



**HAL**  
open science

# Limit of monsoonal precipitation in southern Tibet during the Last Glacial Maximum from relative moraine extents

Marie-Luce Chevalier, Anne Replumaz, Shiguang Wang, Jiawei Pan, Mingkun Bai, Kaiyu Li, Haibing Li

► **To cite this version:**

Marie-Luce Chevalier, Anne Replumaz, Shiguang Wang, Jiawei Pan, Mingkun Bai, et al.. Limit of monsoonal precipitation in southern Tibet during the Last Glacial Maximum from relative moraine extents. *Geomorphology*, 2022, 397, 10.1016/j.geomorph.2021.108012 . hal-03874569

**HAL Id: hal-03874569**

**<https://hal.science/hal-03874569>**

Submitted on 28 Nov 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 **Limit of monsoonal precipitation in southern Tibet during the Last Glacial Maximum from**  
2 **relative moraine extents**

3 Geomorphology 397 (2022), doi:10.1016/j.geomorph.2021.108012

4 **Marie-Luce Chevalier<sup>\*a,b</sup>, Anne Replumaz<sup>c</sup>, Shiguang Wang<sup>a,d</sup>, Jiawei Pan<sup>a,b</sup>, Mingkun Bai<sup>a,e</sup>,**  
5 **Kaiyu Li<sup>a</sup>, Haibing Li<sup>a,b</sup>**

6 **a.** Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology,  
7 Chinese Academy of Geological Sciences, 26 Baiwanzhuang Rd, Beijing 100037, China

8 **b.** Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou  
9 511458, China

10 **c.** ISTerre, Université Grenoble Alpes, CNRS, Grenoble, France

11 **d.** National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing,  
12 China

13 **e.** Peking University, Beijing, China

14

15 **Keywords**

16 Last Glacial Maximum; Yadong rift; moraine; Monsoon; Southern Tibet; Marine oxygen Isotope  
17 Stage; cosmogenic isotopes

18

19 **Highlights**

- 20 1. We dated one MIS-3 moraine at the base of >7000 m-high peaks in the Yadong rift  
21 2. We dated one LGM moraine at the base of ~6000 m peaks with abundant LGM precipitation  
22 3. We compiled ages from three N-S transects from northern Himalaya to central Tibet  
23 4. LGM moraines > MIS-3 moraines only where LGM precipitation are strongest  
24 5. We show new LGM monsoon limit from relative moraine extents

---

\* Corresponding author: E-mail address: [mlchevalier@hotmail.com](mailto:mlchevalier@hotmail.com), Tel.: +8613466654223

## 25 **Abstract**

26           Constraining the timing and extent of past glaciations can help understand how glaciers  
27 respond to climate change as well as study past changes in atmospheric circulation patterns,  
28 precipitation and temperature. Southern Tibet, thanks to its numerous, well-preserved, glacial  
29 deposits, is an ideal place to conduct such study, as it receives occasional winter precipitation from  
30 the mid-latitude Westerlies and abundant summer precipitation (snowfall at high elevation) from the  
31 Indian and East Asian monsoons. The fact that amounts of precipitation varied in space and time  
32 over the plateau, greatly influenced past glaciations, now recorded as successive moraine deposits.  
33 Here, we study two large moraines from the southern Yadong rift (China-Bhutan border) and  
34 determined (using 19 new <sup>10</sup>Be cosmogenic samples) that at Jichu, which is located at the base of  
35 high summits (~7000 m), glacial deposits were abandoned during Marine oxygen Isotope Stage  
36 (MIS)-3 (~29-57 ka), and that at Qudui, located at the base of lower summits (~6000 m), the  
37 moraine was deposited during the Last Glacial Maximum (LGM, 19-26.5 ka). Both moraines  
38 directly rest on top of presumably MIS-6 (~130-191 ka) remnant surfaces. We suggest that while  
39 abundant MIS-3 precipitation allowed MIS-3 moraines to be deposited at the base of the highest  
40 summits (such as at Jichu) despite warmer temperature than during the LGM, smaller amounts of  
41 precipitation occurred during colder MIS-2, blocked by high summits, preventing deposition of  
42 large LGM moraines. By contrast, where restricted LGM precipitation can easily reach across lower  
43 summits, large MIS-2 moraines exist at their base (such as at Qudui). In addition, we compiled  
44 published ages from 22 most extensive moraines ( $\leq$  MIS-6) from the northern Himalaya to central  
45 Tibet (211 samples) along three N-S transects (~50-400 km-long). We found that the relative extent  
46 of LGM and MIS-3 moraines varies between different regions, that we infer is due to spatial  
47 variations in precipitation: in general, MIS-3 (or maybe MIS-4 at places) moraines are more  
48 extensive than MIS-2 moraines, except in the Yadong rift, where LGM monsoon was able to reach,  
49 thanks to low topographic barrier and proximity to the monsoonal front. This thus allows to draw  
50 the limit of monsoonal precipitation during the LGM.

51

52

## 53 **1. Introduction**

54           The Tibetan Plateau being the most glaciated area outside of the polar regions is also called  
55 the third pole (e.g., Qiu, 2008; Yao et al., 2012). It is an ideal place to study past glaciations, in  
56 particular by studying imbricated moraines recording successive past glacial episodes, especially  
57 well-preserved on the flat plateau. Because past glaciations can record past changes in atmospheric  
58 circulation, precipitation and temperature, quantitatively constraining their extent and timing may  
59 help reconstruct past climate and improve our understanding on how glaciers respond to climate  
60 change. Indeed, mountain glaciers are highly sensitive to climate change, especially in zones  
61 influenced by various climatic systems such as the Tibetan Plateau. At present, the mid-latitude  
62 Westerlies bring winter precipitation mostly in northern and western Tibet, sometimes reaching  
63 southern Tibet (e.g., Mölg et al., 2013), and the Indian and East Asian monsoons bring summer  
64 precipitation mostly in southern and eastern Tibet (e.g., Benn and Owen, 1998; Herzschuh, 2006)  
65 (inset in Fig. 1). These climatic systems have varied through time (e.g., Zech et al., 2005; Wang et  
66 al., 2008) hence have greatly influenced glaciers fluctuation in Tibet, especially by controlling the  
67 amount of precipitation, hence the amount of snowfall at high elevation, received during both  
68 summer and winter, resulting in differences between monsoon-influenced regions and others. Due to  
69 its extensive size and high elevation, the Tibetan Plateau has influenced atmospheric circulation  
70 patterns, modified the path of the mid-latitude Westerlies, and modified the monsoon intensity (e.g.,  
71 Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992; Owen et al., 2005), so that past  
72 glaciations have also varied spatially (e.g., Benn and Owen, 1998).

73           Thanks to advances in dating techniques, an increasingly large number of glacial deposits,  
74 although far from exhaustive, has been dated across the Himalayan-Tibetan orogen, revealing the  
75 complex age pattern and apparent asynchronicity between different regions. Marine oxygen Isotope  
76 Stage (MIS)-6 deposits (~130-191 ka), which are among the oldest dated moraines, are observed  
77 both in semi-arid central Tibet such as in the Tanggula Mountains (Schäfer et al., 2002; Owen et al.,

78 2005) and in more humid eastern Tibet (e.g., Chevalier and Replumaz, 2019). However, many are  
79 often poorly-preserved compared to younger deposits hence are undated, making it difficult to  
80 assess their real spatial distribution. For MIS<6 moraines, Owen and Dortch (2014) suggested that  
81 glaciers in more humid regions (such as southern and eastern Tibet) reached their maximum extent  
82 during the global Last Glacial Maximum (gLGM, hereafter LGM, ~19-26.5 ka [Clark et al., 2009],  
83 during MIS-2, ~14-29 ka), later than those in semi- to arid regions (northern, western and central  
84 Tibet), where maximum extent occurred during MIS-3 (~29-57 ka) and LGM advances were  
85 limited. However, in humid eastern Tibet, sites with several imbricated moraines show that in spite  
86 of LGM moraines being the sharpest and best preserved deposits, MIS-6 moraines are the largest,  
87 although less sharp and relatively well-preserved at only a few places, while MIS-3 moraines are  
88 entirely missing from the glacial record (Chevalier and Replumaz, 2019). Note that occasional  
89 older, poorly-preserved moraines are sometimes observed thanks to particular tectonic settings  
90 (Chevalier et al., 2016; Chevalier and Replumaz, 2019). By contrast, in western Tibet, LGM  
91 moraines are limited in extent compared to MIS-3 moraines, hence suggesting that the maximum  
92 extent of glaciations in those regions occurred during MIS-3 (e.g., Gillespie and Molnar, 1995;  
93 Benn and Owen, 1998; Owen et al., 2002, 2010; Finkel et al., 2003; Hedrick et al., 2011). This has  
94 been interpreted as due to increased insolation during MIS-3, which drove monsoonal precipitation  
95 (snowfall) farther into the plateau, hence reaching western Tibet, resulting in a higher positive  
96 glacier mass balance despite higher temperatures during MIS-3 than during MIS-2 (e.g., Finkel et  
97 al., 2003). Therefore, the respective extent of LGM and MIS-3 glaciations appears to vary between  
98 different regions partly due to spatial variations in precipitation, so that glaciers in arid regions may  
99 be more sensitive to changes in precipitation (such as temporal migration of the monsoonal front)  
100 compared to glaciers in more humid regions, which may be more sensitive to changes in  
101 temperature (e.g., Zech et al., 2009; Dortch et al., 2013).

102 We choose the Yadong rift in southern Tibet, along which the Chomo Lhari Range forms a

103 natural border with Bhutan, located on the northern slopes of the Himalaya (Fig. 1A), to assess  
104 glaciers sensitivity to variations in precipitation and temperature. We dated two large moraines,  
105 Qudui and Jichu, which show contrasted results despite their close proximity and appearance, that  
106 we then compare with the handful of results from farther north along the Yadong-Gulu rift (Owen et  
107 al., 2005; Chevalier et al., 2011, 2020; Dong et al., 2014, 2017; Liu et al., 2017; Peng et al., 2019;  
108 Wang et al., 2020). To further compare the relative extent of MIS-2 and MIS-3 glacial advances  
109 with those elsewhere in southern Tibet, we also compile ages of the most extensive moraines from  
110 regional studies north of the Himalaya, along two additional ~N-S transects located west of the  
111 Yadong rift.

