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Quaternary glaciations and glacial landform evolution in the Tailan River valley, Tianshan Range, China

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ABSTRACT

The Tailan River originates on the southern slope of Tumur Peak, the largest center of modern glaciation in the Tianshan Range. Five moraine complexes and associated fluvioglacial deposits in this valley record a complex history of Quaternary glacial cycles and landform evolution. Electron spin resonance (ESR) dating of glacial sediments was carried out using germanium (Ge) centers in quartz grains, which are sensitive to both sunlight and grinding. Based on the dating results as well as geomorphic and stratigraphic data, the Piyazilike end moraines (the second moraine complex) were deposited during Neoglaciation (the largest glacial advances during the last 3–4 ka in western China) and an early Holocene glacial advance, the third set of moraines was deposited in marine isotope stage (MIS) 2–4, and the glacial landforms of the Tailan glaciation (the fourth moraine complex), which include hummocky moraines on the piedmont, were formed in MIS 6 (penultimate glaciation). The end moraines of the innermost moraine complex (the first moraine complex) are inferred to have been deposited during the Little Ice Age (LIA). Thus the landforms and dates indicate compound valley glaciers from the LIA to MIS 2–4, and piedmont glaciers during MIS 6. The oldest tills studied belong to the “Kokdepsang Glacial Stage”, and occur on a high plateau. Based on similar glacial landforms (glacial deposits on a high plateau and a high glacial terrace) and their ESR ages in adjacent valleys on the southern slope of Tumur Peak, the Kokdepsang Glacial Stage is assigned to MIS 12.

1. Introduction

Glaciers are highly sensitive to climate change and have been responsible for shaping some of the most spectacular landscapes throughout the world (Bennett and Glasser, 2009; Benn and Evans, 2010; Ehlers et al., 2011). These spectacular landforms are direct imprints of past glacial fluctuations and represent important archives of past climatic and environmental information. Studies of glacial landforms can define the timing, extent, properties, and types of ancient glaciers, and can improve our understanding of temporal and spatial shifts of past glaciers (Shi et al., 2006, 2011; Ehlers et al., 2011), which can help us understand paleoenvironments. Glaciers are often highly erosive (Hallet et al., 1996; Brocklehurst and Whipple, 2006; Ehlers et al., 2006), and the denudation caused by glaciers has the potential to influence climate by increasing chemical weathering and, ultimately, lowering atmospheric concentrations of CO_2 (Raymo and Ruddiman, 1992). In addition, glaciers enhance rates of valley incision during glaciation and the resulting isostatic rebound can cause high mountain crests to rise, which in turn has an influence on climate (Molnar and England, 1990). Therefore, in tectonically active regions, studies of past glaciation provide important information for understanding the history of uplift.

Dating glacial landforms is a fundamental component of studying landform evolution and also of paleoenvironmental reconstruction. In the past several decades, electron spin resonance (ESR) dating, which utilizes radiation-defects in quartz to determine the ages of sediments, has been increasingly applied to studies of Quaternary geology (Hennig and Grün, 1983; Grün, 1989; Ikeya, 1993; Rink, 1997). Dating of unconsolidated sediment using

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ESR was first proposed by Yokoyama et al. (1985). Tanaka et al. (1985) used germanium (Ge) centers to date sun-bleached sediment for the first time, and obtained results that were consistent with the geological setting. Grün (1991) proposed that Ge centers should be used in future ESR dating studies, and Schwarcz (1994) suggested that glacial till could be dated using ESR. Since then, the potential value of ESR for dating Quaternary glacial deposits has been explored by several scholars (e.g., Yi et al., 2002a,b; Zhou et al., 2002, 2006; Zhao et al., 2006, 2010; Xu and Zhou, 2009; Wang et al., 2011) and comparisons have been made between ESR and other independent dating methods, including optically stimulated luminescence (OSL) and cosmogenic radionuclides (CRN) (Xu et al., 2010; Zhou et al., 2010; Zhao et al., 2012). Additional studies have demonstrated the value of ESR in augmenting conventional mapping and relative dating studies in advancing research on Quaternary glaciation in China (Shi et al., 2006, 2011).

The Tianshan range is a tectonically active mountain system in Central Asia that formed as a result of the collision of the Indian and Eurasian continental plates. The Tumur Peak area of the Tianshan range includes more than forty peaks above 6000 m asl, with Tumur Peak being the highest (7435 m asl) and the largest center of modern glaciation in the range. During Quaternary glacial–interglacial cycles this area was extensively and repeatedly glaciated, and moraines and associated fluvioglacial landforms from multiple glaciations are present in the valleys, basins and the piedmonts of the range. Studies of these landforms can provide insight into temporal and spatial variations of glaciers and contribute to paleoenvironmental reconstructions and understanding the tectonic uplift history of the Tumur Peak area, and the Tianshan range.

Quaternary glacial landforms, including moraines in the Tailan River valley on the southern slope of Tumur Peak have been studied extensively since the 1940s (Huang, 1944; Feidaoluoweiqi and Yan, 1959, 1960; Liu et al., 1962; Shi et al., 1984; Su et al., 1985b). Unfortunately, no geochronological framework for these landforms has been established yet, and this restricts our understanding of the change of past glaciers in this drainage and also of regional paleoenvironmental variations. Thus over the past decade we have used

