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Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions

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Abstract

The sedimentology and geomorphology of landforms along Keriya River, that traverse the Kunlun Mountains and Taklamakan Desert, were studied to examine the relationship between environmental change and landscape evolution in mountains and desert margins of the Taklamakan Desert. The region is divided into four geomorphic provinces: desert with active dunes and sand seas; desert pediment with fans; and foothills with deep gorges and glaciated mountains. A succession of three fans with dunes is differentiated on the basis of morphostratigraphy and relative weathering. The oldest fan and dunes are radiocarbon dated to ~29 ka. This fan probably formed as a response to increased meltwater and sediment loads as glaciers retreated at the end of the local last glacial maximum in the Kunlun Mountains. Periglacial and glacial features throughout the region show that, during the last glacial, the snowline was lowered to ~4000 m a.s.l., permafrost existed down to an altitude of ~1800 m a.s.l., and that the likely temperature depression was ~10°C. Radiocarbon dates on sand dunes and tamarisk hills help define the age of the lower two terraces to >1.5 ka and a few hundred years BP. This suggests that these terraces may have formed in response to increased precipitation during more humid times at ~2 ka and during the Little Ice Age, respectively. The landforms and sediments in this region are polygenetic in origin, being transported, eroded and deposited by glacial, fluvial, aeolian and lacustrine processes. Particle size characteristics show that the fluvial sediments were substantially modified down basin. In contrast, the aeolian sediments were modified as they were transported toward the mountains from the desert by the dominant northerly winds. This complex interaction between environmental change and earth surface processes provides an important framework for examining the environmental consequences of the recently growing population and intensified agricultural activities along the mountain and desert margins of the Taklamakan Desert.

1. Introduction

Since the late 19th century, a large number of scholars, travelers and adventurers have conducted expeditions into the Taklamakan Desert (e.g. Hedin, 1899, 1904; Norin, 1932; Zhu et al., 1981; Hoevermann and Hoevermann, 1991; Yang, 1991). Many of the former studies and reports concentrated on the archaeological, geomorphological and resource-economic aspects of the dune fields (e.g. Zhao and Xia, 1984; Jaekel, 1991; Chinese Academy of Sciences, 1993, 1994; Lehmkuhl and Haselein, 2000). Some of the former studies suggested that central Asia, including the Tarim Basin, became progressively more arid as the Tibetan Plateau uplifted during the Tertiary and Quaternary (e.g. Zhu et al., 1980; Ren, 1980; Shi et al., 1998). However, few detailed studies have examined the nature of Late Quaternary environmental change in the Taklamakan Desert or the relationship between environmental changes on the Tibetan Plateau and within the Taklamakan Desert. In this paper we will, therefore, describe the sedimentological and geomorphic evidence along the Keriya River (Fig. 1) to elucidate the nature of paleoenvironmental change along the southern margin

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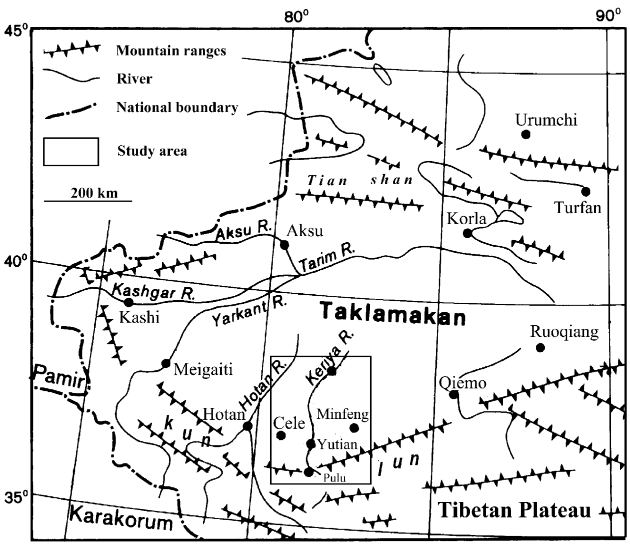

Fig. 1. Mountains and rivers of western China.

of the Taklamakan Desert and to examine the relationship between glaciation in Kunlun Mountains and fluvial–lacustrine sediments in the Taklamakan desert.

The Keriya River basin was chosen as a study area because it provides an opportunity to examine the direct links between mountain and desert environments in western China. Furthermore, the Keriya River is a particularly good study area because it has no tributary channels in the Taklamakan Desert and, therefore, changes in the fluvial regime probably reflect the climatic history and particularly the glaciation of the mountains of Tibet. A systematic investigation of the landscape evolution along the Keriya River provides not only evidence for the glacial history of the Tibetan Plateau, but also the environmental changes that take place along desert margins. This is particularly important for elucidating the evolution of the oasis and dunes in the desert and for predicting future changes in the light of possible human-induced environmental and climatic change. In addition, a clear understanding of the forcing factors for desertification and the development of oases is crucial for environmental protection in such ecologically fragile regions.

2. Regional setting

The Keriya River originates in the Kunlun Mountains at the northern margin of the Tibetan Plateau (Fig. 1). The Kunlun Mountains rise to an altitude of >7000 m a.s.l. and are the consequence of the continued collision of the Indian and Asian continental lithospheric plates since ~ 50 Ma. The Keriya River descends northwards from the Kunlun Mountains into the Taklamakan Desert in the center of the Tarim Basin. The tectonically active Tarim Basin comprises Miocene to Recent continental sedimentary fill that overlies Archaeozoic and Proterozoic basement (Institute of Geology, Academia Sinica, 1958). Unconsolidated sediments are generally 500–600 m thick, but may exceed 900 m thick in the southern margin of Tarim Basin (Li and Zhao, 1964). Along the Kunlun Mountains, the Keriya River has incised 117 m during the Quaternary (Xinjiang Expedition Team, 1978).

