



**HAL**  
open science

## Darhad megaflood (southern Siberia): cause, age and consequence

Sergey Arzhannikov, Nastya Arzhannikova, Regis Braucher, Goro Komatsu

### ► To cite this version:

Sergey Arzhannikov, Nastya Arzhannikova, Regis Braucher, Goro Komatsu. Darhad megaflood (southern Siberia): cause, age and consequence. *Quaternary International*, 2023, 643, 10.1016/j.quaint.2022.10.002 . hal-03814219

**HAL Id: hal-03814219**

**<https://hal.science/hal-03814219>**

Submitted on 13 Oct 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Darhad megaflood (southern Siberia): Cause, age and**  
2 **consequence**

3

4 **Sergey Arzhannikov<sup>a,\*</sup>, Anastasia Arzhannikova<sup>a</sup>, Regis Braucher<sup>b</sup>, Goro Komatsu<sup>c</sup>**

5

6 <sup>a</sup>Institute of the Earth's Crust, Russian Academy of Sciences, Siberian Branch, 664033,

7 Lermontova str., 128, Irkutsk, Russia

8

9 <sup>b</sup>CEREGE, Aix-Marseille Univ., CNRS-IRD UM34, Collège de France, INRAE, BP 80, 13545

10 Aix-en-Provence Cedex 4, France

11

12 <sup>c</sup>International Research School of Planetary Sciences, Dipartimento di Ingegneria e Geologia

13 (INGEO), Università d'Annunzio, Viale Pindaro 42, 65127 Pescara, Italy

14

15 \* Corresponding author.

16 E-mail address: [sarzhan@crust.irk.ru](mailto:sarzhan@crust.irk.ru) (S. Arzhannikov).

17 **Abstract**

18

19 A combined geomorphological and geochronological investigation was carried out aiming at  
20 determining the cause of the Darhad paleolake formation and dating the Darhad megaflood. Based  
21 on the analysis of satellite image mapping, new data were obtained revealing conditions of glacial  
22 dams along the Shishkhid Gol valley. We hypothesize that large glaciers in Khara-Baryangiin Gol  
23 and Ikh-James Gol downstream of the Tengis Gol mouth were the main causes of the highest  
24 Shishkhid Gol backwater. The estimated height of this glacial dam there was about 300 m. The  
25 presence of paleolake shorelines at an altitude of 1713 m in the immediate vicinity of this glacial  
26 dam confirms its dominant role for the formation of the Darhad paleolake. Based on cosmogenic  
27  $^{10}\text{Be}$  exposure ages obtained on boulders from four fields of gravel dunes and of an erratic boulder  
28 exposed within a bar along the Yenisei River valley in the Tuva Basin, we infer that two among  
29 the three age peaks observed may correspond to megafloods at 36-38 ka and 18-23 ka.

30

31 **Keywords**

32

33 Southern Siberia; Late Pleistocene glaciation; Darhad paleolake; Darhad megaflood; Gravel  
34 dunes;  $^{10}\text{Be}$  cosmic-ray exposure dating

35

36 **1. Introduction**

37

38 This study is aimed at identifying the cause-and-effect relationship regarding the Darhad  
39 megaflood, its age and role of shaping landforms in southeastern Siberia and northern Mongolia.  
40 The study of this phenomenon provides crucial information for understanding the development of  
41 topography and deposits in the area impacted by Quaternary glaciation and makes it possible to  
42 reconstruct paleolandscapes over a large area of northern Asia.

43 The global cooling in the late Pleistocene created conditions favorable for glaciation and  
44 advancement of glaciers over large areas both in polar regions and in mountain belts of the world.  
45 Within the ice sheets and in the territories adjacent to them, dammed proglacial lakes of various  
46 sizes with volumes up to several thousand cubic kilometers were formed. However, the subsequent  
47 climatic warming caused destruction of these glacial dams. The consequent glacial lake outbursts  
48 led to catastrophic discharge of water downstream. Discharges in some cases are estimated to be  
49 up to millions of m<sup>3</sup>/s or more (O'Connor and Costa, 2004; Baker et al., 1993; Komatsu et al.,  
50 2009), and flood flows could have been up to 400-500 m deep (Rudoy, 2002).

51 In valleys and basins downstream of the proglacial lakes, specific relief forms of erosional and  
52 depositional origins were formed due to the floodwater passage (Baker, 1973; Baker et al., 1985,  
53 1993; Carling et al., 2002; Komatsu et al., 2009; Margold et al., 2018; Benito and Thorndycraft,  
54 2020). Erosive landforms include canyons, whirlpools, waterfalls, hanging valleys and spillways,  
55 and depositional landforms include gravel dunes and bars. Identification of these landforms have  
56 been used to indicate the past occurrence of megaflooding.

57 Three large paleolakes are known to be responsible for megaflood occurrence in the mountains  
58 of southern Siberia (fig. 1). These are Chuya-Kuray in Altay (Rudoy and Baker, 1993; Baker et  
59 al., 1993), Darhad in northern Mongolia (Grosswald, 1987; Komatsu et al., 2009), and Vitim in  
60 Transbaikalia (Margold et al., 2018). The collapsing of glacial dam is hypothesized to have led to  
61 the catastrophic discharge of water from the Darhad paleolake down the Yenisei valley, and this

62 is considered to be one of the largest megaflood events in the southern Siberian mountains  
63 (Grosswald, 1987; Komatsu et al., 2009, 2016; Batbaatar and Gillespie, 2016a). It is likely that the  
64 megaflood was multiple events and the estimated maximum peak discharge rate is  $\sim 3.5 \times 10^6$  m<sup>3</sup>/s  
65 (Komatsu et al., 2009). The landscape formed by the Darhad megaflood is most fully represented  
66 along the Yenisei valley in northern Mongolia and the Tuva Republic (southern Siberia) (Komatsu  
67 et al., 2009, 2016; Arzhannikova et al., 2014). For instance, erosional and depositional landscapes  
68 formed by the megaflood are found extensively within the Kaa Khem Uplands and Tuva (Kyzyl)  
69 Basin. The study of megaflood landscape has made it possible to determine the conditions for  
70 flood hydraulics.

71 The chronology of the Darhad megaflood has been inferred mostly from the timing of the  
72 Darhad paleolake formation (Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009;  
73 Batbaatar and Gillespie, 2016a, b). There have been limited attempts to determine the age of the  
74 Darhad megaflood from a set of geological data (Arzhannikova et al., 2014). However, detailed  
75 study has not been carried out yet to directly date the flood sediment.

76 There remain questions: in particular, 1) the precise timing of the Darhad megaflood, and 2)  
77 whether the Tengis Gol glacial dam was able to impound the deep Darhad paleolake. Our research  
78 is aimed at determining the timing of the Darhad megaflood and clarifying the conditions for the  
79 Darhad paleolake formation. We combine remote sensing mapping of geomorphology, geological  
80 studies, and in-situ <sup>10</sup>Be dating of exposed flood transported boulders. The work used topographic  
81 data from SRTM and TanDEM-X, geological survey maps of the USSR at a scale of 1:200,000,  
82 topographic maps at a scale of 1:100,000, and high-resolution satellite images available from  
83 Google Earth.

84

## 85 **2. Study area**

86

### 87 **2.1 A brief history of paleolakes studies in Darhad Basin**

89 The presence of ancient lacustrine sediments and coastlines in northern and northwestern  
90 Mongolia testifies for the widespread occurrence of paleolakes during the Quaternary (Selivanov,  
91 1967; Spirkin, 1970; Grunert et al., 2000; Komatsu and Olsen, 2002; Arzhannikov and  
92 Arzhannikova, 2011; Stolz et al., 2012).

93 The largest was the proglacial Darhad paleolake in northern Mongolia (fig. 1). The lake was  
94 named after the depression in which it resided. This ice- or possibly sedimentary-dammed lake  
95 repeatedly formed in the Darhad Basin during the Pliocene and Pleistocene (Selivanov, 1967;  
96 Selivanov, 1968; Spirkin, 1970; Uflyand et al., 1971; Grosswald and Rudoy, 1996; Krivonogov et  
97 al., 2005; Gillespie et al., 2008; Komatsu et al., 2009). The morphology of the basin, surrounded  
98 by mountains peaking above 3000 m and the only runoff through the Shishkhid Gol, are the most  
99 favorable conditions for the formation of a lake basin.

100 According to Selivanov (1967), there were three stages in the formation of the paleolake. Two  
101 of them were associated with volcanic lavas and the last one with the Tengis glacier dam. The  
102 possible age of the existence of lakes is indicated only for the latter as the Lower-Middle  
103 Quaternary. Instead, Spirkin (1970) hypothesized that there had been three stages in the  
104 development of the paleolake: 1) Pliocene-Early Quaternary; 2) Late Quaternary - interglacial; 3)  
105 Late Quaternary - glacial (fig. 2).

106 According to some ideas (Spirkin, 1970; Uflyand et al., 1969), Darhad Basin was formed in the  
107 pre-Pliocene times (all dates are based on palynological analyses) or at the end of the Miocene and  
108 the beginning of the Pliocene, when the deformation front from the Indo-Asian collision reached  
109 this region (Jolivet et al., 2007). As a result of the mountain uplift to the west of the Darhad Basin,  
110 Shishkhid Gol was dammed, and a small lake was formed. Then, the river cut within the uplifted  
111 block, and the lake level lowered and the main elements of the valley were formed. Spirkin (1970)  
112 noted that during the interglacial period of the late Pleistocene (MIS3) the Shishkhid Gol valley  
113 had been dammed by volcanic lavas, leading to the formation of a small lake. However,  $^{39}\text{Ar}/^{40}\text{Ar}$

114 dating of valley lavas showed an age of 6–4 Ma (Perepelov et al., 2017), which excludes the  
115 Quaternary age of the paleolake by the lava damming. It has been hypothesized that the lake  
116 reached its maximum level during the last phase of the Late Pleistocene glaciation (MIS2) due to  
117 damming of Shishkhid Gol by a Tengis glacier. The thickness of the terminal moraine reached 200  
118 meters and the coastline of the paleolake was at 1700-1720 m asl (Spirkin, 1970). Further detailed  
119 studies of glaciation in the eastern Sayan and northern Mongolia significantly improved the  
120 chronology of glacier advances during the Late Pleistocene (Gillespie et al., 2008; Arzhannikov et  
121 al., 2012), and this led to a new discussion about the age of the glacial Darhad lake (Krivonogov  
122 et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009; Batbaatar and Gillespie, 2016a, b).

123

## 124 **2.2 Glacial-dammed Darhad paleolake**

125

126 Researchers of Darhad Basin's Quaternary history have noted the widespread and well-  
127 preserved lake shorelines (Selivanov, 1967; Ufland et al., 1969; Ufland et al., 1971; Spirkin, 1970;  
128 Grosswald, 1987; Grosswald and Rudoy, 1996; Komatsu and Olsen, 2002; Krivonogov et al.,  
129 2005; Gillespie et al., 2008; Komatsu et al., 2009, 2016). On the slopes of the ridges in the basin,  
130 they are clearly traced up to a height of 1713 m asl (Krivonogov et al., 2005). Remote sensing data  
131 show that this level (1713 m asl) dominates throughout the Darhad Basin. The tops of the ridges  
132 and small extended ridges located within the basin have a system of encircling shorelines, which  
133 indicates the presence of islands during the existence of the Darhad paleolake (fig. 3).

134 Lake terraces are located on the slopes of the basin, river valleys, and on the escarpment of the  
135 Jarai terminal moraine. In total, there are 47 shorelines located on the right bank of the Shishkhid  
136 Gol (Tengis Gol mouth) (Krivonogov et al., 2005). According to observational data (Krivonogov  
137 et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009), the lake shorelines are limited by the  
138 Tengis moraine (Tengis Gol mouth). Regarding the timing of the Darhad paleolake, there is no  
139 clear consensus on this matter. Gillespie et al. (2008) believe that the glacier advances from the

140 mountains around the Darhad Basin occurred at 17-19 ka, 35-53 ka, and at least one more time  
141 earlier. Krivonogov et al. (2005) consider that a large lake was formed 110-116 ka and probably  
142 existed until 15 ka, changing in size with time.

143 Geological and geomorphological analyses, mapping and dating of Quaternary deposits showed  
144 that the possible reason for the formation of the Late Pleistocene Darhad lake could have been  
145 glaciers emerging from lateral tributaries of Shishkhid Gol (fig. 4), blocking the river flow down  
146 the valley (Grosswald and Rudoy, 1996; Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu  
147 et al., 2009, 2016). Krivonogov et al. (2005) considered one glacial dam in the area of the Tengis  
148 Gol mouth. According to Gillespie et al. (2008), there were probably two glacial dams at the outlets  
149 of Tengis Gol and Gadar-Usiyin Gol. Komatsu et al. (2009) and Batbaatar and Gillespie (2016a)  
150 hypothesized three glacial dams. The most downstream of them was located at the mouth of the  
151 Barangiin Gol. Highlighting different numbers of glacial dams, the researchers nevertheless agreed  
152 that the main reason has been the glacier advancing from the Tengis Gol valley. The glaciers  
153 downstream of Shishkhid Gol were thinner and could not account for the deep Darhad paleolake  
154 (fig. 4) (Grosswald and Rudoy, 1996; Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu et  
155 al., 2016).

156

### 157 **2.3 The Darhad megaflood**

158

159 While studying the glacial landscape of the Sayan-Tuva uplands (southern Siberia), scientists  
160 discovered landforms resembling gravel dunes. Borisov and Minina (1982) characterized them as  
161 ribbed and cellular ground moraines, an element of the Middle Pleistocene glaciation. However,  
162 the advent of publications about gravel dunes found in Altai (Baryshnikov, 1979; Butvilovsky,  
163 1982; 1985; Rudoy, 1984) and claiming them as the important elements of major hydrological  
164 catastrophes (megafloods) initiated a search for similar landforms in other regions of mountains  
165 in southern Siberia. The first geologist who recognized the complex of erosional-depositional



166 forms in the Yenisei valley as the result of high water discharge from the Darhad paleolake was  
167 M.G. Grosswald. By comparing the data on the Darhad paleolake with a giant canyon (coulee)  
168 carved in volcanic lavas and a system of gravel dune fields in the Tuva Basin formed in the glacial  
169 time, Grosswald (1987) concluded that megaflooding had occurred in the past. Since then, the  
170 Darhad phenomenon has attracted attention of the world scientific community. Various studies  
171 were conducted, and field conferences were held. Some articles have been published on the  
172 morphology, water flow dynamics and velocity, flow modeling, paleogeographic reconstruction,  
173 etc. (Grosswald, 1987; Grosswald, 1996; Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu  
174 et al., 2009, 2016; Arzhannikova et al., 2014; Batbaatar and Gillespie, 2016a, b).

175

### 176 **3. Methods**

177

#### 178 **3.1 Mapping**

179

180 The production of geomorphological maps and schemes for the study area was based on relief  
181 hillshading and visual interpretation of remote sensing data (SRTM V4 (spatial resolution 90 m),  
182 ALOS (spatial resolution 30 m), TanDEM-X DEM (spatial resolution 12 m); topographic maps,  
183 geological maps, satellite and aerial photographs of various scales) and published data  
184 (Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009, 2016; Batbaatar and  
185 Gillespie, 2016a, b). Satellite image analysis, identification of landforms and mapping were carried  
186 out in programs Google Earth and QGIS. The analysis was carried out on the territory of the  
187 Yenisei valley and the adjacent areas spanning over the Darhad Basin to the Sayano-Shushenskoye  
188 reservoir. Attention was paid to the study of the lake terrace complex and glacial landforms located  
189 in the Darhad Basin and in the Shishkhid Gol valley. In order to obtain information about the  
190 Darhad megaflood, Yenisei terrace complexes and gravel dune fields in the Tuva Basin were  
191 analyzed in detail.

192 The process of mapping proceeded as follows. The primary analysis was conducted based on  
193 SRTM (spatial resolution 90 m) data. Then, ALOS data (spatial resolution 30 m) and TanDEM-X  
194 DEM data (spatial resolution 12 m) were also used. Using Google Earth and QGIS we  
195 superimposed satellite images of various scales (Google Earth and QGIS) on topographic data to  
196 obtain high-quality three-dimensional imagery. This way, we were able to perform a detailed  
197 analysis of erosional and depositional features caused by the megaflood. Landforms associated  
198 with other lithological factors (i.e., not by the megaflood) were excluded using geological maps.  
199 Geological data also provided information on the extent of Quaternary deposits, which was  
200 important in interpreting the distribution of Darhad megaflood sediments. Topographic maps were  
201 the source of information regarding names of main topography in the study area, as well as the  
202 basis for the correcting absolute heights (m asl) for radar-derived topographic survey data (SRTM,  
203 ALOS, TanDEM-X DEM). Due to the fact that all radar data have errors in altitude, we checked  
204 the control points (trigopoints) on topographic maps, and if there were errors, we made a  
205 correction.

206

### 207 **3.2 $^{10}\text{Be}$ exposure dating**

208

209 We used beryllium ( $^{10}\text{Be}$ ) in-situ dating (Wagner, 1998; Gosse and Phillips, 2001) to determine  
210 the age of exposed gravel dune boulder surfaces. The accumulation of  $^{10}\text{Be}$  atoms occurs under  
211 the action of cosmic rays on the surface of rocks. It accumulates in silicate minerals, especially  
212 quartz, and is therefore suitable for dating exposed surfaces. Since the in-situ production in quartz  
213 (bedrock: granite, quartzite, quartz vein) is low ( $\sim 4$  at/gSiO<sub>2</sub>/y) (Borchers et al. 2016), 10–30 g of  
214 quartz is required for analysis (Wagner, 1998). The half-life of ( $^{10}\text{Be}$ ) is 1.387 Ma (Chmeleff et  
215 al., 2010; Korchinek et al., 2010), which makes it possible to date surface rocks over a wide time  
216 range.

217 One of the main conditions for obtaining high-quality data is the immobility of the dated  
218 boulder from the moment of its exposure. The boulder exposure should coincide with the end time  
219 of the megaflood, and its location (orientation in space) should be maintained until the moment of  
220 sampling. However, from the moment of exposure, exogenous processes begin to work, affecting  
221 its safety and stability on the surface of gravel dunes. These include river erosion (bottom and  
222 side), thermokarst, solifluction, denudation, wind action and desquamation. Bottom and side  
223 erosion of streams significantly deforms the surface of gravel dunes. However, water erosion is  
224 localized in a narrow area, forming a valley that is excluded from the sampling sites. The  
225 development of thermokarst leads to surface deformation and the appearance of small depressions.  
226 Near-horizontal surfaces of a large area indicate the absence of any active thermokarst processes  
227 within them for a long time and the boulders in the area can be used for sampling.

228 Another factor that can affect the accuracy of determining the exposure of a sample is its  
229 shielding of the surrounding topography. The degree of topographic shading can be determined by  
230 simple circular measurement of the angles and strike of shadow sectors from mountain peaks or  
231 extended ridges, which is taken into account later in dating (Gosse and Phillips, 2001).