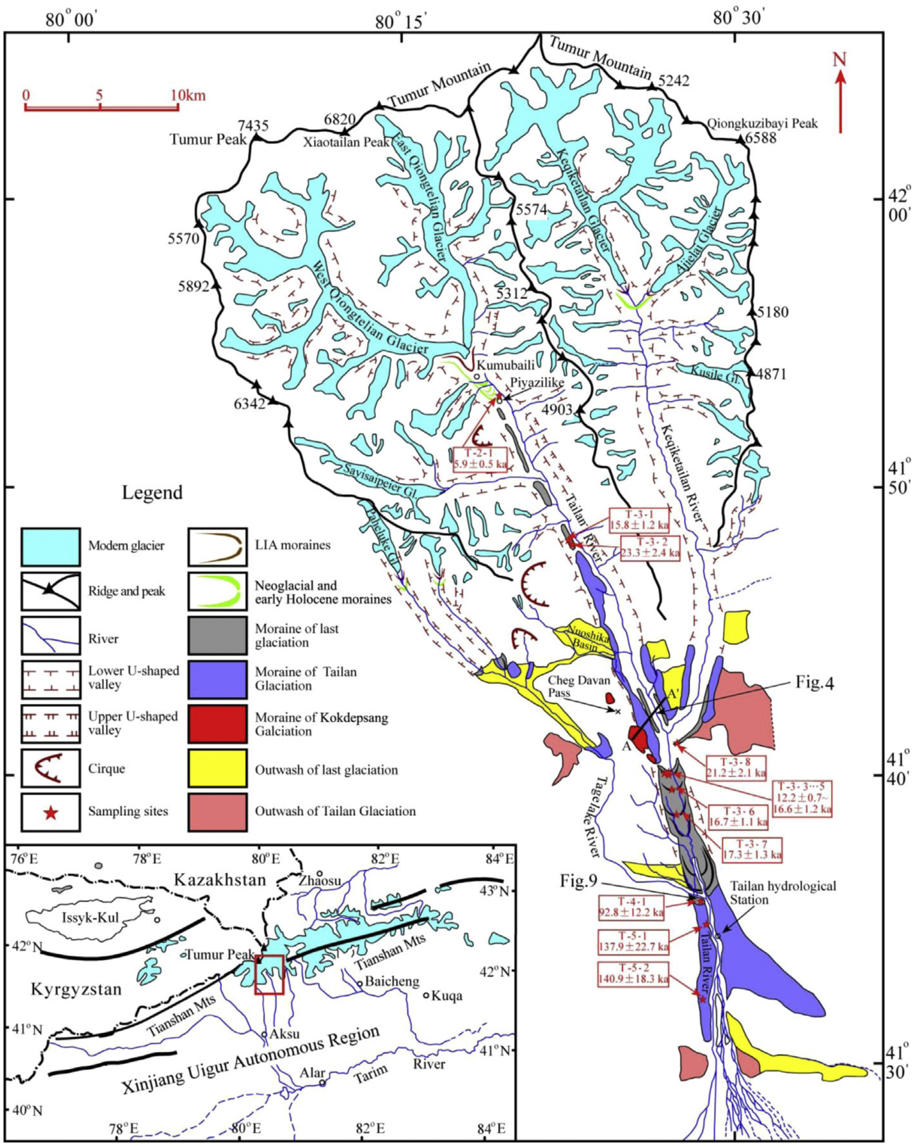

Fig. 1. Geomorphological map of the Tailan River valley.

remote-sensing techniques, field mapping, and ESR dating technique to constrain the timing, style and nature of Quaternary glaciations in the Tailan River valley.

2. The Tailan River valley

The Tailan River originates on the southern slope of Tumur Peak and flows southwards into the Tarim Basin (Fig. 1). The drainage area above the Tailan Hydrological Observation Station is about 1324 km^2 and the length of the river is about 80 km. The river has an annual discharge of about 7.5×10^8 m^3, with more than 60% being glacier meltwater. This runoff provides a vital water resource for the Zhamutai oases in the eastern part of Wensu County, Aksu District.

The heights of the mountain ridges above the drainage are between 4000 and 6500 m asl, and the highest peak is Tumur Peak (7435 m asl). There are 192 modern glaciers within the headwaters of the Tailan River valley with modern equilibrium-line altitudes (ELAs) ranging between 4200 and 4500 m (Lanzhou Institute of Glaciology and Geocryology, CAS, 1987). These include compound valley glaciers, single valley glaciers, cirque glaciers and hanging glaciers, with a total area of about 740 km^2 and an ice volume of about 113 km^3. There are 100 glaciers within this key research area, with a total area of about 417 km^2 and an ice volume of about 70 km^3. Among these 100 glaciers are four valley glaciers with a length of more than 10 km (Table 1). The most notable is the Qiongtelian Glacier, which has a west and east branch, an area of about 165 km^2 and an ice volume of about 39 km^3. The Qiongtelian Glacier is about 23.8 km long, has a terminus at 3080 m asl, and stretches for more than 1200 m below the ELA (~4300 m asl). Most of its ablation area is covered by supraglacial till that becomes thinner with increasing elevation. Approximately 13.5 km of the length of the glacier is covered by supraglacial till and glacier surfaces above 3800 m asl are debris free.

their surfaces. Glacial landforms deposited during the recent retreat are poorly preserved at the terminus of the Qiongtelian Glacier. However, five older moraine complexes occur in locations ranging from close to the terminus of the glacier to the piedmont beyond the end of the main valley (Fig. 1).

The first set of moraines occurs within 1.8 km of the terminus of the Qiongtelian Glacier and consists of several end moraines. The boulders on the innermost moraine crest are fresh and unweathered, whereas those on the outer crests show incipient weathering. There is no soil developed on these end moraines. However, there are some areas covered with grass and sparse shrubs. The tills consist of gray and red granite, gray gneiss and some mixtures of marble fraction from the peak and the high-mountain zone.

The second set of moraines is the Piyazilike moraine complex, which is about 5.5 km from the terminus of the Qiongtelian Glacier. The moraines are distributed over about 1 km of valley length, and extend from 2750 m to 2700 m asl. This moraine complex also consists of several end moraines. The outermost end moraine is the largest, with a crest reaching 2818 m asl. The moraines are about 10–20 m high and there are glaciofluvial depressions between them. Granite boulders 3–5 m in diameter are present on the surface of these end moraines, and the largest boulders are more than 10 m in diameter. The surfaces of these boulders are weathered, and some are covered by moss. A 10–20 cm thick gray soil has developed allowing firs to grow well on these end moraines. The diameters of the large firs are about 50–70 cm, with the largest fir being approximately 78 cm in diameter. The dendrochronology of these large firs indicates that they are more than 300 years old (Shi et al., 1984; Su et al., 1985b). The Tailan River cuts through these end moraines from the east side and has developed a gorge that is about 30–50 m deep. The lithologies of the tills here are similar to that of the first moraine complex and clasts in the till also consist of granite, gneiss and marble fraction.