Seventy one percent of the Keriya River's discharge is a consequence of melting glaciers and snow in the mountainous region of upper reaches, with direct precipitation and groundwater accounting for 9% and 20%, respectively (Cheng, 1991). The middle and lower parts of the drainage basin are characterized by arid to extremely arid climates. Both the daily weather system and the mean atmospheric flow are strongly influenced by the relief in the Tarim Basin and the adjacent mountains. Over the whole Tarim Basin, at altitudes above 4000 m a.s.l., the atmosphere is characterized by a subtropical high-pressure system. Over the desert in the summer, anticyclonic and cyclonic conditions dominate in the lower troposphere (up to 3000 m a.s.l.) in the east and west, respectively. The divergence line near the ground surface is located near the Keriya River. In winter, the entire basin is dominated by a high-pressure system and anticyclonic conditions up to 3000 m a.s.l. The airflow above 3000 m a.s.l. has little connection with the surface air patterns. The annual precipitation increases significantly from the center of the basin ($\leqslant 16.1\ \mathrm{mm\,a^{-1}}$) southwards to the mountain front, with $44.1\ \mathrm{mm\,a^{-1}}$ in Yutian and $195.1\ \mathrm{mm\,a^{-1}}$ in Pulu. The average annual temperature also decreases in the same direction, from 11.2°C to 4.7°C. The temperature difference between sites along the Keriya River is larger in summer than in winter. The average monthly temperature in July and January is 25°C and −6°C and 15.6°C and −9.8°C in Yutian and Pulu, respectively (Lin, 1991).

As a consequence of altitudinal and climatic contrasts, vegetation varies considerably along the Keriya River. On the northern slope of Kunlun Mountains there is spare brush vegetation consisting dominantly of *Artemisia, Ephedra, Zygophyllum, Gymnocarpus, Sympegma* and *Anabasis*. On the old abandoned river channels halophilic plants are common including *Salsola, Suaeda, Kalidium, Tamarix,* whereas along the contemporary river channels the vegetation is comprised mainly of *Populus, Tamarix, Ulmus, Hippophaea, Phragmites* and *Eleagnus* (Yang, 1991).

3. Methods

Along the Keriya River, field investigations concentrated on six main sites (Pulu, Yutian, Yaogantuokelake, Ateyilahe, Kekelike and Daheyan) between 36°

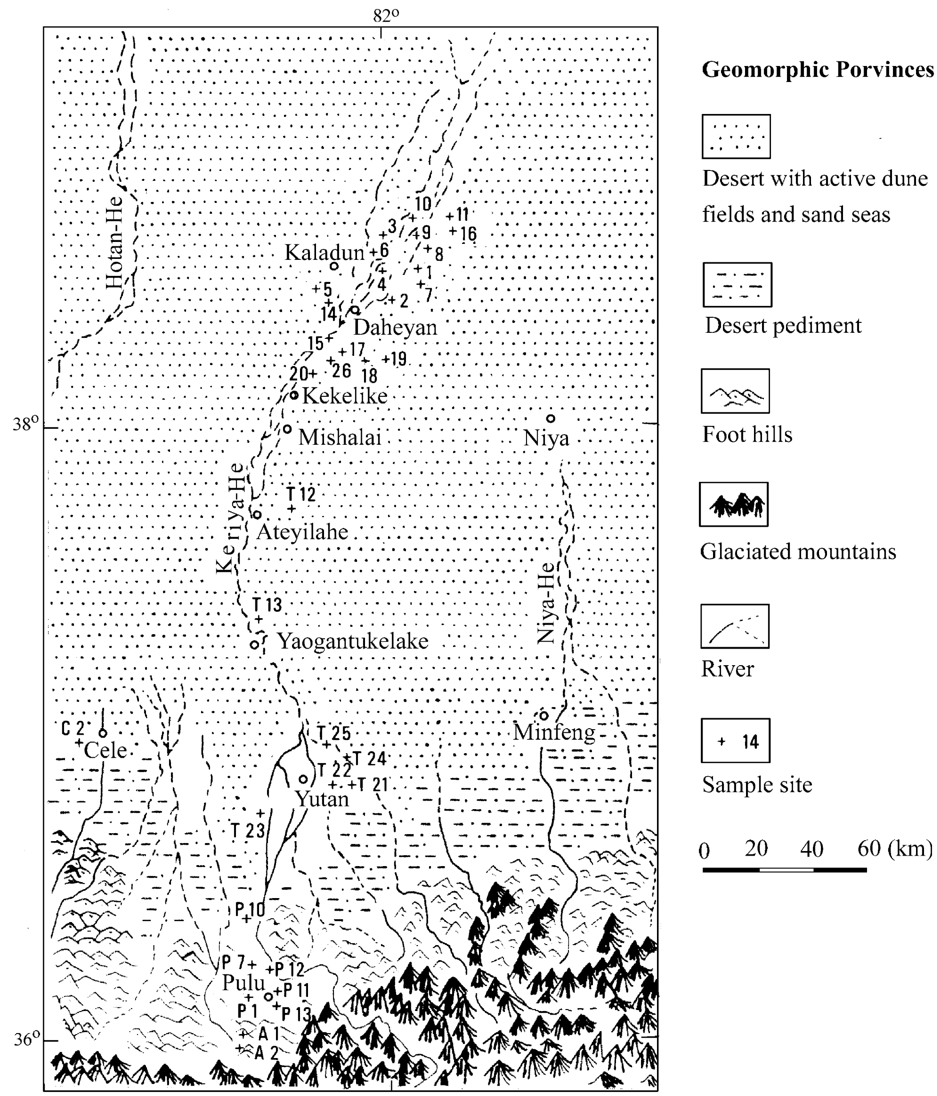

Fig. 2. Landscape types and location of samples along the Keriya River.

and 39°N, and 81° and 83°E (Fig. 2). Chinese 1:100,000 scale topographic maps, 1:500,000 scale Landsat MSS images, 1:60,000 scale aerial photographs and field observations were used to produce geomorphic maps. Graphic sedimentary sections and profiles across sand dunes were measured using basic surveying techniques including simple leveling using a tape measure and a Thrommen level.

Sixty-six samples of glacial, fluvial and aeolian sediment were collected at selected sites along and adjacent to the Keriya River for particle size and heavy mineral analysis (Fig. 2). The composition and particle size characteristics of the sand varied up the dunes. To make the regional comparisons valid, only sand samples from the crest in the dunes areas were collected. Loess samples from the top of the slopes were also collected. Samples were numbered by their geographical location and position within each sedimentary section (Fig. 2 and Table 1).