112

## 113 **2. Regional setting**

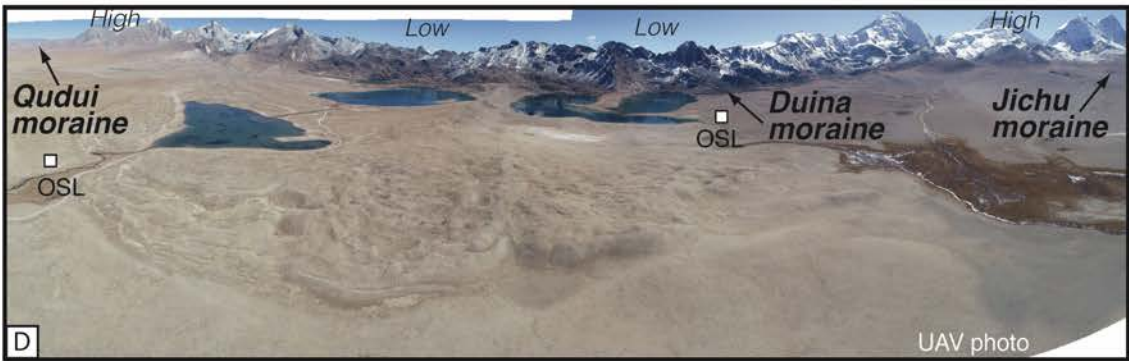
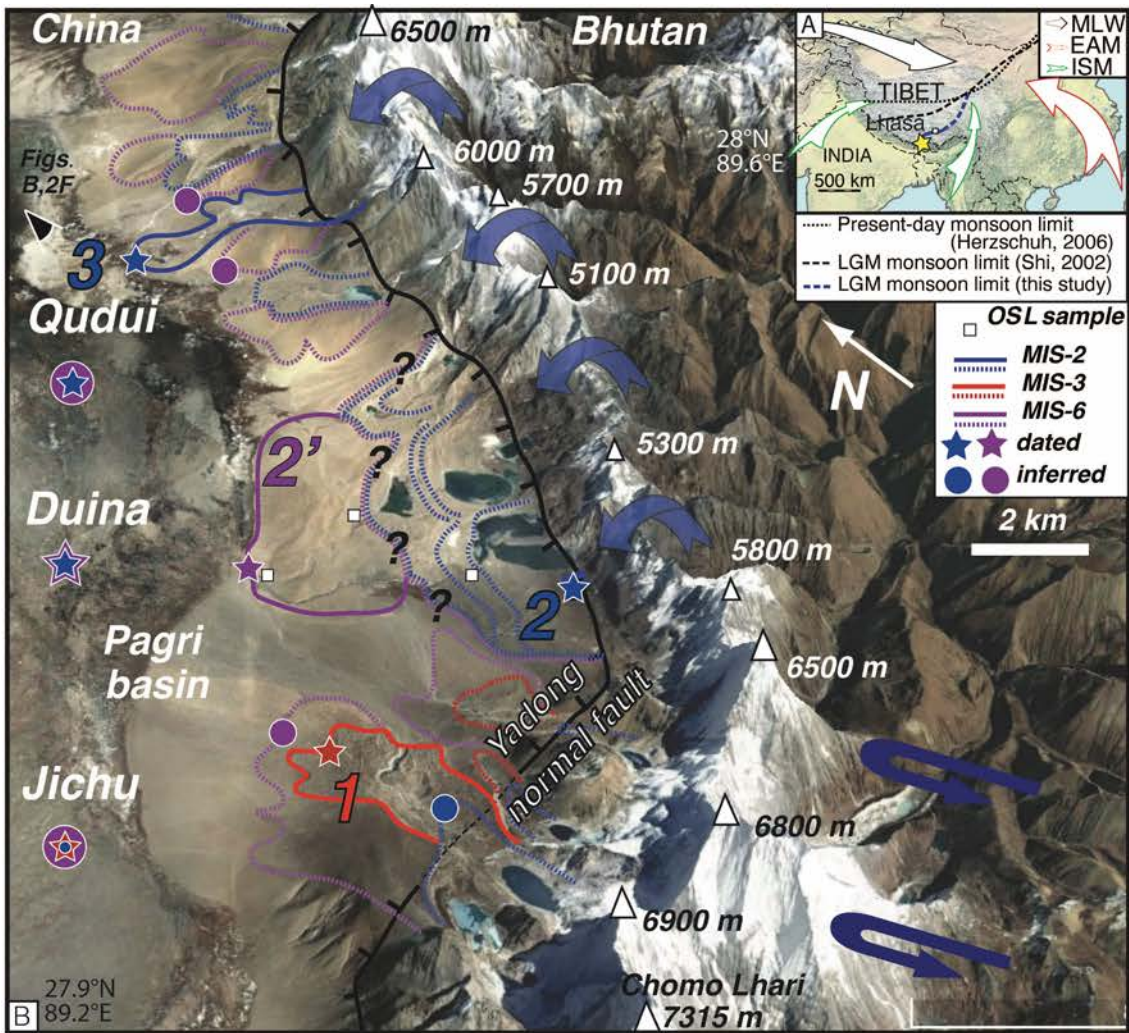
114 The ~500 km-long Yadong-Gulu rift is one of the seven main, ~N-S trending rifts that  
115 dissect the southern Tibetan Plateau, and it is one of the few that crosses the Himalaya. These rifts  
116 are bounded on one or two sides by active normal faults that open up large basins at the foot of high  
117 mountain ranges (e.g., Armijo et al., 1986) (Fig. 1A). The Yarlung Zangbo (or Brahmaputra) River  
118 separates the Yadong-Gulu rift into the northern Yadong-Gulu rift to the north and the Yadong rift to  
119 the south. To the north, the NE-trending Nyainqentanghula (NQTL) Range (summit at 7162 m)  
120 bounds the western side of the rift, while to the south, the Chomo Lhari Range (summit at 7315 m)  
121 acts as a natural border between China and Bhutan (Fig. 1A).

122 Chomo Lhari Range's western slopes (Tibet) are steep and narrow, <4 km from the crest to  
123 the base of the mountain, where the large (up to ~15 km wide) Pagri basin and Duoqing Co Lake lie  
124 (Fig. 1). The sharp limit/change of slope between the range and the flat basin is due to the active  
125 Yadong normal fault, which has vertically offset LGM moraines by ~20 m at rates of  $0.9\pm 0.3$  mm/yr  
126 (corresponding to ~E-W extension rates of  $0.8\pm 0.3$  mm/yr, Wang et al., 2020). By contrast, the  
127 eastern slopes of the range (Bhutan) are gently dipping for tens of km within deeply incised valleys

128 (Fig. 1A). Consequently, moraines to the west can broadly expand in all directions on the Pagri  
129 basin floor while the multiple moraines to the east are long and more confined into narrow valleys  
130 (e.g., Iwata et al., 2002). Present-day glaciers on the western slopes are only ~2 km-long and reach  
131 down to ~5000 m while on the eastern slopes, they are up to ~ 9 km-long and reach elevations of  
132 4100 m. Along the Chomo Lhari Range and Pagri basin, glacial landforms such as cirques, U-  
133 shaped valleys, and moraines abound. In addition, at numerous places, hummocky surfaces with  
134 lobes of various shapes and sizes are present on top of the main moraine's northern, outer flanks,  
135 rarely over the southern flanks (Fig. 1).

136 Data from Duoqing Co Lake weather station shows modern mean annual precipitation of  
137 388 mm and mean annual temperature of ~4°C (1960 to 2010) (Yang et al., 2013), on the same  
138 order as modern precipitation measurements in the nearby Karola pass (~550 mm), eastern NQTL  
139 Range (~400 mm) (Owen et al., 2005), or NW Bhutan (<500 mm, e.g., Bookhagen et al., 2006).

140 We study two moraine complexes from the southern Yadong rift, Qudui and Jichu, which  
141 originate from the western side of the Chomo Lhari Range, close to each other but in different  
142 topographic contexts: the Jichu moraine is located at the base of the highest summits (~7000 m),  
143 while the Qudui moraine is located at that of lower summits (~6000 m), with a series of even lower  
144 peaks (~5000-6000 m) in between the two sites, hence possibly influencing the amount of  
145 precipitation received from the monsoon (Fig. 1). Therefore, quantitatively constraining the timing  
146 and extent of past glaciations in the Yadong rift allows us to study how temperature and  
147 precipitation have influenced past Tibetan Himalayan glaciations. We further assess possible N-S  
148 and/or E-W differences, due to variations in precipitation, by comparing our results with similar  
149 studies farther north along the northern Yadong-Gulu rift, as well as farther west in neighboring  
150 rifts.





152 **Figure 1:** Southern Yadong rift. (A) Location of Yadong rift (yellow star) within Asia, influenced by  
153 various climatic systems of Asia: mid-latitude Westerlies (MLW, black arrow), East Asian summer  
154 monsoon (EAM, red arrow), and Indian summer monsoon (ISM, green arrows). Dotted black line  
155 shows modern limit of monsoonal front (e.g., Herzschuh, 2006), while black (Shi, 2002) and blue  
156 (this study) dashed lines show that during the LGM. (B) Ages and names of dated (stars) and  
157 inferred (from local morphologic comparison, circles) moraines in southern Yadong rift in southern  
158 Tibet, located between highly incised slopes of Bhutanese Himalaya, and flatter Tibetan Plateau,  
159 shown on a 3D Google Earth view (approximate coordinates in corners). Dated Last Glacial  
160 Maximum (LGM, in blue) and Marine oxygen Isotope Stage (MIS)-3 (in red) are determined by <sup>10</sup>Be  
161 surface-exposure cosmogenic dating, while MIS-6 (in purple) are determined by Optically  
162 Stimulated Luminescence dating (OSL) (Ha et al., 2018, number #2' and white squares). The two  
163 moraines dated in this study are Jichu (#1) and Qudui (#3), while Duina (#2) has been dated by  
164 Wang et al. (2020) (Tables 1 and 2). Inferred LGM monsoonal precipitation shown by blue arrows -  
165 dark blue: precipitation blocked by highest peaks near Chomo Lhari summit (7315 m) at the base of  
166 which LGM moraines are small; light blue: abundant precipitation allowed by lower peaks (~5000-  
167 6000 m) near Qudui, where LGM moraines are large. (C) Unmanned Aerial vehicle (UAV a.k.a.  
168 drone) photograph of Qudui site with Chomo Lhari peak and Lake Duoqing Co floodplain. (D) UAV  
169 view of Duina site (location in B). Note low and high peaks along range. Location of two OSL  
170 samples (Ha et al., 2018) indicated by white squares.

171

### 172 **3. Material and methods**

173 We used field investigation and Google Earth satellite imagery to map glacial landforms and  
174 select our sites in the Pagri basin of the southern Yadong rift. We collected 19 samples, seven at  
175 Qudui and 12 at Jichu, from the top few centimeters of large, stable, well-embedded granite  
176 boulders (1 to 4 m in diameter, Figs. S1 and S2) using chisel and hammer, located on lateral  
177 moraine crests at both sites, as well as on hummocky surfaces downstream at Jichu. We used  
178 cosmogenic <sup>10</sup>Be surface-exposure dating (e.g., Lal, 1991) to constrain the moraine abandonment  
179 ages (i.e., onset of deglaciation) following a procedure modified from Kohl and Nishiizumi (1992).

180 Ideally, one wants to sample boulders that have been exposed on moraine crests since

181 deglaciation, with no shielding, rolling or surface erosion since deposition (which tend to skew the  
182 ages toward values that are younger than the actual moraine age), and no exposure prior to  
183 deposition (which tends to skew occasional ages from the age distribution toward older values, e.g.,  
184 Hallet and Pukonen, 1994; Putkonen and Swanson, 2003; Heyman et al., 2011). Despite moraines  
185 being relatively stable landforms over the long term, their crests can become unstable following  
186 glacier retreat, with large boulders being gradually exhumed to the surface as erosion washes the  
187 finer material away, thus with surface boulders representing multiple stages of exhumation as the  
188 surface lowers to a more stable position. It has been shown that erosion does not affect samples on  
189 young ( $\leq$  LGM), sharp, moraine crests as much as those located on sub-rounded MIS  $\geq 6$  moraine  
190 crests, as clearly observed in their respective age distribution: clustered ages with few outliers for  
191 LGM moraines, in contrast to continuous, scattered ages with no outlier for MIS-6 moraines  
192 (Chevalier and Replumaz, 2019). For that reason, one simply cannot accurately determine the  
193 abandonment age of a moraine older than the LGM from only a few individual boulder ages, but  
194 instead, one needs numerous individual boulder ages to determine the abandonment age of a  
195 particular moraine, as well as numerous moraine ages in order to examine the age distribution as a  
196 whole, and thus constrain the regional timing of glaciation (Chevalier and Replumaz, 2019; Balco,  
197 2020). Note that we cannot emphasize enough how important it is to collect a sufficient number of  
198 samples on each moraine in order to increase the likelihood to date the actual age of a moraine  
199 (Chevalier et al., 2011). Our team is one of the few that dates a large number of samples per crest,  
200  $\geq 6$  and often  $\geq 10$  (Table 2).

201         Ages were calculated using the CRONUS Earth calculator version 3 (Balco et al., 2008)  
202 using the St, Lm and LSDn production rate models as shown in Table 1, although we only refer to  
203 the Lm ages (Lal, 1991/Stone, 2000; time-dependent) throughout the paper. Topographic shielding  
204 was determined from Google Earth. We assumed zero erosion and did not correct for snow  
205 (unknown past snow cover data) and vegetation (absence of vegetation at both sites) covers, in

206 agreement with local studies (e.g., Owen et al., 2005; Liu et al., 2017), so that the apparent ages we  
207 calculate for each boulder may represent minimum ages. Statistical tests such as Peirce's criterion  
208 allow to identify and discard outliers from the age distribution of a particular moraine: one oldest  
209 sample at Qudui (14% of the population) and one oldest sample at Jichu (8%) (Table S1). Then,  
210 following Heyman (2014), we assign the Qudui and Jichu moraines to classes B (moderately-  
211 clustered) and C (poorly-clustered, as mainly observed for moraines older than the LGM, Chevalier  
212 and Replumaz, 2019), respectively, using reduced Chi-square analyses with internal (i.e., analytical),  
213 uncertainties (because all samples come from similar geographic setting so that their production rate  
214 is similar). We then take the oldest age of the distribution (after discarding outliers) to represent the  
215 emplacement age of the Qudui and Jichu moraines. Finally, to best assess whether MIS-3 moraines  
216 are more extensive than MIS-2 moraines in southern Tibet, we limit our regional age compilation  
217 (Table S2) to published studies which dated more than two samples from MIS  $\geq 2$  moraines (that  
218 excludes sites with erratics) using  $^{10}\text{Be}$  cosmogenic surface-exposure dating, i.e., a total of 22 sites  
219 and 211 samples, including 159 from our team. Note that sometimes, the MIS age we allocate to  
220 certain dated deposits may differ from that given in the original publication (e.g., Payuwang and Ybj  
221 sites, see Supplementary material) due to differences in the production rate model or statistical  
222 analyses applied (Tables S1 and S2). Detailed description of the data used for the age compilation  
223 can be found in the supplementary material.