Table. 1
Parameters of valley glaciers with length >10 km in the Tailan River valley.[a]

Glacier names or nos	Length/km	Width/km	Orientation	Area/km^2	Ice volume/km^3	Top altitude/m asl	Terminus/m asl	ELA/m asl
Sayisaiper	10.7	1.3	E	14.07	1.4914	6049	3300	4240
Tailan	23.8	7.7	SE	165.38	38.8643	7434	3080	4300
Keqiketailan	17.9	5.9	SE	99.61	19.9220	6640	3180	4200
5Y674C-22	12.0	2.4	SW	28.60	3.8324	6588	3145	4270

[a] Data from Lanzhou Institute of Glaciology and Geocryology, CAS (1987).

The climate of the Tianshan range is dominated by mid-latitude westerlies, with precipitation directly influenced by the westerly circulation (Benn and Owen, 1998). Based on snowpack data above 5000 m at the west branch of Qiongtelian Glacier, Su et al. (1985a) concluded that the average annual precipitation at the ELA is about 750–800 mm. In addition, based on meteorological data at the terminus of the west branch of Qiongtelian Glacier (~3200 m asl) and using an environmental lapse rate of ~0.6 C°/100 m, the mean annual temperature at the ELA is estimated to be −11 to −7 °C (Su et al., 1985a). The estimated annual precipitation and temperature at the ELA in this valley is similar to that of directly observed data in the Ateaoyinake River valley, which is a neighboring drainage to the Tailan River valley in the west of this area (Zhao et al., 2009a).

3. Quaternary glacial landforms

Glaciers in the Tailan River valley have been experiencing extensive melting over the past several decades and most of the glaciers are retreating and have clear glacial karst features on

For about 10 km down valley from the Piyazilike moraine complex the moraines are poorly preserved along the main glacial trough, and talus slopes and alluvial fans are well developed. However, buried moraines can be observed in some sections along the river. In the area stretching 20 km down valley from the confluence of Sayisaiper Glacier meltwater with the Tailan River, two lateral moraines are readily observable on the west side of the river, especially around the Nuoshika Basin. The lower lateral moraine is about 150 m above the current river and the higher moraine is about 350 m above the current river. In addition, at higher elevations above the lateral moraines there are some deeply weathered granite erratics, 1–2 m in diameter, which are deposited on the red coarse sandstone and conglomerate bedrock. These erratics presumably relate to an older glaciation than that which deposited the lateral moraines.

The third moraine complex occurs approximately 30–38 km beyond the terminus of the Qiongtelian Glacier, and extends from 2100 m to 1650 m asl. This moraine complex consists of six relatively high and integrated end moraines that arc to the south. Our field investigation indicates that the degree of cementation and weathering of this moraine complex is similar to that of the Pochengzi Glaciation in the Muzart River valley (Zhao et al., 2010) and this glacial stage has been called the “Pochengzi glaciation” in previous studies (Shi et al., 1984; Su et al., 1985b). Based on geomorphic relationships, the low lateral moraine around the Nuoshika Basin, which is about 150 m above the current Tailan River, was likely formed during this glacial stage. The end moraines are divided into two groups by a gully. There are four end moraines in the inner group, and the other two moraines are in the outer group. In addition, the outer side of the sixth end moraine has been cut through by the Tagelake River, a very important tributary of the Tailan River, and a well exposed section can be observed at the confluence of these two rivers. The till comprises granite, gneiss and marble clasts from the peak and the high-mountain zone, and red coarse sandstone and conglomerate clasts from the middle and lower-alpine zone.

The fourth set of moraines is found at two sites, one at Chegdavan Pass and the other on the piedmont. This glaciation has been named the Chegdavan Glaciation by Huang (1944), and the Tailan Glaciation by Shi et al. (1984) and Su et al. (1985b). At Chegdavan Pass, the glacial tills were deposited on red coarse sandstone and conglomerate of Tertiary age. These glacial landforms are about 100–150 m higher than the multiple end moraines of the third moraine complex and about 200–400 m above the current Tailan River. The moraines are overlain by a 1 m-thick deposit of loess, and only some large erratics are present on the surface of this glacial landform. Based on geomorphic relationships, the high lateral moraine around the Nuoshika Basin, which is about 350 m above the current river was formed during this glacial stage.

On the piedmont, glacial landforms are distributed over about 32 km^2 between the Tianshan range and Mount Gongbaizi, extending from an altitude of 1650 to 1400 m with a gradient of 2–3°. The sediments here are dominated by sub-angular debris, and mixed with only a small percentage of rounded debris. The landforms indicate that a large piedmont glacier once occupied this area. The landforms here are hummocky moraines. The areal extent of the glacial landforms increases away from the mouth of the Tailan River on to the flat piedmont, and the glacial landforms on the flat piedmont occur in two areas separated by the river (Fig. 2). The hummocky moraine areas have been eroded significantly; slope crests have been rounded and some depressions have been partly filled in. The hummocky moraines are about 10–20 m above the Tailan River, and the height difference between high and low points ranges from several meters to as much as 20 m (Fig. 3). Some large granite erratics are present on the surface of the moraines, although the largest at about 24 × 24 × 23 m^3 (Shi et al., 1984; Su et al., 1985b) has been destroyed. Till clasts consist of granite, gneiss, marble fraction, red coarse sandstone and conglomerate.