Particle size analysis was undertaken by combination of dry sieving and sedimentation methods. Folk and Ward (1957) statistics were applied to compare the particle size distributions. Samples for mineralogical analysis were sieved to collect the 10–25 μm fraction and the heavy minerals (densities $>2.9\,g/cm^3$) were separated using heavy liquids. For each sample, 400–500 heavy mineral grains were examined and identified under an optical microscope. Prof. M. Geyh at the ^{14}C and ^{3}H Laboratory in Hannover undertook the radiocarbon dating of calcium carbonate and wood samples.

4. Geomorphic provinces

On the basis of landforms, sediments and geomorphic processes, the Keriya River can be divided into four geomorphic provinces. These include: desert with active dune fields or sand seas below 1400 m a.s.l.; desert

Table 1
Particle size parameters of sediment samples from the area of Keriya River. Fig. 2 shows the location of each sample site, the first part of the sample number refers to the location while the second part refers to the position of the sample within a section

Sample number	Sample type	Mean (∅)	Mean (mm)	Sorting (∅)	Skewness (∅)	Kurtosis (∅)	Position of sample within each section
1_1	Fluvial	4.03	0.0612	0.53	0.63	2.48	Lower part of the fluvial terrace (bottom)
1_2	Fluvial	3.93	0.0656	0.26	0.45	1.97	Middle part of the fluvial terrace (40 cm upwards)
1_3	Fluvial	3.92	0.0661	0.35	0.49	2.77	Upper part of the fluvial terrace (80 cm upwards)
2_1	Aeolian	3.19	0.1096	0.75	−0.32	0.66	Ridge of a 3 m high dune
2_2	Aeolian	3.9	0.0670	0.41	−0.3	1.92	Foot of the dune
3_1	Aeolian	3.25	0.1051	0.68	−0.43	0.78	Foot of the 30 m high dune
3_2	Aeolian	2.92	0.1321	0.68	0.23	0.68	10 m from foot of dune
3_3	Aeolian	3.19	0.1096	0.56	−0.06	0.74	20 m from foot of dune
3_4	Aeolian	3.04	0.1216	0.61	0.06	0.74	Ridge of the dune
4	Aeolian	3.99	0.0629	0.21	−0.08	0.72	New sand ripple on the river bed
5_1	Fluvial	3.91	0.0665	0.25	−0.09	1.08	Lower part of the lower fluvial terrace (50 cm below top of section)
5_2	Aeolian	4.71	0.0382	0.91	0.7	0.98	Aeolian sand bed in the lower fluvial terrace (30 cm below top of section)
5_3	Fluvial	3.28	0.1029	0.64	−0.15	0.7	Upper part of the fluvial terrace (20 cm below top of section)
6	Aeolian	3.89	0.0675	0.27	−0.13	1.54	Ridge of a 1 m high dune
7_1	Aeolian	3.32	0.1001	0.58	−0.22	0.73	Foot of the 40 m high dune
7_2	Aeolian	3.39	0.0954	0.54	−0.44	0.74	10 m from foot of dune
7_3	Aeolian	3.01	0.1241	0.64	0.14	0.7	20 m from foot of dune
7_4	Aeolian	2.9	0.1340	0.62	0.21	0.77	30 m from foot of dune
7_5	Aeolian	2.88	0.1358	0.57	0.23	0.98	Ridge of the dune
8	Aeolian	3.67	0.0786	0.35	−0.38	1.28	Ridge of a dune
9	Aeolian	2.93	0.1312	0.63	0.25	0.74	Ridge of a dune
10_A	Aeolian	2.8	0.1436	0.64	0.36	0.79	Ridge of a 2 m high dune covered by fluvial deposits
10_B	Aeolian	3.44	0.0921	0.53	−0.5	0.91	Ridge of a 2 m high dune
11_1	Aeolian	3.64	0.0802	0.42	−0.43	1.5	1.5 m below the sand surface
11_0	Aeolian	3.49	0.0890	0.49	−0.46	0.86	Lower area between two dunes
14	Aeolian	2.7	0.1539	0.73	0.46	0.87	Ridge of a dune
15	Aeolian	2.3	0.2031	0.57	0.43	1.42	Ridge of a dune
16	Aeolian	2.8	0.1436	0.51	0.16	1.18	Ridge of a dune
17	Aeolian	3.04	0.1216	0.65	0.11	0.65	Ridge of a dune
18	Aeolian	3.82	0.0708	0.33	−0.3	2.33	Ridge of a dune
19	Aeolian	2.44	0.1843	0.99	0.51	0.52	Ridge of a dune
20	Aeolian	3.38	0.0961	0.71	−0.56	0.75	Sand hill with *Populus* growing on it
26_1	Fluvial	3.87	0.0684	0.35	−0.16	1.64	Bottom of the fluvial terrace
26_2	Fluvial	3.51	0.0878	0.68	−0.5	0.74	Middle of the fluvial terrace (2.5 m from the base of section)
26_3	Fluvial	3.95	0.0647	0.27	−0.18	1.05	Upper part of the fluvial terrace (5.5 m from the base of section)
C2	Aeolian	3.59	0.0830	0.61	−0.52	2.08	Ridge of a 2 m high dune on the dried river bed
P1	Aeolian	4.4	0.0474	0.76	0.59	3.75	Surface material
P7	Aeolian	4.07	0.0595	0.41	0.18	2.14	Surface material
P12	Fluvial	2.84	0.1397	1.89	0	0.78	Fluvial sand on the river bed
P10	Aeolian	3.89	0.0675	0.2	0.39	1.18	Surface material
P11	Aeolian	4.7	0.0385	0.88	0.71	0.99	Surface material
P13_2	Glaciolacustrine	4.56	0.0424	0.78	0.69	1.25	Upper part of the section
P13_3	Glaciolacustrine	4.63	0.0404	0.8	0.73	1.1	Lower part of the section
T12_1	Aeolian	3.04	0.1216	0.88	−0.35	1.86	Western foot of the 80 m high dune (see Fig. 11)
T12_2	Aeolian	3.19	0.1096	0.88	−0.63	0.58	10 m from foot of dune (see Fig. 11)
T12_3	Aeolian	2.61	0.1638	0.85	0.66	0.65	20 m from foot of dune (see Fig. 11)
T12_4	Aeolian	3.17	0.1111	0.76	−0.35	0.58	30 m from foot of dune (see Fig. 11)
T12_5	Aeolian	2.8	0.1436	0.74	0.53	0.54	40 m from foot of dune (see Fig. 11)
T12_6	Aeolian	2.95	0.1294	0.68	0.24	0.55	50 m from foot of dune (see Fig. 11)
T12_7	Aeolian	2.75	0.1487	0.77	0.54	0.56	60 m from foot of dune (see Fig. 11)
T12_8	Aeolian	2.24	0.2117	0.24	0.4	0.56	Ridge of the dune (see Fig. 11)
T12_9	Aeolian	2.23	0.2132	0.34	0.33	2.21	60 m from foot of dune (see Fig. 11)
T12_10	Aeolian	2.44	0.1843	0.69	0.53	1.16	50 m from foot of dune (see Fig. 11)
T12_11	Aeolian	3.22	0.1073	0.76	−0.59	0.6	40 m from foot of dune (see Fig. 11)
T12_12	Aeolian	3.01	0.1241	1	−0.44	0.59	30 m from foot of dune (see Fig. 11)

