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Quaternary glacial geomorphology and glaciations of Kongur Mountain, eastern Pamir, China

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Kongur Mountain is the largest center of modern glaciation on the Pamir Plateau. During the glacial-interglacial cycles of the Quaternary, Kongur Mountain was extensively and repeatedly glaciated, and the glacial landforms from multiple glaciations are well-preserved in valleys, in basins, and on the piedmonts. Dating samples have been collected according to the distribution and weathering of the glacial tills, the relationship among the glacial deposits, and the loess or soil developed on the moraines. Electron spin resonance (ESR) dating of the samples was done using the germanium (Ge) centers in the glacial quartz grains, which are sensitive to both sunlight and grinding. The ages of the glacial deposits can be divided into four clusters, i.e., 13.1±0.8–27.0±2.2, 36.4±3.3–48.7±5.7, 65.6±6.8–86.6±8.9, and 105.6±9.4–178.3±17.8 ka. Six glacial advances in this region have been confirmed, which are equivalent in age to the Little Ice Age (LIA), Neoglaciation, marine oxygen isotope stages (MIS) 2, mid-MIS3, MIS4, and MIS6. The largest local last glacial maximum (LGM_L) occurred during MIS4 rather than the global Last Glacial Maximum (LGM_G) of MIS2, and a glacial advance that occurred during mid-MIS3 was also larger than the LGM_G. Furthermore, deeply weathered tills below 3500 m a.s.l. on the western slope of Kongur Mountain, when compared with the ages of the oldest glaciation of the Muztag Ata region, likely occurred prior to the penultimate glacial cycle. The glacial landforms prior to the penultimate glacial cycle on the northern slope are not well-preserved due to erosion after deposition. Several glacial deposits are only speculated to be distributed at higher elevations on the southwest side of the Gaizi Checkpoint. The extensive hummocky moraines on the western slope were formed by multiple glacial advances, and the latest glacial advance corresponded to mid-MIS3.

Kongur Mountain, glacial geomorphology, ESR dating, Quaternary glaciation, hummocky moraine

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The Qinghai-Tibetan Plateau and the bordering mountains is a special geographical unit in the low and middle latitudes in the Northern Hemisphere. Well-preserved glacial landforms throughout the Qinghai-Tibetan Plateau and its bordering mountains contain important information about past glacial processes and climatic changes. Studies of these landforms could provide essential information for reconstructing the paleo-environment in the region. Since the beginning of the last century, many scholars have focused on studying these landforms. Based on the distribution and weathering of the glacial tills, the relationship among the glacial deposits, and the loess or soil development on the

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glacial landforms, more than one hundred local glaciations have been found. Unfortunately, few absolute dating is available for these local glaciations; therefore, controversy remains on the timing of these glacial landforms and sediments. In the past several years, dating techniques have been refined and applied widely, including electron spin resonance (ESR), optically stimulated luminescence (OSL), and terrestrial cosmogenic nuclide (TCN), which can potentially directly determine the ages of glacial landforms and sediments. These techniques have made it possible to determine the timing of glaciations systematically. At present, more studies are focused on the glacial landforms in the eastern and southern parts of the Qinghai-Tibetan Plateau, which are dominated by monsoon circulation [1–9]. By reviewing these publications, we found that the glacial advance during marine isotope stage (MIS) 3 was larger than that during the global Last Glacial Maximum (LGM_G) [4, 5]. However, there are few data regarding the timing of the Quaternary glaciations in the northwestern part of the Qinghai-Tibetan Plateau. Therefore, the timing of glacial landforms in this area should be studied further.

Eastern Pamir, which is located in the northwestern part of the Qinghai-Tibetan Plateau, is adjacent to the western margin of the Tarim Basin. The Pamir Plateau has been one of the most intensive tectonically uplifted regions of the Qinghai-Tibetan Plateau since the collision between the Indian and Eurasian continental plates during the Cenozoic. In addition, it is an outstanding example of crustal shortening during continental collision that may have been accommodated by the formation of a thick crust and/or continental subduction [10, 11]. Most of the land areas of this region lies between 3300 to 6000 m a.s.l. [12]. There are several peaks above 7000 m a.s.l., which are the centers where the alpine glaciers develop. These glaciers experienced large advances and retreats during the glacial-interglacial cycles of the Quaternary, and the glacial landforms from the multiple glaciations are well-preserved in the valley, in the basin, and on the piedmont.

The Quaternary glacial landforms and moraines in Eastern Pamir have been studied since the 1950s [13–18]. Cui [13] carried out fieldwork on the western slope of Muztag Ata in 1959 and proposed four glaciations. Subsequently, a more detailed and extensive field study was undertaken by the Team of Comprehensive Scientific Expedition (1987–1992, sponsored by the Chinese Academy of Sciences) in the Qinghai-Tibetan Plateau; they suggested that the glacial landforms in this region could be assigned to the Little Ice Age (LIA), the Neoglaciation, the Kelayayilake, the Kalakule and Subashidaban Glaciations in the Muztag Ata and Kongur Mountain [14–16]. Ono et al. [17] calculated the equilibrium line altitudes (ELAs) of modern glaciers in Kongur Mountain and Kungai Shan. According to the distribution of moraines, they also calculated the ELAs of the last glacial cycle and the penultimate glacial cycle. Recently, Seong et al. [18] applied the TCN ^{10}Be dating technique to date the timing of the Quaternary glacial landforms between Muztag Ata and Kongur Mountain, and three glacial stages (Olimde, Subaxh and Karasu glacial stages) were found. However, the well-preserved glacial landforms, especially the glacial landforms of the last glacial cycle, are present on the northern slope of Kongur Mountain, unlike those that formed between Muztag Ata and Kongur Mountain. In this paper, we used ESR dating techniques to determine the timing of the glacial landforms on the northern and western slopes of Kongur Mountain and present new chronological evidence for this region. Based on the principles of geomorphology and stratigraphy and the available dates, we will further discuss the Quaternary glaciations in this region.