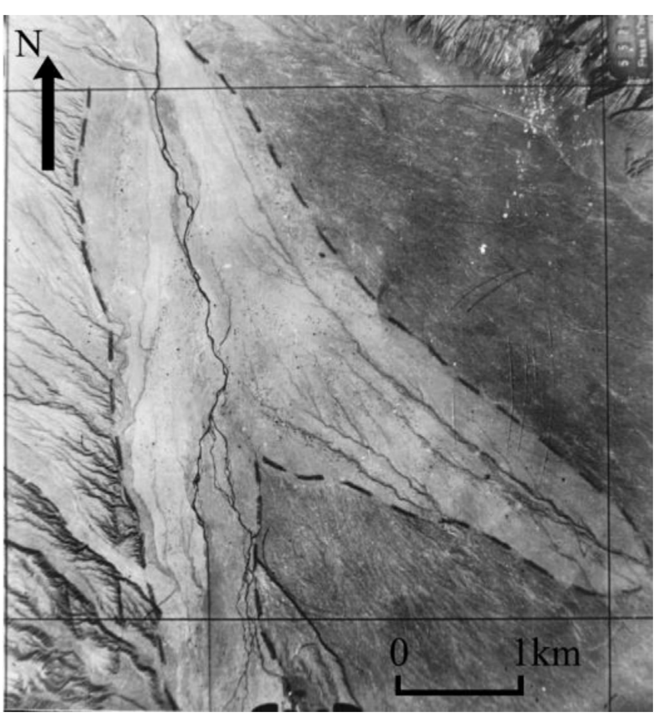

Fig. 2. Aerial photo of glacial landforms of the Tailan Glaciation on the piedmont.

There are moraines on a high plateau of red coarse sandstone and conglomerate at about 2400 m asl on the west side of the Tailan River and about 2 km south of the Chegdavan Pass (Fig. 1). The highest point on this plateau is at 2450 m asl. The plateau is called “Kokdepsang” and so the glacial stage represented by these moraines was named the Kokdepsang Glacial Stage (Huang, 1944). The plateau is about 2 km long from the north to the south, and about 1 km wide from the east to the west. Moraines here are about 10–20 m high. This glacial plateau is about 500–600 m higher than the Tailan River, and about 200 m higher than the landforms of the Tailan Glaciation (Fig. 4). Deeply weathered granite erratics, 3–5 m in diameter (the largest being 10 × 7 × 8 m^3) are present on the surface of this plateau. Till clasts include granite, green schist, gneiss and red coarse sandstone and conglomerate.

4. Methods and results

To constrain the chronology of glaciation in the Tailan River valley, samples for ESR dating were collected from natural or human-made sections from the second, third and fourth sets of moraines (Fig. 1). The samples were kept in opaque plastic bags to ensure that they were not exposed directly to sunlight. Grinding, collision and heating were also avoided during transportation. The samples were pretreated in the OSL chronology laboratory at the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou. Previous studies have shown that the signal intensity of Ge centers in quartz grains exposed under natural room light do not decrease (Walther and Zilles, 1994; Rink, 1997). Therefore, Schwarcz (1994) suggested that samples could be prepared in normal laboratory light. All samples were treated under natural light conditions during preparations in this study following Zhao et al. (2006, 2010). The prepared samples were divided into nine aliquots (about 250 mg each) and irradiated with different artificial doses. Ge centers were chosen as dating signals and measured with an ECS106ESR spectrometer manufactured by Bruker (Germany), in the Open Laboratory of Marine Sedimentology, Qingdao. The measurement conditions were as follows: room temperature; X-band; microwave power = 2 mW; modulation amplitude = 0.1 mT; central magnetic field = 348 mT; sweep width = 5 mT; change time = 5.12 mS; time constant = 40.96 mS; and amplification = 1×10^5. In order to improve the signal to noise (S/N) ratio and obtain a better signal resolution, each aliquot was measured in the same condition with different angles (about 120° between them) three times, and average signal intensity was used. Typical ESR spectra of glacial quartz grains are shown in Fig. 5.

A least-squares analysis was used to fit the data points based on different artificial irradiation doses and corresponding signal intensities using linear fits. The line was then extrapolated to zero to obtain the total dose (*TD*) (Fig. 6). The concentrations of U and Th and the content of K_2O were determined by laser fluorescence, colorimetric spectrophotometry and atomic absorption,

Fig. 3. Close-up view of hummocky moraines on the piedmont.

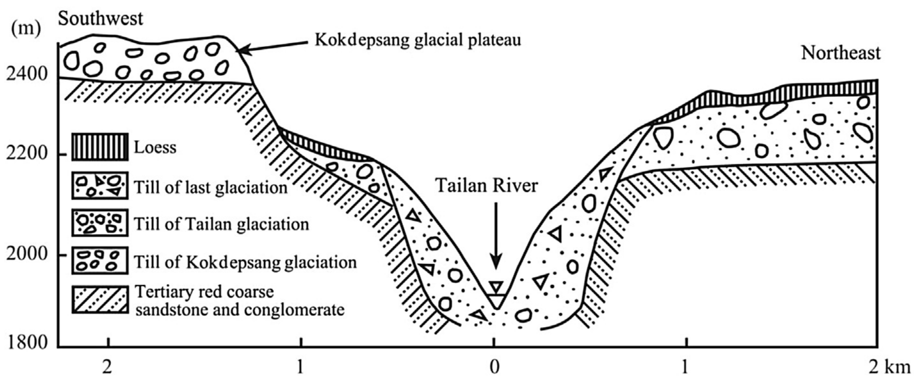

Fig. 4. A cross section in the middle reach of the Tailan River.

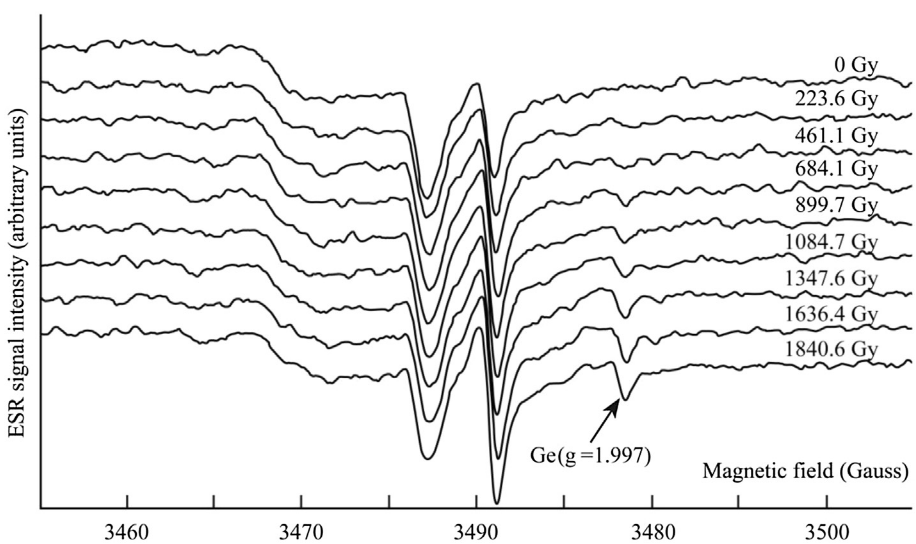

Fig. 5. Typical ESR spectra of the glacial quartz grain samples at room temperature (T-4-1).