Table 1 (*continued*)

Sample number	Sample type	Mean (∅)	Mean (mm)	Sorting (∅)	Skewness (∅)	Kurtosis (∅)	Position of sample within each section
T12_13	Aeolian	3.56	0.0848	0.5	−0.56	1.28	20 m from foot of dune (see Fig. 11)
T12_14	Aeolian	3.42	0.0934	0.66	−0.62	1.1	10 m from foot of dune (see Fig. 11)
T12_15	Aeolian	3.12	0.1150	1.02	−0.71	0.61	Eastern foot of the dune (see Fig. 11)
T13_A	Aeolian	2.51	0.1756	0.47	0.41	1.46	Ridge of a 30 m high dune
T13_B	Lacustrine	4.35	0.0490	0.53	0.5	2.87	Base of the dune (possibly lacustrine)
T21	Aeolian	2.79	0.1446	0.45	0.25	1.32	Ridge of a 30 m high pyramid dune
T22	Aeolian	2.53	0.1731	0.5	0.39	1.23	Ridge of a 50 m high pyramid dune
T23	Aeolian	2.33	0.1989	0.75	0.51	1.61	Aeolian sand on the river terrace
T24_A	Fluvial–lacustrine	5.47	0.0226	1.15	−0.13	0.67	Upper part of 5 m thick section
T24_B	Fluvial–lacustrine	4.32	0.0501	0.5	0.56	2.74	Lower part of a 5 m thick section
T25	Fluvial	3.93	0.0656	0.31	−0.14	1.5	Fluvial sand beneath a 20 cm thick aeolian sand deposit

Fig. 3. View looking eastwards from the crest of a 70 m high dune at Ateyilahe. Secondary dunes are present on the slopes of the longitudinal dune ridges. The orientation of the primary dune ridges is more stable, whereas the trend of secondary dunes varies according to the seasonal winds.

Fig. 4. View of typical dome-shaped dunes at Daheyan. Note the *Tamarix* and *Populus* vegetation that surrounds the dunes.

pediment (Gobi—see Zhao, 1994) between 1400 and 2,000 m a.s.l.; and foothills with desert gorges covered by sand and silt and sandy loess between 2000 and 4500 m a.s.l.; and the glaciated mountains above 4500 m a.s.l.

4.1. Desert with active dune fields and sand seas

In the lower reaches of the Keriya River, especially below 1400 m a.s.l., large areas of the southern Taklamakan Desert are covered with shifting dunes. Dune forms are highly variable, and using a generalized classification adapted from Zhu et al. (1981), they comprise barchans, barchan ridges, longitudinal dune ridges, pyramid dunes and dome-shaped dunes. Superimposed secondary dunes are often developed on the larger primary dunes. The height of the dunes varies considerably from ~100 to <50 m on the east and western side of the Keriya River, respectively (Fig. 3). Most dunes, especially on the eastern side of the Keriya River, trend NW–SE as a consequence of the dominant northeastern winds. In the Daheyan delta region of the Keriya River, dome-shaped dunes dominate and reach 40 m in height (Fig. 4).

The fluvial sediments and landforms along the Keriya River provide an opportunity to produce relative and numerical ages of the sand dunes. A succession of three river terraces is present at Yaogantukelake. The highest river terrace, >20 m above the contemporary riverbed, is overlain by a dark red sand dune. The river terrace comprises fluvial sediment that is dominantly fine silt, weakly cemented with calcium carbonate, and contains calcareous nodules that have been radiocarbon dated to 28,740±1500 yr BP in the upper portion of the terrace (Hv 14896, Fig. 5). The middle river terrace, 8–10 m above the contemporary riverbed, is covered by tamarisk mounds, some of which have been highly deflated. Light yellow sand dunes are present between the tamarisk mounds. Wood directly from the base of a tamarisk mound southeast of Cele provided a radiocarbon date of 1500±90 yr BP (Hv 14818). The lowest river terrace, 1–4 m above the river, has white sand dunes and is covered with *Populus eupharatic*a. Small