1 Study area

Kongur Mountain covers a portion of the southeastern Pamir Plateau, and is situated between Kungai Mountain in the north, Muztag Ata in the south, and the Kangxiwa River in the west, which flows northward and joins the Gaizi River (Figure 1). There are 21 peaks above 7000 m a.s.l. in this range, with an average elevation of approximately 4000 m a.s.l. and with the highest peak at 7719 m a.s.l. (Kongurjiubie). The climate of Kongur Mountain is dominated by mid-latitude westerlies and local air circulation. The effects of the mountain barriers result in moisture from the westerly

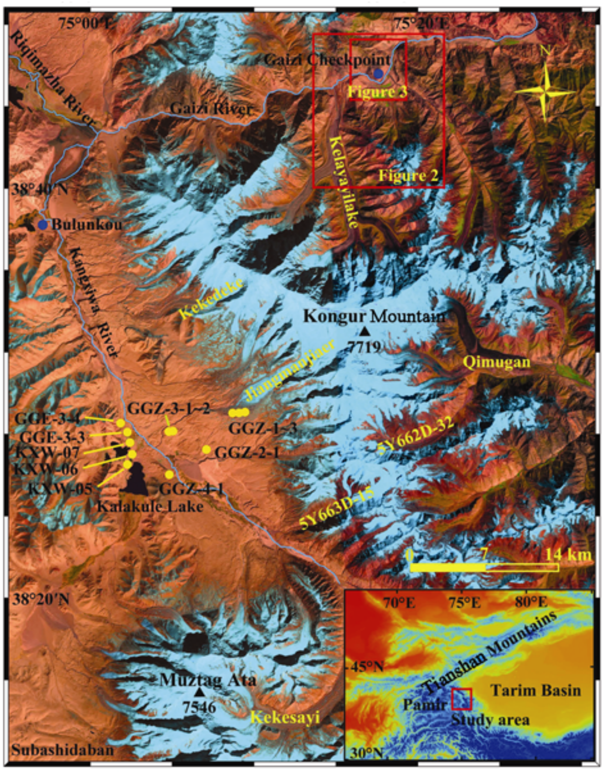

Figure 1 Landsat ETM+(Enhanced Thematic Mapper Plus) image and the sample's location in the Kongur Mountain region.

air masses mainly causing rain in Western Pamir, and make it impossible for the South Asian monsoon to reach the Eastern Pamir; therefore, the Kongur Mountain region stays very dry [19, 20]. At Bulunkou Station (38°44′N, 75°02′N, 3310 m a.s.l.) on the western slope of Kongur Mountain, the mean annual temperature is 0.7°C, and the mean annual precipitation is 131.1 mm. Most of the precipitation occurs between May and September and accounts for 77.2% of the annual total.

Kongur Mountain, the largest center of modern glaciation in the Pamir Plateau, is a typical region with extreme continental glaciers in China. There are 327 modern glaciers with a total area of 640.15 km^2 in this region [21]. It contains six valley glaciers with a length of more than 10 km (Table 1). The most notable glaciers are Kelayayilake and Qimugan, which comprise an area of 128.15 km^2 and 103.71 km^2, respectively [22]. The present ELAs of the southern slope of Kongur Mountain are between 4900 m and 5100 m a.s.l., and the ELAs of the northern slope are approximately 4800 m a.s.l. The mean annual precipitation at present ELAs is 477–679 mm, and the mean annual temperature is approximately −10 to −13.3°C [21]. The hydrological data from the Keleke Station show that the Gaizi River has a mean annual discharge of 9.78×10^9 m^3, 77.83% of which is glacier meltwater [23]. The abundant glacier meltwater acts as a vital supply resource to the rivers in this region.

2 Quaternary glacial sediments

2.1 The northern slope of Kongur Mountain

The Kelayayilake Glacier is the largest valley glacier on the northern slope of Kongur Mountain with an area of 128.15 km^2, a length of 20.3 km, and a present ELA at 4220 m a.s.l. [22]. Six distinctive sets of well-preserved moraines and associated glacial sediments are present from the terminus of the modern glacier (2700 m a.s.l.) to the Gaizi Checkpoint (Figures 2, 3); therefore, this is an ideal region to reconstruct the paleo-glaciation.

The first set of moraines occurs beyond the terminuses of the modern glaciers. The landforms consist of two end moraine ridges, which are 10–20 m higher than the river bed in front of the terminus of the Kelayayilake Glacier. The lateral moraines distributed on both flanks of the glacier are the second set of moraines, which rise approximately 70 m above the glacier surface and extend downward to 2480 m a.s.l. The slopes of the lateral moraines are steep with an outer gradient of 30°–40° and an inner gradient of 60°–70°. The till clasts are fresh and gray and consist mainly of gneiss. There are no loess deposits on their surface.

The extensive hummocky moraines are distributed on the east side of the Kelayayilake valley mouth and extend downward to 2440 m a.s.l. There is a thin loess layer on their surface. This glacial advance was named the Kelayayilake Glaciation after these moraines [16]. Based on the different thicknesses of the overlying loess deposits and the degree of the weathering of the boulders, the moraines of the Kelayayilake Glaciation can be divided into two distinctive sets of moraines, which are the third and fourth sets of moraines. Many erratic boulders and a thinner loess layer are present on the surface of the third set of moraines. However, the loess layer is thicker, and only a few boulders could be found on the surface of the fourth set of moraines. The moraine crests of this set are also flatter than those of the third set. Thin soil has developed in the upper layer of the loess deposits. The surfaces of the gneiss erratics have also been deeply weathered. Furthermore, the moraine platform adjacent to the fourth set of moraines, which is distributed at approximately 2500 m a.s.l. and extends 8 km down to the Gaizi Basin mouth, occurs at the Upper Gaizi Village and rises approximately 200 m above the Gaizi River. There are hummocky moraines of 5–20 m in height present on its surface. The main lithologies of the tills are gneiss, schist, and sandstone. The preserved positions of these hummocky moraines indicate that they were formed during the same depositional period as the fourth set of moraines.

The fifth set of moraines is a moraine platform that is only preserved on the southwest side of the Upper Gaizi Village at a height approximately 150–200 m above the Upper Gaizi Village. Its crest is flat and extends up to 0.9 km. The tills are gray and sub-angular, consisting of primary clumpy granite and some phyllite with some degree of cementation. In addition, a moraine platform is distributed on the west of the Kelayayilake valley mouth, rises ap-

Table 1 Parameters of valley glaciers with length > 10 km in Kongur Mountain [22]

Glacier names or Nos.	Length (km)	Width (km)	Orientation	Area (km^2)	Ice volume (km^3)	Top altitude (m a.s.l.)	Terminus (m a.s.l.)	ELA (m a.s.l.)
5Y662D-32	12.3	3.6	NE	38.43	5.6876	6525	3840	4580
Qimugan	21.0	5.5	E	103.71	21.0531	7649	3120	4420
Kelayayilake	20.3	6.8	N	128.15	27.8086	7530	2780	4220
Kekedeke (5Y663C-15)	10.2	1.6	SW	15.29	1.6666	7400	4260	5360
Jiangmanjiaer (5Y663D-4)	14.8	3.1	SW	45.08	6.9874	7245	4240	5380
5Y663D-15	12.6	2.4	SW	27.53	3.6615	6220	4040	5300

proximately 400 m above the contemporary river valley, and contains scattered surface boulders. This landform probably also represents a glacial advance that occurred during the same period as the fifth set of moraines.

