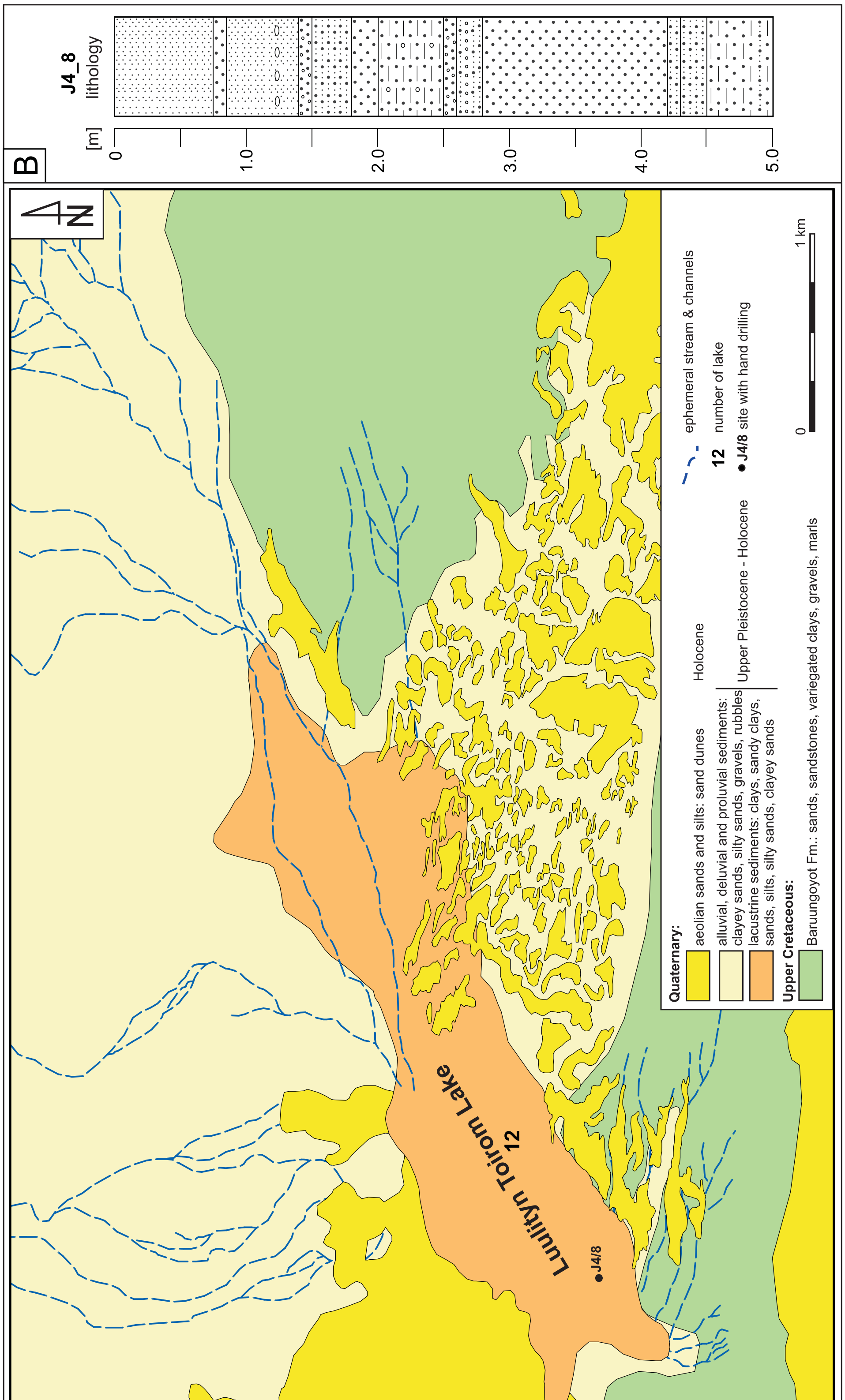

Fig. 15. Geological sketch map around Luulityn Toirom Lake

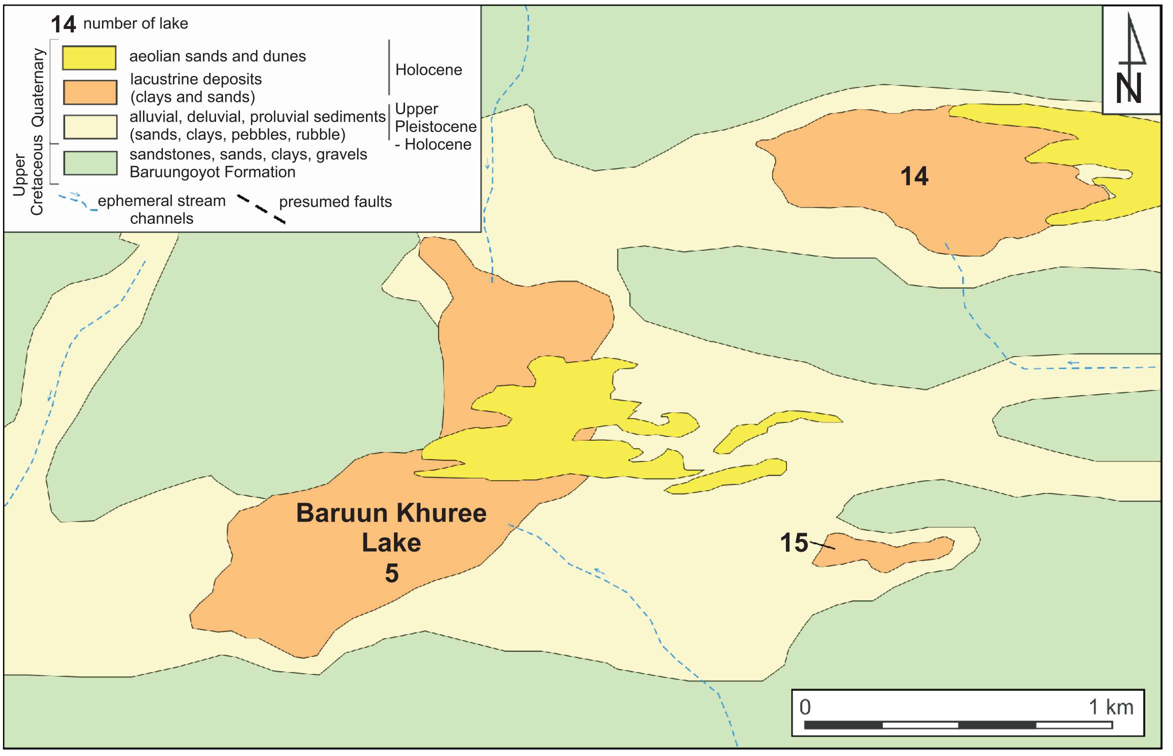

Fig. 16. Geological sketch map around Baruun Khuree Lake

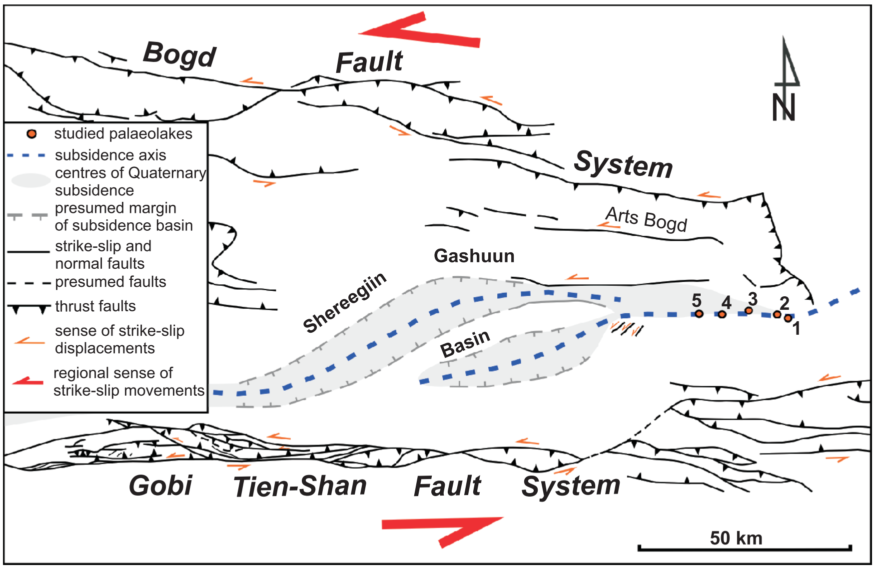

Fig. 17. Schematic model of the Shereegiin Gashuun Basin development as a pull-apart basin (en-echelon) in the Quaternary (faults and thrusts of the Bogd and the Gobi-Tien-Shan systems after Cunningham, 2007, 2010, 2013; Cunningham et al., 2009, modified)