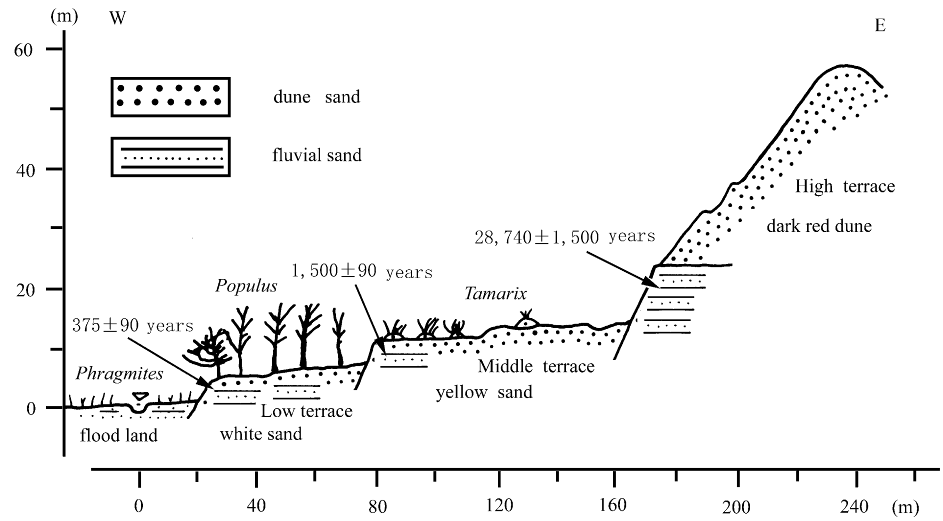

Fig. 5. A schematic profile and section through dunes at Yaogantukelake. The age of the middle fan terrace is correlated with the fan terrace near Cele and the low terrace is correlated with a terrace to the north that has been radiocarbon dated.

barchans and tamarisk mounds are presently forming on this terrace. A 5 m high tamarisk mound on the low terrace at Kekelike contained four organic rich horizons comprising *Populus* leaves. These horizons, from the base up, provided radiocarbon dates of 375 ± 90 BP (Hv 14898), 250 ± 75 BP (Hv 14811), 155 ± 90 BP (Hv 14812) and 95 ± 60 BP (Hv 14814). The top of the tamarisk mound was covered with modern shifting sand.

Using 1:500,000 scale Landsat MSS imagery, the ancient riverbed of the Teriya River can be traced from Daheyan to the Tarim River at the northern edge of Tarim Basin. White sand dunes $\leqslant 10$ m high are present on this ancient riverbed together with exposures of fluvial and pond deposits. Calcium carbonate is concentrated at the base of some of these pond deposit and yield radiocarbon ages of 21.77 ± 0.78, 20.82 ± 0.87, 17.25 ± 0.47, 16.91 ± 0.42, 13.15 ± 0.20 and 13.01 ± 0.48 ka for different ponds (Gibert et al., 1995).

Fig. 6. Granite and gneiss boulders at 1920 m a.s.l., ~20 km west of Yutian. These boulders reach 50 cm in diameter and they were probably transported by glaciofluvial floodwaters from the upper reaches of the Keriya River.

4.2. Desert pediment

A zone of inclined plains (20–80 km wide) is present between the dune fields of the Taklamakan and the Kunlun Mountains. Within these plains, fluvially eroded gullies are filled with aeolian sand. The aeolian sand deposits generally comprise a relatively thin (<1 m) veneer on top of bouldery fanglomerates, but thicker (1–3 m) aeolian sands do occur at a few locations. The boulders within the fanglomerates comprise dm- and m-size granitic and metamorphic rocks that outcrop above 1920 m a.s.l. to the west of the Keriya River (Fig. 6). The fanglomerates have not been dated by any geochronological technique, but along the Keriya River three sets of glaciofluvial fans can be distinguished on the basis of morphostratigraphy and the weathering characteristics of the overlaying dunes (Fig. 7). The oldest and biggest fan originates at an altitude of 2200 m a.s.l. This descends to the oasis of Yutian at 1450 m a.s.l. The fan has an average slope of 1.4% over a distance of 50 km. East of the Keriya, the middle fan has an average slope of 1.8% from 2000 to 1450 m a.s.l. The youngest fan is the smallest in the region, and is located above the older fans. These fans are morphologically separated by the small gullies, which are partially filled with aeolian sand. Slope gradients are very low in the lower stretches of all the fans and the fan form is, therefore, most easily recognized near their apexes along the mountain front. Small southward migrating dunes from the Taklamakan occasionally encroach on to the desert toes of the fans.

The Ice-wedge casts are common throughout the region with notable examples on fans south of Cele at an altitude of ~1800 m a.s.l. Here, the ice-wedge casts are ~50 cm deep and ~20 cm wide and are filled with

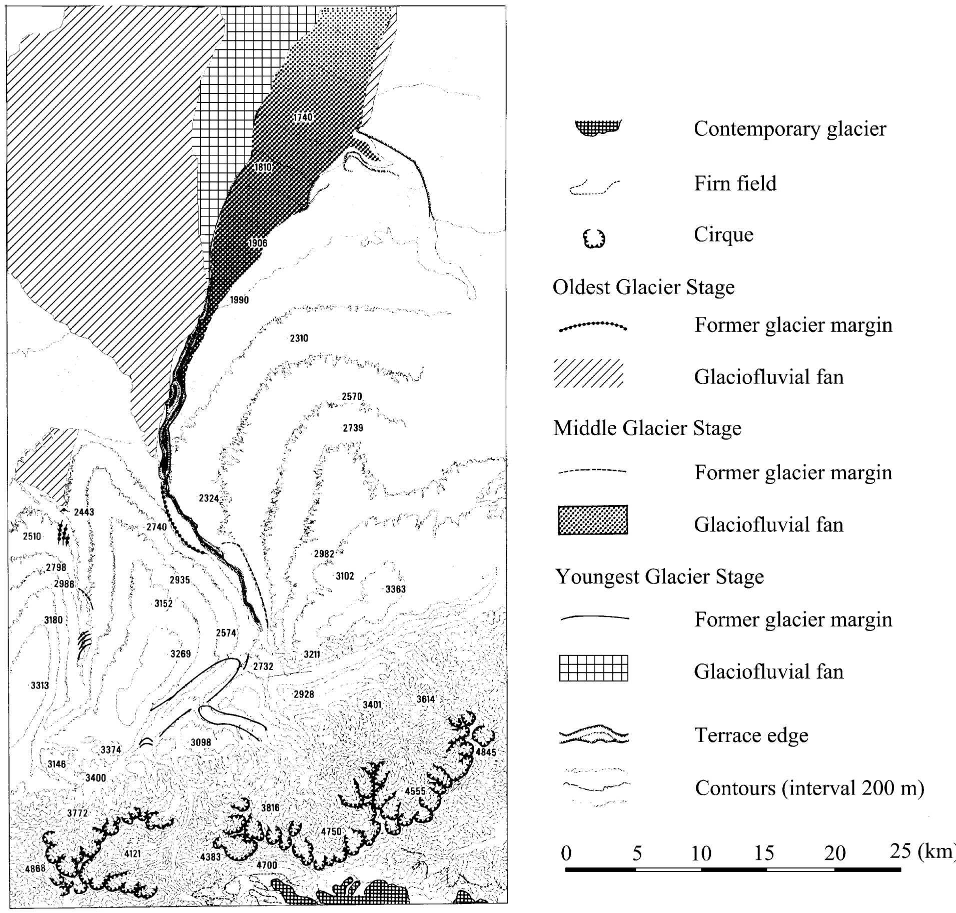

Fig. 7. The former extents of glaciers and fans in the Keriya River basin (modified from Hoevermann and Hoevermann, 1991).