232

### 233 **3.2.1 Sampling**

234

235 Four fields of gravel dunes were chosen for sampling, located over a distance of 150 kilometers  
236 along the Yenisei valley (fig. 13 c, d). A peculiar attention was paid to the sample position at a  
237 maximum distance from nearby slope to exclude solifluction flow and at where no thermokarst is  
238 observed. The geographic position and altitude of each sample were obtained using a portable GPS  
239 (horizontal uncertainty  $\pm 5\text{m}$ ). The topographic shielding was also measured for each sample.

240 *Gravel dune field I* (51°33.883N; 93°59.016E) (fig. 5 a) is located on the right bank of the  
241 Yenisei River and its dimension is 8 x 2 km. Gravel dunes occur at several terrace levels with a  
242 total area of 11.5 km<sup>2</sup>. The maximum level above the Yenisei River is 30-40 m, the minimum level

243 is 14-16 m. The continuous transition of gravel dunes from higher to lower levels indicates their  
244 simultaneous formation. The presence of a depression in the rear part of the dunes in the area of  
245 contact with the slope and its absence at the head of the dunes indicates possible existence in the  
246 past of a terrace level 10–12 m high, buried during the Darhad megaflood. This fact implies a thick  
247 deposit (~20 m) formed by the Darhad megaflood in this part of the Yenisei valley. The swell-like  
248 structure of the dunes is distinguished in the longitudinal and transverse profiles. Ridges 1-2 m  
249 high prevail on the surface of the gravel dunes and their heights increase towards the central part  
250 up to 6-8 m. 5 samples (Tuva-16-1, 2, 3, 4, 5) were taken from the surface of boulders located in  
251 the dunes.

252 *Gravel dune field II* (51°43.101N; 94°33.670E) (fig. 5 b) is located on the right bank of the  
253 Yenisei River. There are two levels of gravel dunes at 35 and 70 m. The total area is 12 km<sup>2</sup>. The  
254 height of the gravel dune ridges is on average 2-4 m, or rarely reaching 4-6 m. On the surface,  
255 many boulders up to 1 m in size, and in some places 2-4 m, are found everywhere. In the eastern  
256 part of Gravel dune field II, 5 samples were taken from the surface of boulders (Tuva-16-6, 7, 8,  
257 9, 10).

258 *Gravel dune field III* (51°40.020N; 94°53.032E) (fig. 5 c). This is one of the largest gravel dune  
259 fields in the Yenisei valley. It is located on the right bank of the river. Its area is more than 20 km<sup>2</sup>.  
260 The gravel dunes are positioned at three levels at 14, 30-40 and 70 m relative to the Yenisei River.  
261 5 samples (Tuva-16-12, 13, 14, 15, 16) were taken from the surface of boulders on a gravel dune  
262 located on the 30 m terrace.

263 *Gravel dune field IV* (51°40.020N; 94°53.032E) (fig. 5 c). The sampling field is the surface of  
264 a gravel dune located 14 m above the current water level in the Yenisei River. The height of the  
265 ridges is 0.5-0.7 m. 5 samples were taken from this level (Tuva-16-17, 18, 19, 20, 21).

266 An additional sample was obtained from, the bar area (51°18.397N; 95°44.375E) (fig. 5 d), on the  
267 right bank of the Yenisei River, in the western part of the Kaa Khem Uplands. This sample (Tuva-  
268 16-11) was taken from a boulder measuring 8 x 4 m and 2-2.5 m high. The mass of the boulder is

269 estimated to be about 172 tons. The sampling point is located on the 25 m terrace. The dimensions  
270 of the granite boulder testify for the significant power of the water flow, as the nearest bedrock of  
271 granites is located 15 km upstream.

272 Overall, we collected 21 samples from the surface of gravel dunes with heights of 12-14 m, 30  
273 m, 40-50 m and from the surface of a 25 m terrace within the bar.

274

### 275 **3.2.2 Samples preparation and measurements; Exposure ages calculation**

276

277 Samples preparation was done at LN2C, the French National Laboratory for Cosmogenic  
278 Nuclides located at CEREGE (Aix en Provence).

279 Samples were crushed and sieved (0.25 to 1 mm fraction) then purified with a mixture of  
280 hydrochloric and fluorosilicic acids (2/3 – 1/3 ratio) until pure quartz was obtained. Three leaching  
281 steps in diluted HF were then performed to eliminate the adsorbed atmospheric  $^{10}\text{Be}$ , resulting in  
282 the loss of ~30% of the initial material.

283 A weighed amount (~0.1 g) of  $^9\text{Be}$  solution ( $3025\pm 9$  ppm) was added to the decontaminated  
284 quartz. Beryllium was subsequently separated from the solution by successive anionic and cationic  
285 resin extractions and precipitations. The final precipitates were dried and heated to  $800^\circ\text{C}$  to obtain  
286  $\text{BeO}$  which was finally mixed with niobium powder prior to analysis by Accelerator Mass  
287 Spectrometry at ASTER (Cerege, Aix en Provence). The beryllium data were calibrated directly  
288 against STD11 standard (Braucher et al., 2015) with a  $^{10}\text{Be}/^9\text{Be}$  ratio of  $1.191\times 10^{-11}$  ( $\pm 1.09\%$ ).  
289 Uncertainties on measurements include the counting statistics, the standard variability during the  
290 run, the uncertainty on STD11 standard (1.09%) and an external machine uncertainty of 0.5%  
291 (Arnold et al., 2010).  $^{10}\text{Be}/^9\text{Be}$  samples ratios are 8 to 82 times higher than the chemical blank  
292 ratio ( $5.8\times 10^{-15}$ ).

293 To calculate the exposure ages, a sea level high latitude production rate of 4.02 at/g/a was used  
 294 and scaled to the latitude and altitude of the studied area using the Stone (2000) polynomial law.  
 295 The muons scheme follows Braucher et al. (2011).

296 The general equation used to model  $^{10}\text{Be}$  concentrations considering the three types of  
 297 particles involved is given by eq. (1):

298

$$\begin{aligned}
 300 \quad N(x, \varepsilon, t) = & \frac{P_n \cdot e^{-\frac{\rho x}{\Lambda_n}} \left( 1 - e^{-t \left( \frac{\rho \varepsilon}{\Lambda_n} + \lambda \right)} \right)}{\frac{\rho \varepsilon}{\Lambda_n} + \lambda} + \frac{P_{\text{slow}} \cdot e^{-\frac{\rho x}{\Lambda_{\text{slow}}}} \left( 1 - e^{-t \left( \frac{\rho \varepsilon}{\Lambda_{\text{slow}}} + \lambda \right)} \right)}{\frac{\rho \varepsilon}{\Lambda_{\text{slow}}} + \lambda} + \frac{P_{\text{fast}} \cdot e^{-\frac{\rho x}{\Lambda_{\text{fast}}}} \left( 1 - e^{-t \left( \frac{\rho \varepsilon}{\Lambda_{\text{fast}}} + \lambda \right)} \right)}{\frac{\rho \varepsilon}{\Lambda_{\text{fast}}} + \lambda} \\
 299 \quad & + N(0, \varepsilon_2) \cdot e^{-\lambda t} \text{ (eq.1)}
 \end{aligned}$$

301

302 where  $P_n$ ,  $P_{\text{stop}}$  and  $P_{\text{fast}}$  are the production of neutrons, stopping and fast muons respectively,  $\rho$   
 303 is the material density,  $\square \square$  is the denudation rate (set to zero in this study),  $t$  is time,  $\Lambda_{\text{neut}}$ ,  $\Lambda_{\text{stop}}$   
 304 and  $\Lambda_{\text{fast}}$  are the attenuation lengths of neutrons ( $150 \text{ g/cm}^2$ ), stopping ( $1500 \text{ g/cm}^2$ ) and fast  
 305 muons ( $4320 \text{ g/cm}^2$ ), respectively. The term  $N(0, \varepsilon_2)$  is a potential inheritance coming from a  
 306 previous exposure.  $\lambda$  is the radioactive decay constant ( $\lambda = \ln 2 / \text{half-life}$ ).

307

## 308 4. Results

309

### 310 4.1 The water level of the Darhad paleolake according to the interpretation of satellite images 311 and radar-derived topographic data

312

313 The analysis of shorelines of the Darhad paleolake based on satellite images and SRTM data  
 314 shows that the highest coastline of the paleolake corresponds to an altitude of 1713 m asl. The  
 315 most interesting result of remote sensing in the area of the Shishkhid Gol valley is the presence of  
 316 shorelines of a paleolake observed downstream of the Tengis Gol mouth. These shorelines are well  
 317 identifiable on the slopes of the valley up to a height of 1713 m asl. For example, on the right bank

318 side of the Shishkhid Gol valley, 12 km downstream the Tengis Gol mouth, lake terraces are  
319 clearly visible, tracing slopes of the main valley and partially visible on slopes of lateral tributaries  
320 (figs. 5, 6). Several shoreline features are clearly visible starting from the Tengis mouth down the  
321 Shishkhid Gol valley (figs. 6 a, b, c, d, 7). Each extended shoreline visible on the satellite image  
322 corresponds to an isoline, with its characteristic height, determined from the SRTM and ALOS  
323 data and refined from the topographic maps of the USSR.

324 Shoreline group I (fig. 6 a) is located 2.2 km downstream of the Tengis mouth. The slope of the  
325 valley is terraced along a distance of 1.2 km between 1680 and 1713 m asl. Shoreline group II (fig.  
326 6 b) is located in the valley of the right lateral tributary of Shishkhid Gol. On one of the capes  
327 formed by the main valley and tributary, a series of shorelines 1.4 km long is visible, and they are  
328 positioned from 1640 to 1713 m asl. Shoreline group III (fig. 6 c) is located 7 km downstream  
329 from the Tengis Gol mouth. On the slope of the western exposure, the terrace levels of the  
330 paleolake, 0.7 km long, are clearly visible at two levels. They are concentrated between 1550 and  
331 1713 m asl. Shoreline group IV (fig. 6 d) is located 12 km downstream from the Tengis Gol mouth.  
332 On the slope of the right tributary in its mouth part, a series of parallel coastlines 1 km long is  
333 clearly visible. They are positioned between 1520 and 1713 m asl. An abraded slope 1.2 km long  
334 downstream from the mouth of this tributary is also clearly visible (fig. 6 d).

335 The shorelines were formed also on a slope in the Sarig Gol valley (the left tributary of  
336 Shishkhid Gol). Furthermore, there is a fragment of the Tengis terminal moraine (fig. 8 f). This  
337 indicates that the height of the Tengis glacier, which dammed the Shishkhid Gol valley, did not  
338 block it up to the height of 1713 m asl. This should have allowed the formation of a paleolake bay  
339 in this valley, which is marked by Krivonogov et al., 2005. In Darhad Basin, in the border parts  
340 and in the inner area, there are small ridges and hills. During the existence of the paleolake, they  
341 were peninsulas and islands. Coastal ridges and terraces formed on their slopes when the water  
342 level changed.

343 Analysis of satellite images and DEM data showed that the highest paleoshoreline was not  
344 constant in elevation and varied from 1713 m asl down to 1686 m asl (figs. 7, 8). For example, the  
345 upper lake line is traced at an altitude of about 1705-1703 m asl on the southern slopes of a small  
346 ridge located north of Dood-Nur and Targan-Nur lakes (fig. 8 g, h, j, k). If we move to the  
347 southwest, we see that the height of the upper coastline changes to 1696 m asl, and further south  
348 it changes to 1686 m asl (fig. 8 l, m). Thus, the change of the upper paleolake shoreline elevation  
349 possibly indicates significant tectonic deformations within the Darhad Basin that have occurred  
350 since its drainage.

351

#### 352 **4.2 Tectonic and gravitational deformations**

353

354 The Darhad Basin is part of the southwestern segment of the Baikal rift zone and is  
355 characterized by its latitudinal extension. The Darhad Basin is controlled by normal faults  
356 extending from the east and west. The thickness of the sedimentary cover is 300-400 m (Logachev,  
357 1993). The analysis of satellite images and DEM data made it possible to detect seismogenic  
358 ruptures and gravitational displacements within the Darhad lake basin (fig. 9). The activation of  
359 faults apparently occurred both during the existence of the lake and after its drainage. In the  
360 northern part of Darhad Basin, a fault of meridional strike was found with a displacement  
361 amplitude from 25 m in the south to 60 m in the north. The displacement along the fault led to  
362 partial subsidence and burial of the Khogorgyn Gol valley (fig. 9 a). A latitudinal normal fault  
363 with a displacement amplitude of about 50 m is located to the north of Lake Dood Tsagan Nur. It  
364 extends from the Khogorgyn Gol valley, crossing the southern part of the meridional fault and  
365 ends in the region of Lake Targan-Nur (fig. 9). Another complex of deformations is located to the  
366 east and is represented by a NE-trending scarp on the southern slope of a small ridge (fig. 9 b).

367 The revealed seismogenic faults in the eastern part of the Darhad Basin (fig. 7), in the area of  
368 the Jarai terminal moraine (Logachev, 1993), indicate ongoing active tectonic movements in this



369 area. Seismogenic ruptures with a maximum amplitude of 8 m displaced proluvial, colluvial, and  
370 glacial deposits. The length of the fault visible on the surface is 13 km. Along with the faults  
371 displacing bedrock and sedimentary deposits, landslides are widespread, which are located at the  
372 foot of small ridges within the Darhad Basin.

373

#### 374 **4.3 Reconstruction of glacial dam No. 1 at the Tengis Gol outlet**

375

376 The main landforms that help in reconstructing dimensions of a glacier are terminal and lateral  
377 moraines, spillways and meltwater channels. The absolute height of the left (1715-1737 m asl) and  
378 right (1720-1745 m asl) lateral moraines located at the Tengis Gol mouth and the height of the  
379 spillway thalweg (1700-1740 m asl) suggest the possibility of dam formation in the Shishkhid Gol  
380 valley by the Tengis glacier (Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009,  
381 2016; Batbaatar and Gillespie, 2016 a, b;). This is confirmed by the fact that some part of the  
382 terminal moraine is located on the opposite side of Shishkhid Gol at the mouths of its left  
383 tributaries. Here, the absolute height of the terminal moraine is 1640 m asl. We can assume that  
384 there were two levels of standing of the Tengis glacier in MIS2, based on the presence of spillways  
385 with different absolute heights in the mouth part of Tengis Gol and also <sup>10</sup>Be ages (Gillespie et al.,  
386 2008; Batbaatar and Gillespie, 2016b).

387 The Level I standing of the Tengis glacier is determined by upper spillways (1700-1740 m asl),  
388 fragments of the terminal moraine (1640 m asl), abraded slopes and meltwater channels on the  
389 right and left banks of Shishkhid Gol (fig. 10 a, b, c, d). The Level II standing can be reconstructed  
390 from a lower spillway (1657 m asl) and lake terraces located on the slopes at the Tengis Gol mouth  
391 (fig. 11). Level I in front of the Tengis Gol mouth had a height of 1750 m asl. However, as the  
392 Tengis glacier entered the Shishkhid-Gol valley, its level dropped to 1650 m asl. This is the height  
393 of the terminal moraine and the height of the upper part of the abraded slope on the left bank of  
394 Shishkhid Gol (fig. 10, profiles AB, CD). The exposure age of the terminal moraine in the Sarig

395 Gol valley (Batbaatar and Gillespie, 2016b) characterizes the glacier advance in the LGM (MIS2).  
396 The reconstruction of the Tengis glacier on profile CD (fig. 10) shows that Level I on the left bank  
397 of Shishkhid Gol was significantly lower than the maximum (1713 m asl) transgression of Darhad  
398 paleolake.

399 Paleolake terraces are widespread on the right slope of the Shishkhid Gol valley at the mouth  
400 of the Tengis Gol. They abrade the surface of glacial deposits of Level I. The terraces are not  
401 covered by moraine deposits (fig. 11). Their location and height suggest a significant decline in  
402 the glacial level (meltwater channel 1657 m asl, fig. 11). The exposure age ( $^{10}\text{Be}$ ,  $20.7\pm 1.1$ ,  
403  $18.2\pm 1.0$  ka) of the melt water channel (Gillespie et al., 2008) agrees with MIS2 after LGM (fig.  
404 11). The AB and CD profiles (fig. 11) show a significant reduction in the Level II ice within the  
405 Tengis dam.

406

#### 407 **4.4 Glacial features and parameters of glacial dam No. 4 at the Khara-Baryangiin Gol and** 408 **Ikh-Jams Gol mouths (right and left tributaries of Shishkhid Gol)**

409

410 Khara-Baryangiin Gol is the right tributary of Shishkhid Gol (fig. 4). The valley is located  
411 within a mountain range with elevations over 3000 m asl. Glacial cirques and troughs are  
412 widespread in the upper reaches of this river basin. There are different levels of lateral moraines  
413 on the slopes of the valleys. In the mouth part of the river there is a large terminal moraine, and  
414 there are lateral moraines in the valley. They are clearly visible both on satellite images and on the  
415 ALOS DEM. The absolute height of the left lateral moraine in the Khara-Baryangiin Gol valley  
416 (at the mouth) is 1890 m asl (figs. 4, 12 a).

417 Ikh-James Gol is the left tributary of Shishkhid Gol. The ice-catchment is located within a  
418 mountain range with elevations of 2700-3000 m asl. On the slopes of the river valley, fragments  
419 of lateral moraines have been preserved, giving information about the thickness (300-500 m) of

420 the glacier. The elevations of the glacier at the mouth on the left and right slopes are 1770 m asl  
421 and 1745 m asl, respectively (fig. 12 b).

422 The mouths of these tributaries (Khara-Baryangiin Gol and Ikh-James Gol) are located opposite  
423 to each other. The glaciers joined in the Shishkhid Gol valley and formed a large glacial dam with  
424 the level corresponding to 1715-1720 m asl (fig. 12 c). The altitude of the glacial dam is determined  
425 from the elevation of the melt water channel (fig. 12 d) on the left side of Shishkhid Gol. Additional  
426 evidence for the presence of a glacial dam is a series of erosional grooves on the slope, which  
427 record a decrease in the elevation of the glacier in this part of the Shishkhid Gol valley.

428

#### 429 **4.5 The main erosional and depositional landforms of the Yenisei valley**

430

431 The Yenisei valley in the Tuva Basin (fig. 1 b) presents the existence of two main erosional-  
432 depositional landforms formed during and after the Darhad megaflood (fig. 13). The main  
433 landscape elements formed after the Darhad megaflood include low and high floodplains (fig. 13  
434 c, d), which have special features distinguishing them from other erosion-depositional forms. The  
435 combination of bottom and lateral erosion led to the formation of clearly defined escarpments of  
436 terraces, meanders and oxbow lakes. The seasonal rise of water in the river resulting from rains  
437 and melting of snow lead to changes in channel configuration, death of old and birth of new  
438 meandering channels and islands.