respectively. All measured radioactive elements were converted to alpha, beta and gamma dose rates using the conversion factors of Guérin et al. (2011). Finally, the annual dose rate (D) was estimated from these radioactive elements, along with the water content and the cosmic ray contribution which was estimated and calculated following the formulas suggested by Prescott and Hutton (1994). Ages were calculated using the following equation:

$$T = \frac{TD}{D}$$

where TD is the total dose and the D is the annual dose rate.

The total uncertainty for each sample was affected by systematic and random errors in the TD values, water content, the concentrations of U and Th, and the content of K_2O, the contribution of cosmic ray, etc. The water content can reduce the annual dose rate. Because the secular water content could not be obtained, water attenuation for each sample was calculated following the formulas proposed by Grün (1994). In addition, glacial deposits and fluvial sediments can be very heterogeneous, and this will also affect the annual dose. Total uncertainty for each sample was estimated from the information available. The ESR ages in stratigraphic order are consistent with the geological setting, the degrees of cementation and weathering of the glacial tills. The details of the sampling sites, the results of the dating, and the correlated parameters are listed in Table 2.

Table. 2
ESR dating results as well as the correlated parameters.

Sample number	Sample locations and descriptions					U (10^{-6})	Th (10^{-6})	K_2O (%)	Cosmic ($mGy*a^{-1}$)	Water (%)	*TD* (Gy)	Age (ka)
	Longitude/E	Latitude/N	Altitude/ m asl	Depth/m	Sample description							
T-2-1	80°19.224′	41°52.810′	2809	0.8	Sand lenses sandwiched between tills in the largest end moraine of Piyazilike	4.23	14.5	3.83	0.3033	1.71	35.18	5.9 ± 0.5
T-3-1	80°24.349′	41°46.281′	2305	3.5	Till of the low lateral moraine around the Nuoshika Basin	5.40	24.1	3.30	0.1745	2.83	99.07	15.8 ± 1.2
T-3-2	80°24.405′	41°46.239′	2314	3.6	Till of the low lateral moraine around the Nuoshika Basin (10 m above T-3-1)	2.94	16.0	3.29	0.1721	1.97	117.82	23.3 ± 2.4
T-3-3	80°27.997′	41°38.930′	1951	8.5	Till of the first end moraine − 1 (on the inside) of the third moraine complex	3.32	19.6	3.39	0.0803	3.78	65.29	12.2 ± 0.7
T-3-4	80°27.886′	41°39.011′	1994	9.3	Till of the first end moraine − 2 (on the inside) of the third moraine complex	3.07	18.0	3.84	0.0734	3.15	71.53	12.8 ± 0.9
T-3-5	80°27.820′	41°39.223′	1967	8.7	Till of the first end moraine − 3 (on the crest) of the third moraine complex	3.39	17.3	3.31	0.0785	2.08	86.63	16.6 ± 1.2
T-3-6	80°27.774′	41°39.264′	1982	9.8	Till of the second end moraine of the third moraine complex	4.50	17.2	3.94	0.0691	3.14	99.32	16.7 ± 1.1
T-3-7	80°27.621′	41°39.669′	2049	7.9	Till of the third end moraine of the third moraine complex	2.74	10.8	3.88	0.0883	2.39	87.02	17.3 ± 1.3
T-3-8	80°27.550′	41°41.269′	1912	3.1	Till of the lateral moraine on the east side of the Tailan River (~2000 m asl)	5.91	25.2	3.76	0.1722	1.77	147.54	21.2 ± 2.1
T-4-1	80°29.119′	41°36.245′	1661	7.2	Well-sorted fluvial gravel	3.45	9.53	2.56	0.0897	4.59	359.09	92.8 ± 12.2
T-5-1	80°28.989′	41°35.582′	1663	3.1	Till of Tailan glaciation − 1	3.97	11.1	2.29	0.1641	2.84	556.32	137.9 ± 22.7
T-5-2	80°29.644′	41°31.770′	1507	2.9	Till of Tailan glaciation − 2	3.53	8.22	2.28	0.1646	2.03	524.12	140.9 ± 18.3

5. Discussion

5.1. Resetting of the Ge centers in glacial quartz grains

Previous studies have confirmed that Ge centers in quartz grains are sensitive to sunlight, UV-light and grinding (Tanaka et al., 1985; Buhay et al., 1988; Jin et al., 1991; Ye et al., 1993, 1998; Walther and Zilles, 1994; Rink, 1997), and these mechanisms can reset Ge centers effectively. Given the structure and movement of alpine glaciers (Shi et al., 1989) and processes of lateral moraine formation by ice-marginal dumping of debris (Small, 1983), it is reasonable to assume that debris transported by glaciers can be exposed and subject to grinding. The absorption band of Ge centers is 4.43 eV (Jin et al., 1991), corresponding to a wavelength of 280 nm. At higher elevations, this wavelength produces energy in the Ge absorption band at higher levels than at lower elevations. Subglacial and englacial clasts are subject to grinding during glacial transport and the high silt content in glacial deposits and microscopic studies of till quartz grains confirm that abrasion and crushing are prevalent (Mahaney et al., 1988; Yi, 1997). The samples for dating were collected from glacial deposits at high elevations, and it is therefore reasonable to assume that the Ge centers in the glacial quartz grains were reset during glacial transport and deposition. Further support for the potential value of ESR dates has been provided by studies that compared ESR dates with dates using other methods. Zhou et al. (2010) used CRN (^{10}Be) and ESR dating techniques to