Gobi-Tien Shan Deforming Belt to the south (Cunningham, 2007, 2010, 2013). Moreover, it is diagonally oriented to the Bogd Fault Zone and the Gobi-Tien Shan Zone. In this context, the intramontane basins (including the Shereegiin Gashuun Basin) that extend along the ridge appear to be the result of lithospheric stretching between sinistral fault zones. These are large-scale, present-day active en-echelon structures that have been developing since at least the late Cretaceous, and their development led to the formation of a pull-apart basin (Fig. 17). Such a long development of the basin is corroborated by the increase in the thickness of Cretaceous strata in their centre and the development of depressions in the present-day topography,

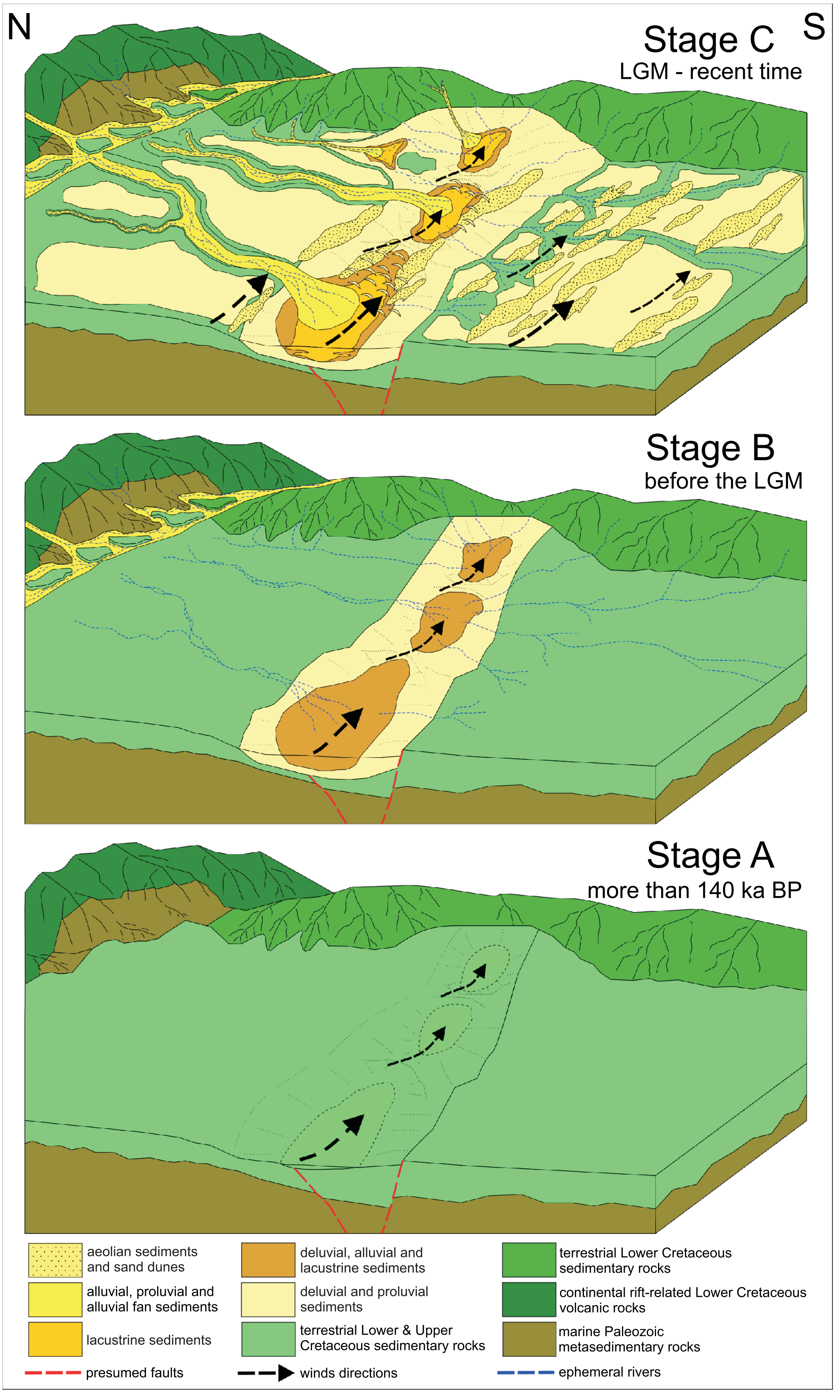

Fig. 18. Schematic model of playa lake development in the Tsakhiurtyn Hondi Lakeland (south of the Arts Bogd Massif)