unweathered laminated sands. Networks of frost cracks on terraces near Cele are also present (Hoevermann and Hoevermann, 1991).

4.3. *Foothills and glaciated mountains*

The foothills rise between ~2100 and 4500 m a.s.l. where they are replaced by the glaciated mountains of the Kunlun. At altitudes of between 2100 and 2500 m a.s.l., the foothills are deeply incised by vertical or v-shaped gorges. Large boulders are present on the walls of these gorges. A thin (<10 m) deposit of aeolian sand and silt caps the hills between the gorges (Fig. 8). Above 3100 m a.s.l., periglacial landforms and processes dominate. Solifluction terraces are present on the slopes between 3100 and 5500 m a.s.l. Inactive funnel-shaped nivation hollows and ramparts are the most conspicuous landforms between 3100 and 3800 m a.s.l. Based on the distribution of periglacial stone circles, Hoevermann and Hoevermann (1991) suggested that they probably did not form below 4000 m a.s.l. during the local last glacial.

Glacial deposits are also present along the walls of some of the valleys. Cirque basins occur on the northern slope of the Kunlun Mountains at elevations of ~5500 m a.s.l. The heights of the cirques suggest that the snowline in the upper reaches of the Keriya River is

Fig. 8. View looking south from Pulu at an altitude of 2800 m a.s.l. at the desert gorges and glaciated upland. The floor of the deep gorge in the foreground is at 2500 m a.s.l. Sandy loess is present on the lower slopes and nivation hollows and ramparts can be seen on the steep mountain slopes. The elevation of the cirque basin in the center of the plate is about 5500 m a.s.l.

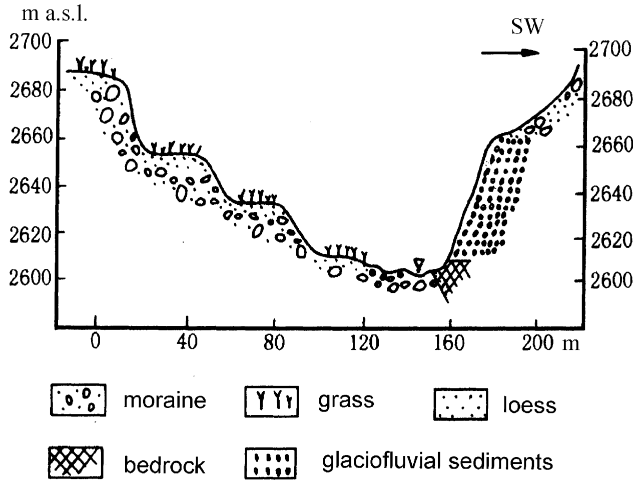

Fig. 9. Schematic cross section and profile at Pulu.

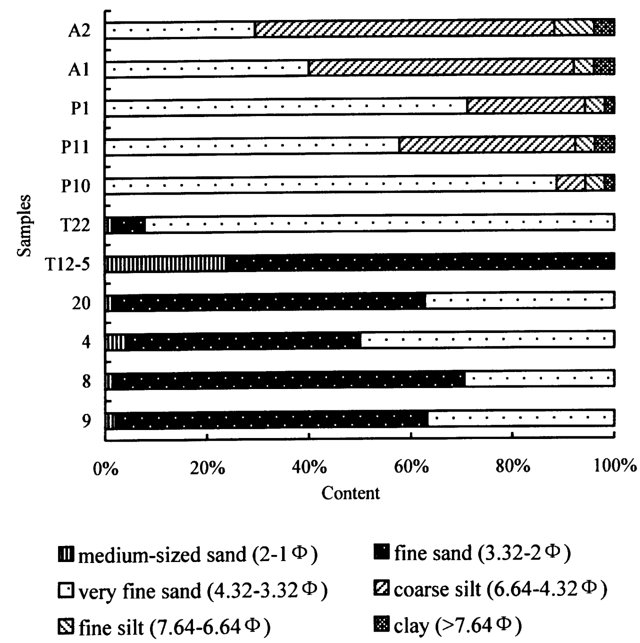

Fig. 10. Particle size distribution for selected aeolian sediments along the Keriya River (see Fig. 2 for sample locations). Samples A2 and A1 are loess, P1, P11 and P10 are sandy loess and T22, 20, 4, 8 and 9 are dune sands.

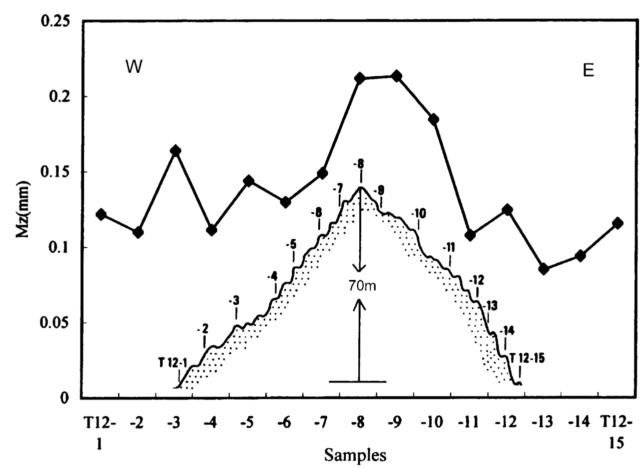

Fig. 11. Variation in the mean particle size for sand from a 70 m high sand dune at Ateyilahe (see Fig. 2 for the sample locations).