439 The second complex of erosional-depositional landforms is positioned 12 m above the low  
440 relief (fig. 13 c, d). The distinguishing characteristics are the absence of meanders and the presence  
441 of linear structures on the surfaces of high terraces, which indicates the formation of this relief  
442 with certain dynamic conditions. These linear structures are a system of gravel dunes (or giant  
443 current ripples, terminology in old literature) (fig. 13) as described in Komatsu et al. (2009), who  
444 also documented their morphology, topographic setting and correlations with megaflood  
445 hydraulics.

446 The nature of the Yenisei valley within the Tuva Basin predetermined the wide distribution and  
447 preservation of terraces of various levels. Some of them were formed by the Yenisei cutting into  
448 deposits of the Darhad megaflood; in other cases, megaflood deposits cover or lie on the surface  
449 of ancient terraces. The width and length scales of the terrace surfaces are kilometers and even a  
450 few tens of kilometers. In the Yenisei valley, there are a low floodplain (2–4 m), a high floodplain  
451 (6–8 m) and terrace levels of 12–14, 18–20, 30, 40–50, and 100 meters (fig. 13). On all levels of  
452 the terraces, except for the low and high floodplains and the 100 m level, gravel dune fields are  
453 observed. There is even a level of gravel dunes located at an altitude of 70 m above the level of  
454 the Yenisei River.

455

#### 456 **4.6 Water level and depth of the Darhad megaflood in Tuva Basin**

457

458 Based on the analysis of satellite images and DEM data, we discovered and subsequently  
459 examined in the field a series of terraces formed in the process of lateral erosion during a decrease  
460 in the water level of the paleoflow along the Yenisei valley (fig. 14 c). These terraces are horizontal  
461 levels, more than 5 km long, and formed into colluvial-diluvial deposits overlying Jurassic  
462 sedimentary rocks and Paleozoic granodiorites (fig. 14 a, b). It should be noted that we are talking  
463 about high-level terraces (about 100 m, relative to the current water level in the Yenisei River).

464 In total there are 7 levels of different preservation. The highest of them were recorded at a  
465 height of 725 m asl. In (fig. 14 a, b), and elements of terraces with well-defined horizontal surfaces  
466 and escarpments are clearly visible both from the Yenisei side and in temporary streams. Such relief  
467 elements can often be seen on the slopes of artificial reservoirs with seasonal fluctuations in water  
468 levels. The terraced surface contains poorly rounded fragments of various metamorphosed and  
469 igneous rocks. Outcrops of Jurassic rocks are located in the lower part of the ledge of a 50-meter  
470 terrace. Analysis of geomorphological profiles (fig. 14 c, d) drawn along lines AB and CD  
471 covering the complex of terraces and different levels of gravel dunes showed that the depth of the

472 Darhad megaflood stream above the present level of the Yenisei River was 90-100 m and above  
473 the lowest level of gravel dunes at 60-65 m.

474

#### 475 **4.7 Morphological analysis of gravel dunes**

476

477 A large volume of water and various topographic conditions of the Yenisei valley (from wide  
478 depressions to narrow canyons) along the path of the glacial superflood created a complex of  
479 erosion-depositional landforms. First of all, it is necessary to note that fields of gravel dunes are  
480 widespread in the Tuva Basin. Gravel dunes are a system of extended ridges and depressions  
481 oriented perpendicularly or at an angle to the general direction of the water flow (fig. 15 a, c).  
482 Gravel dunes are composed of sand, gravel, pebbles and boulders (fig. 15 b). And the composition  
483 varies within a single gravel dune field, which is influenced under conditions of different water  
484 flow rates.

485 On the surface of the gravel dunes many boulders up to a few meters in diameter can be  
486 encountered. Sometimes there are stone "monsters" up to 8-10 m in size. The basalt fragments  
487 found in gravel dune surfaces showed that the movement of boulders 0.5-1 m in size (fig. 16 f)  
488 could have occurred over a distance of over 100 km. The height of the gravel dunes varies from 1-  
489 2 m to 6-7 m. Their length can reach several hundred meters. These gravel dunes are essentially  
490 bedforms of diluvial flows. The main area of gravel dune formation is concentrated in Tuva Basin  
491 along the Yenisei valley from the Kaa Khem Uplands to the river's entrance to the canyon of the  
492 Western Sayan Ridge (fig. 13 c, d). The total length of the river stretch with observed gravel dune  
493 fields reaches for more than 200 km, and their number approaches two dozen.

494 The periodicity of the Darhad paleolake formation (Gillespie et al., 2008; Komatsu et al., 2009)  
495 suggests that there could have been several catastrophic discharges of water from this lake. The  
496 surviving gravel dune fields are in many cases located in the stream shadow zone created by the  
497 bend of the river and the protruding cape of bedrock as observed by Komatsu et al. (2009). In some

498 cases, in the zone where gravel dune deposits adjoin bedrock slopes, there are depressions in the  
499 relief, representing a through or blind valley, on the surface of which gravel dunes are also located.  
500 The granulometric composition of the gravel dunes ranges from pebbles mixed with boulders to  
501 gravel and well washed horizontally-lying sand. Coarser sediment is often found in areas of shade  
502 along river bends. Downstream of the river, the dimension of alluvium decreases to gravel and  
503 sand fractions.

504 The deposits formed by the Darhad megaflood are concentrated within the Tuva and Minusa  
505 Basins, and partly in the river valleys located in the Western Sayan Ridge and Kaa Khem Uplands  
506 (Komatsu et al., 2009, 2016; Arzhannikova et al., 2014). The deposits are represented by clastic  
507 material of various sizes: sand, gravel, pebble, boulder and hummock (fig. 16 a-g). Sandy sediment  
508 occurs as large in-situ units (fig. 16 a, b) and as heavily wind-blown (fig. 16 c) (aeolian sand units).  
509 In-situ sand units are usually located in the narrowing zones of the valley, in the peripheral mouth  
510 parts of lateral tributaries, and at the exits from narrow valleys into its wide parts or into  
511 depressions (Arzhannikova et al., 2014). A typical in-situ sand unit (6–8 m) located on the right  
512 bank of the Yenisei valley is represented by horizontally stratified deposits of various thicknesses  
513 from 2–3 mm to 15–20 cm with inclusions of rare pebbles (fig. 16 a), which occur on pebbles and  
514 covered with loess-like light sandy loams.

515 In sandy deposits, there are blocks that are also composed of sand, however, having a different  
516 texture from their surrounding sediments. The intactness of the blocks suggests their frozen state  
517 during transport by water, as evidenced by subsidence of overlying sediments after the blocks have  
518 melted and compacted (fig. 16 b). In some cases, unconformities of sands with underlying  
519 sediments are recorded (fig. 16 b). Perhaps they indicate multiple episodes of discharge from the  
520 Darhad paleolake.

521 Aeolian sand unit are located both in the Yenisei valley and beyond. They were formed by  
522 intense eolian processes. In present day, some units of sand sea (fig. 16 c) are located 100 km from  
523 their original formation site.

524 Gravel and pebble units are widespread within gravel dunes (fig. 16 d, e). In some sections,  
525 deformed gravel deposits with rare large pebbles overlain by sandy loams are recorded. Such  
526 deformations are recorded in deposits about 1 m thick. They may be associated with strong paleo-  
527 earthquakes and represent seismic convolutions. A high degree of seismic activity is indicated by  
528 numerous falls in mountainous areas in the immediate vicinity of the deformed deposits.

529 Boulder units are located in terrace outcrops and on the gravel dune surfaces. Their sizes vary  
530 from 0.5 m to 1 m (fig. 16 f, g). Some of them are well rounded and have a spherical or ellipsoidal  
531 shape. Other boulders have a low degree of roundness and are represented by angular large  
532 fragments.

533 Hummock units occur within gravel-pebble deposits and on the surface of gravel dunes (fig. 16  
534 h, g). The size of such fragments reaches 8 m.

535

#### 536 **4.8 $^{10}\text{Be}$ surface exposure dating**

537

538 For the gravel dunes in the Yenisei River valley, the exposure age was obtained for 19 samples  
539 out of 21 selected. Two samples did not have enough quartz for dating. The exposure age was  
540 distributed over a large time range from 137.5 to 18.6 ka (table 1). We interpret these ages to  
541 reflect the formation timing of the gravel dunes and thus approximate the formation chronology  
542 of the Darhad megaflood.

543 The samples were collected from terrace surfaces with height levels of 40, 30, 25 and 15  
544 m (fig. 13 c, d) with the intention to determine exposure ages of boulders composing gravel dunes  
545 at various topographic positions.

546 The Gravel dune field I samples (T1, T3, T4, T5) obtained in the western part of the Yenisei  
547 River valley (fig. 13 c) has a significant scatter of exposure ages (Table 1). The oldest of them at  
548 ~79.5 ka (T1) and ~137.5 ka (T5) were sampled from bedrock granitic rocks located within the

549 gravel dunes. There are two samples (T3, T4) taken from boulders that have similar exposure ages  
550 of ~31 ka and ~30 ka and the ages belong to the final MIS3.

551 The Gravel dune field II samples (T6, T7, T8, T9, T10) were located on the surface of a  
552 30-m terrace 45 km east of the I group (fig. 13 d). The ages of these samples refer to the periods  
553 of MIS 3 and MIS 2. The closest ages are for samples T7 (~26.9 ka) and T10 (~27.8 ka). It is  
554 possible to distinguish samples T6 (~31.1 ka) and T8 (~37.6 ka), which are also close in time. The  
555 T9 sample has a younger age of ~18.6 ka. The sample T11 was taken from a large boulder at the  
556 eastern edge of the gravel dune fields (fig. 13 d). The exposure age of this sample is ~20.3 ka and  
557 it can be considered valid and reliable (even though it is a single sample) since its position and  
558 dimension (fig. 16 j) exclude movement of the boulder during the entire history of its exposure.

559 The Gravel dune field III samples (T12, T13, T14, T15, T16) were located on a 30-m high  
560 terrace (fig. 13 d). The exposure ages of the boulders have a significant scatter ranging from ~94.7  
561 ka to ~20.2 ka, which indicates a complex exposure history.

562 The Gravel dune field IV samples (T17, T18, T19, T20) were located on a 15-m high  
563 terrace (fig. 13 d) and they are characterized by a significant scatter of exposed ages ranging from  
564 ~72.6 ka to ~23.7 ka. The samples T18 (~23.7 ka) and T20 (~29.3 ka) have the closest ages.

565 Our exposure age analysis of the gravel dune surfaces shows a significant time spread. In some  
566 cases, older age is likely because the sample was taken from a remnant of bedrock embedded  
567 within the gravel dunes. The wide time range might also be indicative of a complex exposure  
568 history associated with significant movements in space of the dated boulders. On the time scale,  
569 older samples are represented by dates ranging from 137 ka to 51 ka (fig. 17 b). These samples  
570 were ignored in further analysis because they should have significant inherited numbers of atoms.  
571 The rest of the samples make up three age groups (three peaks): series of the samples I is 36-38 ka  
572 (3 samples) corresponding to MIS3; series of the samples II is 27-31 ka (7 samples) corresponding  
573 to MIS3-MIS2; series of the samples III is 18-23 (4 samples) corresponding to MIS2.

574



575 **5. Discussion**

576

577 **5.1 Conditions of the Darhad paleolake formation**

578

579 The existence of paleolakes in the Darhad depression during the Late Pleistocene is recorded  
580 from ancient lacustrine terraces and a sedimentary complex. The main backwater site for the  
581 Darhad paleolake has been considered to be the Tengis Gol mouth, where traces of a glacial dam  
582 are preserved (Krivonogov et al., 2005; Gillespie et al., 2008; Komatsu et al., 2009; Batbaatar and  
583 Gillespie, 2016a).

584 However, our newly discovered evidence for the existence of a paleolake extension downstream  
585 of the Tengis Gol mouth (fig. 6) indicates a more complex system of dams in the Shishkhid Gol  
586 valley than it was previously accepted. The lake shorelines discovered below the Tengis dam are  
587 identical in elevation (1710-1713 m asl) to the maximum level of the Darhad paleolake (fig. 7). In  
588 this case, a question arises whether the Tengis glacier was the main dam for the Darhad paleolake?  
589 Determining the parameters of the glacier based on the elements of the glacial features at the  
590 Tengis Gol mouth is important for checking the possibility of forming a glacial dam for the  
591 formation of the Darhad paleolake.

592 At the Tengis Gol mouth there are glacial and lacustrine features. Glacial features include lateral  
593 moraines, terminal moraines and meltwater channels. All of them provide information about the  
594 parameters of the glacier. The lacustrine features include ancient shorelines preserved on the slopes  
595 of Shishkhid Gol testifying for the level and water contact with bedrock (figs. 10, 11).

596 The elevation of the lateral moraines at the Tengis Gol mouth, exposure age of the terminal  
597 moraine at the left tributary, melt water channels, and lake shorelines on the slope of the Shishkhid-  
598 Gol valley provide evidence for two elevational levels of the glacial dam at MIS 2 (figs. 10, 11).  
599 This has been pointed out (Gillespie et al., 2008) by giving the upper glacial level an older  
600 indeterminate age. The exposure age of boulders ( $20.8 \pm 1.1$  ka and  $18.2 \pm 1.0$  ka) within the melt

601 water channel (Gillespie et al., 2008) characterizes the late stage of development of the Tengis  
602 glacier (fig. 11). The exposure age of boulders ( $23.8\pm 1.5$  ka and  $20.7\pm 1.4$ ) from the terminal  
603 moraine (fig. 10 d) of the left tributary of Sarig Gol (Batbaatar and Gillespie, 2016b) belongs to  
604 the early stage and correlates with LGM. However, based on the reconstruction results, doubts  
605 arise whether the Tengis glacier could really have been a dam for the Darhad paleolake, since the  
606 observed shorelines of the paleolake there are positioned at higher elevations than the surface of  
607 the glacier (figs. 10, 11).

608 The analysis of satellite images and topographic data provided new information on the  
609 conditions of formation and size of the Late Pleistocene Darhad lake. The existence of abrasion  
610 lake levels upstream and downstream of the Tengis dam, as well as their coincidence in elevation  
611 (1713 m asl), suggests the presence of a large backwater below the confluence of Tengis Gol and  
612 Shishkhid Gol. We identified the confluence area of the Khara-Baryangiin and Ikh-Djams glaciers  
613 as a likely backwater site (fig. 12). Here a large 300-m high dam was formed in the Shishkhid Gol  
614 valley. Prior to this work this glacial dam was identified by Komatsu et al. (2009) and Batbaatar  
615 and Gillespie (2016a), but they did not distinguish it as the main dam for the Darhad paleolake  
616 since its elevation was considered to be much lower than the 1713 m paleolake (fig. 4). The  
617 conditions for the glacial dam formation are determined by the parameters of ice-catchment and  
618 the thickness of glaciers in both valleys. We think that the combining of the two glaciers in the  
619 area of dam No. 4 (figs. 4, 12) in the Shishkhid Gol valley led to the stable glacier standing, thereby  
620 providing a stable high backwater conditions for the formation of the Darhad paleolake at the 1713  
621 m level.

622

## 623 **5.2 The maximum water level in the Darhad paleolake during the Late Pleistocene and lake** 624 **shoreline deformation after its drainage**

625

626 The maximum water level recorded on satellites and topographic data corresponds to 1713 m  
627 asl (the western side of the Darhad Basin) and 1711 m asl (fig. 7) (the eastern side of the Darhad  
628 Basin, Gillespie et al., 2008) with an uncertain level of ~1825 m pointed out by Gillespie et al.  
629 (2008). The 1825 m asl level is debatable since it is not identifiable in the areal photo-  
630 interpretation. All other maximum high levels in the inner water area of the paleolake are much  
631 lower and vary from 1713 m asl up to 1686 m asl.

632 The difference in the elevation of the upper terrace may indicate the existence of large tectonic  
633 subsidence within the Darhad Basin, which could have led to significant deformation of the  
634 paleoshorelines. If the main tectonic movements took place after the drainage of the basin and the  
635 terrace complex was affected, this can complicate the lake level interpretation.

636 According to (Gillespie et al., 2008), in MIS 2 there was a lake with a level of 1679 m asl. This  
637 level was suggested based on the lake terrace elevation within the Jarai terminal moraine (17-19  
638 ka; Gillespie et al., 2008). However, on the eastern side of the Darhad lake in the area of the Jarai  
639 moraine, there are seismogenic deformations with a normal fault amplitude of 8 m (Logachev,  
640 1993; Bacon et al., 2003). Thus, the 1679 m asl level may not be a true indicator of the level of the  
641 paleolake, instead resulting from tectonic deformation. Moreover, beach sands with an elevation  
642 of 1711 m asl (Gillespie et al., 2008), which may correspond to the 1713 level m asl on the western  
643 shore of the lake, were found on a foothill slope 2 km south of the Jarai moraine. In this regard,  
644 consideration of various paleolake levels can be rather complicated.

645

### 646 **5.3 Age and number of Darhad megafloods recorded in the Yenisei Valley**

647

648 As a result of  $^{10}\text{Be}$  dating boulders from the surface of gravel dunes, three series of dates were  
649 obtained. For analysis and their correlation with the main events of the Late Pleistocene, we present  
650 a diagram with the distribution of exposure samples ( $^{10}\text{Be}$ ) dating the main stages of glacier  
651 advances in the East Sayan Ridge of the southern Baikal region and northern Mongolia (Gillespie

652 et al., 2008; Arzhannikov et al., 2012; Arzhannikov et al., 2015; Batbaatar and Gillespie, 2016b)  
653 (fig. 18 a). Another diagram shows exposure age of boulders from gravel dunes (our work), from  
654 the moraine surface in the Sarig Valley (Batbaatar and Gillespie, 2016b) and from melt water  
655 channel boulders (Gillespie et al., 2008), luminescence ages of sand units in the Darhad core,  
656 stages of the marine isotope scale (MIS), and the Darhad paleolake stages according to Gillespie  
657 et al., 2008 (fig. 18 b).

658 As can be seen in (fig. 18 b), series of the samples I and III correspond to MIS 3 and MIS 2.  
659 The most numerous series of the samples II is located in the transition zone between these stages.  
660 The correspondence of series I and III to the timings of the Darhad paleolake existence (17-19 ka  
661 and 35-53 ka, Gillespie et al., 2008) indicates the spatial and temporal relationship between  
662 glaciation and outburst flood events. A good example sample for the megaflood in MIS 2 is a giant  
663 boulder (8 x 4 x 2.5 m) with an age of  $20.3 \pm 1.7$  ka located on the 25 m terrace surface (fig. 16 j).

664 In our opinion, the two groups of exposure ages (samples I and III series) correspond to two  
665 megafloods that occurred in the periods 38-36 ka and 23-18 ka (fig. 18 b). This is indirectly  
666 confirmed by drilling data in the Darhad Basin. The analysis and dating of the core showed that in  
667 the periods of  $34.7 \pm 8.1$  and  $19.5 \pm 2.6$  ka, there were dramatic changes of the lake depth (the depth  
668 decreased significantly) and sands with a large proportion of the heavy fraction began to  
669 accumulate (Batbaatar and Gillespie, 2016b).