The sixth set of moraines has not been well-preserved. A high ridge similar to a watershed is formed by lateral moraines at locations where the Kelayayilake valley joins the Gaizi River valley. Some big boulders are scattered on its surface and are found up until approximately 700 m above the valley bed. Furthermore, yellowish grey moraines, rising 500–700 m above the Gaizi River, are present on the southwest side of the Upper Gaizi Village. The glacial clasts consist of garnet mica schist and gneiss with no distinct angularity. Most of the surface boulders have deep weathering pits (cm- to dm-size) and exhibit varying degrees of exfoliation. Moreover, several suspected glacial deposits, which are present at higher elevations on the southwest side of the Upper Gaizi Village, are probably older than other sets. Unfortunately, due to a steep cliff, we could not gain access to identify them.

Five glaciofluvial terraces, rising approximately 10 m (T_1), 20 m (T_2), 40 m (T_3), 55 m (T_4) and 75 m (T_5) above the contemporary river, are present along the Gaizi River valley below the Upper Gaizi Village (Figures 2, 3). The Lower Gaizi Village is located on T_5, which is the most widely distributed in this valley. These glaciofluvial terraces are based on glacial sediments comprising sub-rounded and rounded glaciofluvial gravel. Their top layer consists mainly of glaciofluvial gravel and is occasionally interbedded with tills. For example, the frontal edge of T_5 on the south side of Gaizi River is composed of a glaciofluvial gravel layer of partial cementation, and surface boulders that reach 11 m in diameter are scattered on the trailing edge.

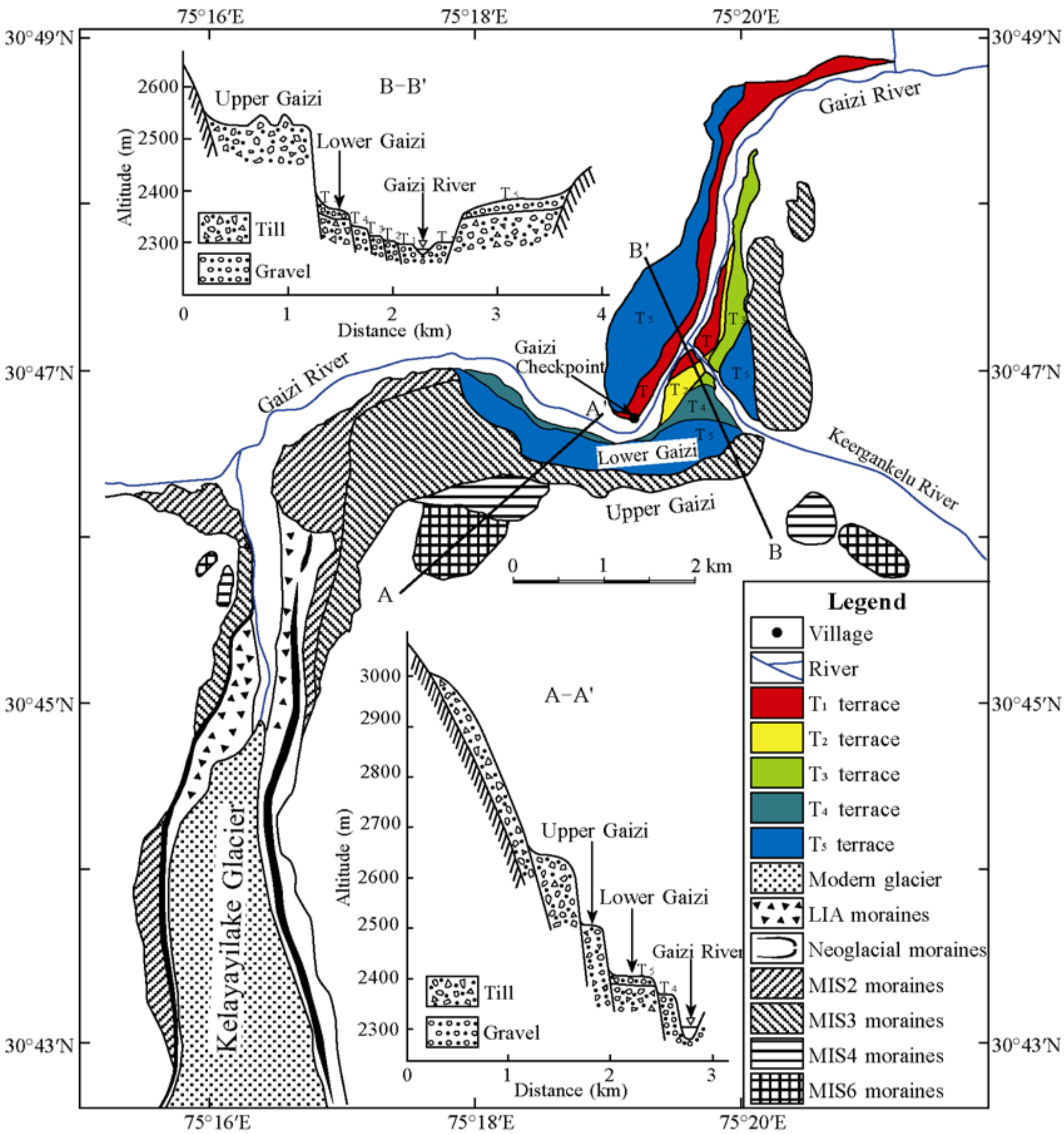

Figure 2 Geomorphological map near the Gaizi Checkpoint.