towards which the river network is directed. The centres of these basins are subject to subsidence, which contrasts with the uplifted neotectonic mountain areas where regional fault zones are situated. The palaeolakes studied have a linear pattern, stretching E–W along the axis of the depression separating the Bogd Deforming Belt from the Gobi-Tien Shan Deforming Belt (Figs. 8 and 17). This situation suggests the existence, in the basement of this depression, of faults parallel to the Bogd Deforming Belt and the Gobi-Tien Shan Deforming Belt. The dip-slip component of the displacement favours subsidence of this basement and thus has a major impact on the location and geometry of the lakes.

Another important factor influencing the development and geometry of the palaeolakes is wind activity. The parallel course of the surrounding elevated mountain massifs and depressions between them favours the intensification of aeolian processes caused by the influence of generally westerly winds (of a WNW–ESE wind system; the so-called Westerlies), which can cause the development of deflation basins in tectonic depressions. The basins formed in this way collected water from streams and rivers draining the mountainous areas, as well as rainwater. The formation of deflation basins is a typical phenomenon in arid (dry) desert climates (Hutchinson, 1957), especially on bedrock composed of poorly lithified sedimentary rocks. From this perspective, the lakes under investigation must be considered to have both tectonic and aeolian origins. Tectonic lakes are documented in the surroundings of the Gobi-Altai Range, and aeolian lakes are common in southern Mongolia and the Gobi area (Orkhonselenge and Bulgan, 2021; Orkhonselenge et al., 2022). An approximate model of the development of deflation basins on a bedrock comprising Upper Cretaceous sedimentary rocks deformed by faults is shown on Figure 18. This model also illustrates the course of variable lacustrine-aeolian-fluvial sedimentation within the palaeolakes studied, as was previously described in relation to Luulityn Toirom Lake (Michalec et al., 2025).

CLASSIFICATION OF THE LAKES STUDIED

Most (9) of the identified and documented lakes are shallow, ephemeral, closed, freshwater, low-altitude, prairie lakes (Table 2). Of these, the Zuun Khuree, Luulityn Toirom and L12 lakes are small, and the rest are very small. Eleven have a tectonic-aeolian genesis, and four have a fluvial genesis.

The lakes of the Tsakhiurtyn Hundi Lakeland, including five analysed in detail, are typical of those found in southern Mongolia and the Gobi Desert (Orkhonselenge et al., 2022).

Surprisingly, the lakes studied may be classified as freshwater lakes, despite closed water bodies commonly being characterised by highly mineralised water (Langbein, 1961; Zhang et al., 2022). However, at the current stage of research, there are no geochemical analyses of the deposits, and the classifica-

Table 2

Geomorphologial classification of lakes of the Tsakhiurtyn Hondi Lakeland (after Hutchinson, 1957; Tserensodnom, 1971, 2000; Orkhonselenge et al., 2022)

no	Name of the lake	Origin	Landscape type	Area	Altitude	Stability	Depth	Salinity	Presense of outlet
1	Talingaryn Shal (Lake 1)	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
2	Chavgantsyn Shal (Lake 2)	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
3	Zuun Khuree (Lake 3)	tectonic/aeolian	prairie	smaller	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
4	Luulityn Toirom (Lake 4)	tectonic/aeolian	prairie	smaller	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
5	Baruun Khuree (Lake 5)	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
6	Lake 6	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
7	Lake 7	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
8	Lake 8	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
9	Lake 9	fluvial?	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
10	Lake 10	fluvial?	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
11	Lake 11	fluvial?	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
12	Lake 12	tectonic/aeolian	prairie	smaller	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
13	Lake 13	fluvial?	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	open
14	Lake 14	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed
15	Lake 15	tectonic/aeolian	prairie	very small	low-altitude	ephemeral	shallow	dried up/periodically freshwater	closed

tion is based on observations of periodic flooding. Future research may include to determination of the salinity of the lake waters in the past. According to Orkhonselenge et al. (2022), 58.2% of lakes in Mongolia are saline and semi-saline, and in southern Mongolia the number of freshwater lakes and saline/brackish lakes is similar (11.4 and 12.2%, respectively).