670 The exposure age of the samples from series II could be the result of a more complex exposure  
671 history of the boulders exhumed during the first and second megaflood events. One can propose  
672 that these boulders were not well anchored in the sediment and might have subjected to further  
673 movements or partial burial. Then when stabilized in the landscape they were exposed to cosmic  
674 rays and were able to accumulate cosmogenic nuclide until present day.

675 The depth of the megaflood flow in the Tuva Basin was at least 60-65 m. This is determined by  
676 the difference in the elevation of the upper terrace (fig. 14 a, b), located on the right side of the  
677 Yenisei valley and resulting from lateral erosion, and the minimum elevation of the gravel dunes

678 (fig. 14 c, d). The unconformity observed in alluvial deposits (fig. 16 b) on the high 30 m terraces  
679 may indicate several stages (at least two) outbursts flood from the Darhad paleolake.

680 We believe that the last megaflood took place in the winter or in a colder month. This is  
681 evidenced by sand blocks laid within this environment. The melting of these blocks during the  
682 warm season led to subsidence of the overlying deposits and the formation of bending  
683 deformations.

684 Summing up the above, we present a new vision of the Darhad paleolake formation and the  
685 Darhad megafloods. The formation and development of the Darhad paleolake coincided with the  
686 periods of glacier advance in northern Mongolia (Gillespie et al., 2008; Batbaatar et al., 2018).  
687 Based on the parameters of the two levels of the Tengis glacier (figs. 10, 11) and the distribution  
688 of lake terraces below the Tengis dam (figs. 6, 7), we can state that the Tengis glacier was not  
689 responsible for the highest stand (1713 m asl) the Darhad paleolake. The main damming role was  
690 played by a large glacier located downstream of the Tengis dam at least for the presumed highest  
691 paleolake level of 1713 m asl. The destruction of this dam occurred during periods of global  
692 warming (Batbaatar et al., 2018) which probably led to the occurrence of megafloods at least twice  
693 in MIS 3 and MIS 2. The influence of megafloods was reflected in the formation of a new  
694 erosional-depositional features (canyons, hanging valleys, gravel dunes, sand massifs, etc.) in the  
695 Yenisei valley and adjacent territories.

696

## 697 **6. Conclusion**

698

699 The studies carried out in the Darhad and Tuva basins and the dating of gravel dunes in the Yenisei  
700 valley made it possible to reconstruct the conditions of the Darhad paleolake formation and  
701 determine the stages of the Darhad outburst floods:

702 - satellite image interpretation and radar-derived topographic data analysis suggest  
703 significant deformations of the Darhad paleolake paleoshorelines. The maximum elevation

704 of the shoreline at 1711-1713 m asl, located along the periphery of the Darhad Basin,  
705 decreases to 1686 m asl in the interior of the depression. The deformation of the shoreline  
706 is associated with tectonic deformations as expressed as recent normal fault earthquakes.  
707 The deformation of the shoreline occurred after the drainage of the lake;

- 708 - lake shorelines were found on the slopes of the Shishkhid Gol valley (downstream of the  
709 Tengis Gol outlet), identical to the shorelines of the Darhad lake with a maximum elevation  
710 of 1713 m asl;
- 711 - reconstruction based on the analysis of glacial and lacustrine landforms at the Tengis Gol  
712 outlet showed that there were 2 glacier levels in MIS 2. The upper level corresponds to  
713 LGM and the lower level is later than LGM. The Tengis glacial dam, although it formed  
714 backwater, was not the main one responsible for the maximum level of the Darhad  
715 paleolake at 1713 m asl;
- 716 - analysis of remote sensing data made it possible to identify a glacial dam at the mouths of  
717 the Khara-Baryangiin and Ikh-James Gol rivers and position it as the main backwater in  
718 the formation of the highest Darhad paleolake;
- 719 - the main source of the Darhad megaflood formation was the Darhad glacial lake. The  
720 reason for the drainage of the lake was the destruction of glacial dams in the Shishkhid-  
721 Gol valley.
- 722 - in the Tuva Basin (the Yenisei valley), a series of erosion terraces was found, formed by  
723 the outburst of the Darhad paleolake. These terraces are the highwater marks indicating the  
724 maximum depth of the Darhad megaflood. The height of the upper terrace is estimated to  
725 be 100 m above the present-day water surface in the Yenisei River and 60-65 m above the  
726 surface of the lowest level of gravel dunes;
- 727 - exposure dating of boulders ( $^{10}\text{Be}$ ) sampled from gravel dune surfaces in the Yenisei valley  
728 allows identifying two stages in the formation of the Darhad megaflood at 36-38 ka and  
729 18-23 ka.

730

731 **Author contributions**

732

733 AS, AA, RB devised the research concept, planning, and ideas. AS, AA, participated in field  
734 work. AS took the lead in writing the manuscript. RB did the dating ( $^{10}\text{Be}$ ). GK guided the  
735 structure and editing of the results and discussion. All authors contributed to the analysis and  
736 helped shape the study.

737

738 **Data availability**

739

740 Geological samples are kept at the Institute of the Earth's crust SB RAS, Russia.

741

742 **Declaration of competing interest**

743

744 The authors declare that they have no known competing financial interests or personal  
745 relationships that could have appeared to influence the work reported in this paper.

746

747 **Acknowledgments:**

748

749 The reported study was funded by the Russian Foundation for Basic Research grant № 20-55-  
750 15002. Remote sensing analysis was possible thanks to the TanDEM-X project DEM\_GEOL1188.  
751 The ASTER AMS national facility (CEREGE, Aix-en-Provence) is supported by the INSU/CNRS,  
752 the ANR through the “Projets thématiques d’excellence” program for the “Equipements  
753 d’excellence” ASTER-CEREGE action and IRD.

754

755 **References**

756

757           Arnold, M., Merchel, S., Bourlès, D.L., Braucher, R., Benedetti, L., Finkel, R.C., Aumaître,  
758 G., Gott dang, A., Klein, M., 2010. The French accelerator mass spectrometry facility ASTER:  
759 improved performance and developments. Nuclear Instruments and Methods in Physical Research  
760 B 268, 1954e1959. doi:10.1016/j.nimb.2010.02.107.

761           Arzhannikov, S.G., Arzhannikova, A.V., 2011. The Late Quaternary geodynamics of the  
762 Hyargas Nuur Basin and bordering scarps (western Mongolia). Russian Geology and Geophysics  
763 52, 2, 220-229.

764           Arzhannikov, S.G., Braucher, R., Jolivet, M., Arzhannikova, A.V., Vassallo, R., Chauvet,  
765 A., Bourlès, D., Chauvet, F., 2012 History of late Pleistocene glaciations in the central Sayan-Tuva  
766 Upland (southern Siberia). Quaternary Science Reviews 49, 16-32.

767           Arzhannikov, S.G., Braucher, R., Jolivet, M., Arzhannikova, A.V., 2015. Late Pleistocene  
768 glaciations in southern East Sayan and detection of MIS 2 terminal moraines based on beryllium  
769 (<sup>10</sup>Be) dating of glacier complexes. Russian Geology and Geophysics, 56, 11, 1509-1521.

770           Arzhannikova, A.V., Arzhannikov, S.G., Akulova, V.V., Danilova, Yu.V., Danilov, B.S.,  
771 2014. The origin of sand deposits in the South Minusa basin. Russian Geology and Geophysics  
772 10, 1495-1508.

773           Batbaatar, J., and Gillespie, A.R., 2016. Outburst floods of the Maly Yenisei. Part I.  
774 International Geology Review 14, 1723-1752.

775           Batbaatar, J., Gillespie, A.R., 2016. Outburst floods of the Maly Yenisei. Part II – new age  
776 constraints from Darhad basin. International Geology Review 14, 1753-1779.

777           Batbaatar, J., Gillespie, A.R., Fink, D., Matmon, A., and Fujioka, T., 2018. Asynchronous  
778 glaciations in arid continental climate. Quaternary Science Reviews, 182, 1-19.

779           Bacon, S.N., Bayasgalan, A., Gillespie, A.R., Burke, R.M., 2003. Paleoseismic  
780 displacement measurements from landforms subjected to periglacial processes: observations along



781 the Jarai Gol fault near the Tamyn Am Hills, Darhad Depression, northern Mongolia. XVI Inqua  
782 Congress, Abstract with Programs, 103.

783 Baker, V.R., 1973. Paleohydrology and sedimentology of Lake Missoula flooding in  
784 Eastern Washington. Geological Society of America Special Paper 144, 1–79.

785 Baker, V.R., Bunker, R.C., 1985. Cataclysmic late Pleistocene flooding from Glacial Lake  
786 Missoula: a review. Quaternary Science Review 4, 1–41.

787 Baker, V.R., Benito, G., and Rudoy, A.N., 1993. Paleohydrology of Late Pleistocene  
788 superflooding, Altay Mountains, Siberia. Science 259, 348–350.

789 Baryshnikov, G.Ya., 1979. On the issue of the formation of large boulder alluvium of the  
790 Biya River. Geology and minerals of the Altay Territory (abstracts). Barnaul, 112. (in Russian)

791 Benito, G., Thorndycraft, V., 2020. Catastrophic glacial lake outburst flooding of the  
792 Patagonian Ice Sheet. Earth-Science Reviews 200, 102996.

793 Borisov, B.A., Minina, E.A., 1979. Ribbed and mesh-cellular basic moraines of the Eastern  
794 Pamirs and Gorny Altay. Geomorphology 2, 69-74. (in Russian)

795 Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K.,  
796 Phillips, F., Schaefer, J., and Stone, J., 2016. Geological calibration of spallation production rates  
797 in the CRONUS-Earth project. Quaternary Geochronology 31, 188-198.

798 Braucher, R., Guillou, V., Bourlès, D.L., Arnold, M., Aumaître, G., Keddadouche, K.,  
799 Nottoli, E., 2015. Preparation of ASTER in-house  $^{10}\text{Be}/^{9}\text{Be}$  standard solutions. Nuclear  
800 Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and  
801 Atoms 361, 335–340. doi:10.1016/j.nimb.2015.06.012

802 Braucher, R., Merchel, S., Borgomano, J., Bourlès, D.L., 2011. Production of cosmogenic  
803 radionuclides at great depth: A multi element approach. Earth and Planetary Science Letters 309.  
804 doi:10.1016/j.epsl.2011.06.036

805 Butvilovsky, V.V., 1982. On traces of catastrophic discharges of glacier-dammed lakes in  
806 the Eastern Altai. Evolution of the river systems of the Altai Territory and practical issues:  
807 Abstracts of the report for the conference, Barnaul, 12-16. (in Russian)

808 Butvilovsky, V.V., 1985. Catastrophic outbursts and runoff of near-glacial lakes of the  
809 South-Eastern Altai and their traces in the relief. *Geomorphology* 1, 65-74. (in Russian)

810 Carling, P.A., Kirkbride, A.D., Parnachov, S., Borodavko, P.S., Berger, G.W., 2002. Late  
811 Quaternary catastrophic flooding in the Altai Mountains of south-central Siberia: a synoptic  
812 overview and introduction to flood deposit sedimentology. In: Martini, I.P., Baker, V.R., Garzon,  
813 G. (Eds.), *Flood and Megaflood Processes and Deposits: Recent and Ancient Examples*.  
814 International Association of Sedimentologists Special Publication, vol. 32. Blackwell Science,  
815 London, pp. 17–35.

816 Chmeleff, J., von Blanckenburg, F., Kossert, K., Jakob, J., 2010. Determination of the  $^{10}\text{Be}$   
817 half-life by multicollector ICP-MS and liquid scintillation counting. *Nucl. Instrum. Methods Phys.*  
818 *Res., Sect. B* 268, 192—199.

819 Grosswald, M.G., 1987. The last glaciation of the Sayano-Tuva highlands: morphology,  
820 feeding intensity, dammed lakes. Interaction of glaciation with the atmosphere and ocean. (Editors  
821 V.M. Kotlyakov, M.G. Grosswald) M.: Nauka, 250. (in Russian)

822 Grosswald, M.G., Rudoy, A.N., 1996. Quaternary ice-dammed lakes in the mountains of  
823 Siberia. *Proceedings of the Academy of Sciences. Geographical series* 6, 112-126. (in Russian)

824 Gillespie, A.R., Burke, R.M., Komatsu, G., and Bayasgalan, A., 2008. Late Pleistocene  
825 glaciers in Darhad Basin, northern Mongolia. *Quaternary Research* 69, 169–187.

826 Gosse, John C., Phillips, Fred M., 2001. Terrestrial in situ cosmogenic nuclides: theory  
827 and application. *Quaternary Science Review* 20, 1475—1560.

828 Jolivet, M., Ritz, J.-F., Vassallo, R., Larroque, C., Braucher, R., Todbileg, M., Chauvet,  
829 A., Sue, C., Arnaud, N., De Vicente, R., Arzhanikova, A., Arzhanikov, S., 2007. Mongolian  
830 summits: An uplifted, flat, old but still preserved erosion surface. *Geology* 10, 871–874.

831 Logachev, N.A. (Ed.), 1993. Seismotectonics and seismicity of the Khubsugul region.  
832 Nauka, Novosibirsk, 184. (in Russian)

833 Komatsu, G., and Olsen, J.W., 2002. Geological and archaeological exploration of caves  
834 in Mongolia. *Cave and Karst Science* 29, 75—86.

835 Komatsu, G., Arzhannikov, S.G., Gillespie, A.R., Burke, R. M., Miyamoto, H., Baker,  
836 V.R., 2009. Quaternary paleolake formation and cataclysmic flooding along the upper Yenisei  
837 River. *Geomorphology* 104, 143–164.

838 Komatsu, G., Baker, V.R., Arzhannikov, S.G., Gallagher, R., Arzhannikova, A.V.,  
839 Murana, A., Oguchi T., 2016. Catastrophic flooding, palaeolakes, and late Quaternary drainage  
840 reorganization in northern Eurasia. *International Geology Review*, 58, 1693-1722.

841 Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G.,  
842 Wallner, A., Dillmann, I., Dollinger, G., Lierse von Gostomski, Kossert, K., Maitia, M.,  
843 Poutivtsev, M., Remmert A., 2010. A new value for the half-life of  $^{10}\text{Be}$  by heavy-ion elastic  
844 recoil detection and liquid scintillation counting. *Nucl. Instrum. Methods Phys. Res., Sect. B* 268,  
845 187—191.

846 Krivonogov, S.K., Sheinkman, V.S., Mistryukov, A.A., 2005. Stages in the development  
847 of the Darhad dammed lake (Northern Mongolia) during the Late Pleistocene and Holocene.  
848 *Quaternary International* 136, 83-94.

849 Margold, M., Jansen, J., Codilean, A., Preusser, F., Gurinov A., Fujioka, T., Fink D., 2018.  
850 Repeated megafloods from Lake Vitim, Siberia, to the Arctic Jcean over the past 60000 years.  
851 *Quaternary Science Reviews* 187, 41-61.

852 O'Connor, J.E., and Costa, J.E., 2004. The world's largest floods —Their causes and  
853 magnitudes: U.S. Geological Survey Circular 1254: Reston, VA, U.S. Geological Survey, 13 p.

854 Perepelov, A.B., Kuzmin, M.I., Tsypukova, S.S., Demonterova, E.I., Ivanov, A.V.,  
855 Shcherbakov, Yu.D., Puzankov, M.Yu., Odgerel, D., Bat-Ulzii, D., 2017. Eclogite trace in  
856 evolution of late Cenozoic alkaline basalt volcanism on the southwestern flank of the Baikal Rift

857 Zone: geochemical features and geodynamic consequences. *Doklady Akademii Nauk* 5, 553–558.  
858 (in Russian)

859 Rudoy, A.N., 1984. The giant current ripples are proof of the catastrophic outbursts of the  
860 glacial lakes of the Altay Mountains. *Modern geomorphological processes in the territory of the*  
861 *Altay: Abstracts of reports. Biysk* 60-64. (in Russian)

862 Rudoy, A.N., and Baker, V.R., 1993. Sedimentary effects of cataclysmic late Pleistocene  
863 glacial outburst flooding, Altay Mountains, Siberia. *Sedimentary Geology* 85, 53–62.

864 Rudoy, A.N., 2002. Glacier-dammed lakes and geological work of glacial superfloods in  
865 the Late Pleistocene, Southern Siberia, Altai Mountains. *Quaternary International*, 87, 119-140.

866 Selivanov, E.I., 1967. Neogen-chetvertichnye ozera-giganty v Zabaikalyei Severnoi  
867 Mongolii (Neogen-quaternary giant lakes in Transbaikalia and North Mongolia). *Doklady AN*  
868 *USSR* 177, 175–178 (in Russian).

869 Selivanov, E.I., 1968. Spushennye ozera (Drained lakes). *Priroda* 3,81–82 (in Russian)

870 Spirkin, A.I., 1970. O drevnih ozerah Darhadskoj kotloviny (Zapadnoye Prihubsugulye)  
871 (About ancient lakes of the Darhad depression (Western Prehovsgol)). In: Devyatkin, E.V. (Ed.),  
872 *Geologiya mezozoya i kainozoya Zapadnoi Mongolii (Cenozoic and Mesozoic geology of*  
873 *Western Mongolia)*. Nauka, Moscow, 143–150 (in Russian)

874 Stolz, C., Hülle, D., Hilgers, A., Grunert, J., Lehmkuhl, F., and Dasc D., 2012.  
875 Reconstructing fluvial, lacustrine and aeolian process dynamics in Western Mongolia. *Zeitschrift*  
876 *für Geomorphologie* 3, 267–300.

877 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical*  
878 *Research* 105, 23753-23759.

879 Ufland, A.K., Iljin, A.V., Spirkin, A.I., 1969. Vpadiny baikalskogo tipa Severnoi Mongolii  
880 (The Baikal-type depressions of the North Mongolia). *Bulletin of the Moscow Society of*  
881 *naturalists, Geological Series* 44, 5–22. (in Russian)

882 Ufland, A.K., Iljin, A.V., Spirkin, A.I., Shilova, G.N., 1971. Osnovnye cherty stratigrafii i  
883 usloviya formirovaniya kainozoiskih obrazovaniy Prikosogolya (MNR) (Main features of  
884 stratigraphy and formation of Cenozoic deposits in Prekosogol (MPR)). Bulletin of the Moscow  
885 Society of naturalists, Geological Series 46, 54–69. (in Russian)

886 Wagner, G.A., 1998. Age determination of young rock and artifacts. Springer, 466.

887

## 888 **Figure captions**

889

890 Fig. 1. Locations of the three largest paleolake basins (Chuya-Kuray, Darhad, Vitim) hypothesized  
891 to be the sources of megaflooding in southern Siberia. Their megaflood routs are also shown  
892 (dotted lines). The bottom figure shows the study area of this article.

893 Fig. 2. The Pliocene-Quaternary history of the Darhad Paleolake development (Spirkin, 1970).

894 Fig. 3. This satellite image (Google Earth) clearly shows ancient shorelines of the Darhad  
895 paleolake, located on ridge slopes.