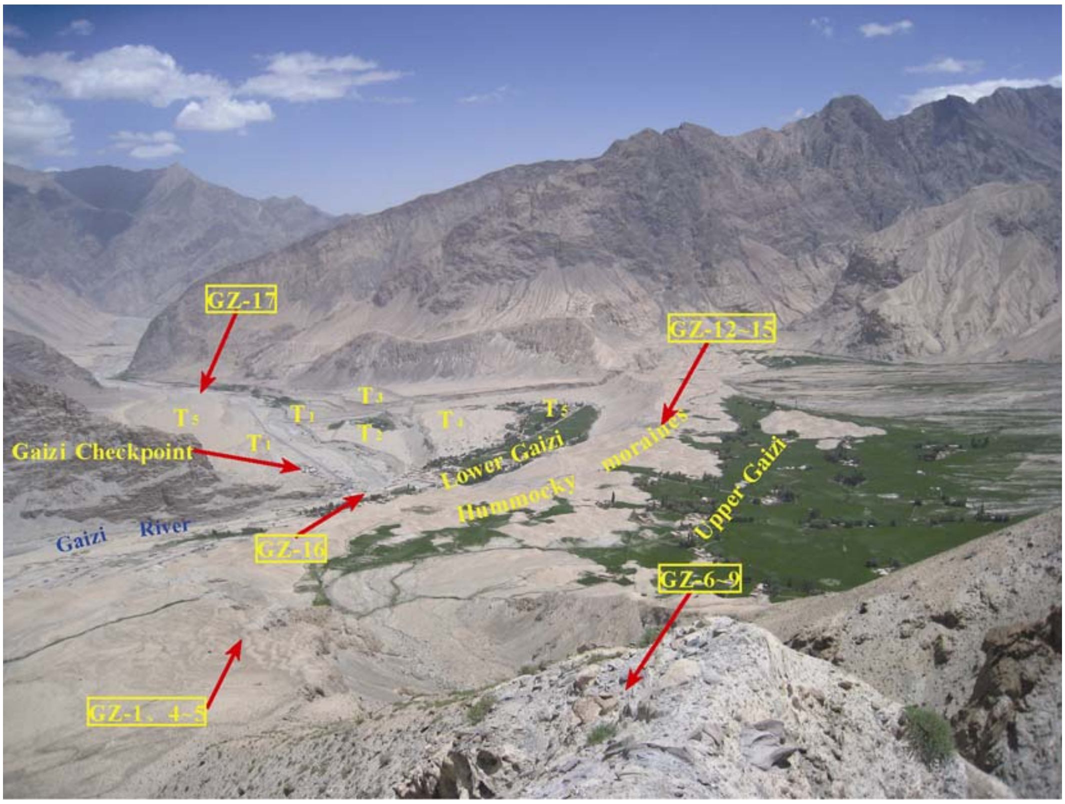

Figure 3 Moraine platforms and sampling sites in the Gaizi River Valley.

2.2 The western slope of Kongur Mountain

Many sub-parallel modern glaciers are distributed on the western slope of Kongur Mountain. There are three glaciers longer than 10 km, such as Kekedeke (5Y663C-15), Jiangmanjiaer (5Y663D-4) and the 5Y663D-15 Glacier. The Yamaya Valley of the Middle and Lower Kangxiwa River is a tectonic basin [14] with an east-west width of 5–10 km. In addition, due to the intensive uplift of Kongur Mountain, the shape of the basin is asymmetric, and the Kangxiwa River lies on the western edge of the basin. Glacial sediments from different periods are present on both sides of the river.

The first set of moraines is located between several hundred meters and 1 km from the terminuses of the modern glaciers and consists of two to three moraine ridges. The moraines are fresh and loose with no soil or vegetation and contain scattered surface boulders. The second set of moraines is usually distributed 1–2 km from the terminuses of the modern glaciers with an altitude ranging from 4200 to 4300 m a.s.l. These moraines are wide-ridged in shape, and their surface is gray, with sparse grass development. In some cases, they are partly overlain by the first set of moraines.

The third set of moraines is distributed 2–5 km from the terminuses of the modern glaciers. The moraines' ridges are well-preserved, and are overlain by a 10-cm-thick loess layer. These tills are yellowish gray. Boulders reaching more than 3 m in diameter are scattered on the surface of this moraine set.

The fourth set of moraines is an extensive and well-preserved set of hummocky moraines in this region, and extends continuously to approximately 3450 m a.s.l. on the north side of Kalakule Lake (Figure 4). Consequently, the period during which these moraines are deposited is named the Kalahu Glaciation [13] or the Kalakule Glaciation [16]. The hummocky moraines rise approximately 150 m above the Kangxiwa River bed on the east side of Kalakule Lake. The hummocky moraines are overlain by an approximately 15-cm-thick loess layer, and have a relative height of approximately 5–15 m on the north side of the lake. The surface boulders are sparse, and the largest ones reach up to 7 m in diameter. The tills consist of gneiss, schist and greyish-white coarse sand. During this glaciation, as the moraines, which were deposited by the glaciers coming from the western slope of Kongur Mountain and the northern slope of Muztag Ata, blocked the Kangxiwa River valley, several moraine-dammed lakes were formed, such as the Kalakule, Shatewalade and Bashiku Lake.

The fifth set of moraines is approximately 6–15 m thick, and is distributed on both sides of the Kangxiwa River below 3500 m a.s.l. The till clasts mainly comprise deeply-weathered gneiss with sub-angular gravel. In some cases, the moraines are present below the glaciofluvial terraces, which rise approximately 20–30 m above the contemporary bed and intermittently extend to Bulunkou.

Figure 4 Extensive hummocky moraines on the western slope of Kongur Mountain.

3 Methods

ESR dating samples were derived from the natural or man-made sections on the western and northern slope (around the Gaizi Village) of Kongur Mountain, and at least three samples were collected from each set of moraines (Figures 1, 3). The samples were kept in opaque plastic bags to ensure that they were not exposed to sunlight. Grinding, collision and heating were also avoided during transportation. The samples were prepared in the chronology laboratory at the MOE Key Laboratory of Western China's Environmental System, Lanzhou University, Lanzhou. Previous studies have shown that the signal intensity of the Ge centers in quartz grains exposed under natural room light does not decrease [24, 25]; therefore, all of the samples were treated under natural light conditions, and no special measurements were used. The sample preparations and measurements follow the literature [26, 27].

The prepared samples were irradiated by ^{60}Co with different doses. The dose rate was 28.51 Gy/min. The irradiated samples were determined in the chronology laboratory at the Institute of Geology, China Earthquake Administration, Beijing. The Ge centers in the quartz grains were chosen as dating signals and were measured with an EMX1/6ESR spectrometer manufactured by Bruker (Germany). The measurement conditions and parameters were as follows: room temperature, X-band, microwave power= 2.021 mW, central magnetic field=3525 G, sweep width=50 G, frequency = 9.852 GHz, modulation frequency=100 kHz, modulation amplitude = 1 G (1 G=10^{-4} T), time constant= 40.96 ms, and sweep time =10.486 s. The typical ESR spectra are shown in Figure 5. It is obvious that the signal intensity of the Ge centers increased with an increased dose of artificial irradiation. A least-squares analysis was used to fit the data points on the basis of different artificial irradiation doses and corresponding signal intensities. Linear fits were chosen in this study. The line was then extrapolated to zero in order to obtain the equivalent dose (*ED*). The concentrations of U and Th and the content of K_2O were determined by neutron activation analysis (NAA) at the China Institute of Atomic Energy. The annual dose rate (*D*) was estimated from these radioactive elements, the water content and the cosmic ray contribution which was estimated and calculated following the formulas suggested by Prescott and Hutton [28]. Ages were calculated using the following equation:

$$T = \frac{ED}{D},$$

where *ED* is the equivalent dose and *D* is the annual dose rate.

The dating results and correlated parameters are listed in Table 2.

A prerequisite of the ESR dating technique is that the signals of the paramagnetic centers in the mineral grains are removed when they are heated, collided, exposed to sunlight, re-crystallized, or impacted by other geological processes. The Ge centers in glacial quartz grains, which are 0.125–0.250 mm in diameter, were chosen as dating signals. Previous studies have shown that Ge centers are sensitive to sunlight and grinding, and these two mechanisms are capable of removing them effectively [29–32]. First, according to the theory of the structure and the movement of mountain glaciers [33], it is possible for the debris that the glacier carries to be exposed. In addition, the debris is subject to grinding during this movement, and the high silt content in glacial deposits could indicate this [34, 35]. Second, the absorption band of Ge centers is 4.43 eV [36], corresponding to a wavelength of 280 nm. This wavelength produces energy in the Ge absorption band at higher levels at higher elevations; the dating samples were collected from a region at higher elevation. Therefore, the ESR signals of the Ge centers in glacial quartz grains could be removed. Previous studies have shown that ESR dating results are reliable and credible, and that this technique can be applied to Quaternary glaciation research [2, 3, 26, 27, 37]. Furthermore, the dating results are consistent with the morphological relationship of the moraines/terraces with the exception of the GZ-15 from the moraine platform, where the Upper Gaizi Village is located, and the KXW-06 from the hummocky moraines, which are distributed around the Kalakule Lake. This suggests that the dating results in this study are reliable.