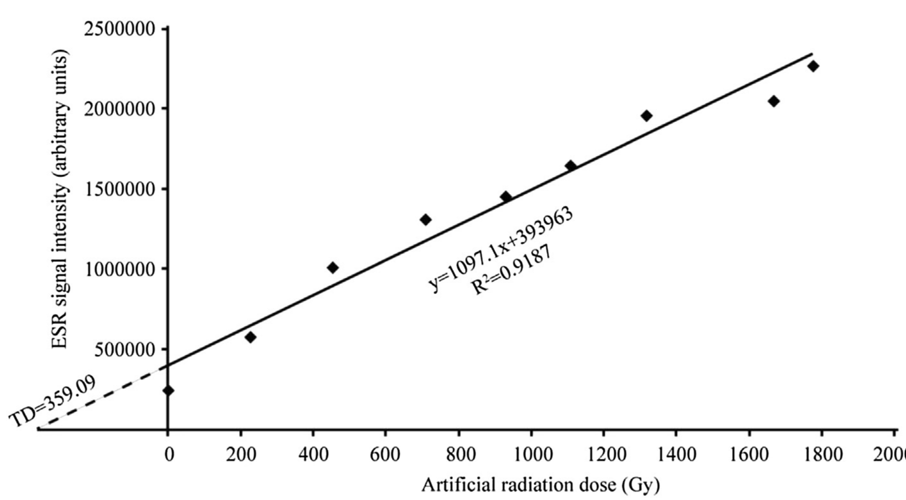

Fig. 6. Best-fit line between artificial radiation doses and ESR signal intensity (T-4-1).

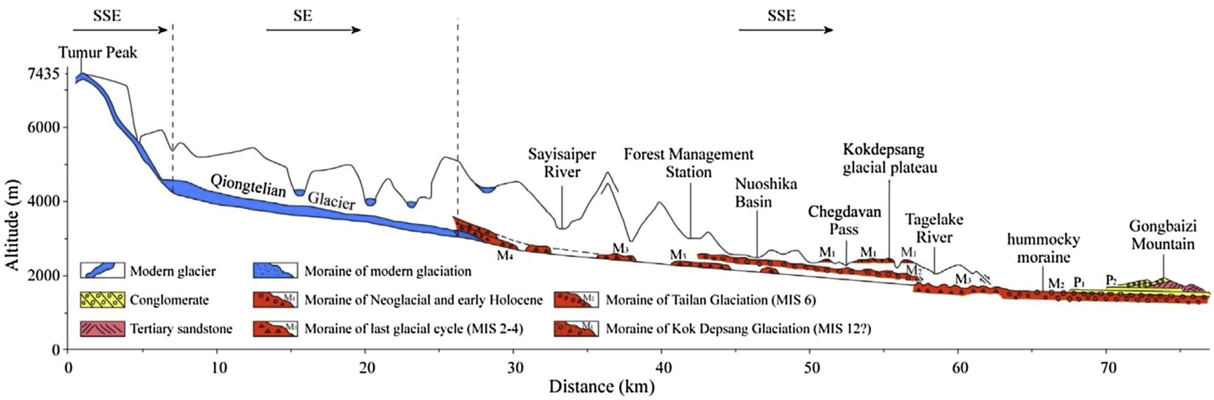

Fig. 7. Longitudinal section of the Tailan River valley.

determine the age of the Baiyu Glaciation in southeastern Tibet, and obtained comparable dates. Xu et al. (2010) obtained consistent OSL and ESR ages for the same moraine complex in the Queer Shan, northern Hengduan Mountains, and similar results have been found in the Bogeda Peak area, eastern Tianshan range (Zhao et al., 2012). These studies give confidence that the ESR dating technique can be used independently to investigate the ages of moraine complexes.

5.2. Glacial sequences and glaciations

The ESR results (Table 2) contribute new data for a temporal framework for examining rates of glacial landscape evolution in the Tailan River valley and show a long and complex history of landscape evolution in this drainage (Figs. 1, 4 and 7). Modern glaciers in the Tailan River valley have experienced extensive retreat over the past eighty years. Comparing aerial photos, topographic maps and satellite images, it has been shown that the Qiongtelian Glacier retreated by about 600 m from 1942 to 1976 (Su et al., 1985a) and by about 340 m from 1977 to 1997 (Liu et al., 2000). Lateral moraines from this period are about 10–20 m higher than the glacier's surface and are very distinct on both sides of the Qiongtelian Glacier (Fig. 8).

Based on data from studies of Quaternary glaciations across western China (Shi et al., 2006, 2011), the presence of weathered boulders and well growing firs on the Piyazili end moraines suggests that the second moraine complex was formed before the Little Ice Age (LIA). Glaciofluvial deposits (sand lenses sandwiched between tills in moraines) from the inner side of the outermost end moraine were dated to 5.9 ± 0.5 ka (T-2-1). Based on the relationship between this largest end moraine and the others, as well as palaeoenvironmental and palaeoclimatic data in western China (Shi et al., 2000) and the ages of the third moraine complex, it is likely that there were significant glacier fluctuations during the formation of the Piyazili end moraines. We surmise that the outermost large end moraine was deposited during the early Holocene, and based on the Guliya ice core record in the West Kunlun Mountains (Wang et al., 2002) the largest end moraine may represent an advance during the 8.2 ka cooling event. Similarly, based on the pattern of Quaternary glaciations in western China and the chronology of the first and second sets of moraines in the Urumqi River valley (Chen, 1989; Yi et al., 1998, 2004), eastern Tianshan range, we surmise that the other end moraines of this moraine complex are associated with the Neoglaciation (glacial advances during the last 3–4 ka), and that the innermost moraine complex (the first moraine complex) was deposited during the LIA (the large glacial advances that occurred during the cold periods since the 16th century). The landforms indicate that the Qiongtelian glacier was about 26 km and 29 km long during these two periods (i.e., last 3–4 ka and LIA).