896 Fig. 4. Interpretation of the glacial dam locations in the Shishkhid Gol valley by various authors  
897 (Gillespie et al., 2008; Komatsu et al., 2009; Batbaatar and Gillespie, 2016a). Pictures and profiles  
898 were built using SRTM V4 data.

899 Fig. 5. Terrace levels, gravel dunes and bars indicated on a digital elevation model (TanDEM-X  
900 DEM). The red dots show sampling site locations for  $^{10}\text{Be}$  dating (a, b, c, d). The color symbols  
901 and the position of the red squares are the same as in fig. 13. Photos (e, f) show examples of dated  
902 boulders.

903 Fig. 6. Satellite images a, b, c, d (Google Earth) show the locations of ancient shorelines that  
904 indicate paleolake levels. All satellite images show the right bank side of the Shishkhid-Gol valley,  
905 located downstream of the Tengis Gol outlet.

906 Fig. 7. The map of the Late Quaternary glaciation and locations of key study localities within the  
907 Darhad paleolake and the Shishkhid Gol valley discussed in this paper. SRTM V4 data were used  
908 as the base map.

909 Fig. 8. Satellite images (Google Earth) show shorelines (the location of each image is indicated in  
910 Fig. 7) and their elevations are given. The variability of the lake terrace elevations along the  
911 periphery of the Darhad Basin probably indicates intense tectonic deformations.

912 Fig. 9. The digital elevation model (SRTM v4) and satellite images a, b (Google Earth) show linear  
913 tectonic deformation features observed in the northern part of the Darhad Basin.

914 Fig. 10. Paleogeographic reconstruction of the glacial dam in the Tengis Gol mouth, which existed  
915 during the Last Glacial Maximum (MIS2). A – meltwater channel located on the right bank of  
916 Tengis Gol. B - meltwater channel, located on the left bank of Tengis Gol. C - reconstruction of  
917 the Tengis glacier level (left side of the mouth part of Tengis Gol) during the LGM. D - the left  
918 bank of Shishkhid Gol (Sarig Gol mouth) and elements of the glacial landforms (an abraded slope  
919 by the glacier and a fragment of the Tengis terminal moraine). On the digital topography map, the  
920 camera symbols indicate orientations of satellite images (A, B, C, D) and the positions of the  
921 topographic profiles (below) are also shown. The topographic profiles show parameters of the  
922 reconstructed Tengis glacier and reflect its role in the dam formation of the Darhad paleolake. The  
923 figure uses SRTM v4 data and Google Earth satellite images.

924 Fig. 11. The glacial dam reconstruction at the Tengis Gol outlet after the LGM (20-18 ka). The  
925 topographic profiles show the glacier levels and the surface of the Darhad paleolake.

926 Fig. 12. Reconstruction of the glaciers that formed the Darhad paleolake dam. The Khara-  
927 Baryangiin and Ikh-James glaciers network (a, b, c) is shown with the ALOS DEM. This satellite  
928 image illustrates the dam area and the elevation of the meltwater channel (d).

929 Fig. 13. The photographs show a gravel dune field and a 30-meter terrace scarp capped by gravel  
930 dunes (a, b). The geomorphological map is based on the interpretation of TanDEM-X DEM data,  
931 revealing the nature of the erosional-depositional activity of the Darhad megaflood and Yenisei

932 River in Tuva Basin (c, d). The red squares are the sampling sites for  $^{10}\text{Be}$  dating (c, d). They are  
933 shown in more detail in Fig. 5. The yellow rectangle is the location of the terraces formed by the  
934 Darhad megaflood (Fig. 14).

935 Fig. 14. The photographs show a complex of terraces up to 100 m high above the current Yenisei  
936 River, formed as a result the Darhad megaflood erosion (a, b). The location of high terraces in the  
937 Yenisei valley (c) and their relationship with gravel dune fields (e).

938 Fig. 15. The photographs and satellite image (Google Earth) reveal the morphology and structure  
939 of gravel dunes distributed in the Yenisei valley (a, b, c).

940 Fig. 16. Sedimentary complex of various fractions, formed in the Yenisei Valley as results of the  
941 erosion-depositional activity of the Darhad megaflood (a, b, d, e, f, j, h, g) and aeolian processes  
942 (c).

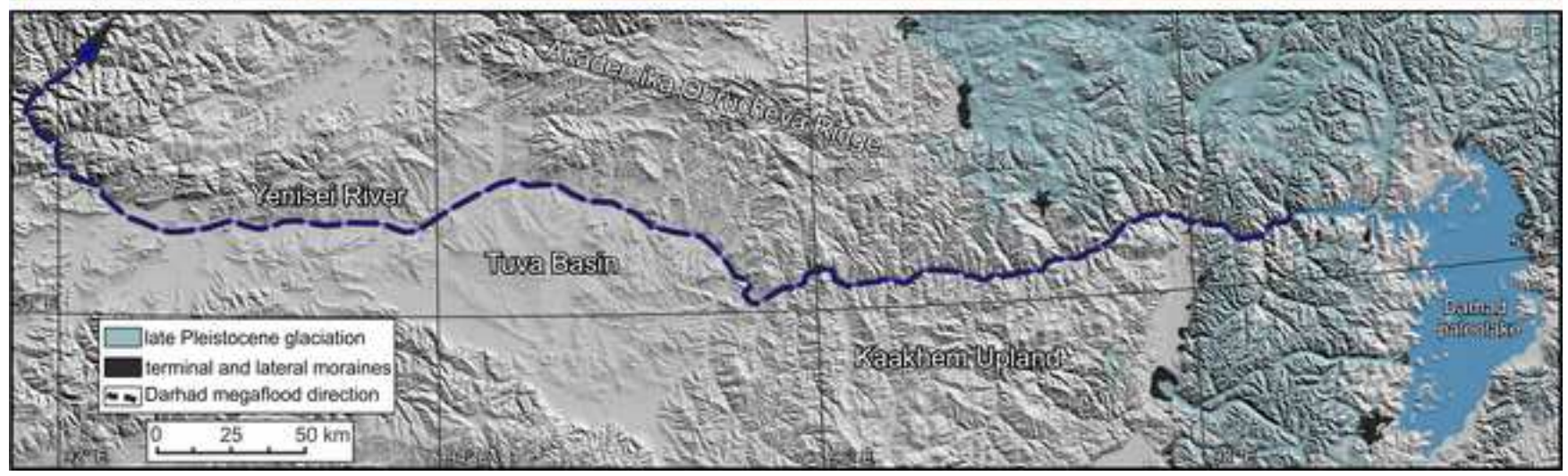
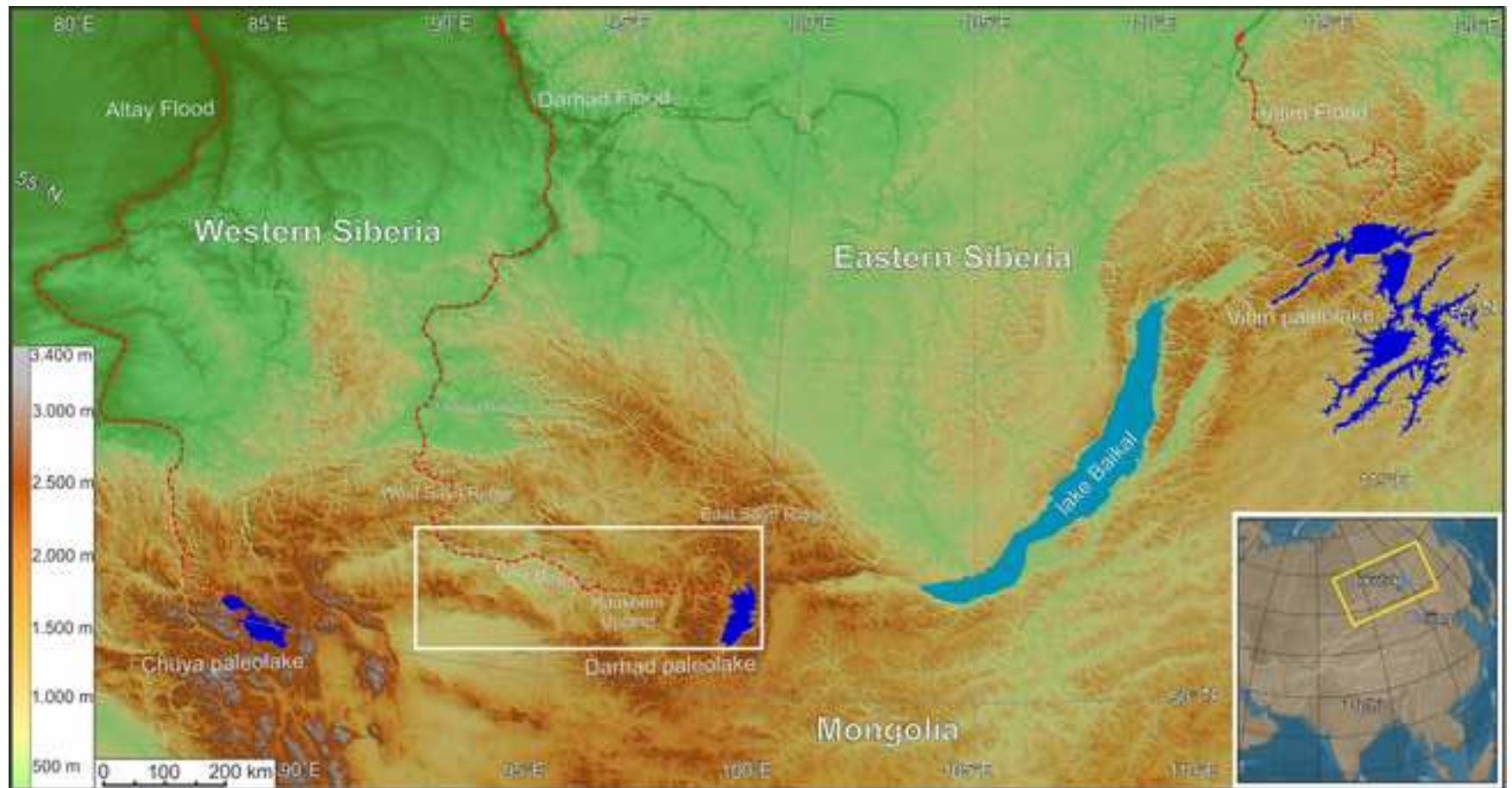
943 Fig. 17. Plot of the in-situ exposure age ( $^{10}\text{Be}$ ) distribution obtained from the boulders within  
944 gravel dunes of the Yenisei River valley.

945 Fig. 18. Plot (a) displays the exposure ages of glacial deposits of the Eastern Sayan Ridge and  
946 northern Mongolia. Plot (b) shows three peaks of exposure ages ( $^{10}\text{Be}$ ) associated with two Darhad  
947 megafloods and one with the loss of  $^{10}\text{Be}$  atoms due to changes in boulder exposure during the  
948 second Darhad megaflood event. The red circles indicate the ages of significant change in the  
949 fraction of the Darhad paleolake deposits. The green circles show the exposure ages of the  
950 maximum advance of the Tengis glacier (LGM MIS2). The white circles show the formation ages  
951 of the meltwater channels.

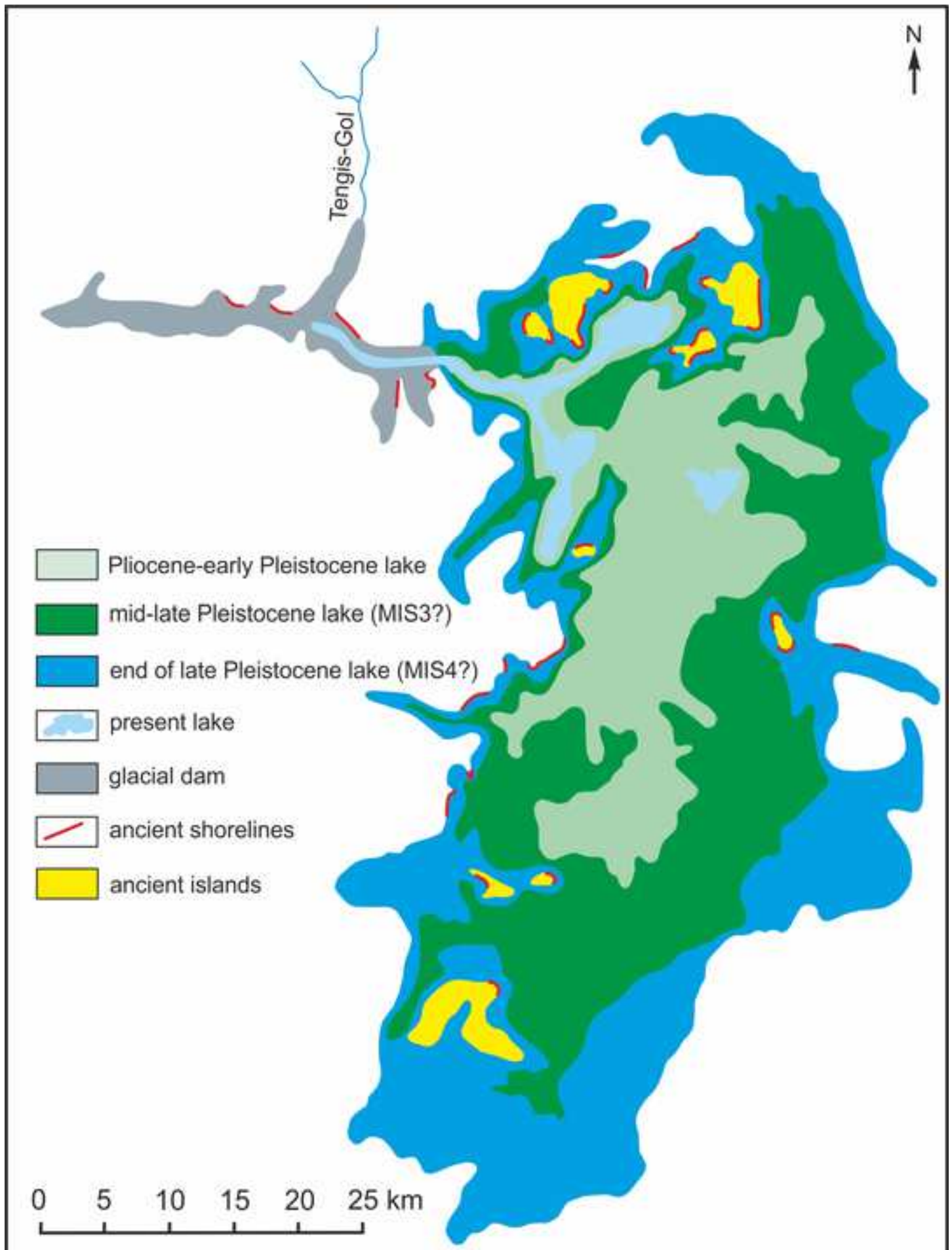
952

953 Table 1. Description of samples dated by  $^{10}\text{Be}$  cosmogenic nuclides.



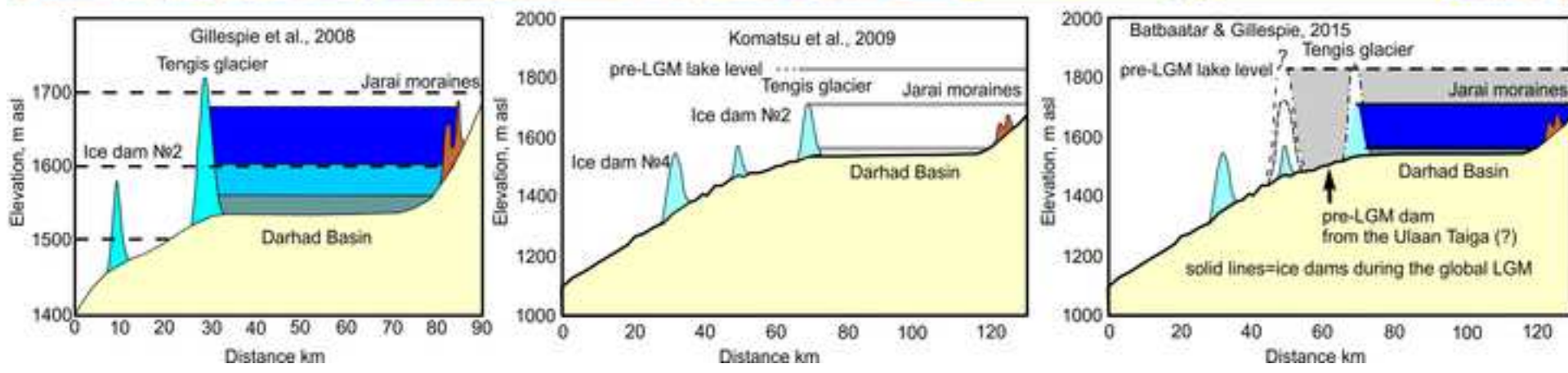
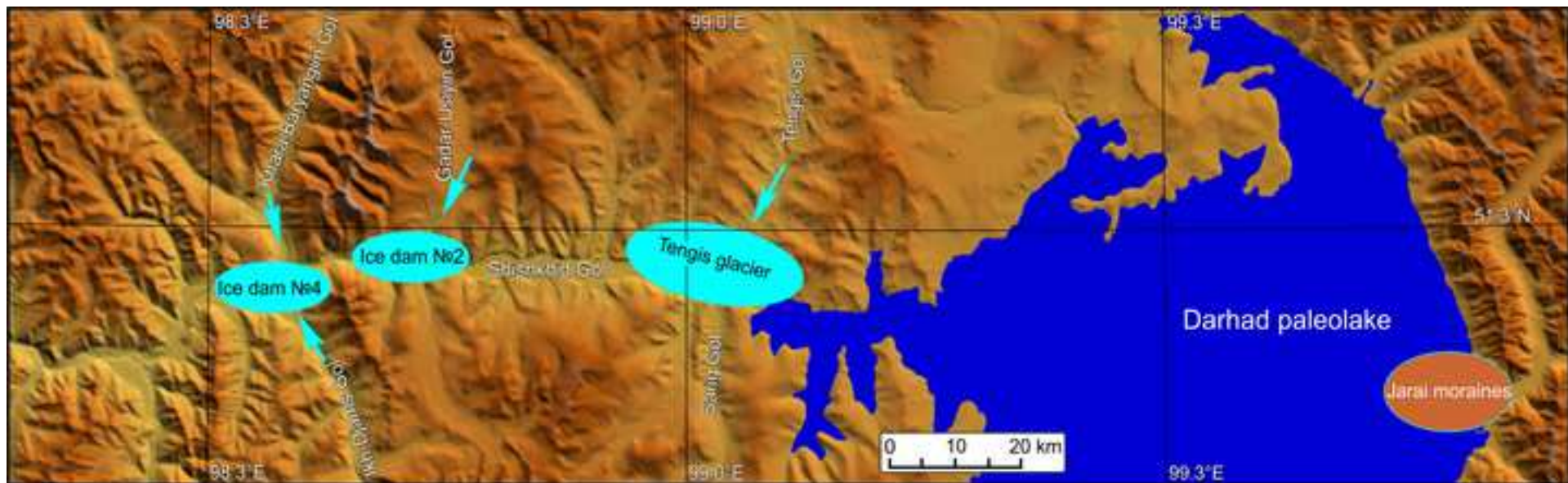