Table 2 ESR dating results and the correlated parameters and sampling sites

Sample No.	Lab No.	Samples' locations and description					U (μg/g)	Th (μg/g)	K_2O (%)	Cosmic (mGy/a)	Water (%)	ED (Gy)	Age (ka)
		Longitude (E)	Latitude (N)	Altitude (m a.s.l.)	Sample's description	Depth (m)							
GZ-01	9392	75°18.319′	38°46.249′	2635	Till of the fifth set on the northern slope of Kongur Mountain	3.5	4.7263±0.2788	19.8811±0.5567	4.4715±0.1252	0.1814	4.26	581.79±45.41	86.6±8.9
GZ-04	9395	75°18.301′	38°46.180′	2642	Till of the fifth set on the northern slope of Kongur Mountain	0.8	1.6699±0.1653	5.7787±0.2543	4.7203±0.1322	0.2855	0.73	352.57±36.63	65.6±6.8
GZ-05	9396	75°18.297′	38°46.174′	2641	Till of the fifth set on the northern slope of Kongur Mountain	5.0	4.5396±0.2860	22.2380±0.6004	4.7151±0.1320	0.1443	2.02	491.22±37.27	68.4±5.6
GZ-06	9397	75°17.946′	38°45.805′	2985	Till of the sixth set on the northern slope of Kongur Mountain	3.0	3.1766±0.1970	14.4101±0.4323	4.5153±0.1174	0.2105	2.27	696.38±90.09	114.2±11.9
GZ-07	9398	75°17.945′	38°45.803′	2984	Till of the sixth set on the northern slope of Kongur Mountain	4.0	3.2195±0.1900	14.2392±0.4129	4.7525±0.1188	0.1796	2.07	663.87±73.06	105.6±9.4
GZ-08	9399	75°18.105′	38°45.940′	2777	Till of the sixth set on the northern slope of Kongur Mountain	4.2	4.5549±0.2277	14.9475±0.4484	4.0590±0.1096	0.1672	3.27	1068.65±137.02	178.3±17.8
GZ-09	9400	75°18.138′	38°45.966′	2751	Till of the sixth set on the northern slope of Kongur Mountain	1.7	2.7882±0.1868	10.7429±0.3545	2.9376±0.0823	0.2495	1.94	552.94±34.24	126.0±14.8
GZ-12	9403	75°19.014′	38°46.315′	2489	Moraine platform in the Upper Gaizi	3.9	5.8874±0.2944	18.7698±0.5256	3.9714±0.1191	0.1656	1.31	303.98±23.07	45.5±4.5
GZ-13	9404	75°19.077′	38°46.300′	2498	Moraine platform in the Upper Gaizi	3.0	6.3547±0.2987	21.0168±0.5885	4.3065±0.1249	0.1914	1.31	355.16±35.32	48.7±5.7
GZ-14	9405	75°19.133′	38°46.294′	2503	Moraine platform in the Upper Gaizi	6.0	7.7384±0.3173	24.7659±0.6439	4.5102±0.1263	0.1216	1.26	332.85±32.55	41.3±4.3
GZ-15	9406	75°19.316′	38°46.222′	2484	Moraine platform in the Upper Gaizi	3.0	4.6986±0.2584	16.8892±0.4898	3.8940±0.1129	0.1909	1.62	132.16±3.96	21.5±1.5
GZ-16	9407	75°18.993′	38°46.535′	2387	Gravel layer at the Lower Gaizi (derived from the top of T_5)	7.0	5.0304±0.2565	22.4700±0.5842	3.9624±0.1109	0.1036	0.40	177.85±8.94	26.4±1.9
GZ-17	9408	75°19.624′	38°47.390′	2369	Till on the north side of Gaizi River (derived from the bottom of T_5)	5.0	5.0027±0.2651	24.8880±0.6720	4.6249±0.1295	0.1369	4.92	194.47±11.42	27.0±2.2
KXW-05	9389	75°02.891′	38°27.318′	3670	Hummocky moraines on the west side of Kalakule Lake	3.2	8.2954±0.3484	32.5052±0.8451	4.7762±0.1385	0.2330	1.77	344.26±29.30	37.8±4.0
KXW-06	9390	75°02.939′	38°27.941′	3667	Hummocky moraines on the north side of Kalakule Lake	3.5	14.9363±0.4630	34.7199±0.8680	4.6797±0.1357	0.2220	2.25	207.03±13.15	19.0±1.6
KXW-07	9391	75°02.965′	38°28.409′	3650	Hummocky moraines on the north side of Kalakule Lake	4.0	7.3154±0.3072	27.9899±0.6997	4.5321±0.1224	0.2046	2.73	298.14±20.85	36.4±3.3
GGE-1-1	9359	75°10.617′	38°29.717′	4348	Till of the first set on the western slope of Kongur Mountain (2 km from Jiangmanjiaer Glacier)	5.2	6.5662±0.3283	29.9790±0.7795	4.2426±0.1146	0.1966	0.88	190.44±10.78	23.7±2.0
GGE-1-2	9360	75°10.433′	38°29.653′	4328	Till of the first set on the western slope of Kongur Mountain (2 km from Jiangmanjiaer Glacier)	2.7	6.3431±0.2854	31.5690±0.8524	4.3271±0.1168	0.2886	2.21	106.85±2.05	13.1±0.8
GGE-1-3	9361	75°10.107′	38°29.655′	4297	Till of the first set on the western slope of Kongur Mountain (2 km from Jiangmanjiaer Glacier)	3.0	5.8800±0.2705	30.0741±0.7519	3.9452±0.1026	0.2731	1.65	175.94±8.29	23.1±1.9
GGE-2-1	9362	75°7.385′	38°28.023′	3809	Hummocky moraines on the east side of Kalakule Lake	5.0	6.8062±0.3267	27.5872±0.7449	3.8166±0.1030	0.1813	1.89	321.49±11.79	43.2±3.0
GGE-3-1	9363	75°5.102′	38°29.032′	3731	Hummocky moraines on the east side of Kalakule Lake	5.2	4.9705±0.2386	18.3597±0.5324	3.2580±0.0880	0.1733	3.11	244.05±12.14	42.9±3.6
GGE-3-2	9364	75°5.097′	38°29.035′	3729	Hummocky moraines on the east side of Kalakule Lake	5.8	3.9541±0.2096	18.8897±0.5478	3.3021±0.0892	0.1588	2.33	266.46±17.78	48.2±4.6
GGE-3-3	9365	75°2.592′	38°29.222′	3604	Hummocky moraines on the north side of Kalakule Lake	5.3	8.5013±0.3401	23.9451±0.7184	4.4713±0.1207	0.1664	2.73	305.76±23.53	37.8±3.6
GGE-3-4	9366	75°2.715′	38°28.828′	3631	Hummocky moraines on the north side of Kalakule Lake	6.0	3.1868±0.2773	18.2782±0.6032	4.8870±0.1319	0.1513	2.45	254.79±21.69	38.3±4.1
GGE-4-1	9367	75°5.775′	38°27.207′	3660	Hummocky moraines on the east side of Kalakule Lake	8.0	5.3511±0.3264	39.7500±0.9938	4.5414±0.1272	0.1163	3.13	332.19±27.19	39.2±3.7