224

## 225 **4. Site description and results**

### 226 **4.1. Qudui moraine**

227 The NW-trending Qudui moraine originates from numerous glaciers in a large glacial cirque  
228 upstream, and consists of a single, large U-shaped valley (~1.5 km wide) bounded by sharp-crested  
229 lateral moraines downstream. Three young moraines limiting current glacial lakes are present far  
230 upstream in the valley, and two main debris-flow deposits (including one called DQ, Wang et al.,

231 2020), are confined within the main Qudui moraine (Fig. 2B). The Qudui moraine extends for ~7  
232 km and almost reaches the current floodplain of Lake Duoqing Co (Figs. 1B and 2). The sharp,  
233 steep and high (~200 m) SW lateral moraine, and that, less steep and less high (<150 m) to the NE,  
234 with large lobate, hummocky deposits on its outer flank, lie on top of extensive, much smoother  
235 moraine surface remnants, visible as orange hues on satellite images, observed north and south of  
236 the Qudui valley (Figs. 1A and 2A,F). Fifteen km south of Qudui, similar deposits in the Duina area  
237 have been dated as MIS-6 (two ages,  $135\pm 21$  and  $181\pm 25$  ka, Ha et al., 2018) using Optically  
238 Stimulated Luminescence (OSL) dating (Fig. 1).

239 We collected a total of seven samples from the SW sharper, crest (C204-211), whose ages  
240 range from  $20\pm 2$  to  $41\pm 3$  ka (Figs. 2B, 3 and Table 1). The oldest age (C209) has been identified as  
241 a statistical outlier and was discarded (see methods section). The remaining ages are moderately-  
242 clustered (Class B moraine) and the oldest age ( $24\pm 2$  ka) is clearly LGM. An inner deposit (DQ,  
243 crossing the Yadong fault) has been dated by Wang et al. (2020) at  $13\pm 1$  ka (recalculated oldest age,  
244 Table S2) using  $^{10}\text{Be}$  dating (nine sample ages, no statistical outlier, Table S1), in agreement with its  
245 position within the LGM moraine (Fig. 2B-D). Similarly, the three sharp, inner moraines upstream  
246 must also be younger than the LGM (Fig. 2B-D).

247

248

249 **Table 1:** Analytical results of  $^{10}\text{Be}$  geochronology and surface exposure ages of Jichu and Qudui

250 moraines in the Yadong rift

Name	Lat (°N)	Long (°E)	Elev (m)	Quartz (g)	Shieldi ng (mg)	Be carrier (mg)	$^{10}\text{Be}/^9\text{Be}$  ( $10^{-12}$ )#	$^{10}\text{Be}$  ( $10^6$ )at/g	St  (years) §	Internal uncert. (yrs)	<b>Lm</b>  (years) §	Internal uncert. (yrs)	LSDn  (years) §	Interna l uncert. (yrs)
<b>Qudui moraine</b>														
C204	28.06138	89.43633	4836	18.7757	0.994	0.2226	18.6749	1.4795±0.03	1976	491	<b>22695±1774</b>	463	±1417	461
C205	28.06212	89.43575	4830	18.1260	0.994	0.236	18.3699	1.5987±0.035	26099±7	588	<b>24337±1917</b>	548	±1538	545
C206	28.06302	89.43523	4823	18.8365	0.973	0.2265	16.9312	1.3607±0.031	22764±5	530	<b>21697±1713</b>	505	±1381	504
C207	28.06435	89.43473	4802	19.9462	0.977	0.2437	18.006	1.4704±0.030	24746±7	521	<b>23245±1821</b>	490	±1458	487
C208	28.06511	89.43366	4784	18.2144	0.977	0.2449	15.245	1.3701±0.026	23238±3	449	<b>22035±1716</b>	425	±1372	424
C209	28.06619	89.43172	4753	19.1133	0.977	0.2456	30.3256	2.6048±0.055	45059±3	968	<b>40476±3188</b>	869	±2553	865
C211	28.06736	89.42472	4687	18.6321	0.976	0.2405	13.2389	1.142±0.0325	20241±1709	579	<b>19737±1592</b>	565	±1308	569
<b>Jichu moraine</b>														
Crest														
C101	27.89423	89.30846	5065	18.9897	0.978	0.2415	25.827	2.1951±0.049	2736	744	<b>30037±2369</b>	676	±1896	671
C102	27.89737	89.30816	5047	15.8719	0.978	0.2476	17.379	1.8117±0.039	27442±4	602	<b>25411±1998</b>	557	±1594	552
C103	27.90011	89.3085	5022	9.8849	0.978	0.2357	8.5489	1.3625±0.031	1722	477	<b>20241±1595</b>	463	±1287	463
C104	27.90303	89.30837	4987	15.6752	0.997	0.2387	11.9794	1.219±0.0282	18547±1534	432	<b>18351±1447</b>	427	±1168	427
Eastern hummocky deposit														
C106	27.91631	89.31726	4819	17.6505	0.989	0.2427	16.0811	1.4779±0.031	24472±2	521	<b>23016±1804</b>	490	±1445	488
C107	27.91916	89.31902	4773	17.1958	0.989	0.2356	8.0084	0.7334±0.015	12361±8	268	<b>13015±1019</b>	283	±822	283
C108	27.92141	89.3193	4734	17.4240	0.983	0.2481	6.9263	0.659±0.0149	11367±937	258	<b>12175±957</b>	277	±776	278
C110	27.92427	89.31915	4701	17.2629	0.983	0.2372	36.4167	3.3449±0.050	59290±5	909	<b>55567±4313</b>	851	±3393	841
Western hummocky deposit														
C111	27.92372	89.31061	4685	18.5931	0.98	0.2476	21.9473	1.9531±0.030	34774±3	545	<b>31745±2451</b>	497	±1959	498
C113	27.92234	89.30717	4703	17.4952	0.98	0.2333	18.6453	1.6617±0.033	29302±1	589	<b>26935±2105</b>	541	±1687	541
C115	27.91862	89.30649	4747	18.2415	0.98	0.2231	13.7341	1.1225±0.025	19351±5	443	<b>19012±1498</b>	435	±1215	438
C116	27.91874	89.30434	4729	17.9351	0.98	0.2398	30.279	2.7055±0.040	47365±6	720	<b>41888±3239</b>	636	±2548	628

*Samples were processed at the Institute of Crustal Dynamics, China Earthquake Administration, Beijing (now called National Institute of Natural Hazards, Ministry of Emergency Management of China); and the  $^{10}\text{Be}/^9\text{Be}$  ratios were measured at Xi'an AMS Center, China.*

*Ages are calculated with the CRONUS v3 calculator.  $St = \text{Lal (1991)/Stone (2000)}$  time-independent production rate model,  $Lm = \text{Lal (1991)/Stone (2000)}$  time-dependent production rate model,*

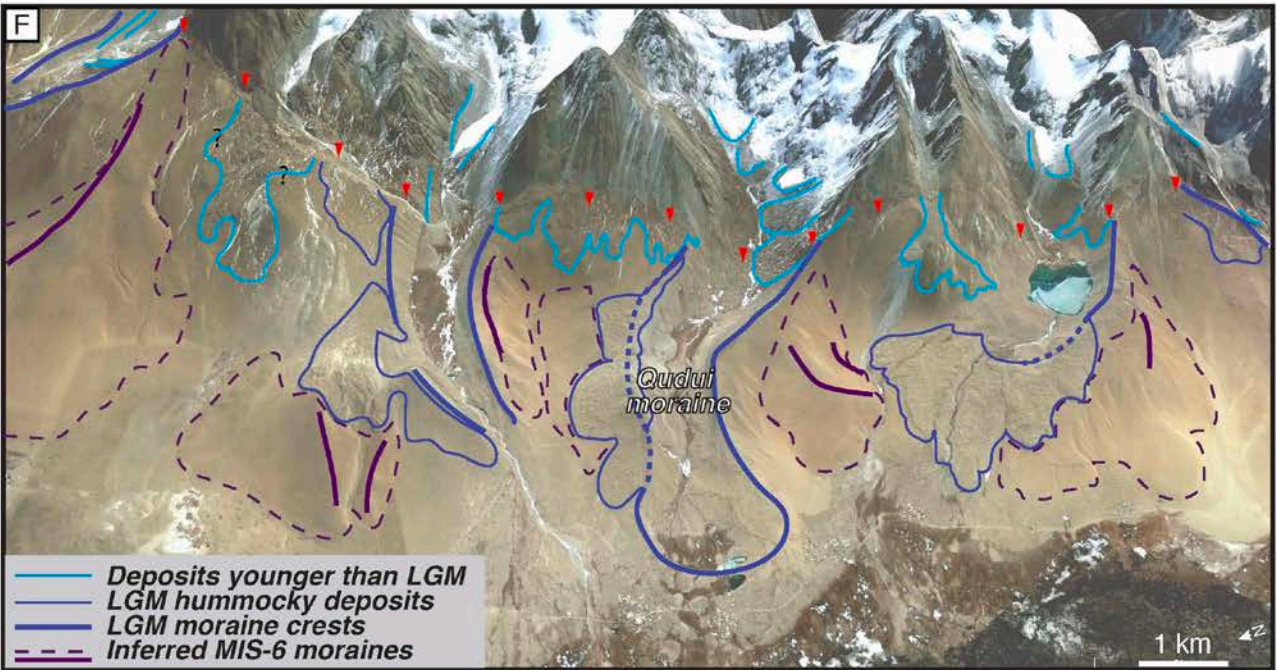
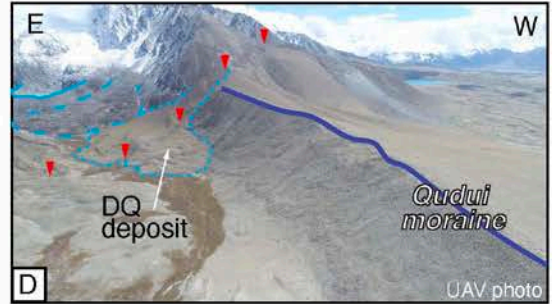
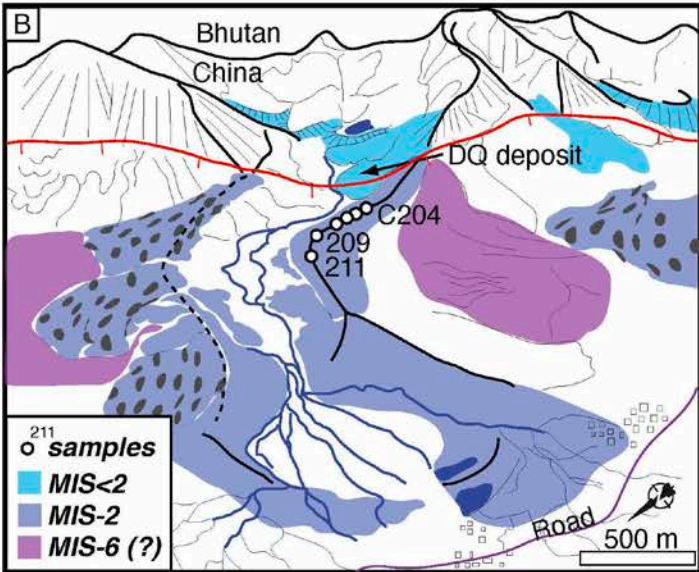
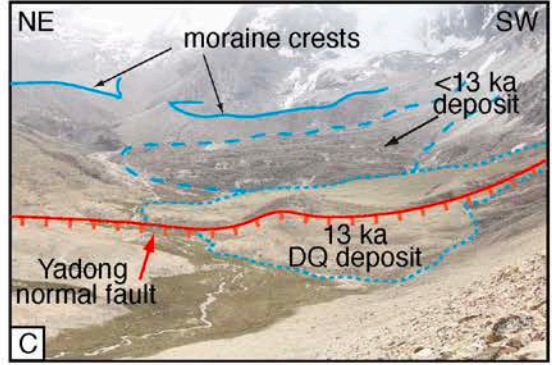
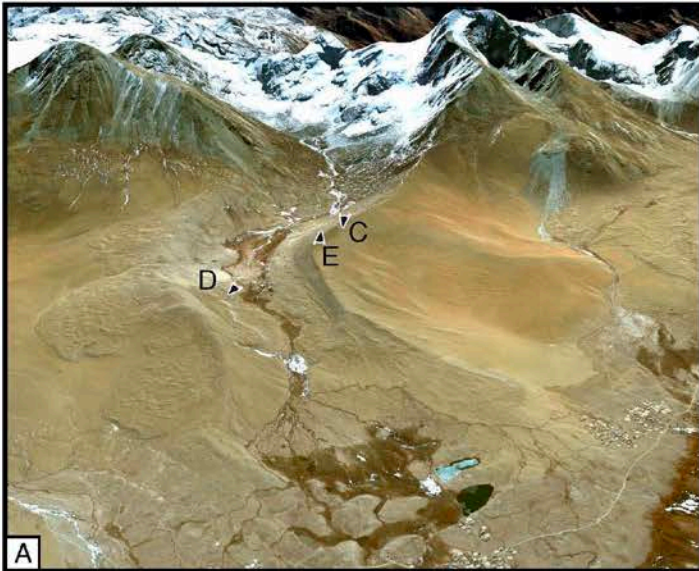
*LSDn = Lifton et al. (2014) production rate model.*