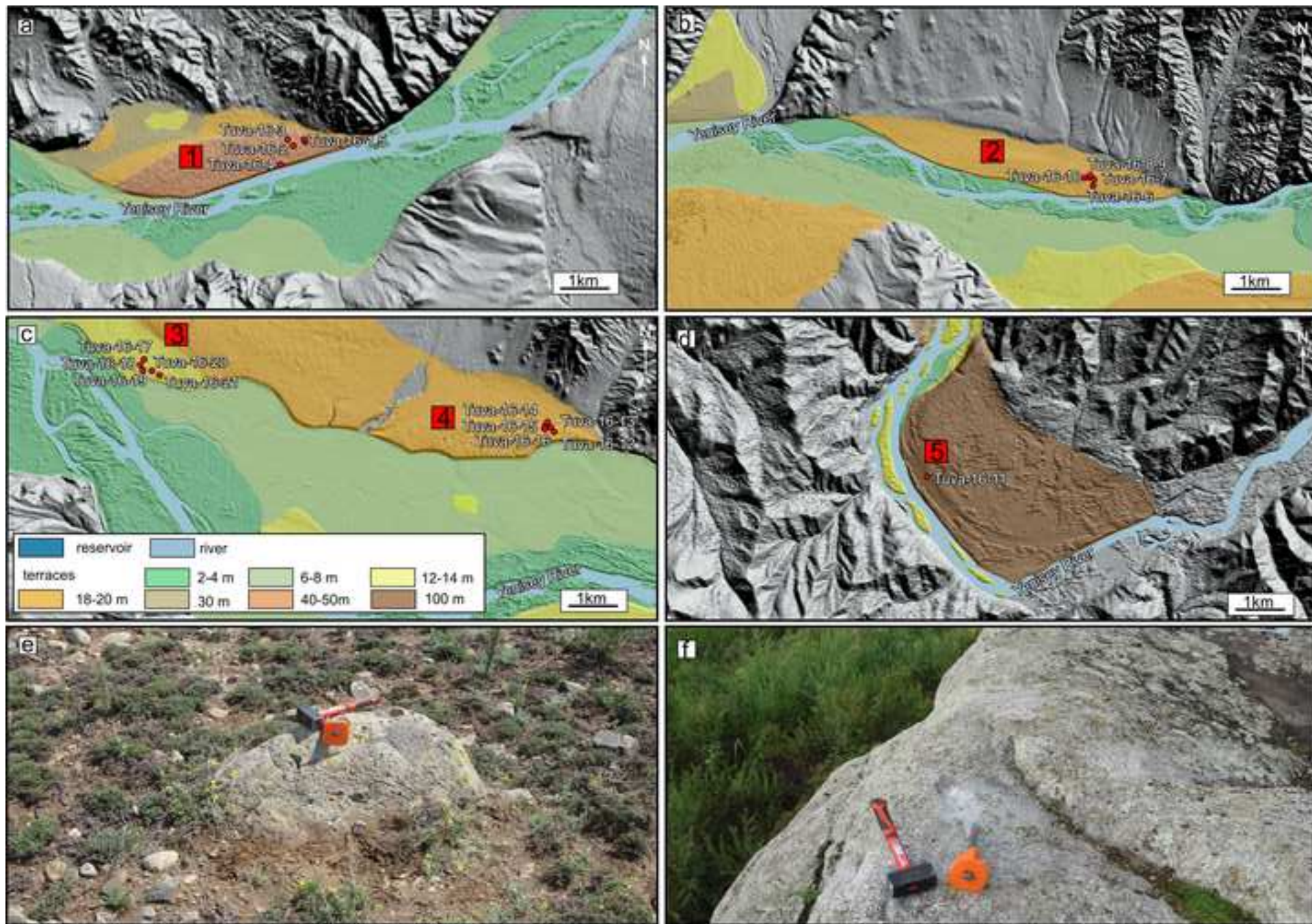




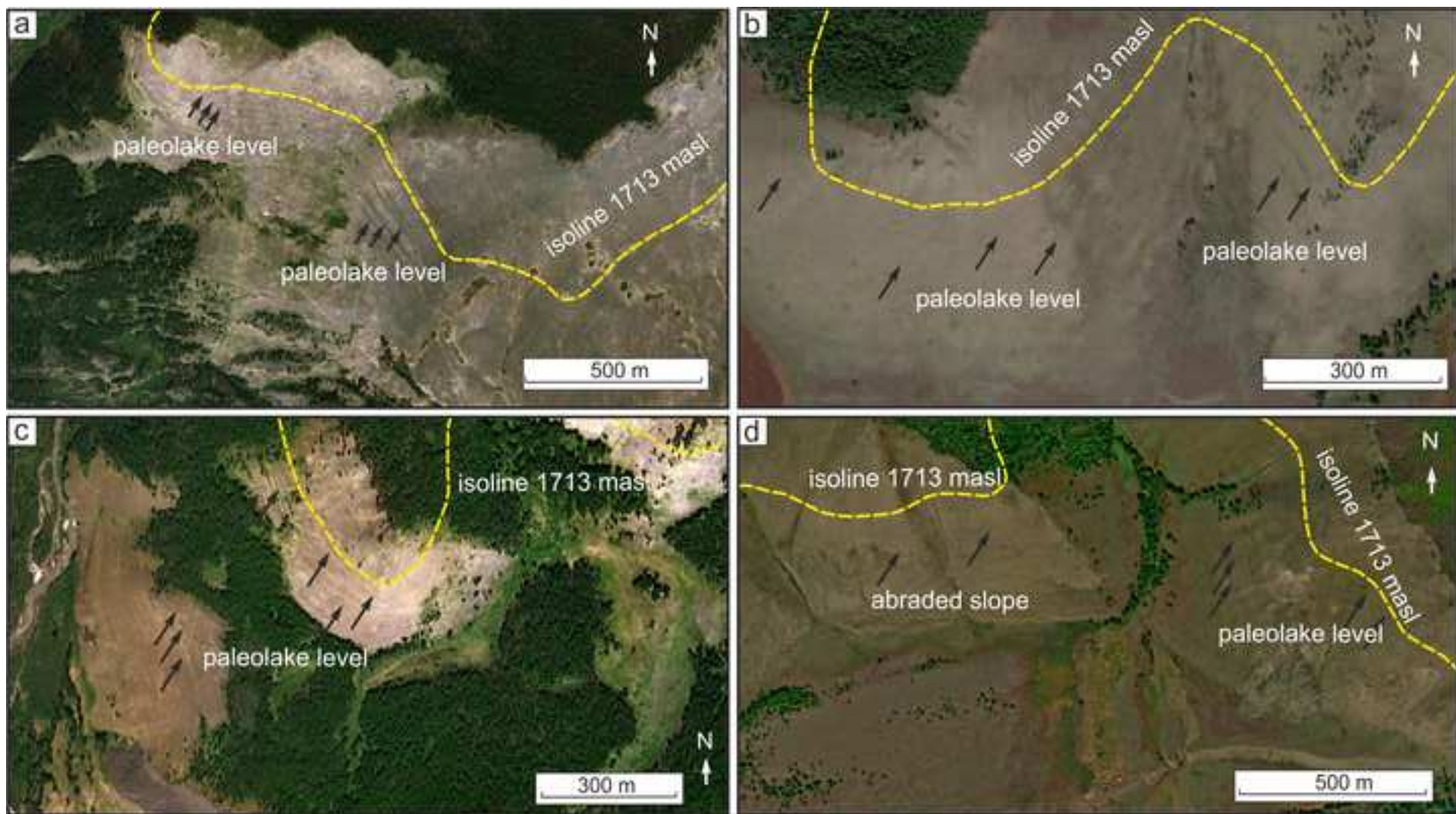




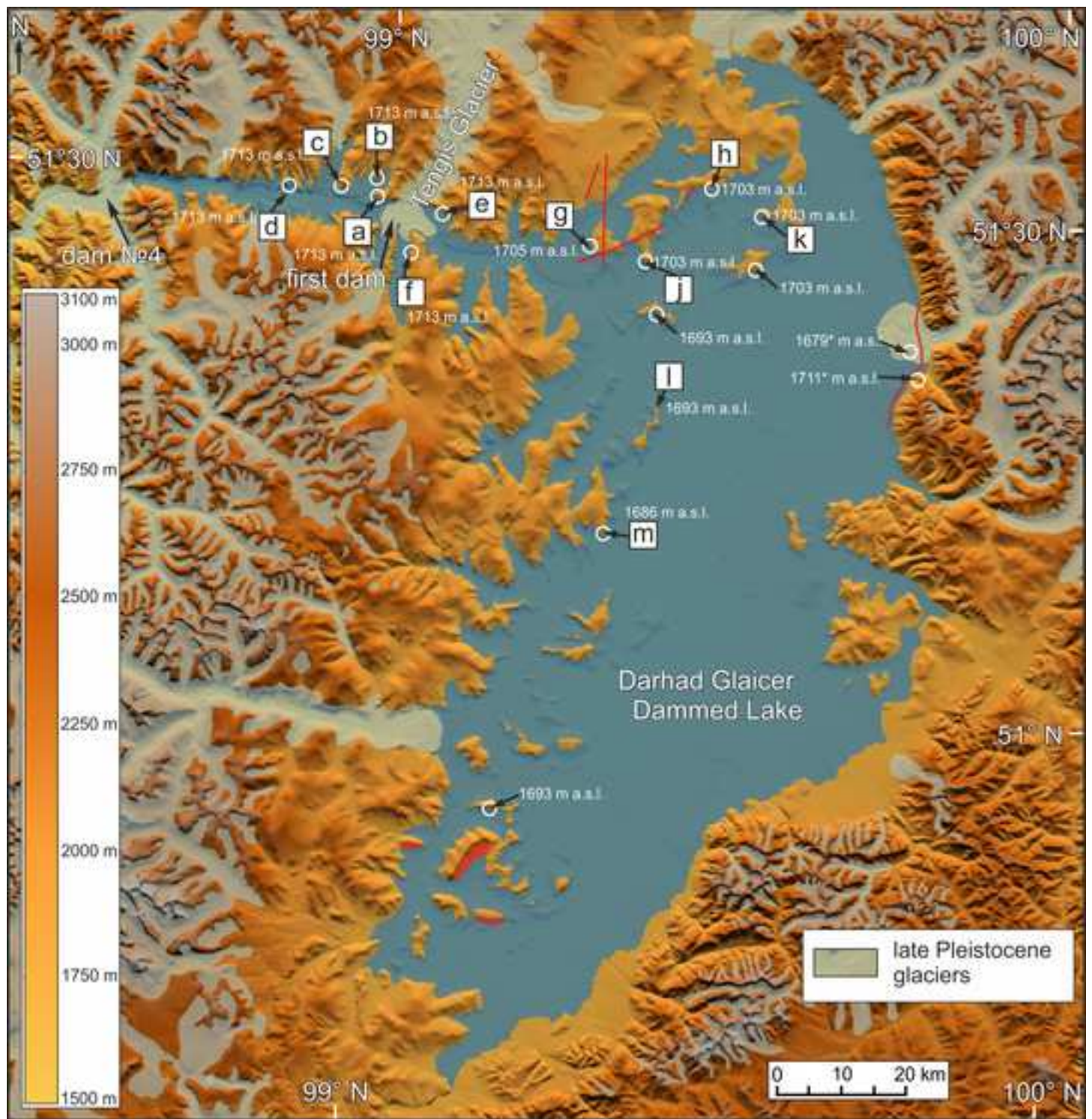




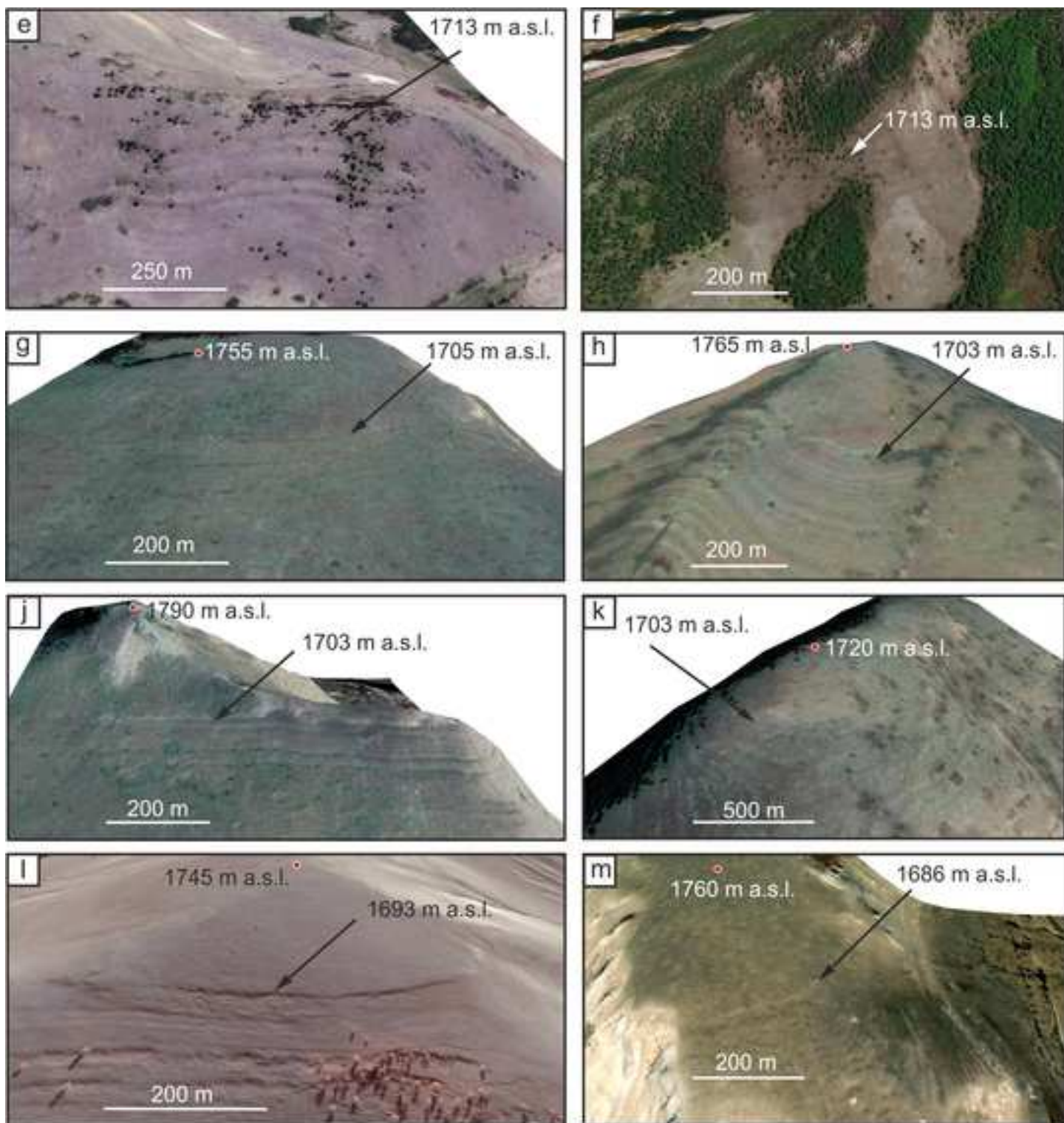


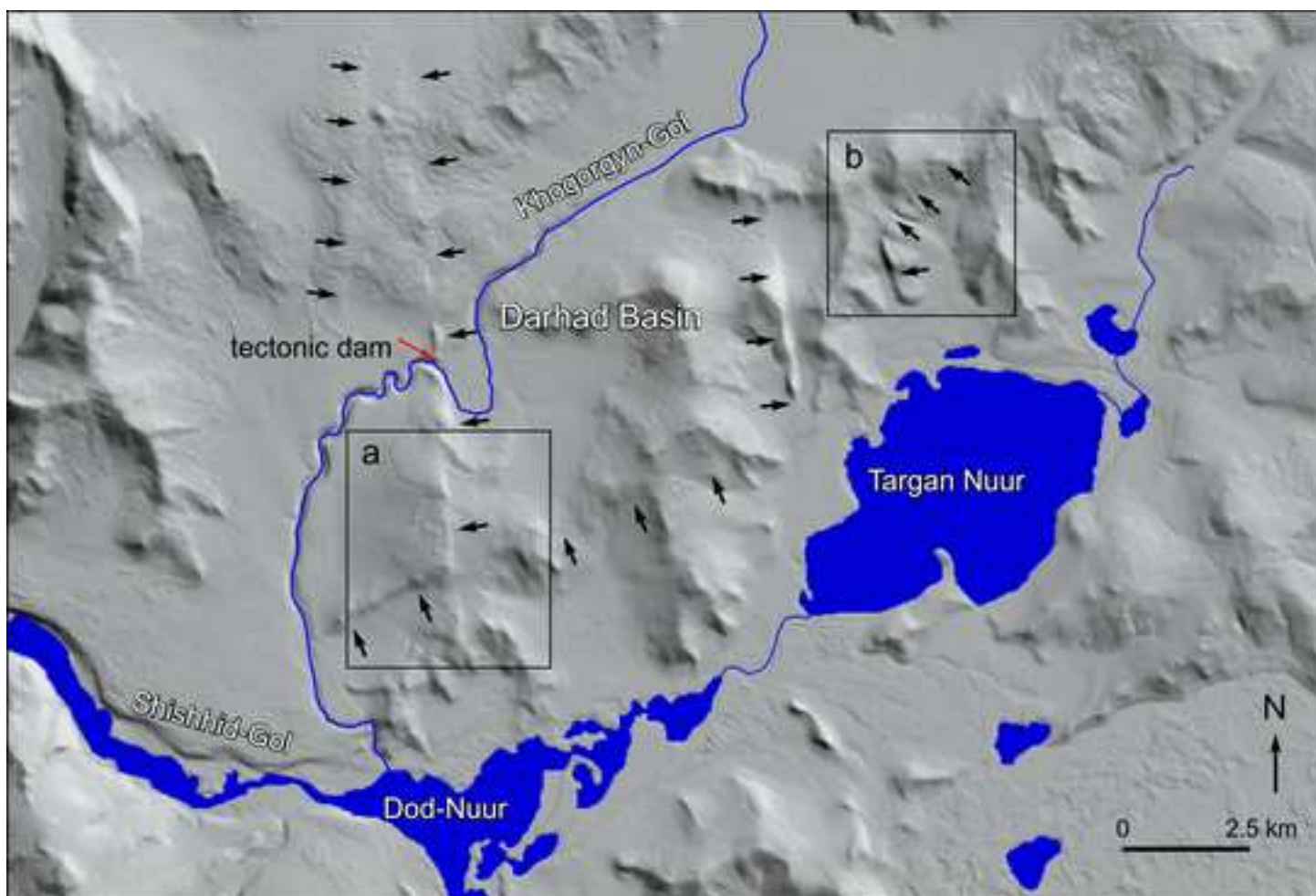




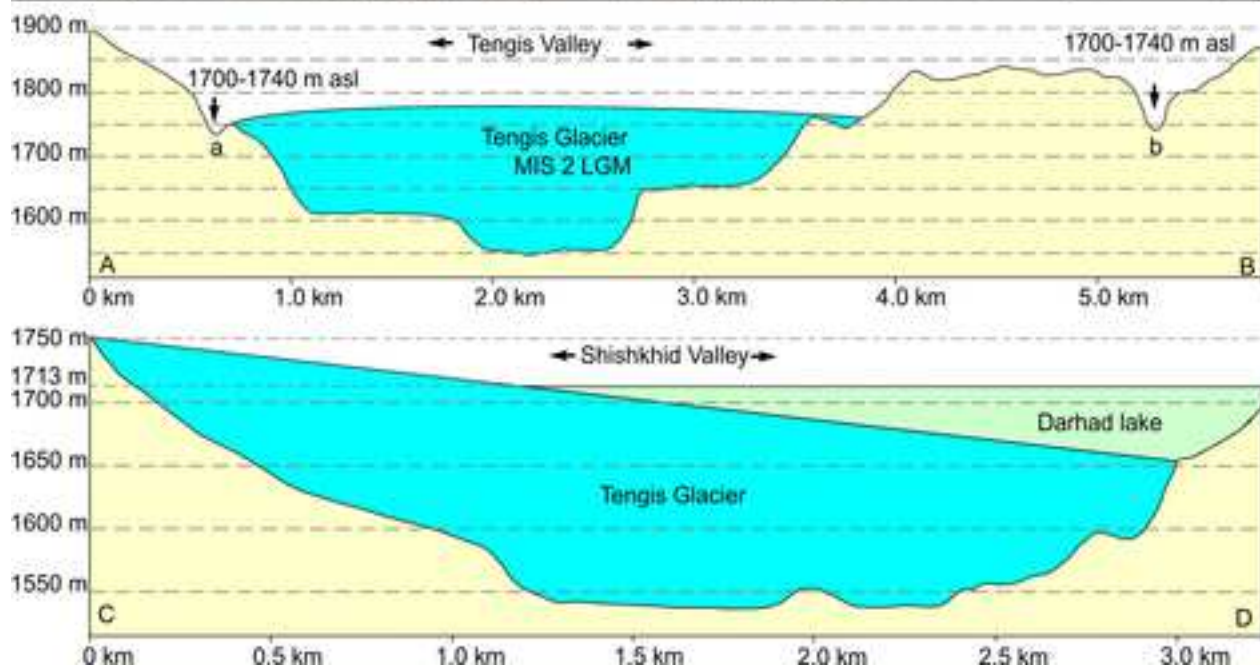