~5500 m a.s.l. (Hoevermann and Hoevermann, 1991). Hoevermann and Hoevermann (1991) described the glacial landforms in the Pulu basin that lie at an altitude of between 2700 and 2450 m a.s.l. (Fig. 7). They believed that these landforms were produced during the last glacial. In this basin, however, we have also mapped moraines up to an altitude of more than 3000 m a.s.l. The moraines comprise bouldery diamicts and occur at several locations along the basin floor. At the western edge of the basin, the river has cut through moraine deposits to bedrock (Fig. 9). The height of the moraines and depth of the glaciated valley shows that the glaciers in this basin must have reached a thickness of ~300 m. Terraces are associated with these moraines and they comprise meter-size boulders of plutonic igneous rocks. These boulders are derived from the high mountain ranges of Kunlun, whose summits are more than 6000 m a.s.l. The catchment area for the Keriya River extends well into the Tibetan Plateau. The river valley traverses several mountain ranges, and therefore the glacial boulders in the moraines may be derived from extreme distances via this conduit. A layer of sand beneath a moraine in Pulu that is believed to represent the local last glacial maximum has a TL-date of 31,000 $\pm$ 1500 BP (Hoevermann and Hoevermann 1991).

5. Sedimentological analysis

5.1. Granulometric analysis

Both the mean particle size and the particle size distributions show that fluvial sediment becomes finer from the upper to lower reaches of the Keriya River (Table 1). The aeolian sediments, however, coarsen into the basin. Loess dominates at altitudes of between 2500 and 3400 m a.s.l., being replaced by sandy loess-like sediment between 2000 and 2500 m a.s.l. and very fine to fine dune sands at lower altitudes (Fig. 10). The particle size characteristics also vary within dunes. For example, a 70 m high dune at Ateyilahe shows a progressive increase in mean particle size up the dune (Fig. 11). Furthermore, particle size analysis also shows that the older dune sands are coarser than in the younger dunes. Fig. 12 shows the general decrease in particle size for aeolian sediments from Daheyan in the lower reaches to the upper reaches of the Keriya River. The coarsest aeolian sediments are from dark red dunes on river terraces near Yaogantukelake and Ateyilahe.

Overall, the particle size distributions show considerable variability from very well to poorly sorted, and dune sands are not better sorted than the fluvial and lacustrine sediments. The aeolian sediment does not show any progressive sorting of aeolian sediment into the basin. However, the fluvial sediments clearly become better sorted into the basin. A large number of samples are very positively skewed (>0.3), however, negatively skewed distributions are common from the foot of dunes or from riverbeds. Generally, the samples are platykurtic to mesokurtic ($K_G<1.11$), but some of the loess-like sediments from the foothills are very leptokurtic ($K_G>1.5$).

5.2. Mineralogical analysis

Most of the sediment comprises feldspar and quartz with the heavy mineral content varying from 4.8% to 17.5% (Fig. 13). The light yellow or white–gray sand dunes had the highest percentages of heavy minerals. The heavy mineral assemblages are similar for all the

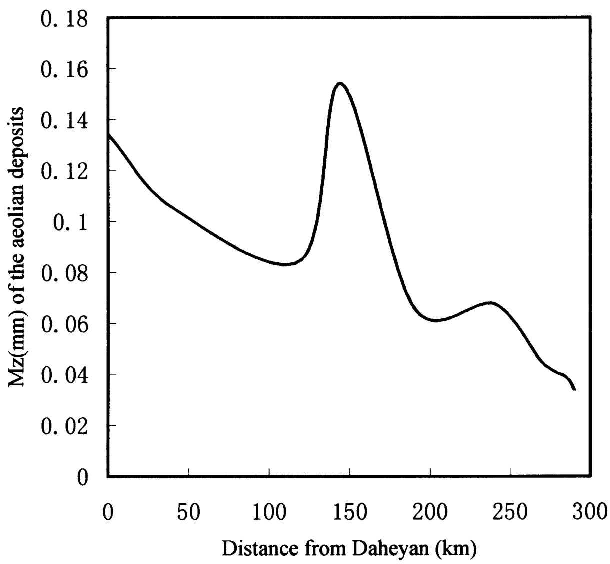

Fig. 12. Variation in the mean particle size for aeolian sediments up the valley from Daheyan. The samples were collected from the crests of dunes in the dune field and from top of slopes in foothills of Keriya River basin.

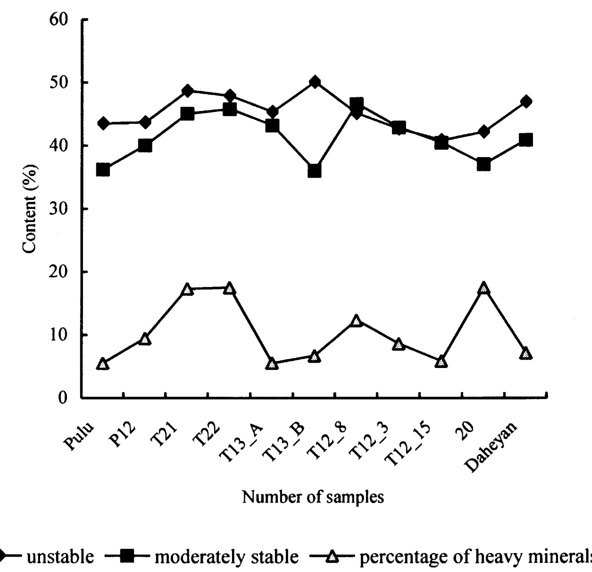

Fig. 13. Variation in the heavy mineral content (unstable and moderately stable fractions) for aeolian sediments that were collected along the Keriya River (see Fig. 2 for the sample locations). Pulu—average of four samples, Daheyan—average of four samples.