*All samples are granite (density is  $2.7 \text{ g/cm}^3$ ); Thickness was taken as 5 cm. No erosion rate was applied.*

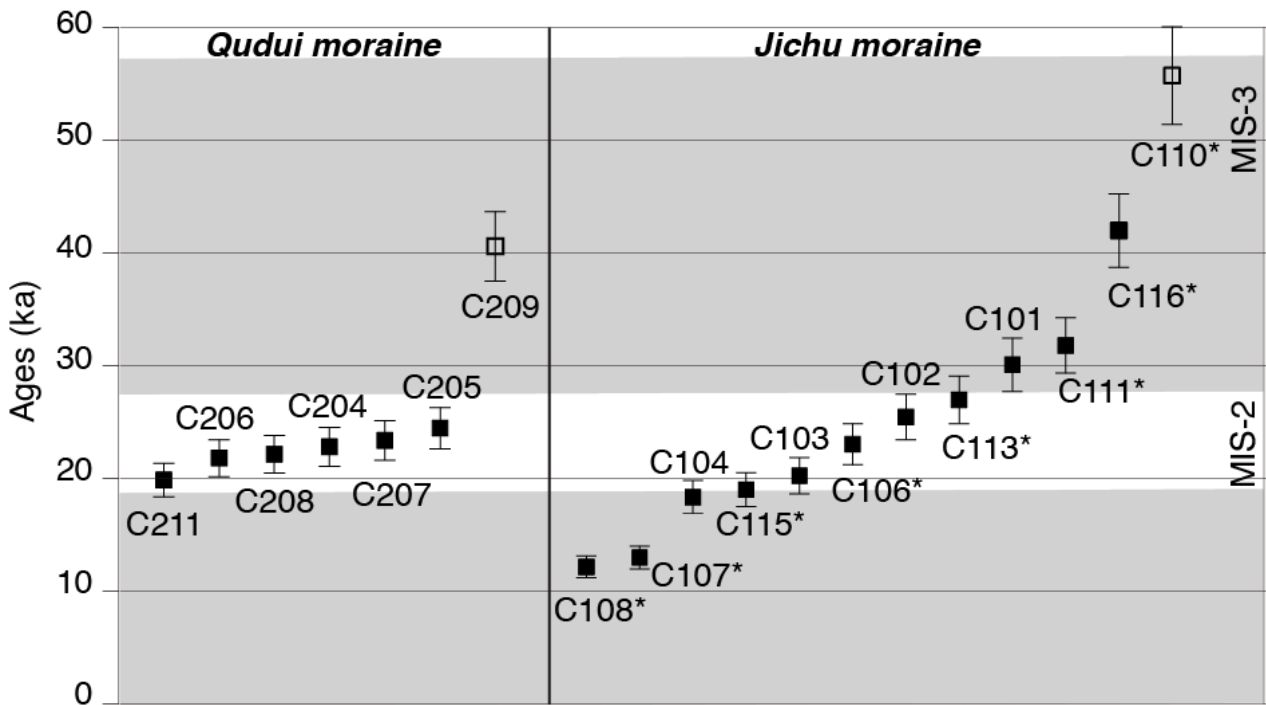
*Standards used at Xi'an AMS Center are '01-5-3' and '01-5-4' with  $^{10}\text{Be}$  isotope ratios of  $6.32 \times 10^{-12}$  and  $2.85 \times 10^{-12}$ , respectively, equivalent to 07KNSTD.*

*#Blank correction was applied with each 15 samples corresponding to a blank.*

*§ External Uncertainties (analytical and production rate, Balco et al., 2008) are reported at the  $1\sigma$  confidence level.*



253 **Figure 2:** Qudui moraine site. (A,B) Google Earth image of Qudui moraine and its interpretation  
 254 with samples location as white circles. Red line represents Yadong normal fault in B. (C) Field  
 255 photograph of young (<LGM) deposits inset into Qudui moraine. Dotted, light blue line  
 256 encompasses ~13 ka DQ deposit, which is vertically offset by Yadong normal fault (red line with tick  
 257 bars) by ~11 m (Wang et al., 2020). Note additional moraines upstream (dashed and solid light blue  
 258 lines). (D,E) UAV views of Qudui moraine crest with Lake Duoqing Co and its floodplain  
 259 downstream. Red triangles indicate Yadong fault. (F) Google Earth image (location in Fig. 1A) of  
 260 Qudui moraine and adjacent, most likely LGM deposits, on top of remnant, most likely MIS-6,  
 261 moraine surfaces (orange hues, highlighted by purple dashed lines with crests in solid lines). Red  
 262 triangles indicate Yadong fault.  
 263



264  
 265 **Figure 3:**  $^{10}\text{Be}$  cosmogenic surface-exposure ages of Qudui and Jichu moraines, using the 'Lm' Lal  
 266 (1991)/Stone (2000) time-dependent model in CRONUS calculator v3 (Balco et al., 2008) with  $1\sigma$   
 267 uncertainty. Numbers next to samples refer to sample names in Table 1. Outliers in white are  
 268 discarded (using Peirce's criterion) when assigning a moraine age (see methods section). Grey  
 269 sectors represent Marine oxygen Isotope Stages (MIS). Note the difference in age spread between  
 270 samples collected from hummocky (\* symbol, ages more scattered) deposits at Jichu and the lateral  
 271 Jichu and Qudui crests (more clustered).  
 272

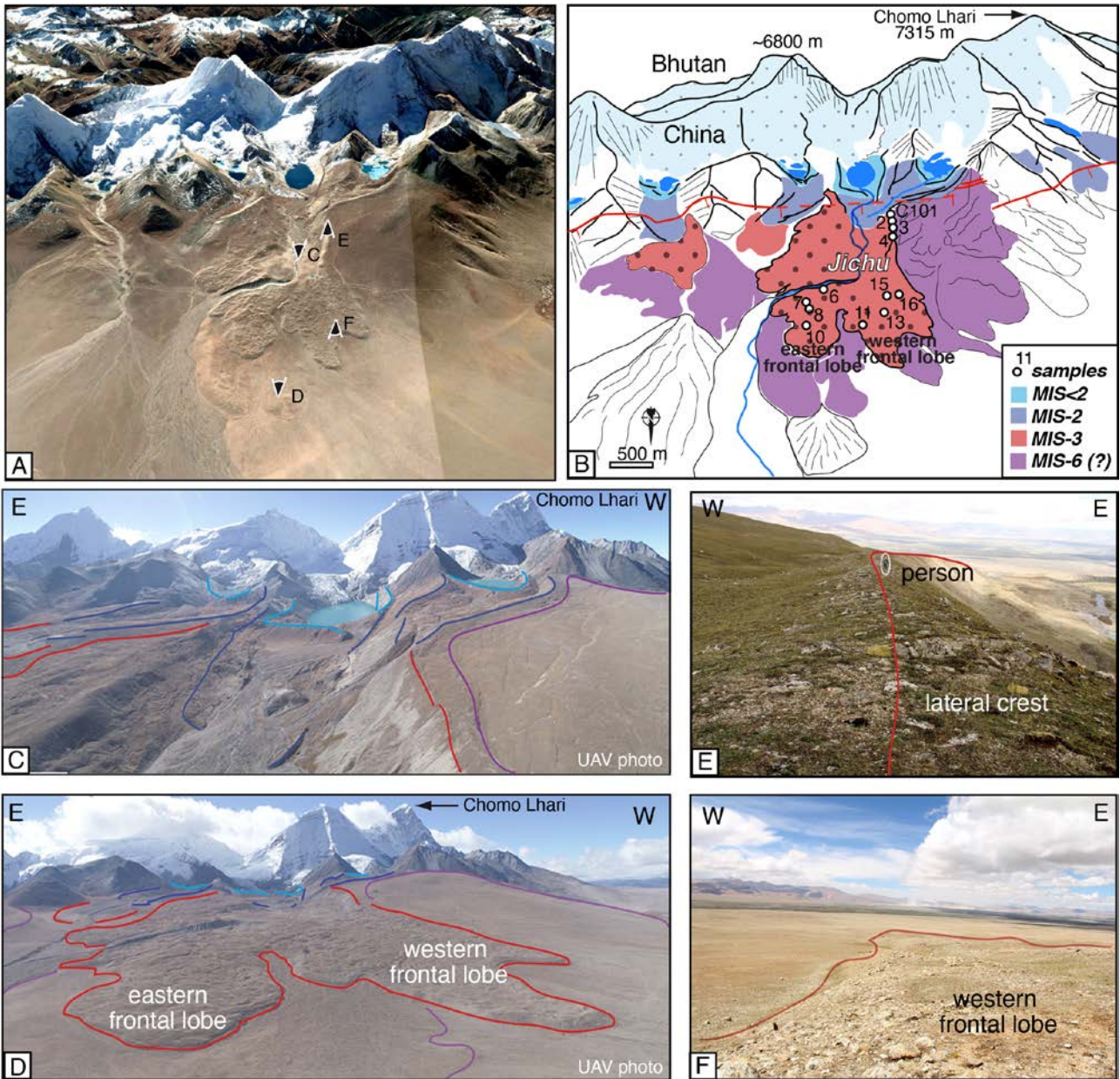


## 273 **4.2. Jichu moraine**

274           The Jichu moraine complex is one of the largest in the entire Pagri basin, with three large  
275 glacial cirques from which large glaciers flow northward, and where several present-day, ~1 km-  
276 long, glacial lakes exist, each surrounded by several sharp moraine crests (light blue in Fig. 4A-C).  
277 Downstream and outside of these frontal moraines, relatively sharp crests (dark blue in Fig. 4) reach  
278 the Jichu U-shaped valley, with clear breach of their frontal crest (Fig. 4C). The largest moraine,  
279 Jichu, which extends ~7.6 km from the current glacier snout located at ~5100 m, consists of lateral  
280 crests (sharper to the west) surrounded by hummocky deposits to the east and front. These Jichu  
281 deposits also lie on top of extensive, much smoother moraine surface remnants (Fig. 4A,B) which  
282 may also be inferred to belong to MIS-6 by comparison with the two OSL ages from the smooth  
283 surfaces downstream from Duina (Fig. 1).

284           We collected a total of 12 samples at the Jichu site: four samples (C101-104) from the sharp  
285 and linear lateral, western crest upstream, and eight samples (C106-116) from the hummocky  
286 deposits downstream (Fig. 4B). Ages are scattered from  $12\pm 1$  to  $56\pm 4$  ka (Fig. 3 and Table 1). Note  
287 that ages on the hummocky surfaces are more scattered (ranging from 12 to 56 ka) than those on the  
288 moraine crest (18 to 30 ka). The oldest age (C110 at 56 ka) has been identified as a statistical outlier  
289 (see methods section). The deposits (moraine crest and hummocky surfaces) are Class C (taken  
290 together or separately, Table S1) so that the oldest age is taken to represent their abandonment age,  
291 i.e., MIS-3 (with or without discarding outlier). Considering no outlier, as observed for moraines  
292 older than the LGM in SE Tibet (Chevalier and Replumaz, 2019), and as explained in the methods  
293 section, Jichu is assigned to early MIS-3.