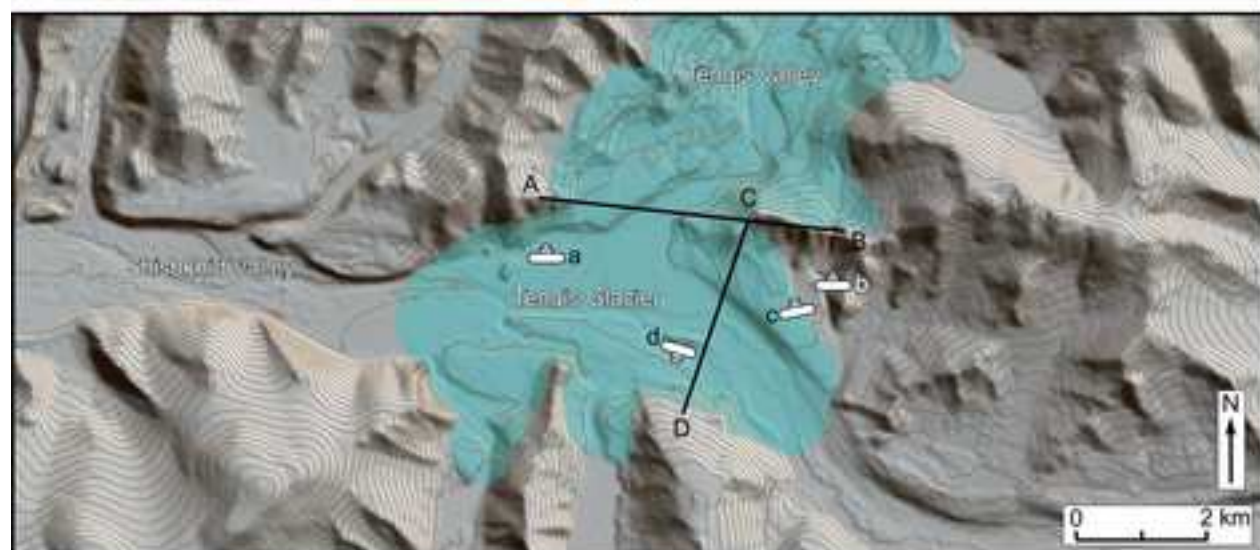
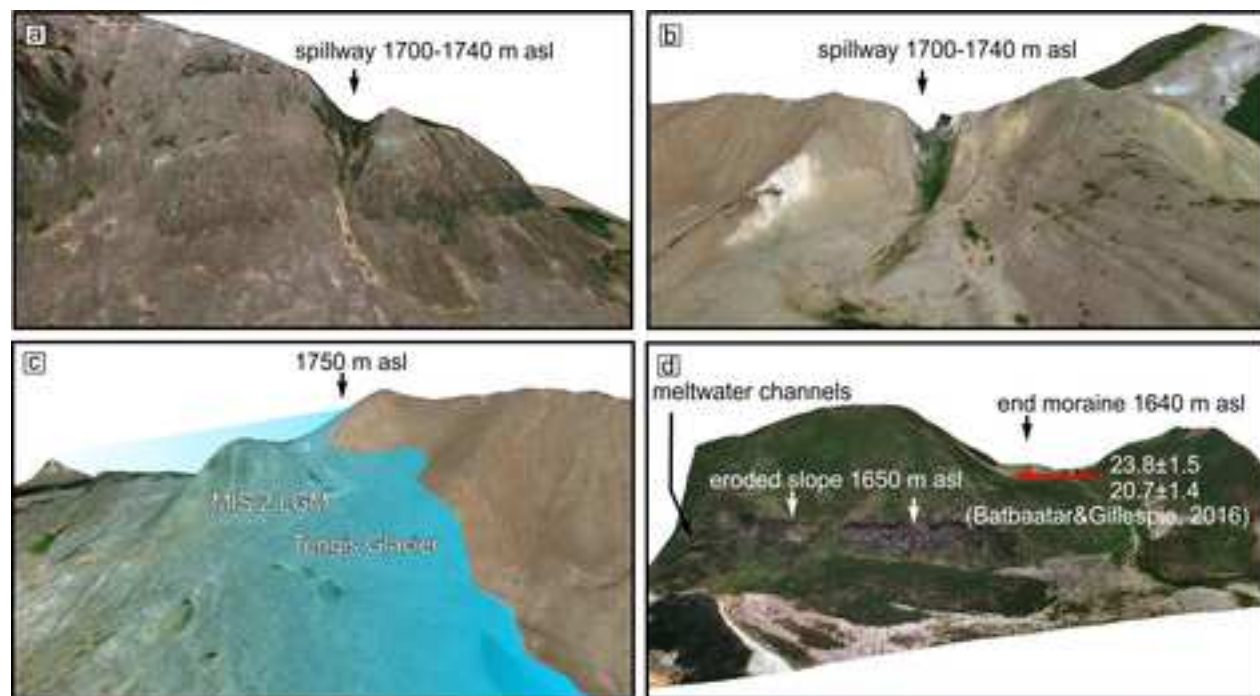


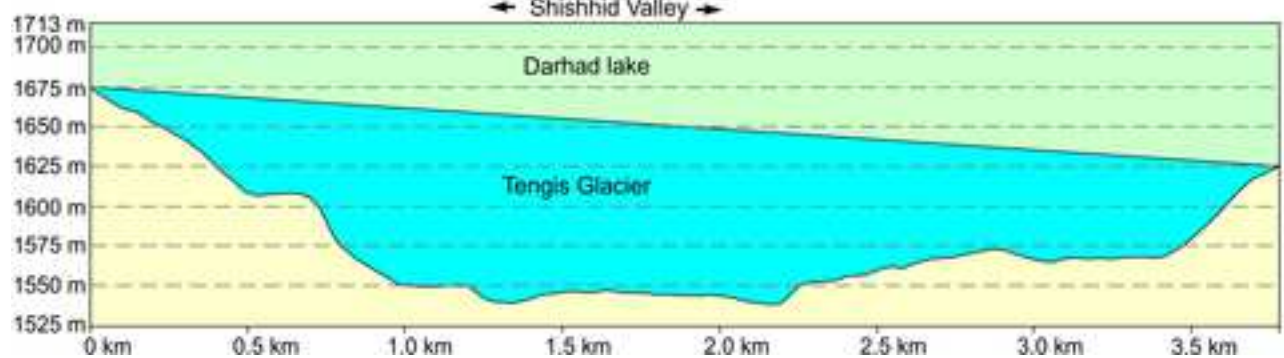
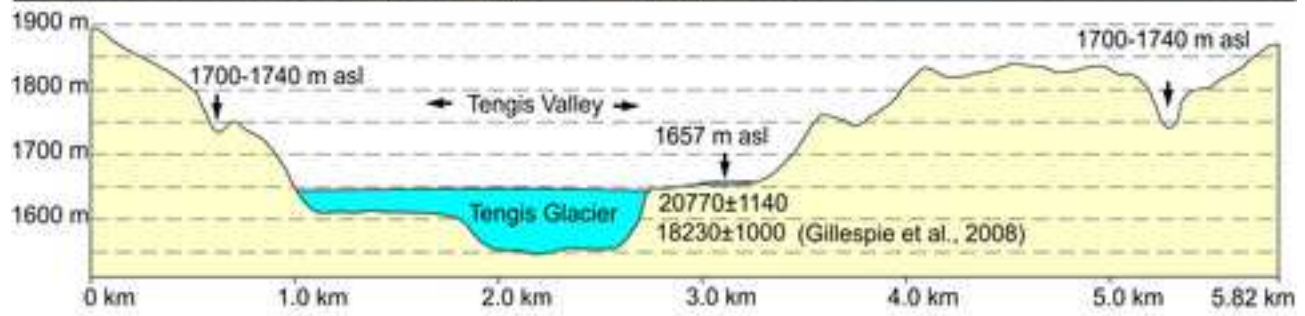
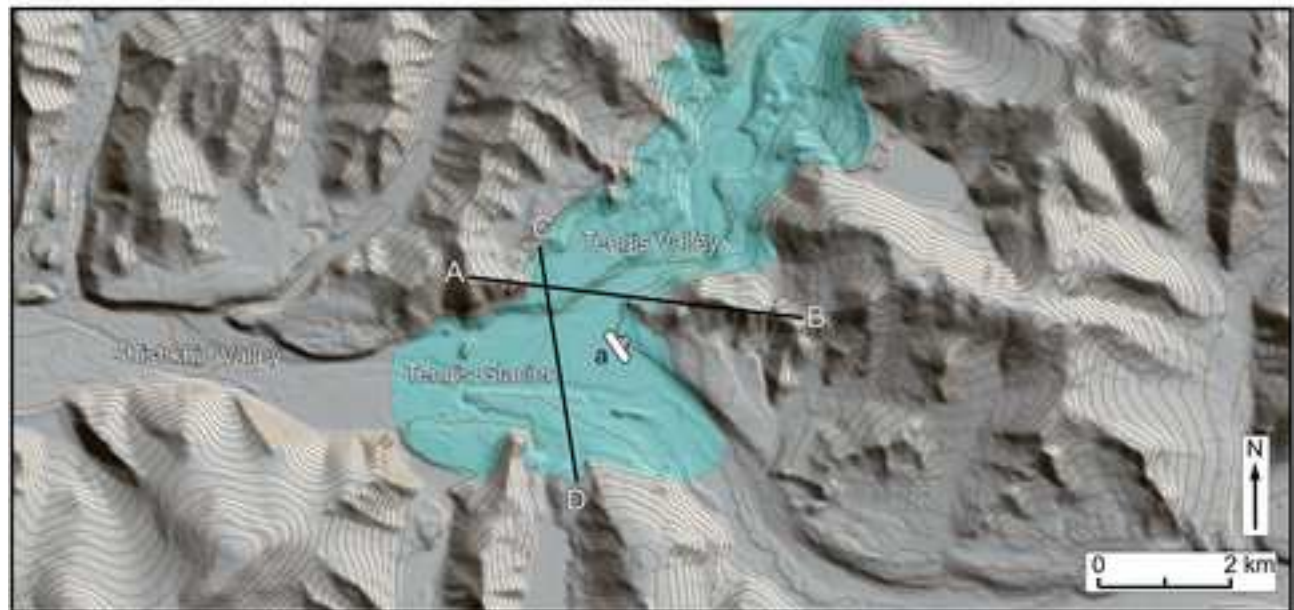
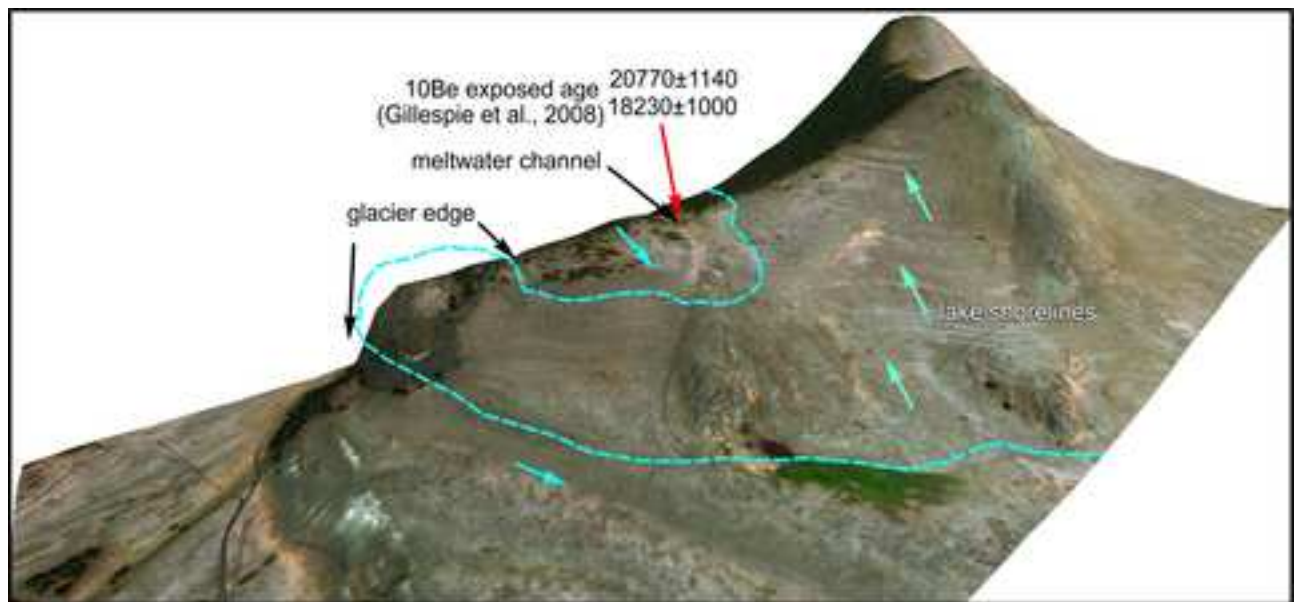