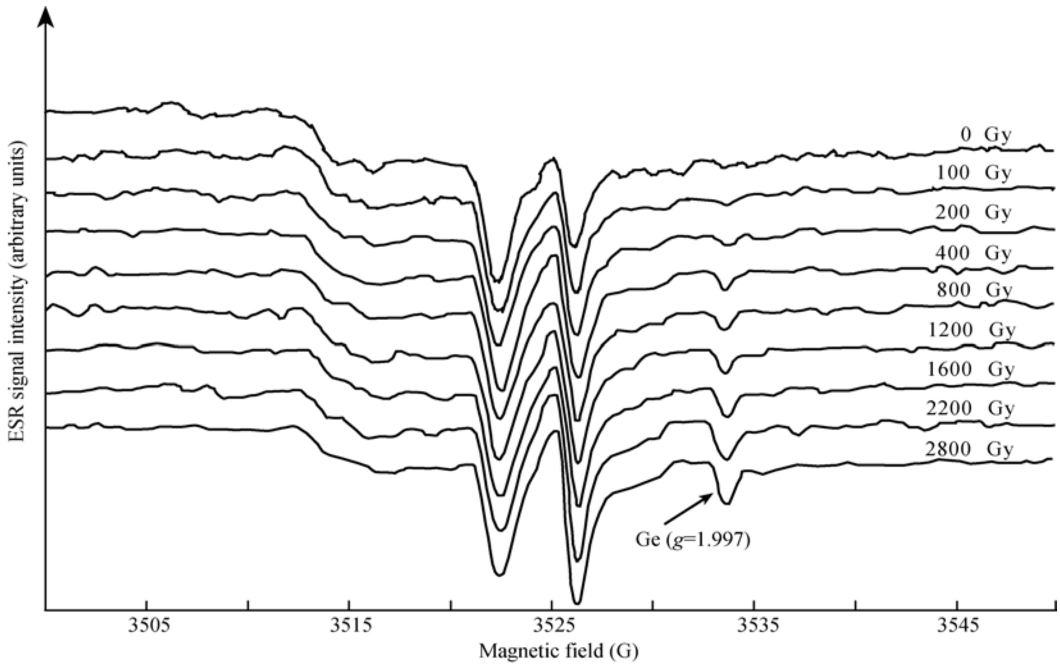

Figure 5 Typical ESR spectra of the glacial quartz grain samples at room temperature.

4 Results and discussion

4.1 Chronology of glaciations

On both the northern and western slopes of Kongur Mountain, the first set of moraines is distributed between several tens of meters and 1 km from the present glaciers' terminuses, and the lateral moraines remain separated from the modern glacier. Therefore, it is reasonable to conclude that the first set of moraines was deposited during the LIA. The second set of moraines is fresh with no soil or vegetation on its surface. Its landform is higher and more extensive than that of the first set of moraines. Stratigraphically, the second set is older than the first set. Based on the reconstructed extent of this set of moraines, the type of glacier during that period was a single valley glacier. Boulders from the huge lateral moraines on the east side of the Kelayayilake Glacier have TCN ^{10}Be surface exposure ages ranging from 0.4±0.1 to 1.5±0.1 ka [18]. These ages suggest that the lateral moraines were formed during the Neoglaciation. Seong et al. [18] termed the latest two sets of landforms the Olimde Glacial Stage and applied TCN ^{10}Be surface exposure dating to date the boulders on the moraines belonging to the Olimde Glacial Stage between Muztag Ata and Kongur Mountain. The dating results show that the two sets of moraines were deposited after the Late Glacial. A comparison of these dates with multiple paleo-climatic proxy records of the Northern Hemisphere suggests that, since the LGM_G, the glaciers between Muztag Ata and Kongur Mountain likely responded to Northern Hemisphere climate oscillations (rapid climate changes on millennial time scales) with minor influences from the south Asian monsoon [18].

Terrace 5, on which the Lower Gaizi Village is located, corresponds to the third set of moraines near the Gaizi Checkpoint. The ESR age for the glaciofluvial deposits on its top is 26.4±1.9 ka (GZ-16). In addition, the base of Terrace 5, which is approximately 2.3 km from the Gaizi Checkpoint on the north side of the Gaizi River, dates to 27.0±2.2 ka (GZ-17). Three samples collected from the moraine ridge (approximately 2 km from the terminus of the Jiangmanjiaer Glacier) on the western slope of Kongur Mountain are dated as 23.7±2.0, 13.1±0.8 and 23.1±1.9 ka (GGE-1-1–3). Based on the numerical ages discussed above, it is likely that the third set of moraines in the Kongur Mountain region represents a glacial advance during the LGM_G in MIS2. As for the ages of four samples obtained from the moraine platform of the Upper Gaizi Village, with the exception of GZ-15's large deviation from the mean of the ages, their ages range between 41.3±4.3 and 48.7±5.7 ka. These results indicate that this moraine platform was deposited during the middle part of the last glacial cycle corresponding to the cold period during mid-MIS3. The ages for seven samples from the hummocky moraines on the western slope of Kongur Mountain, with the exception of KXW-06 (19.0±1.6 ka), whose age has a large deviation, range between 36.4±3.3 and 48.2±4.6 ka. The dating suggests that the hummocky moraines on the western slope were also formed during mid-MIS3. Samples GZ-15 and KXW-06 have significantly younger ages than the other samples from the same moraine set. This may be attributed to reworking after deposition. The dating results demonstrate that the Kelayayilake Galciation must have occurred during the middle and late parts of the last glacial cycle, equivalent to MIS2–3.