294



295

296 **Figure 4:** Jichu moraine site. (A,B) Google Earth image of Jichu moraine and its interpretation  
 297 with samples location as white circles. Red line with tick bars in B represents Yadong normal fault.  
 298 (C,D) UAV photographs of moraines and hummocky deposits, respectively, with crests highlighted  
 299 by colors according to their ages (legend in B). (E) Field photograph of the western, lateral Jichu  
 300 crest. (F) Field photograph of hummocky deposit downstream.

301

302

## 303 **5. Discussion**

### 304 **5.1. Past glacial advances at Qudui and Jichu**

305 Surprisingly, the age distribution of the two largest, imbricated moraines we study at Qudui  
306 and Jichu, both located in the Pagri basin of the southern Yadong rift, is very different despite their  
307 close proximity (~20 km) (Fig. 1A). At Qudui, the largest and sharpest moraine shows tightly  
308 clustered ages between 20 and 24 ka with one statistical outlier at ~40 ka. Such clustering allows to  
309 firmly conclude that the Qudui moraine belongs to the LGM, as observed all around Tibet (e.g.,  
310 Owen and Dortch, 2014; Chevalier et al., 2011; Chevalier and Replumaz, 2019). The Qudui  
311 moraine lies on top of more extensive, older, smoother remnant moraine surfaces, with partly  
312 preserved, sub-rounded crests (orange hues on satellite images, purple in Fig. 2F). Similar surfaces  
313 located downstream from the Duina moraine south of Qudui (#2' in Fig. 1A) have been dated as  
314 MIS-6 with two OSL samples (Ha et al., 2018).

315 By contrast, the Jichu moraine ages are scattered and continuous from 12 to 56 ka, that we  
316 interpret as MIS-3 considering the oldest ages of the scattered age distribution as representative of  
317 the age of the moraine, as observed for moraines older than the LGM (Chevalier and Replumaz,  
318 2019). Whether the oldest sample is an outlier does not affect the moraine's MIS assignment. The  
319 Jichu moraine also lies on top of moraine surfaces similar to those observed regionally and dated as  
320 MIS-6 (Figs. 1A and 4). Much sharper, although smaller, moraine crests are observed upstream,  
321 closer to the glacial lakes and are most likely LGM and younger (dark and light blue, respectively,  
322 Figs. 1A and 4B,C).

323 In summary, extensive LGM moraines lie directly on top of presumably MIS-6 moraines at  
324 Qudui, with no MIS-3 deposits in between. At Jichu by contrast, extensive MIS-3 moraines rest  
325 directly atop most likely MIS-6 moraines, with less extensive LGM moraines located upstream  
326 within the MIS-3 deposits (Fig. 1A). Therefore, we infer that while the most extensive moraines in  
327 the southern Yadong rift may be MIS-6 everywhere, the relative extent of MIS-3 and MIS-2

328 moraines varies at places, depending on the elevation of the surrounding peaks, that influences local  
329 precipitation, as further explained below.

## 330 **5.2. Influence of temperature and precipitation**

331 Both moraines originate from the western side of the Chomo Lhari Range, uplifted by the  
332 Yadong normal fault and forming a topographic boundary between China and Bhutan (Fig. 1A).  
333 However, despite only being ~20 km apart, their topographic setting is different, with the Jichu site  
334 located at the base of the highest summits (~7000 m) while Qudui is located at the base of lower  
335 summits (<6000 m), just north of a series of even lower summits (~5000 m) (Fig. 1). We thus infer  
336 that these two sites may have received different amounts of monsoonal summer precipitation from  
337 Bhutan, with Jichu lying in a rain shadow behind the highest peaks acting as a topographic barrier,  
338 while precipitation could more easily reach the Qudui moraine thanks to the lower elevation of the  
339 nearby summits (blue arrows, respectively, Fig. 1A). Therefore, although the LGM period was very  
340 cold and arid (temperature 6-9°C and precipitation 30-70% lower than today, e.g., Shi, 2002), with  
341 low monsoon intensity (Wang et al., 2008) hence low effective moisture (Herzschuh et al., 2006)  
342 and minimum insolation (Berger and Loutre, 1991), we infer that the lower summits near Qudui  
343 nevertheless allowed precipitation to reach the Pagri basin, hence favoring LGM glacier advance  
344 now visible as the large LGM Qudui moraine and its neighbors. By contrast, in spite of similar low  
345 temperature conditions during the LGM near the high summits of the Chomo Lhari Range at Jichu,  
346 sufficient to sustain glaciers growth, its location shielded from LGM precipitation prevented large  
347 LGM advances, as now observed upstream at Jichu as restricted LGM moraines (Figs. 1A and 4). At  
348 Jichu, the MIS-3 moraine is much more extensive than the LGM moraines, despite the fact that  
349 MIS-3 was warmer (2-4°C higher than today, Shi, 2002) than the LGM period but with more intense  
350 moisture (40-100% higher than today, e.g., Shi, 2002; Herzschuh, 2006) that brought more snowfall  
351 at the highest elevations (e.g., Finkel et al., 2003), hence allowing larger glaciers to grow and larger  
352 MIS-3 moraines to be deposited at the base of the highest summits.

353 At Jichu, we have dated both the western, well-preserved crest, as well as the hummocky  
354 deposits downstream from it, with scattered ages between ~10 and 55 ka (Fig. 3). As shown in our  
355 regional compilation of southern Tibet (Fig. 5), and in that of eastern Tibet (Chevalier and  
356 Replumaz 2019), such scattered age distribution with several ages older than the LGM (here 4 out  
357 of 12, i.e., 33% for Jichu), clearly indicates that deposition occurred prior to the LGM. Such highly  
358 lobate, hummocky morphology, observed at Jichu and at numerous places in the Yadong rift, may be  
359 due to extensive ice-avalanche/glacier-derived debris flows, that may have been triggered by  
360 earthquakes on the Yadong fault. Interestingly, the fact that, in general, the right bank of the glacial  
361 valleys displays such hummocky surfaces rather than the left bank, which seems intact with well-  
362 preserved, well-defined moraine crests (such as those we sampled at Qudui and Jichu), may be due  
363 to valley curvatures. The limited extent of such ice-avalanches, 'spilling' over the main moraine  
364 crest rather than spreading far down the foreland basin, may reflect their somewhat viscous, more  
365 ice-based than water-based nature. This suggests that these hummocky deposits most likely occurred  
366 toward the end of glacial periods when the climate was still cold, with sufficient ice left in the valley  
367 and limited water accumulation within glacial lakes, rather than during interglacials. This is indeed  
368 what we observe at Jichu, where both the hummocky deposits and the main crest have been dated as  
369 MIS-3.

370 One OSL sample was collected at depth, below the hummocky surfaces (because OSL dating  
371 requires collecting samples that have been protected from light after deposition) between the  
372 upstream Duina moraine (which is LGM, Wang et al., 2020, #2 in Fig. 1A) and the MIS-6 remnant,  
373 smooth surfaces (#2', Fig. 1A,C), and its age is MIS-5/6 within uncertainties ( $129 \pm 21$  ka, Ha et al.,  
374 2018). However, because hummocky deposits are not uniformly thick, we speculate that this sample  
375 may be overestimated because it may have been collected, for example, in a low zone, i.e., dating  
376 what lies underneath it. Instead, we infer that the series of intermediate surfaces surrounding large,  
377 present-day glacial lakes (dashed blue lines in Fig. 1A) most likely belong to the LGM, representing

378 successive, recessional moraines, the latter (most recent) of which is the Duina moraine, which was  
379 eventually abandoned at ~17 ka past the Yadong fault (Wang et al., 2020). Additional <sup>10</sup>Be samples  
380 would clearly be necessary to assess this discrepancy.

381 In summary, we suggest that while climatic conditions during the LGM were sufficient to  
382 sustain glaciers growth everywhere in the Chomo Lhari Range region thanks to low temperatures, 1)  
383 glaciers shielded from limited LGM precipitation only slightly advanced, such as near the high  
384 summits at Jichu, where only restricted LGM moraines exist (Figs. 1A and 4); and 2) glaciers that  
385 received more LGM precipitation thanks to lower summits, as observed near Qudui, show extensive  
386 LGM moraines. By contrast, we suggest that MIS-3 moraines were able to be deposited at the base  
387 of the highest summits thanks to intense precipitation which brought abundant snowfall at high  
388 elevations despite global temperatures warmer than during the LGM. Lastly, MIS-6 being the  
389 coldest period in recent climate history (e.g., Lisiecki and Raymo, 2005), such glacial advances  
390 occurred all along the southern Yadong rift (Fig. 1A).

### 391 **5.3. Age compilation shows limit of LGM monsoonal precipitation**

392 To further assess the relative extent of MIS-2 and MIS-3 glacial advances elsewhere in  
393 southern Tibet, we compiled ages (Fig. 5, Tables 2 and S2, plus details on each study in the  
394 Supplementary material) of the most extensive moraines from regional studies north of the eastern  
395 Himalayas from three ~N-S transects of ~400, ~300 and ~50 km-long, from the Himalaya to central  
396 Tibet: the Yadong-Gulu, Dinggye-Xainza, and Kung Co transects, respectively, from east to west  
397 (Fig. 6). This compilation allows to assess whether timing and extent of glaciations may have varied  
398 in a N-S and/or E-W direction, due to variations in topography and amounts of precipitation.

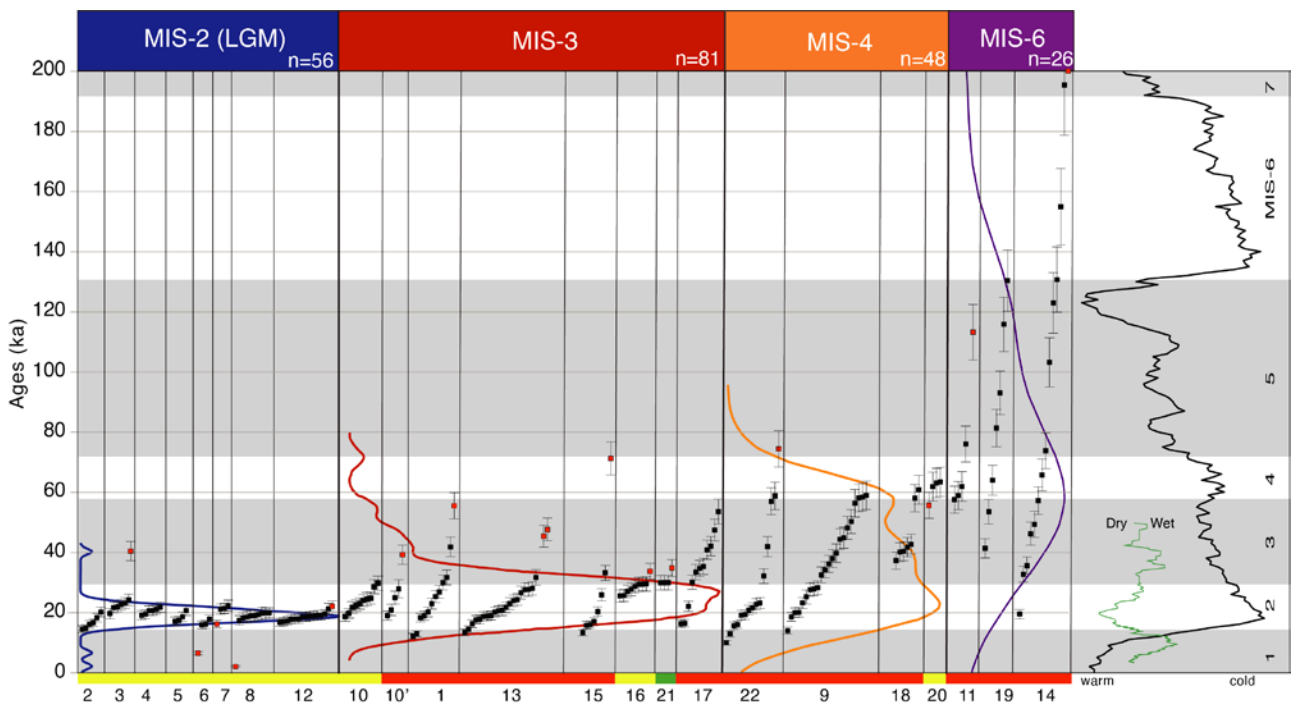
399 The compilation clearly shows very different individual boulder age distributions: clustered  
400 ages with few outliers for MIS-2 moraines and scattered but continuous ages for moraines older  
401 than the LGM (Fig. 5). This clearly distinct distribution pattern has already been observed in a  
402 similar compilation from eastern Tibet, interpreted as limited erosion on young (LGM) moraine

403 crests which remain sharp with numerous boulders on top, while erosion strongly affected sub-  
404 rounded, older moraine crests with fewer boulders on top, showing a scattered but continuous age  
405 distribution with oldest ages being MIS-6 (Chevalier and Replumaz, 2019). Similarly, here, the  
406 oldest ages in the scattered age distributions fall into MIS-6 and correspond to widely observed  
407 smooth surfaces, visible as orange hues on satellite images (Figs. 1A and 2F). Ages older than MIS-  
408 6 have been obtained occasionally on highly degraded moraines (Owen et al., 2009; Chevalier et al.,  
409 2011). These oldest surfaces, preserved in specific settings which need to be studied in more details,  
410 are beyond the scope of this paper, hence are not shown in the compilation. Therefore, as  
411 documented in more humid eastern Tibet (Chevalier and Replumaz, 2019), as well as in arid central  
412 Tibet (Schafer et al., 2002; Owen et al., 2005), the MIS-6 moraines are observed throughout Tibet.  
413 Indeed, our compilation and that of Chevalier and Replumaz (2019) show uniform MIS-6 ages of  
414 the most extensive moraines in southern and eastern Tibet, respectively, rather than a northward  
415 increase of their age, from more humid southern Tibet to more arid central Tibet, as previously  
416 suggested (Owen et al., 2005; Owen and Dortch, 2014).