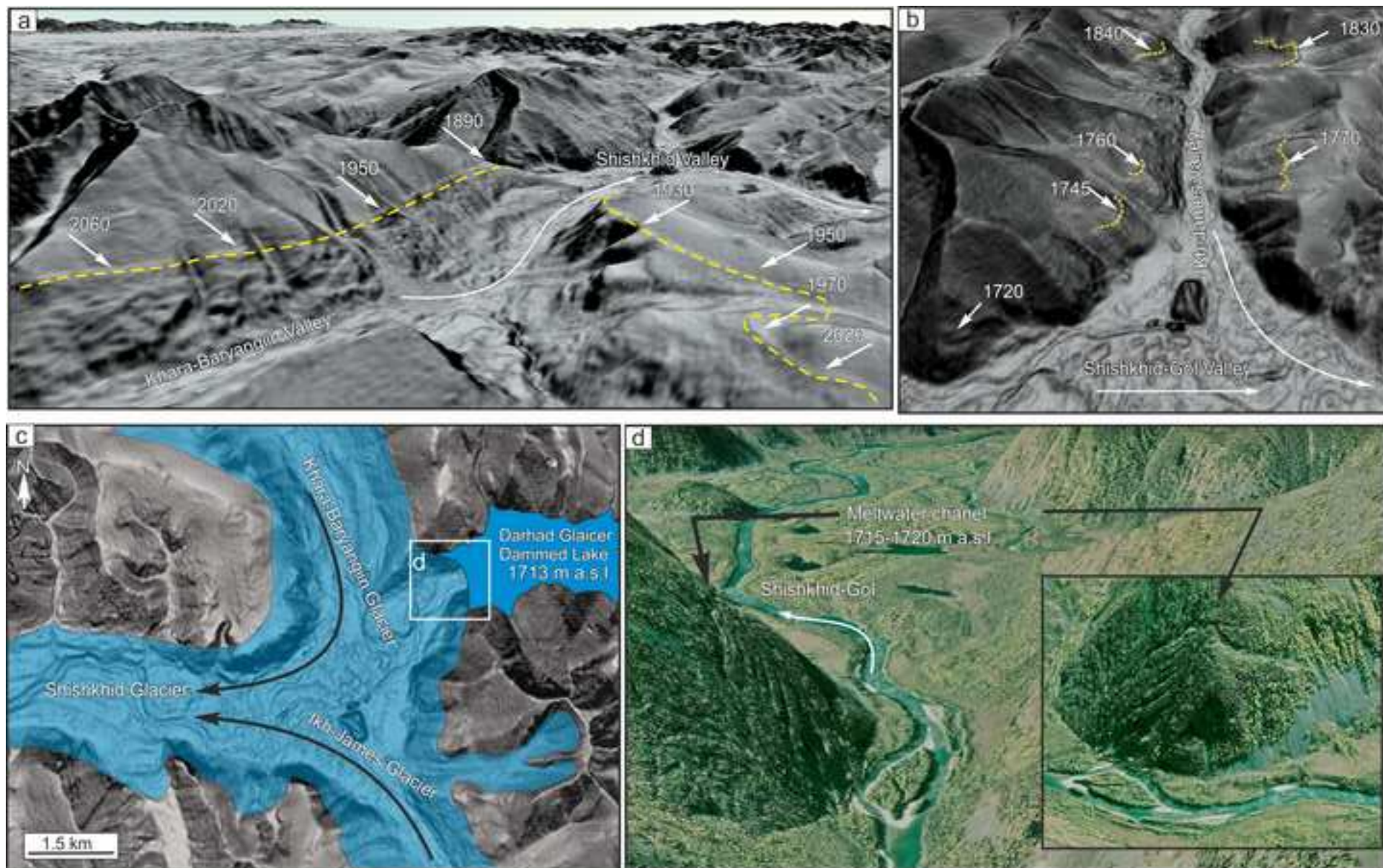




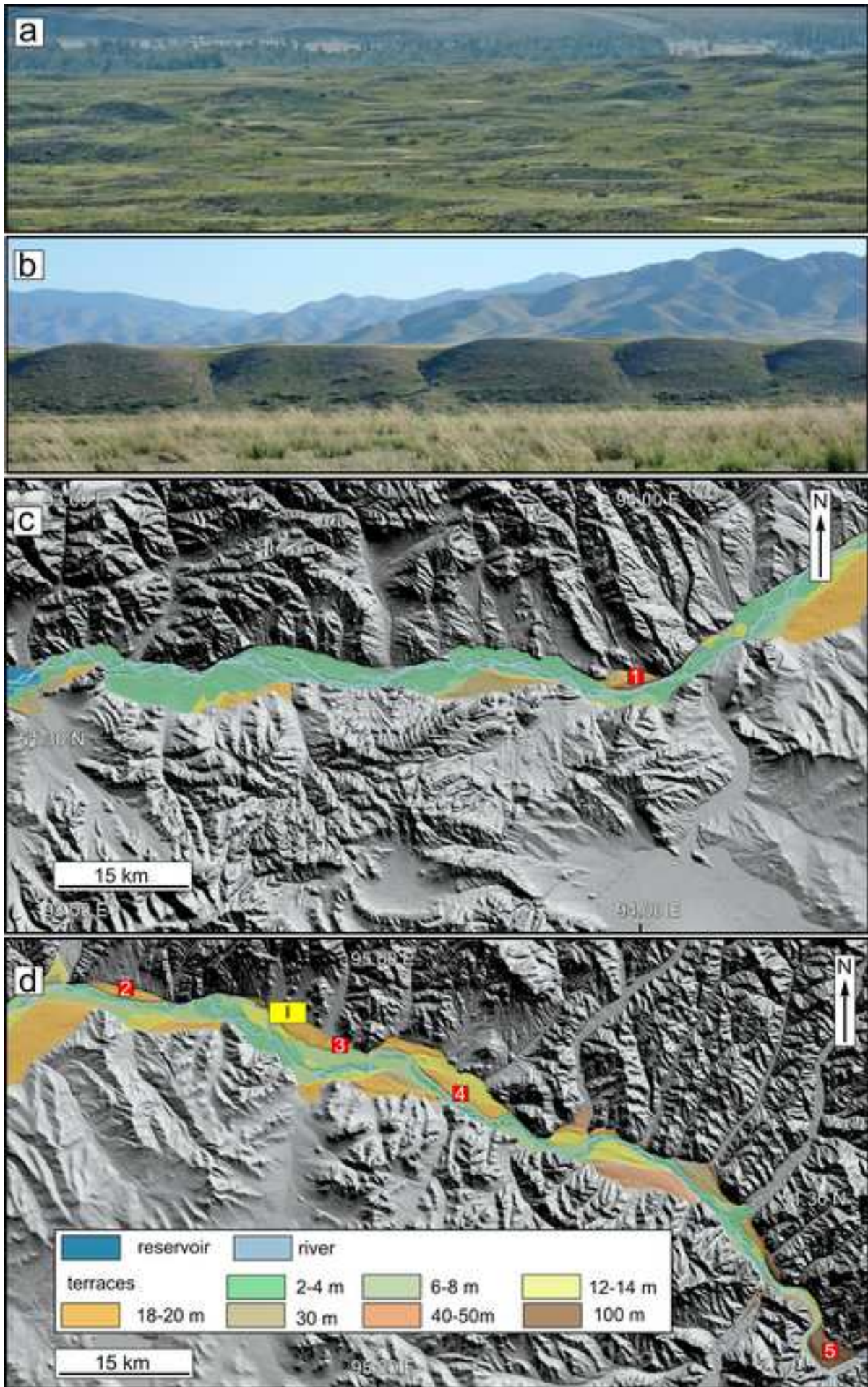




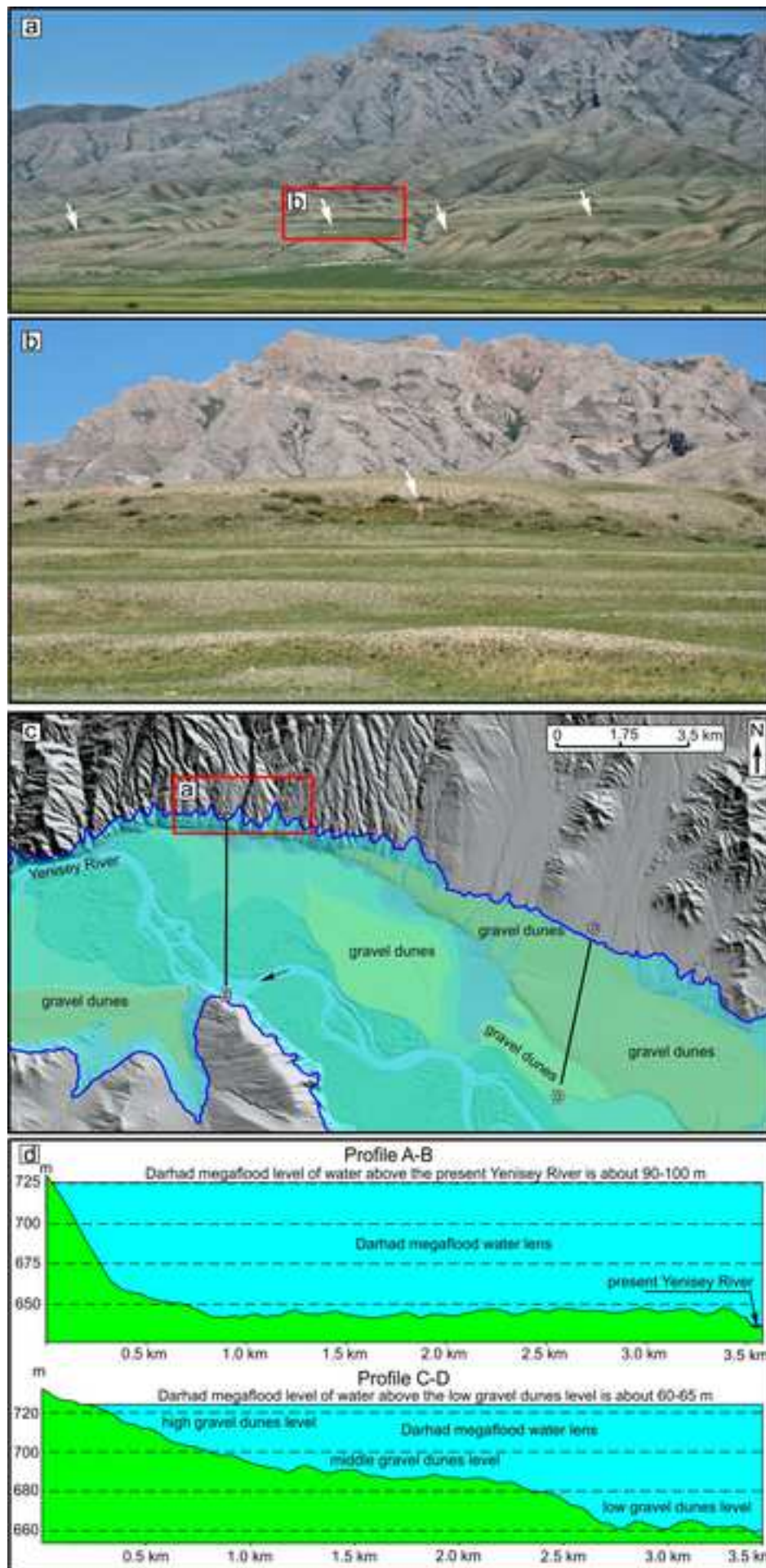








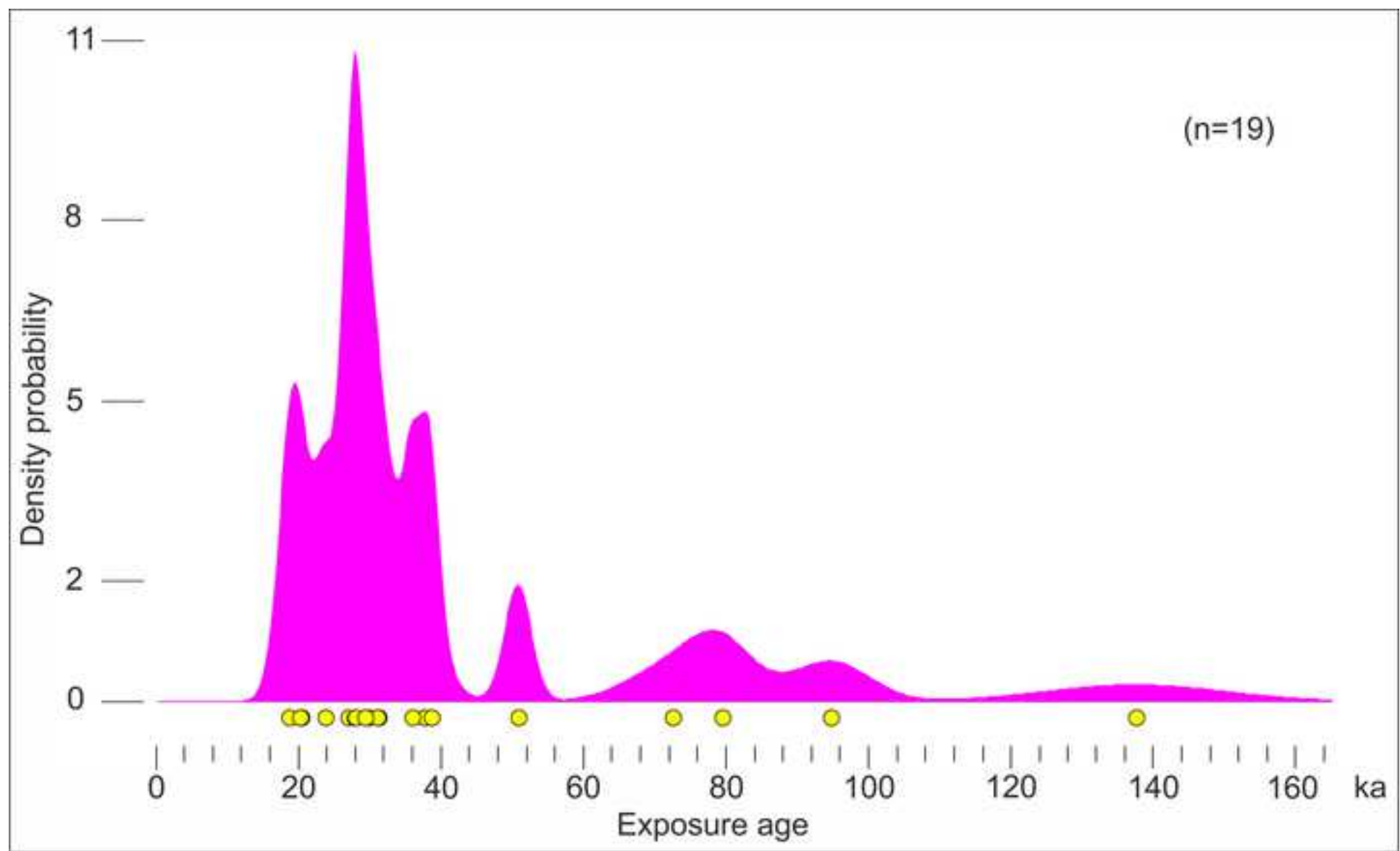




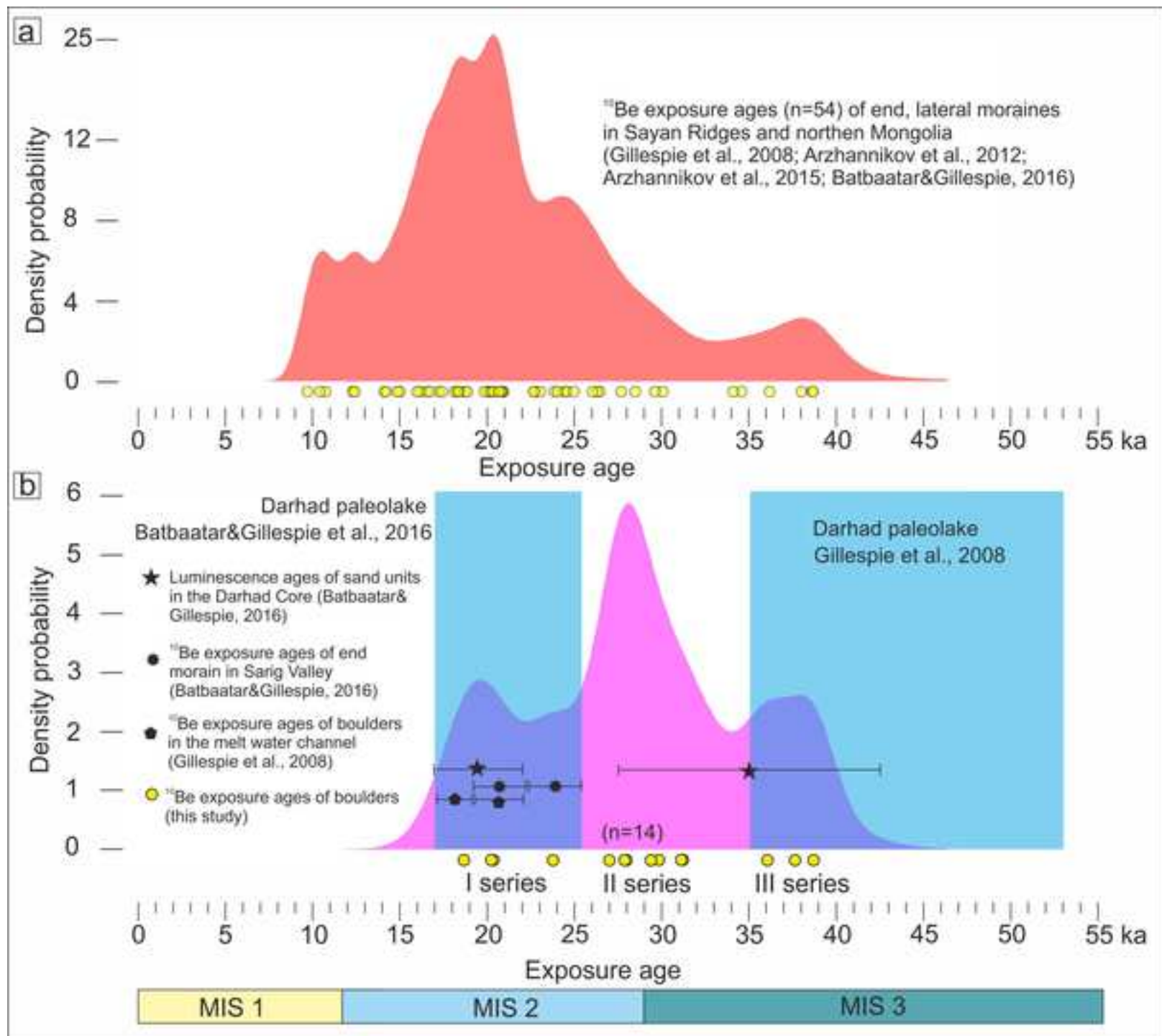












Sample	Latitude (N) (decimal degrees)	Longitude (E) (decimal degrees)	Altitude (m asl)	<sup>10</sup> Be (at/g)	Uncert	Min Age (yr)	Uncert (yr)
T1	51.567367	94.015250	624	574 981	32 819	79 536	4 540
T3	51.568117	94.008667	629	230 402	15 215	31 360	2 071
T4	51.562050	94.006050	623	218 543	20 945	29 811	2 857
T5	51.567367	94.015250	624	980 548	92 456	137 574	12 972
T6	51.710217	94.597467	661	234 350	20 058	31 142	2 665
T7	51.711283	94.596950	669	205 506	11 750	26 983	1 543
T8	51.711900	94.595433	663	284 043	23 740	37 607	3 143
T9	51.711900	94.595433	663	141 539	12 459	18 645	1 641
T10	51.712017	94.594450	662	210 779	12 929	27 840	1 708
T11	51.306617	95.739583	748	165 882	14 300	20 352	1 755
T12	51.652917	94.945500	687	216 061	9 741	27 944	1 260
T13	51.653350	51.653350	690	157 924	20 011	20 211	2 561
T14	51.653483	94.943017	688	721 106	41 889	94 723	5 503
T15	51.653483	94.943017	688	391 622	14 766	50 893	1 919
T16	51.653483	94.943017	688	278 197	10 534	36 021	1 364
T17	51.665917	94.839617	662	543 193	47 323	72 613	6 326
T18	51.665017	94.838800	660	179 750	10 322	23 767	1 365
T19	51.664567	94.839050	660	291 188	9 448	38 646	1 254
T20	51,6642667	94.841383	655	220 694	17 442	29 348	2 319

Samples have a density of 2.5 and are ~3 cm thick. Samples were crushed, sieved (0.5-1mm) and chemically etched. Pure quartz was dissolved in HF in the presence of <sup>9</sup>Be carrier (100 µg of 3.025 x 10<sup>-3</sup> g/g <sup>9</sup>Be solution). Ion exchange columns (Dowex 1x8 and 50Wx8) were used to extract <sup>10</sup>Be. <sup>10</sup>Be/<sup>9</sup>Be ratios were measured by accelerator mass spectrometry at ASTER the French National Facility (CEREGE, Aix en Provence). Concentrations are reported relative to NIST SRM4325 standard, using an assigned value for the <sup>10</sup>Be/<sup>9</sup>Be ratio of 2.79x10<sup>-11</sup> and a <sup>10</sup>Be half-life of 1.387 Ma (Korschinek et al., 2010). A sea level high latitude spallation production rate of 4.49 ± 0.29 atoms g<sup>-1</sup> y<sup>-1</sup> and the stone scaling factors (Stone, 2000) were applied. Muons scheme is based on Braucher et al., (2003).

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

### Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. Arzhannikov S. is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs Signed by all authors as follows:

Arzhannikov S.

Arzhannikova A.

Regis Braucher

Goro Komatsu

AS, AA, RB devised the research concept, planning, and ideas. AS, AA, participated in field work. AS took the lead in writing the manuscript. RB did the dating ( $^{10}\text{Be}$ ). GK guided the structure and editing of the results and discussion. All authors contributed to the analysis and helped shape the study.