Three samples were collected from the fifth set of moraines on the southwest side of the Upper Gaizi Village (moraine platform approximately 150–200 m above the Upper Gaizi Village). Their ages range between 65.6±6.8 and 86.6±8.9 ka, and their mean age is 74 ka. These dates show that this moraine platform was formed during the early part of the last glacial cycle corresponding to MIS4. It is also suggested that the largest local last glacial maximum (LGM_L) in this region should have occurred during MIS4 rather than the LGM_G of MIS2. Currently, only several regions preserving the glacial deposits during MIS4 are found in the Qinghai-Tibetan Plateau and the bordering mountainous, such as the Muzart River valley [26], the Ateaoyinake River Valley [27], the Yashikul Lake of the Western Pamir [38], and Tanggula Mountain [39]. The glacial advance during MIS4 may have been less extensive than the late part of the last glacial cycle (MIS2 or LGM_G) in most regions; any evidence of the older moraines, therefore, would have been destroyed by the subsequent glacial advance. In addition, the scarcity of the glacial deposits during MIS4 is more likely to be explained by the limited control on numerical dating of glacial successions.

Four samples were dated to define the sixth set of moraines rising 550–700 m above the Gaizi River bed on the southwest side of the Upper Gaizi Village. Their ages range between 105.6±9.4 and 178.3±17.8 ka, and their mean age is 131 ka. These dates suggest that this landform was formed during the penultimate glacial cycle corresponding to MIS6. This part of the Gaizi valley is so narrow that the surface of the paleo-glacier is higher than those in other regions. Moreover, as this region is adjacent to the western margin of the Tarim Basin which is an area of intensive tectonic uplift, intensive river incisions also occur in this area. As a result, this set of moraines is distributed at a higher relative elevation.

The fifth set of moraines on the western slope of Kongur Mountain likely represents an older glacial advance. The oldest moraines of the adjacent Muztag Ata are distributed mainly on the Subashidaban part of the southwestern slope of Muztag Ata with a landform of moraine platform. Consequently, this glacial advance was named the Subashidaban Glaciation by Li [16]. The tills consist of granite, biotite schist and hornblende gneiss and have been deeply weathered. Based on the distribution of these moraines, the glaciers during this glaciation have overlain the entire Muztag Ata and formed a small ice cap. Seong et al. [18] also termed this glaciation the Karasu Glacial Stage and dated five boulders from the surface of these moraines using TCN ^{10}Be surface exposure dating, finding ranges of age between 151 and 367 ka. The youngest ages may represent significant erosion and/or the exhumation of boulders. Although the ages of this stage were not equivalent to a specific marine oxygen isotope stage, the authors believed that this stage could be broadly assigned to a glaciation prior to the penultimate glacial cycle. Therefore, it is likely that the fifth set of moraines on the western slope of Kongur Mountain was also deposited prior to the penultimate glacial cycle.

4.2 Mechanism of formation of the hummocky moraines

The extensive hummocky moraines are the most marked glacial landforms between Kongur Mountain and Muztag Ata. Many scholars have already undertaken studies of these landforms. On the basis of the distance from the terminus of the modern glacier and the characteristics of weathering, Li [16] suggested that these landforms should be assigned to two different glacial stages, which are equivalent in age to the last (Kelayayilake Glaciation) and the penultimate glacial cycle (Kalakule Glaciation). These landforms were also assigned a glacial stage name (Subaxh Glacial Stage) by Seong et al. [18], and they dated the boulders of this stage in six valleys using TCN ^{10}Be surface exposure dating. Despite the scattering of ages, they believed that landforms assigned to this glacial stage likely represented multiple glacial advances during the penultimate glacial cycle and/or the last glacial cycle. Consequently, it is important to discuss the forming mechanism and timing of the hummocky moraines.

Our dating results, especially the ages of the six moraine sets on the northern slope of Kongur Mountain, also confirm the inferences of Seong et al. [18]. The δ^{18}O records in the Guliya ice core [40] and in the TS95 core [41] from Tianshuihai Lake in the Western Kunlun Mountains both show there was a series of rapid climate changes on a millennial-century time scale during the last glacial cycle, and that the magnitude of the temperature fluctuations in the Guliya ice core was larger than that in the Greenland ice sheet (Figure 6(c), (d)). These records can provide an important reference for paleo-climatic studies of this region. Furthermore, the piedmont below the terminuses of the modern glaciers between Kongur Mountain and Muztag Ata is a foreland basin, which has a width of approximately 10 km from east to west and an average elevation of approximately 3500–4100 m a.s.l. The basin is characterized by its gentle slopes. If a temperature decline or a precipitation increase should lead to a glacial advance, the glaciers from the southwestern slope of Kongur Mountain and the northern slope of Muztag Ata could very easily reach there. Consequently, it is difficult to divide the landform that was probably formed by multiple glacial advances during the last glacial cycle. A scattering of dates could also be well-interpreted.

Because abrupt climatic warming results in a rise of the ELA and a rapid retreat of the glacier on the gentler sloping terrain, a large part of the glacier lobe would become debris-covered, stagnant, and waste in a dead-ice terrain. During this melting period, the stagnant ice would form the extensive hummocky moraines. Based on our dates, the timing of the latest glacial advance that resulted in the for-

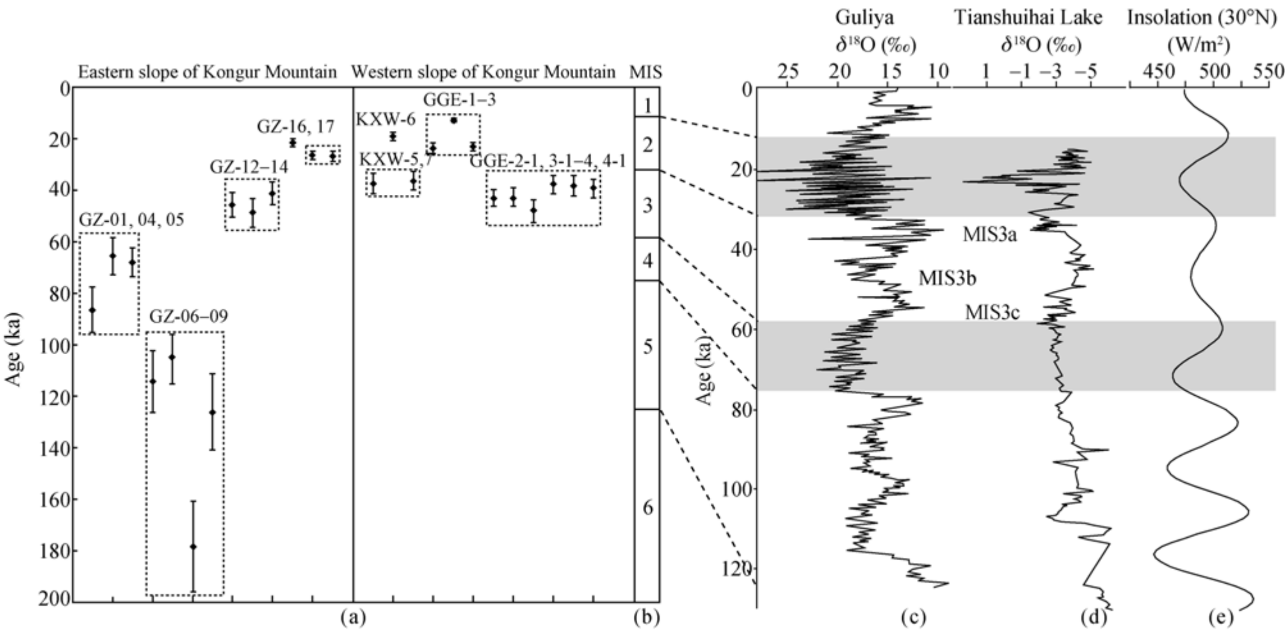

Figure 6 A comparison of Quaternary glacial chronology in the Kongur Mountain region with different records. (a) Dating results and their errors; (b) marine oxygen-isotope stages (MIS); (c) the δ^{18}O record in the Guliya ice core [40]; (d) the δ^{18}O record in lacustrine carbonate from Tianshuihai Lake [41]; (e) June insolation at 30°N [42].