417       Following Chevalier and Replumaz (2019)'s approach, we suggest that the oldest ages from  
418 numerous scattered, continuous age distributions from moraines older than the LGM best represent  
419 the age of such moraines. Too often, moraines with scattered age distribution are simply disregarded  
420 and MIS are not allocated (e.g., Blomdin et al., 2018), hence no new data are added to the growing  
421 database, and no contribution to the debate on which age best represents the actual moraine age can  
422 be made. Indeed, such moraines older than the LGM are harder to date, and more samples are  
423 needed to estimate their abandonment age ( $\geq 6$  samples, Chevalier et al., 2011), to eventually  
424 reconstruct past glaciations that recorded past changes in atmospheric circulation, precipitation and  
425 temperature, i.e., past climatic changes.

426       Between the clustered ages of MIS-2 moraines and the scattered but continuous ages of MIS-  
427 6 moraines, i.e., narrow *vs* broad probability density function (pdf) peaks, respectively, the

428 compilation shows intermediate pdf widths, such as MIS-3 for Jichu (Fig. 5). Such MIS-3 advances  
 429 are clear and have commonly been observed in Tibet (e.g., Owen et al., 2002, 2010; Finkel et al.,  
 430 2003; Hedrick et al., 2011). While the MIS-3 pdf peak is wider than that of the LGM, it is much less  
 431 broad than that of MIS-6 (Fig. 5). Interestingly, some sites show age distributions with slightly older  
 432 oldest ages at MIS-4 with an even broader pdf peak (Fig. 5), suggesting MIS-4 advances (see review  
 433 by Doughty et al., 2021). Further dating would be necessary to advance on this topic, which is  
 434 beyond the scope of this paper, as the two sites we study here do not show such MIS-4 ages.



435  
 436 **Figure 5:** Age compilation (recalculated as ages in Fig. 3) of most extensive moraines between  
 437 Marine oxygen Isotope Stages (MIS)-2 and MIS-6 in southern Tibet (Yadong-Gulu, Dinggye-Xainza  
 438 and Kung Co rifts). Samples in red are outliers rejected by Peirce's criterion (Table S1). We  
 439 classified moraines per MIS ages according to their oldest ages, excluding outliers (Table 2) as well  
 440 as plotted probability density functions (pdfs) within each MIS group. Vertical lines separate  
 441 different studies with corresponding numbers at bottom as in Figures 1, 6, Table 2 and Suppl. To the  
 442 right, global climatic proxy curve of Lisiecki and Raymo (2005) in black, effective moisture  
 443 (Herzschuh, 2006) in green, and gray-shaded sectors showing MIS. Colors at bottom refer to well-  
 444 clustered (green, Class A), moderately-clustered (yellow, B) and poorly-clustered (red, C) moraine  
 445 ages distribution, obtained using reduced Chi-square analyses (Heyman, 2014) (Table S1).



446 **Table 2.** Compilation of most extensive, pre-LGM moraine ages from southern Tibet

Site name	# in Figs. 1 and 5	Lat-Long (°N - °E)	Reference	Number of samples	Outliers rejected ‡	Moraine class	Age (ka)†	MIS assignment	Elev. of highest peak (m)
<b>Yadong rift</b>									
Jichu	1	27.91 - 89.3	<b>This study</b>	12	1 old	C	42±3	MIS-3	6800-7300
Duina	2	27.92 - 89.38	Wang et al. (2020)	6	/	B	20±2	LGM	5100-5300
Downstream Duina	2'	27.97 - 89.34	Ha et al. (2018)	/	/	/	/	MIS-6 (OSL ages)	5100-5300
Qudui	3	28.06 - 89.43	<b>This study</b>	7	1 old	B	24±2	LGM	5500-6000
Cogarbu M5	4	28.3 - 89.9	Peng et al. (2019)	6	/	B	22±2	LGM	5500-6300
Karola	5	28.89 - 90.25	Owen et al. (2005)	4	/	B	21±2	LGM	6000-6300
M4W	6	28.97 - 90.12	Liu et al. (2017)	4	1 young	B	18±1	LGM	6500-7200
M4E	7	28.9 - 90.25	Liu et al. (2017)	4	1 young	B	22±2	LGM	7200 (E of the range)
<b>N Yadong-Gulu rift</b>									
Quemuqu	8	29.85 - 90.06	Dong et al. (2017)	10	1 young	B	20±2	LGM	7000 (E of the range)
Ybj	9	30.02 - 90.24	Chevalier et al. (2011, 2020)	22	/	C	59±5	MIS-4	6000 (E of the range)
Payuwang inner	10	30.61 - 90.76	Dong et al. (2014)	10	/	B	30±2	MIS-3	5800
Payuwang outer	10'	30.61 - 90.76	Dong et al. (2014)	5	1 old	C	28±3	MIS-3	5800
Gulu south	11	30.76 - 91.58	Owen et al. (2005)	5	1 old	C	76±6	inferred MIS-6*	5900-6200 (E of the range)
Gulu	12	30.8 - 91.56	Chevalier et al. (2011, 2020)	15	1 old	B	21±2	LGM	6600 (E of the range)
<b>Dinggye rift</b>									
Dinggye S	13	28.14 - 87.66	Chevalier et al. (2011)	22	2 old	C	32±3	MIS-3	6200-6400
Dinggye N	14	28.31 - 87.73	Chevalier et al. (2011)	14	1 old	C	195±17	MIS-6	5800-6100
<b>Xainza rift</b>									

M	15	29.81 - Chevalier et al. (2011)	88.2	8	1 old	C	33±3	MIS-3	6000-6200
M1	16	29.92 - Chevalier et al. (2011)	88.3	9	1 old	B	30±2	MIS-3	6000
M2	17	30.09 - Chevalier et al. (2011)	88.4	11	/	C	54±4	MIS-3	5800
M3 main	18	30.59 - Chevalier et al. (2011)	88.51	7	/	C	61±5	MIS-4	6000 (E of the range)
M4	19	30.64 - Chevalier et al. (2011)	88.56	7	/	C	130±10	MIS-6	6000 (E of the range)
Mt Jaggang JM1	20	30.82 - Dong et al. (2018)	88.71	4	1 young	A	63±5	MIS-4	6500 (E of the range)
<b>Kung Co rift</b>									
Cho Oyu	21	28.35 - Chevalier et al. (2011)	86.63	4	1 old	A	30±0.03	MIS-3	8200 (Himalayan moraine)
	22	28.77 - Chevalier et al. (2011)	86.46	15	1 old	C	59±5	MIS-4	5900

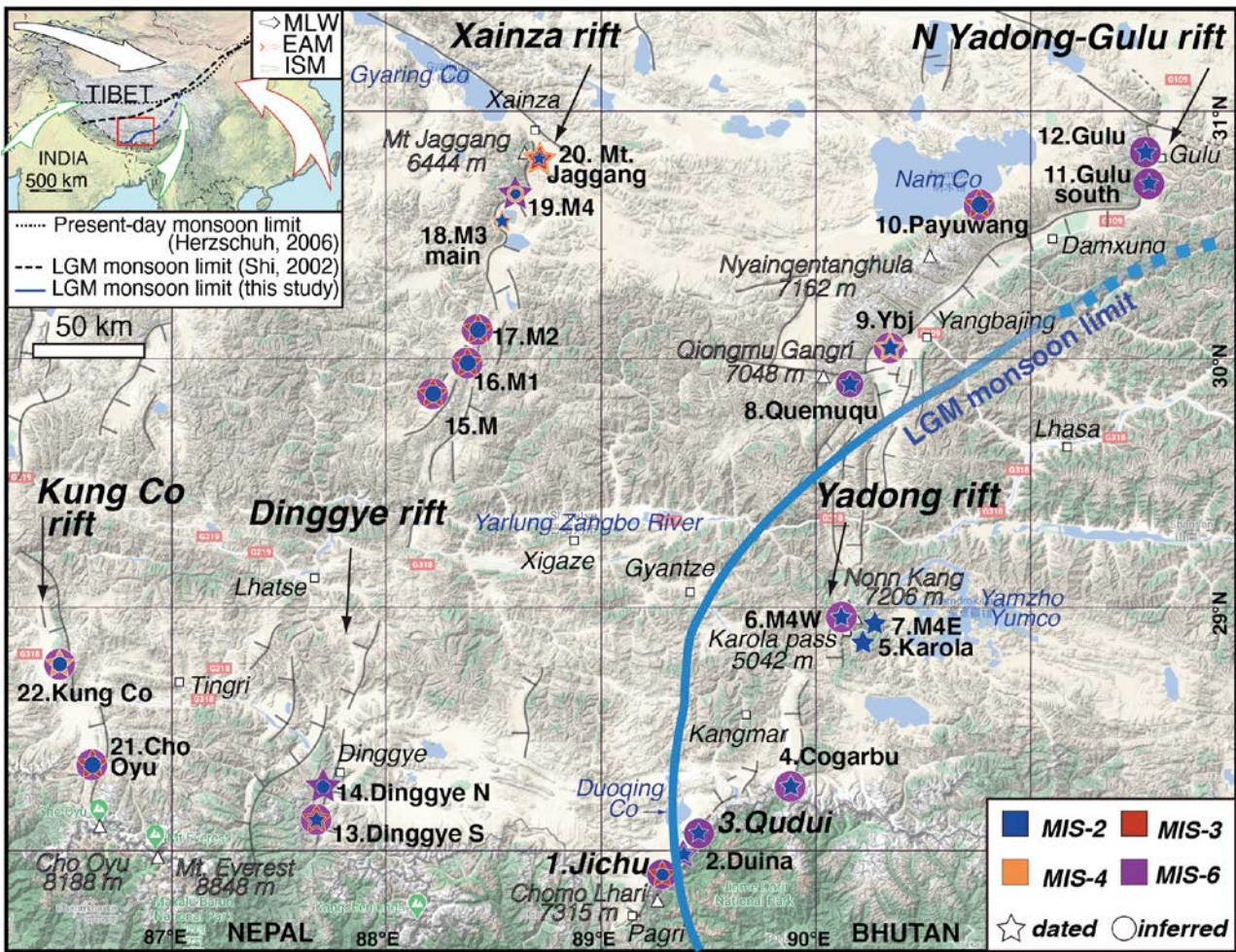
‡Outliers rejected using Peirce's criterion. †Average age if Class A, oldest age if Classes B and C (Heyman, 2014).