Eight ESR ages for the third moraine complex and its equivalent moraines: 12.2 ± 0.7 ka (T-3-3), 12.8 ± 0.9 ka (T-3-4) and 16.6 ± 1.2 ka (T-3-5) for the first end moraine; 16.7 ± 1.1 ka (T-3-6) for the second end moraine and 17.3 ± 1.3 ka (T-3-7) for the third one. The three ESR ages for the lateral moraine, two of them are 15.8 ± 1.2 ka (T-3-1) and 23.3 ± 2.4 ka (T-3-2) for the low lateral moraine at about 5 km north to the Nuoshika Basin, and one is 21.2 ± 2.1 ka (T-3-8) for the lateral moraine on the east side of the Tailan River at about 2000 m asl. Taken together, these dates indicate that the inner group of end moraines and the low lateral moraine on both sides of the Tailan River were formed during the late period of the last glacial cycle, corresponding to marine oxygen isotope stage (MIS) 2. However, the samples from the inside of the first end moraine have much younger ages (T-3-3, 12.2 ± 0.7 ka and

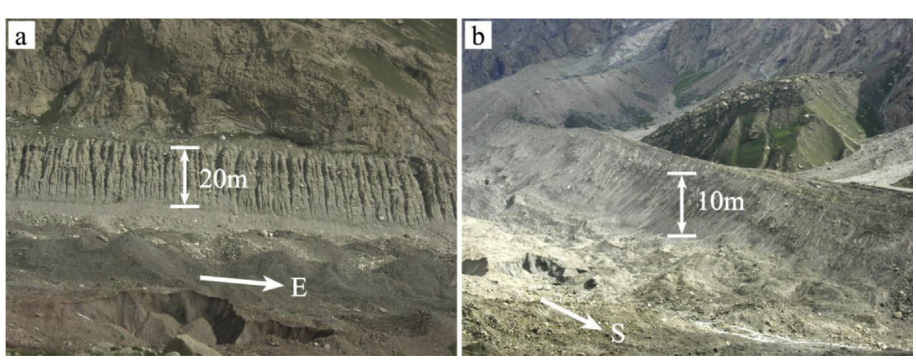

Fig. 8. Modern lateral moraines on the north side of west branch (a) and east side of east branch (b) of the Qiongtelian Glacier.

Fig. 9. Section of glacial tills and underlying well-sorted fluvial deposits (41°36.245′N, 80°29.119′E, 1661 m asl).

T-3-4, 12.8 ± 0.9 ka) that are consistent with the global Younger Dryas (YD) stade. Therefore, we conclude that the glacier re-advanced to the position of the first end moraine for a short time during the YD stade. No absolute ages have been derived for material in the outer group of the end moraines. However a section on the outer side of the outermost end moraine (the sixth end moraine) includes glacial tills superimposed on well-sorted fluvial gravels dated to 92.8 ± 12.2 ka (T-4-1). The superposition relationship indicates that the tills are younger than the fluvial gravels (Fig. 9) and thus that the third moraine complex was deposited during the last glacial cycle. Considering the similarity of the cementation and weathering between this moraine complex with that of the Pochengzi moraine complex in the Muzart River valley (Zhao et al., 2010), we conclude that the multiple end moraines of the third set of moraines were formed during MIS 2–4. The ancient Qiongtelian glacier was 53–62 km long during this glacial cycle.

Well-preserved glacial landforms with age control allow for reconstruction of the palaeo-ELA, which is an indicator of changes in local climate. The present ELAs of four valley glaciers with lengths of more than 10 km in the study area have been observed and calculated (Table 2), and the total ablation area of the Qiongtelian Glacier indicate that it has an accumulation area ratio (AAR) of 0.68 (Lanzhou Institute of Glaciology and Geocryology, CAS, 1987). The AAR value for this retreating (negative mass balance) modern glacier provides a minimum limiting value for the AAR for the palaeo-glacier at its maximum extent. Topographic maps and satellite images have been used to reconstruct the area and palaeo-ELA of the Qiongtelian Glacier at its maximum extent during the last glaciation, assuming an AAR of 0.68. Based on above data and reasonings, we estimated that its past areas was about 880 km^2, its palaeo-ELA about 3780 m asl, and thus the ELA was about 520 m lower than at present.

The age of the event that deposited the hummocky moraines is constrained by two consistent ESR ages, 137.9 ± 22.7 ka (T-5-1) and 140.9 ± 18.3 ka (T-5-2). These ages indicate that the Qiongtelian glacier was an extensive piedmont glacier during the penultimate glaciation (Fig. 1), and the landforms indicate that the glacier was at least about 73 km long during this period. An even older glaciation is recorded by the moraines on the Kodepsang plateau. The degree of weathering of the erratics indicates that the tills are much older