The study area, thus, is a unique testing ground for research into the relationships between intraplate tectonics and the geomorphological evolution of intracontinental regions. This also applies to the reactivation of older structures and the progression of deformation resulting from distant processes occurring in continental collision zones. The changes in the topography of the young orogen and their significant impact on climatic factors are significant and could be further explored. This is especially true given that similar relationships between the development of playa lakes and topography affected by orogenic deformation, the occurrence of strike-slip zones, and the presence of arid and semi-arid climate have been described, for instance, in the Gaxun Nur Basin in north China (south of Gobi-Altai Range; Hartmann at al., 2009), and Basin and Range province (Peterson, 1981; Jansson et al., 1993) and the Southern High Plain (Casula, 1995) in North America, and in the fold-and-thrust belt region in southern Spain (Jiménez-Bonilla, 2023; Rodríguez-Rodríguez, 2024). The most similar conditions between topography and the development of playa lakes are known from Death Valley (Blackwelder, 1931; Jansson et al., 1993). Deflation processes deepening tectonic depressions developed in pull-apart basins have also been described in North Africa (Mohammad et al., 2025). This indicates that they can occur in both foreland and intramontane basins. Studies on the role of tectonics in shaping climate processes conclude that tectonic deformation drives the development of long-term endorheic intramontane and intracontinental basins (Garcia-Castellanos, 2006). Tectonic reshaping of topography affects the drainage system and, by extension, humidity and hydrological conditions, as demonstrated by research in the Rio Grande Valley (Han and Wilson, 2024). Considering the above examples and the results of our research, we believe that, in the future, it will be possible to identify standard features of such areas and to gain a deeper understanding of the processes occurring there. This is important because the presence of lakes in an arid, marginal environment has a significant impact on the migration of fauna and the functioning of human communities, especially in north-west China, central and western Asia (Tan et al., 2018). Therefore, research on the causes of lake development and the conditions under which they occur is an important aspect of supporting adaptation to climate change.

The unique environmental conditions that once existed in the study region, along with their changes in response to local and global climatic factors, provide a new perspective for future sedimentological, mineralogical and geochemical studies of sediments deposited within the palaeolakes. In turn, their dating will allow us to establish the chronology of geological events and relate them to the results of archaeological research. The presence of prehistoric hunter-gatherer communities in the study area has been confirmed by the findings of Masojć et al. (2017, 2024), Bobrowski et al. (2025) and Michalec et al. (2025).

CONCLUSIONS

South of the Arts Bogd Massif (Gobi area, S Mongolia), fifteen palaeolakes form the Tsakhiurtyn Hundi Lakeland. New remote sensing and geomorphic analysis supported by field observations indicate that the genesis of the largest of these is complex, involving both tectonic and aeolian processes. The tectonic factor refers to large-scale structural elements in the basement of the northern part of the Gobi. The palaeolakes studied are situated along an E–W directed zone parallel to active, regional-scale strike-slip faults. The largest lakes of the Tsakhiurtyn Hundi Lakeland developed in the axis of the endorheic Shereegiin Gashuun Basin, which is interpreted here as pull-apart in origin, which favoured subsidence of the basement. Within this zone, a regional change in slope orientation is observed. In addition, the E–W alignment of valleys and ridges favoured the intensification of aeolian processes associated with the so-called Westerlies, the intensive erosional activity of which caused the formation of deflation basins in the tectonically depressed parts of the terrain. Both processes led to the development of lakes collecting waters drained mainly from nearby hills and the Arst Bogd Massif.

The geomorphological classification indicates that they typically represent very small, shallow and ephemeral closed lake bodies, as are also characteristic for the other areas of the Gobi area. Our research shows that, under dry climatic conditions, lakes can develop in areas with similar geological and geomorphological features. These conditions were favourable for early human habitation.

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