\* See supplementary text for details

447

448 Interestingly, the spatial distribution of the MIS-3 or MIS-4 moraines (Fig. 6) suggests that  
449 they are located mostly west and north of the Yadong rift, at the base of high regional peaks (>5800  
450 m, Table 2) such as the Chomo Lhari (Jichu moraine). By contrast, in the Yadong rift, LGM  
451 moraines are located at the base of both high and low summits (between 5100 and 7200 m, Table 2),  
452 but are larger where LGM precipitation are abundant such as near the low (~5000 m) Karola pass or  
453 at Qudui. Indeed, considering that temperature was most likely broadly similar in the entire study  
454 region at a given period, the fact that LGM moraines appear more extensive in the Yadong rift than  
455 anywhere else at similar elevation may reflect a strong link to precipitation. Therefore, while low  
456 temperature during the LGM allowed glaciers to advance at most places on the Tibetan Plateau,  
457 LGM moraines seem more extensive at places where LGM precipitation could reach, such as at  
458 Qudui and in the northern Yadong rift via the low Karola pass, rather than being blocked by high  
459 summits (such as at Jichu) or being located too far from the monsoonal front, such as farther north  
460 (N Yadong-Gulu rift) and west (Dinggye-Xainza and Kung Co rifts) (Fig. 6). There, away from the

461 LGM monsoonal front, LGM moraines are less extensive than older moraines (MIS-3 or MIS-4),  
 462 suggesting that in more arid regions, moraines older than the LGM are preserved thanks to less  
 463 extensive advance of LGM glaciers. Therefore, the relative spatial distribution of LGM vs MIS-3/4  
 464 moraines shown by our compilation allows to tentatively draw new limits of monsoonal  
 465 precipitation during the LGM (Fig. 6).  
 466



467  
 468 **Figure 6:** Compilation of moraine ages from southern Tibet (numbers and names of sites as in Table  
 469 2). Details of each study can be found in supplementary material and Table S2. Stars indicate dated  
 470 moraine ages while circles indicate inferred ages, with colors according to their MIS as in legend.  
 471 Main cities and towns, mountain peaks and geographic landmarks (lakes and rivers) are indicated.  
 472 Yadong-Gulu, Dinggye-Xainza and Kung Co rifts are bounded by active normal faults represented  
 473 as grey lines with tick bars. We suggest a new LGM monsoonal precipitation front as represented by  
 474 thick blue line (see text for details). Inset as in Figure 1A.

## 475 **6. Conclusion**

476 By studying two moraines in the southern Yadong rift in southern Tibet, Qudui and Jichu,  
477 and compiling the ages of the most extensive moraines from three N-S transects from southern to  
478 central Tibet (22 sites, 211  $^{10}\text{Be}$  samples), we suggest that:

- 479 **1)** the limit of monsoonal precipitation during the last glacial maximum (LGM, 19-26.5 ka) can  
480 be determined considering that LGM moraines extend farther than MIS-3 moraines where  
481 LGM monsoonal precipitation were able to reach. Indeed, during MIS-3, large glaciers  
482 advanced from high summits ( $\geq 5800$  m) thanks to the large increase in precipitation (hence  
483 snowfall) at high elevation despite temperature warmer than during the LGM. During MIS-2  
484 however, glacier growth was sustained all over Tibet even from lower summits ( $\geq 5100$  m)  
485 thanks to colder temperature, but their extent spatially varied depending on the amount of  
486 monsoonal precipitation received during that period. At places easily reached (absence of  
487 topographic barrier or closer to the monsoonal precipitation front), MIS-2 moraines are the  
488 most extensive (such as at Qudui). By contrast, away from the monsoonal front or where  
489 LGM precipitation was blocked by topographic barrier (such as at Jichu), MIS-2 advances  
490 were limited and MIS-3 advances were preserved downstream. Overall, MIS-6 moraines are  
491 the largest deposits in most places in Tibet, including in more humid regions such as the  
492 Tibetan Himalaya or eastern Tibet, as well as in more arid regions such as central Tibet.
- 493 **2)** Glaciers from the Yadong-Gulu region, located in a climatic transition zone between the  
494 mid-latitude Westerlies and the monsoon, are thus sensitive to both variations in temperature  
495 and precipitation. Detailed study of imbricated moraines that record successive past glacial  
496 advances allows to study changes in atmospheric circulation, precipitation and temperature,  
497 as well as to reconstruct paleoclimate, and advance our understanding on the LGM  
498 monsoonal precipitation limit.

499

500 **Acknowledgements**

501 This project was financially supported by the Second Tibetan Plateau Scientific Expedition of the  
502 Ministry of Science and Technology of China [2019QZKK0901], the National Natural Science  
503 Foundation of China [42020104007, 41941016], the China Geological Survey [DD20190059]. All  
504 data are found in Tables 1, 2, S1 and S2.

505

506 **References**

- 507 Armijo, R., Tapponnier, P., Mercier, J.L., Han, T.L., 1986. Quaternary extension in southern  
508 Tibet: Field observations and tectonic implications. *Journal of Geophysical Research*, 91,  
509 13,803 – 13,872.
- 510 Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of  
511 calculating surface exposure ages or erosion rates from <sup>10</sup>Be and <sup>26</sup>Al measurements.  
512 *Quaternary Geochronology*, 8, 174–195.
- 513 Balco, G., 2020. Glacier Change and Paleoclimate Applications of Cosmogenic-Nuclide Exposure  
514 Dating, *Annual Review of Earth and Planetary Sciences*, 48, 21-48, doi: 10.1146/annurev-  
515 earth-081619-052609.
- 516 Benn, D.I., Owen, L.A., 1998. The role of the Indian summer monsoon and the mid-latitude  
517 westerlies in Himalayan glaciation: review and speculative discussion. *Journal of the*  
518 *Geological Society, London*, 155 (2), 353-363.
- 519 Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years.  
520 *Quaternary Science Reviews*, 10, 297–317.
- 521 Blomdin, R., Stroeven, A.P., Harbor, J.M., Gribenski, N., Caffee, M.W., Heyman, J., et al., 2018.  
522 Timing and dynamics of glaciation in the Ikh Turgan Mountains, Altai region, High Asia.  
523 *Quaternary Geochronology*, 47, 54-71, doi:10.1016/j.quageo.2018.05.008.

524 Bookhagen, B., Burbank, D.W., 2006. Topography, relief, and TRMM-derived rainfall variations  
525 along the Himalaya, *Geophysical Research Letters*, 33, L08405,  
526 doi:10.1029/2006GL026037.

527 Chevalier, M.L., Hilley, G., Tapponnier, P., Van DerWeerd, J., Liu-Zeng, J., Finkel, R.C.,  
528 Ryerson, F.J., Li, H., Liu, X., 2011. Constraints on the late Quaternary glaciations in Tibet  
529 from cosmogenic exposure ages of moraine surface. *Quaternary Science Reviews*, 30, 528–  
530 554. doi:10.1016/j.quascirev.2010.11.005.

531 Chevalier, M.L., Leloup, P.H., Replumaz, A., Pan, J., Liu, D., Li, H., Gourbet, L., Metois, M., 2016.  
532 Tectonic-geomorphology of the Litang fault system, SE Tibetan Plateau, and implication for  
533 regional seismic hazard ; *Tectonophysics*, 682, 278-292, doi:10.1016/j.tecto.2016.05.039.

534 Chevalier, M.L., Replumaz, A., 2019. Deciphering old moraine age distributions in SE Tibet  
535 showing bimodal climatic signal for glaciations: Marine Isotope Stages 2 and 6. *Earth and  
536 Planetary Science Letters*, 507, 105-118, doi:10.1016/j.epsl.2018.11.033.

537 Chevalier, M.L., Tapponnier, P., van der Woerd, J., Leloup, P.H., Wang, S., Pan, J., Bai, M., Kali,  
538 E., Liu, X., Li, H., 2020. Late Quaternary Extension Rates Across the Northern Half of the  
539 Yadong-Gulu Rift – Implication for East-West Extension in Southern Tibet. *Journal of  
540 Geophysical Research*, 125, e2019JB019106, doi:10.1029/2019JB019106.

541 Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X.,  
542 Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. *Science*, 325, 710-713.

543 Dong, G.C., Yi, C.L., Caffee, M., 2014. <sup>10</sup>Be dating of boulders on moraines from the last glacial  
544 period in the Nyainqentanglha mountains, Tibet. *Science China (Earth Sciences)*, 57, 221–  
545 231. Doi:10.1007/s11430-013-4794-z.

546 Dong, G., Xu, X., Zhou, W., Fu, Y., Zhang, L., Li, M., 2017. Cosmogenic <sup>10</sup>Be surface exposure  
547 dating and glacier reconstruction for the last glacial maximum in the Quemuqu valley,  
548 western Nyainqentanglha mountains, south Tibet. *Journal of Quaternary Science*, 32, 639-

549 652.

550 Dong, G., Zhou, W., Yi, C., Fu, Y., Zhang, L., Li, M., 2018. The timing and cause of glacial  
551 activity during the last glacial in central Tibet based on <sup>10</sup>Be surface exposure dating east of  
552 Mount Jaggang, the Xianza range. *Quaternary Science Reviews*, 186, 284-297.

553 Dortch, J.M., Owen, L.A., Caffee, M.W., 2013. Timing and climatic drivers for glaciation across  
554 semi-arid western Himalayan Tibetan orogen. *Quaternary Science Reviews*, 78, 188-208.

555 Doughty, A.M., Kaplan, M.R., Peltier, C., Barker, S., 2021. A maximum in global glacier extent  
556 during MIS 4. *Quaternary Science Reviews*, 261, 106948, ISSN 0277-3791,  
557 Doi:10.1016/j.quascirev.2021.106948.

558 Finkel, R.C., Owen, L.A., Barnard, P.L., Caffee, M.W., 2003. Beryllium-10 dating of Mount  
559 Everest moraines indicates a strong monsoon influence and glacial synchronicity throughout  
560 the Himalaya. *Geology*, 31, 561–564.

561 Gillespie, A., Molnar, P., 1995. Asynchronous maximum advances of mountain and continental  
562 glaciers. *Review of Geophysics*, 33, 311–364.

563 Ha, G., Wu, Z., He, L., Wang, S., 2018. Late Cenozoic Sedimentary Evolution of Pagri-Duoqing Co  
564 graben, Southern End of Yadong-Gulu Rift, Southern Tibet. *Acta Geologica Sinica*, 92, 972-  
565 987. doi: 10.1111/1755-6724.13586.

566 Hallet, B., Putkonen, J., 1994. Surface dating of dynamic landforms: young boulders on aging  
567 moraines. *Science*, 265, 937– 940.

568 Hedrick, K.A., Seong, Y.B., Owen, L.A., Caffee, M.C., Dietsch, C., 2011. Towards defining the  
569 transition in style and timing of Quaternary glaciation between the monsoon-influenced  
570 Greater Himalaya and the semi-arid Transhimalaya of Northern India. *Quaternary  
571 International*, 236, 21-33.

572 Herzschuh, U., 2006. Palaeo-moisture evolution in monsoonal Central Asia during the last 50,000  
573 years. *Quaternary Science Reviews*, 25, 163–178.

574 Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: evaluating  
575 cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. *Earth  
576 and Planetary Science Letters*, 302 (1–2), 71–80.

577 Heyman, J., 2014. Paleoglaciation of the Tibetan Plateau and surrounding mountains based on  
578 exposure ages and ELA depression estimates. *Quaternary Science Reviews*, 91, 30–41,  
579 doi:10.1016/j.quascirev.2014.03.018.

580 Iwata, S., Narama, C., Karma, 2002. Three Holocene and late Pleistocene glacial stages inferred  
581 from moraines in the Lingshi and Thanza village areas, Bhutan. *Quaternary International*  
582 97–98, 69–78.

583 Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in situ-produced  
584 cosmogenic nuclides. *Geochimica et Cosmochimica Acta*, 56, 3583–3587

585 Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion  
586 models. *Earth and Planetary Science Letters*, 104, 429–439.

587 Lifton, N., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using  
588 analytical approximations to atmospheric cosmic-ray fluxes. *Earth and Planetary Science  
589 Letters*, 386, 149–160. doi: 10.1016/j.epsl.2013.10.052.

590 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic  
591  $\delta^{18}\text{O}$  records. *Paleoceanography*, 20 (1). Doi:10.1029/2004PA001071.

592 Liu, J., Yi, C., Li, Y., Bi, W., Zhang, Q., Hu, G., 2017. Glacial fluctuations around the Karola Pass,  
593 eastern Lhagoi Kangri Range, since the Last Glacial Maximum. *Journal of Quaternary  
594 Science*, 32, 516–527.

595 Mölg, T., Maussion, F., Scherer, D., 2013. Mid-latitude westerlies as a driver of glacier variability  
596 in monsoonal High Asia. *Nature Climate Change*, 4, 68–73.

597 Owen, L.A., Finkel, R.C., Caffee, M.W., 2002. A note on the extent of glaciation in the  
598 Himalaya during the global Last Glacial Maximum. *Quaternary Science Reviews*, 21, 147–



599 157.