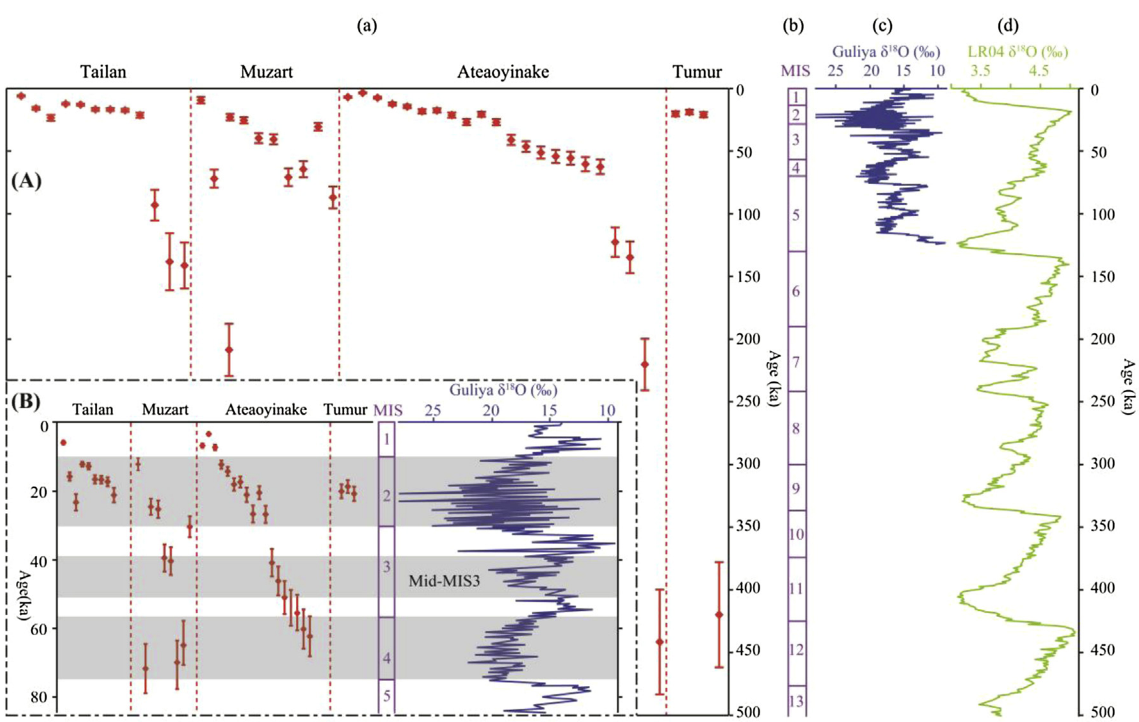

Fig. 10. A comparison of Quaternary glacial chronology in the Tumur Peak area with different records. (a) different dating results and their errors (this study and Zhao et al., 2009a,b; 2010); (b) marine oxygen isotope stage (MIS); (c) the δ^{18}O record of the Guliya ice core (modified after Yao et al., 1997); (d) the δ^{18}O record of 57 globally distributed benthic sediments (modified after Lisiecki and Raymo, 2005).

than other tills in the study area. The weathering and cementation of the glacial tills on this plateau are similar to those of glacial tills on the Qingshantou plateau in the Ateaoyinake River valley and the highest glacial terrace in the Tumur River valley. ESR ages of 440.6 ± 41.7 ka and 418.9 ± 41.9 ka for these deposits (Zhao et al., 2009a,b) lead us to suggest that the Kokdepsang glacial deposits were formed during MIS 12 glaciation.

From the terminuses of the modern valley glaciers to the mouth of the Tailan River, the valley form is a well-developed glacial trough. The length of this glacial trough is about 40 km and the width is about 2–3 km. Based on the glacial landforms in the valley and on the piedmont, and their ages, as well as known rates of landform modification by glacial erosion (e.g., Harbor, 1992; Hallet et al., 1996) we conclude that the glacial trough reflects significant modification of the landscape during the last and the penultimate glacial cycles.

5.3. Quaternary glaciations in the Tumur Peak area

The ESR and OSL ages presented here and in other published literature provide an opportunity to propose a comprehensive reconstruction of the Quaternary glaciations in the Tumur Peak area and to compare this with other regional records. Based on the current work and other published studies (Zhao et al., 2009a,b; 2010), dated glacial landforms record periods of enhanced glaciation in the Tumur Peak area during the LIA, Neoglaciation, early Holocene, MIS 2, mid-MIS 3, MIS 4, penultimate glaciation (MIS 6) and MIS 12 (Fig. 10). The locations and ages of glacial landforms from the last glacial cycle indicate that the largest local last glacial maximum (LGM_L) occurred during MIS 4 rather than the global Last Glacial Maximum (LGM_G, MIS 2). Furthermore, a large glacial advance that was slightly larger than that of MIS 2 occurred in this area during mid-MIS 3 (Fig. 10b).

The glacial landforms of the Tailan glaciation in the Tailan River valley, the fifth set of moraines in the Ateaoyinake River valley (Zhao et al., 2009a), and the Kezibulake glacial plain in the Muzart River valley (Zhao et al., 2010) indicate that piedmont glaciers were well developed and prevalent in the Tumur Peak area in MIS 6. The glacial till of the “Qingshantou Glacial Stage” and its ESR age (440.6 ± 41.7 ka) in the Ateaoyinake River valley (Zhao et al., 2009a), the highest glacial terrace and its ESR age (418.9 ± 41.9 ka) in the Tumur River valley (Zhao et al., 2009b), as well as the two ESR ages (459.7 ± 46 and 471.1 ka) of the Gaowangfeng till near the headwaters of the Urumqi River in the eastern segment of the Tianshan range (Zhao et al., 2006; Zhou et al., 2006), indicate that the central and the eastern segments of the Tianshan range were sufficiently elevated to develop glaciers during the mid-Pleistocene.

6. Conclusions

Geomorphological mapping, absolute age dating using ESR, and field investigations of the sedimentology and lithology of glacial and fluvioglacial deposits in the Tailan River valley provide new insight into the record of glaciation in the Tumur Peak area, and also contribute to a better understanding of patterns of paleoglaciation along the Tianshan range in central Asia. The end moraines that are present at the terminuses of the modern glaciers in the Tailin River valley were deposited during the LIA. The outermost end moraine of the Piyazili end moraines was deposited in the early Holocene and the other end moraines of this moraine complex were formed during the Neoglaciation (glacial advances during the last 3–4 ka). Multiple end moraines of the third moraine complex were deposited during the last glacial cycle, corresponding to MIS 2–4, and hummocky moraines of the Tailan Glaciation on the piedmont were formed during MIS 6. Moraines on the Kokdepsang plateau are the oldest glacial landforms in this drainage, and are assigned to deposit during MIS 12 glaciation.

The landforms and chronology indicate that the ancient Qiongtelian glaciers were large compound valley glaciers during the LIA, Neoglaciation and early Holocene periods and the last glaciation, and were piedmont glaciers during MIS 6. At their maximum extensions, the ancient Qiongtelian glaciers during these glacial advances were approximately 26 km, 29 km, 62 km and 73 km long. The palaeo-ELA was about 520 m lower than present during the maximum extent of the last glacial cycle.

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