mation of hummocky moraines on the western slope of Kongur Mountain corresponded to mid-MIS3, and the type of glaciers that prevailed during that period are piedmont glaciers. Consequently, the older moraines here had been overlain or reworked. We also have other paleo-environmental evidence to confirm our dating results. Zech et al. [38] applied TCN ^{10}Be dating to determine four moraine sets (M1, M2, M3 and M4) in the Orto Bogchigir I valley on the southwest side of Yashikul Lake, western Pamir. The landform of M2 is composed extensively of hummocky moraines, and the exposure ages of M2 are scattered over a wide range. However, the extent of M2 lies between M1 (52.6±6.8–61.2±8.0 ka) and M3 (26.9±3.5–39.5±5.1 ka) with a tight clustering of ages. Accordingly, the authors considered that the oldest age of boulder on M2 was probably the best estimate for the deposition age (45.1±5.9 ka and 46.9±6.1 ka). In addition, a comparison of their data with the records in the Guliya ice core showed that the M2 glacial advance event corresponded with cold periods during mid-MIS3 [38]. The above-mentioned studies suggest that a larger glacial advance occurred during mid-MIS3 in both Eastern Pamir and Western Pamir, and the rapid and frequent climate fluctuations during that period resulted in the formation of the extensive hummocky moraines.

Gillespie and Molnar [43] reviewed published evidence from over 50 glaciated mountain areas around the world. They found that the glaciation in the Himalaya and Tibet was asynchronous with the maximum extent of the Northern Hemisphere ice sheets. In particular, it appears that in many regions, such as the Hunza valley, Khumbu Himal and NE Tibet, glaciers reached their maximum extent during the insolation maximum of MIS 3. Subsequently, the studies of Phillips et al. [4] and Owen et al. [5] partly confirmed this view in the southern margin of the Qinghai-Tibet Plateau climatically, which is dominated by the south Asian monsoon. Recently, geomorphological and chronological evidence shows that glacial advances also occurred during MIS3 in many regions in central Asia, which are climatically dominated by the mid-latitude westerlies, such as the Muzart River valley [26] and the Ateaoyinake River Valley [27] on the southern slope of the Tianshan Range, and the Alay-Turkestan range (Kyrgyzstan) [44] and Yashilkul Lake in Pamir (Tajikistan) [38, 44]. Researchers usually consider that glaciers in the Tibetan Plateau and its bordering mountains reached their maximum extent during MIS2 (LGM_G) [45]. What is unknown is why a glacial advance occurred during the interstadial of the last glacial cycle, and why it was even more extensive than that of the LGM_G. The δ^{18}O records in the Guliya ice core from the West Kunlun Mountains show that MIS3 (58–32 ka) was remarkably warmer (even warmer than at present) and might have been as warm as the Last Interglacial [40]. Based on the records and corresponding climatic characteristics, Shi and Yao [46] divided MIS3 into MIS3a, MIS3b and MIS3c. The temperatures in MIS3a and MIS3c were 3 and 4°C higher than at present, respectively. MIS3b was a cold period that began at 54 ka, and δ^{18}O decreased from −13‰ to −17‰ during that time, corresponding to a temperature decrease of 6°C. The δ^{18}O value decreased abruptly to −19‰ around 45 ka, and the temperature was approximately 8°C lower than that of MIS3c. Around 40 ka, the δ^{18}O record indicated the beginning of a warm climate in MIS3a [46]. The δ^{18}O records in the TS95 core and the evidence of geomorphology and sedimentology from Tianshuihai Lake indicate the presence of high lake levels during 59–56 ka (I), 49–47 ka (II), 45–41 ka (III), 35.5–34.0 ka (IV) and 28–25 ka (V), and that the II, III and V stages were caused by a cold-humid climate [47]. The alpine glacier change depends not only on temperature but also on precipitation. The modern glaciers distributed on Kongur Mountain are typical extreme continental glaciers and, therefore, are more sensitive to changes of precipitation rather than those of temperature [48]. The retreating of the ice sheet during MIS3 caused cold anticyclone weakening in high latitude areas; therefore, the north branch of the mid-latitude westerlies retreated northward and weakened. However, the total insolation during MIS3 was higher than that during the LGM_G, and the insolation during the early MIS3 was the highest of the entire MIS3 (Figure 6(e)). The δ^{18}O records of the planktonic foraminifers in the V23–82 core from the North Atlantic show that the sea surface temperature (SST) during the early MIS3 is 5°C higher than that during mid-MIS3 and 6°C higher than the SST during the LGM_G [49]. In addition, the warming of the SST lags behind the insolation change; therefore, the SST remained at a high level during mid-MIS3. The two reasons discussed above led to intensive sea-surface evaporation (including the Mediterranean, the Black Sea, and the Caspian Sea) during mid-MIS3. Consequently, the climatology of the regions dominated by the mid-latitude westerlies could have received abundant precipitation brought by the westerly air masses during mid-MIS3. Combined with the low temperature during mid-MIS3, glaciers advanced in the Tianshan Range, Pamir Plateau, and the West Kunlun Mountains.

5 Conclusions

Six glacial advances in the Kongur Mountain region have been confirmed; they are equivalent in age to the LIA, Neoglaciation, MIS2, mid-MIS3, MIS4 and MIS6. The LGM_L occurred during MIS4 rather than the LGM_G of MIS2, and a glacial advance that occurred during mid-MIS3 was also larger than the LGM_G. Furthermore, deeply weathered tills preserved below 3500 m a.s.l. on the western slope of Kongur Mountain, when compared with the ages of the oldest glaciation of the Muztag Ata region, likely occurred prior to the penultimate glacial cycle. The glacial landforms prior to the penultimate glacial cycle on the northern slope are not well-preserved due to erosion after deposition. Several glacial deposits are only speculated to be distributed at higher elevations on the southwest side of the Gaizi Checkpoint. The extensive hummocky moraines on the western slope were formed by multiple glacial advances, and the latest glacial advance corresponded to mid-MIS3.

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