600 Owen, L.A., Finkel, R.C., Barnard, P.L., Haizhou, M., Asahi, K., Caffee, M.W., Derbyshire, E.,  
601 2005. Climatic and topographic controls on the style and timing of Late Quaternary  
602 glaciation throughout Tibet and the Himalaya defined by <sup>10</sup>Be cosmogenic radionuclide  
603 surface exposure dating. *Quaternary Science Reviews*, 24 (12), 1391-1411.

604 Owen, L.A., Robinson, R., Benn, D.I. et al., 2009. Quaternary glaciation of Mount Everest.  
605 *Quaternary Science Reviews*, 28, 1412–1433.

606 Owen, L.A., Yi, C., Finkel, R.C., Davis, N., 2010. Quaternary glaciation of Gurla Mandata  
607 (Naimon'anyi). *Quaternary Science Reviews*, 29, 1817-1830.

608 Owen, L.A., Dortch, J.M., 2014. Nature and timing of Quaternary glaciation in the Himalayan-  
609 Tibetan orogen. *Quaternary Science Reviews*, 88, 14-54.

610 Peng, X., Chen, Y., Liu, G., Liu, B., Li, Y., Liu, Q., Han, Y., Yang, W., Cui, Z., 2019. Late  
611 Quaternary glaciations in the Cogarbu valley, Bhutanese Himalaya. *Journal of Quaternary*  
612 *Science*, 31, 40-50. Doi: 10.1002/jqs.3079.

613 Prell, W.L., Kutzbach, J.E., 1992. Sensitivity of the Indian monsoon to forcing parameters and  
614 implications for its evolution. *Nature* 360, 647–652.

615 Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. *Quaternary Research*,  
616 59, 255-261.

617 Qiu, J., 2008. China: The third pole. *Nature* 454, 393-396.

618 Ruddiman, W.F., Kutzbach, J.E., 1989. Forcing of Late Cenozoic northern hemisphere climate by  
619 plateau uplift in Southern Asia and the American West. *Journal of Geophysical Research*,  
620 94, 18409–18427.

621 Schäfer, J.M., Tschudi, S., Zhao, Z., Wu, X., Ivy-Ochs, S., Wieler, R., Baur, H., Kubik, P.W.,  
622 Schluchter, C., 2002. The limited influence of glaciations in Tibet on global climate over the  
623 past 170000 yr. *Earth and Planetary Science Letters*, 194, 287-297.

- 624 Shi, Y., 2002. Characteristics of late quaternary monsoonal glaciation on the Tibetan plateau and in  
625 east Asia. *Quaternary International*, 97/98, 79-91.
- 626 Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical*  
627 *Research*, 105, 23753–23759.
- 628 Wang, Y., Cheng, H., Edwards, R.L., Kong, X., Shao, X., Chen, S., Wu, J., Jiang, X., Wang, X.,  
629 An, Z., 2008. Millennial- and orbital-scale changes in the East Asian monsoon over the past  
630 224,000 years. *Nature*, 451, 1090–1093.
- 631 Wang, S., Chevalier, M.L., Pan, P., Bai, M., Li, K., Li, H., Wang, G., 2020. Quantification of the  
632 late Quaternary activity of the Yadong rift, southern Tibet. *Tectonophysics*,  
633 10.1016/j.tecto.2020.228545.
- 634 Yao, T., Thompson, L.G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., Xu, B., et al., 2012. Third  
635 Pole Environment (TPE), *Environmental Development*, 3, 52-64,  
636 <https://doi.org/10.1016/j.envdev.2012.04.002>.
- 637 Yang, X., Li, L., Laba, Yang, X., Li, L., 2013. Study on the variation of lake area and its reasons  
638 of Duoqing Lake in Tibet. *Journal of Natural Research*, 28, 625–634 (in Chinese with  
639 English abstract).
- 640 Zech, R., Abramowski, U., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2005. Late Quaternary  
641 glacial and climate history of the Pamir Mountains derived from cosmogenic  $^{10}\text{Be}$  exposure  
642 ages. *Quaternary Research*, 64, 212–220.
- 643 Zech, R., Zech, M., Kubik, P.W., Kharki, K., Zech, W., 2009. Deglaciation and landscape history  
644 around Annapurna, Nepal, based on  $^{10}\text{Be}$  surface exposure dating. *Quaternary Science*  
645 *Reviews*, 28, 1106-1118. Doi:10.1016/j.quascirev.2008.11.013.

646 **Supplementary Material**

647 **Detailed description of the age compilation**

648 **1. Eastern transect: the Yadong-Gulu rift**

649 In the southern part of the Yadong rift, in the Pagri basin, the two moraines we dated, Qudui  
650 and Jichu (#3 and #1 in Figs. 5, 6 and Table 2, respectively), are LGM and MIS-3, respectively, as  
651 discussed in the main text. Between Jichu and Qudui, Wang et al. (2020) obtained a LGM age for a  
652 small recessional moraine (?) located on the western slopes of the Chomo Lhari Range (moraine  
653 Duina, #2). Downstream from Duina (#2'), Ha et al. (2018) dated the smooth surfaces as MIS-6  
654 using OSL dating, as explained in main text. Farther north in the central Yadong rift, on the northern  
655 slopes of the Bhutanese Himalaya, Peng et al. (2019) dated seven of the nine imbricated moraines  
656 from the Cogarbu Valley (#4), the largest of which (M5) is LGM. In the northern Yadong rift near  
657 the Karola pass, Owen et al. (2005) dated the most extensive moraine as LGM ('Karola', #5),  
658 similarly to Liu et al. (2017) on the western and eastern sides of the neighboring Nonn Kang Range  
659 (M4W and M4E, #6 and 7, respectively).

660 In the northern Yadong-Gulu rift, there are four studies from the SE slopes of the NQTL  
661 Range and one from its NW slopes. In the Quemuqu Valley of the Qiongmu Gangri Mountain (7048  
662 m), located at the SW end of the NQTL Range, Dong et al. (2017) dated the inner Quemuqu  
663 moraine as LGM (#8). About 20 km to the north, Chevalier et al. (2011, 2020) dated two imbricated  
664 moraines near Yangbajing, the inner one being LGM and the outer one being MIS-4 ('Ybj', #9). On  
665 the northern slopes of the NQTL Range at Payuwang, Dong et al. (2014) dated two imbricated  
666 moraines, which oldest ages are both MIS-3 (#10 and 10'). At the northern end of the range, Owen et  
667 al. (2005) dated a small moraine in the 'Gulu south' valley as LGM as well as a hummocky moraine  
668 much farther downstream (on the opposite side of the Gulu basin) (#11), with a scattered and  
669 continuous age distribution, that we interpret as a degraded MIS-6 (hence the purple circle in Fig. 6)  
670 as inferred from eastern Tibet (Chevalier and Replumaz, 2019). In the valley just to the north,

671 Chevalier et al. (2011, 2020) determined a LGM age for the Gulu moraine (#12).

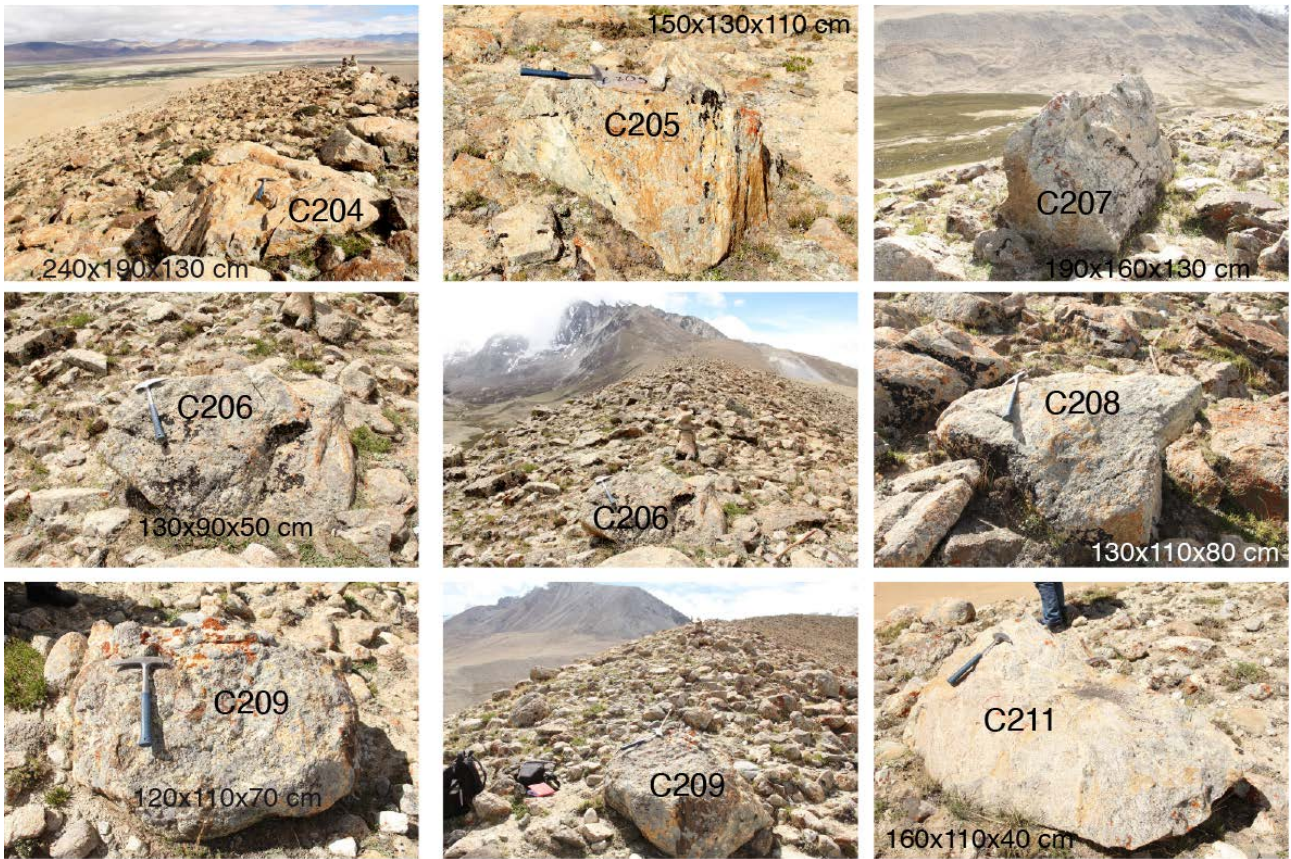
## 672 **2. Central N-S transect: the Dinggye-Xainza rift**

673 West of the Yadong-Gulu rift, two moraines have been dated in the Dinggye rift on the  
674 eastern slopes of the Ama Drime massif (Chevalier et al., 2011). The most extensive moraine at  
675 “Dinggye S” is MIS-3 (#13 in Figs. 5, 6 and Table 2) and the inner one is LGM. Ages from the  
676 “Dinggye N” moraine (#14) continuously range from 20 to 195 ka (after rejecting one outlier at 320  
677 ka) hence it belongs to MIS-6. In the Xainza rift to the north, Chevalier et al. (2011) dated five  
678 moraines: the southernmost three are MIS-3 (moraines #15, 16 and 17, respectively), moraine #18 is  
679 MIS-4, and moraine #19 is MIS-6. At the northern end of the Xainza Range, Dong et al. (2018)  
680 dated seven imbricated moraines from Mt. Jaggang: three LGM, three MIS-3 (not shown in Fig. 5  
681 because not the largest), and one MIS-4 (#20). This site is the only one where both MIS-3 and MIS-  
682 4 advances have been documented so far, suggesting a MIS-4 glacial advance at least at some places  
683 in Tibet (Doughty et al., 2021). Nevertheless, as said in the main text, further dating would be  
684 necessary to advance on this topic, which is beyond the scope of this paper, as the two sites we  
685 study here do not show MIS-4 ages.

## 686 **3. Western N-S transect: Kung Co rift**

687 The two moraines from yet the next rift to the west, the Kung Co rift, are MIS-3 (Cho Oyu,  
688 #21 in Figs. 5, 6 and Table 2), and MIS-4 (Kung Co, #22) (Chevalier et al., 2011).

689



690

691 **Figure S1:** Photos of boulders collected for  $^{10}\text{Be}$  surface-exposure dating at the Qudui moraine site

692 with their approximate sizes.



693

694 **Figure S2:** Photos of boulders collected for  $^{10}\text{Be}$  surface-exposure dating at the Jichu moraine site  
 695 with their approximate sizes.

696

697 **Table S1:** Application of Peirce's criterion on the age compilation.

698

699 **Table S2:** Age compilation of the most extensive moraines from the broad Yadong region.