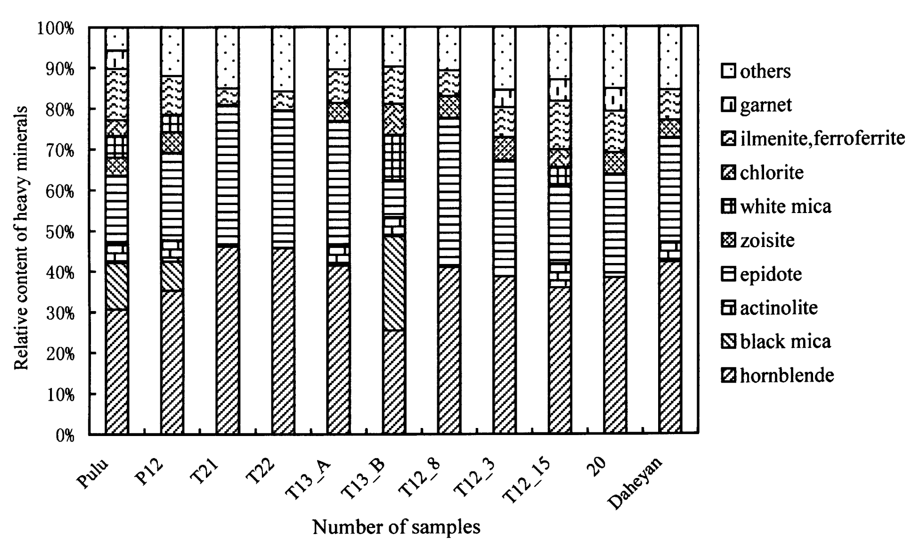

Fig. 14. Variation in the heavy mineral assemblages for the aeolian sediments along the Keriya River (see Fig. 2 for the sample locations). Pulu—average of four samples, Daheyan—average of four samples.

samples, with hornblende and epidote accounting for most of the sediment (Fig. 14). The percentage of unstable minerals and moderately stable minerals in the heavy mineral assemblages varied from 38.7% to 51.0% and from 30.1% to 46.6%, respectively.

6. Discussion

Reconstruction of the changes in the hydrological regime in the Tarim Basin and adjacent mountains during the last glacial cycle is not straightforward, but the terraces and dune successions along the Keriya River provide good insight into the paleoenvironmental changes that have taken place in this region. The geomorphology and Landsat imagery show that during the last glacial the Keriya River was much more extensive than at present and at times it extended northwards to join the Tarim River at the northern edge of the Tarim Basin. Radiocarbon dates on pond sediments that are associated with Keriya River deposits all date to the late last glacial (Gibert et al., 1995) indicating that the Keriya River was actively flowing into the Tarim River at this time. Prior to this, the upper reaches of the Keriya River, in the Kunlun Mountains, were extensively glaciated. The moraines at Pulu show that the local last glacial maximum occurred shortly after $\sim 31 \pm 1.5$ ka. This was probably a time of increased precipitation, although the lacustrine record from the Lake Manas in the Zhungar Basin (Rhodes et al., 1996) suggests that the maximum increased humidity occurred between 37–32 ka. It is feasible that deglaciation may have been important in providing more waters to the Keriya River and that sedimentation increased during this time to produce the extensive highest fan along the Keriya River that is dated to $\sim 28.7 \pm 1.5$ ka. If this is the case, then the highest fan may be described as paraglacial (Ryder, 1971a, b) in origin. Furthermore, the younger fans in this region may have also been produced during times of landscape readjustments when glaciers are retreating. Owen and Sharma (1998) and Barnard et al. (2000) suggest this is an important factor in the formation of fans in high mountain regions, such as the Himalayas and Tibet.

The glacial record and our observation of ice-wedge casts leads to the conclusion that temperature decreased considerably in the Tarim Basin during the last glacial and permafrost conditions occurred down to elevations as low as 1800 m a.s.l. Presently, the average annual temperature at 1400 m a.s.l. at Cele is 11.7°C, and using an environmental lapse rate of $7.2°C\,km^{-1}$ between Yutian and Pulu, the average annual temperature at 1800 m a.s.l. is estimated to be 7.9°C. With an average annual temperature of $\leqslant -2°C$ for ice-wedges to form (Washburn, 1980), the average annual temperature depression along the southern margin of the Taklamakan Desert during the last glacial must have been $\sim 10°C$. Similarly, Owen et al. (1998) showed that permafrost conditions existed in the Gobi of Mongolia during 22–15 ka and they estimated that average mean annual temperature was $\sim -6°C$.

The map of China produced during the Chinese Xihan Dynasty (206 BC–25 AD) shows that the Keriya River flowed across the Taklamakan Desert into the Tarim River, thus confirming wetter conditions. Furthermore, artifacts of middle Stone Age found in Pulu and ruined settlements in the dune fields also confirm wetter conditions (Yang, 2001). Therefore, it is possible that the middle fan along the Keriya River was formed during this wetter time. Presently, however, its age is only defined by a radiocarbon date of 1500 ± 90 BP on a tamarisk mound on the top of the terrace. The fan, therefore, may be considerably older than the tamarisk mound and might possibly relate to an Early Middle Holocene wet phase that was described by Rhodes et al. (1996) in the Zhunger Basin.

Historical documentation and maps also show that the Keriya River flowed into the Tarim River during the 16th and the beginning of the 19th centuries (Yang, 1991). These periods are broadly coincident with the Little Ice Age (Grove, 1988). The relatively young ages of the dunes on the different fans confirm that the fluvial areas, and consequently the oasis, were much larger before the formation of these dunes.

Along the Keriya River basin, the sediments and landforms have been reworked continuously by glacial, nival, glaciofluvial, fluvial and aeolian processes. This is evident from the progressive degrees of weathering between the terraces and dune successions, and the sedimentary characteristics of the samples that were examined in this study. The particle size analysis, for example, suggests that the dunes along the Keriya River are relatively youthful. The positive skewness (high percentage of fine grains) of the most samples is indicative of very active ergs (Besler, 1980). In addition, the high concentrations of unstable heavy minerals are indicative of little chemical weathering that is associated with youthfulness. Furthermore, the heavy mineral assemblages show a higher concentration of unstable heavy mineral assemblages in sand samples from the younger white colored dune than the more weathered older yellow and dark red dunes.

The mesokurtic or even platykurtic ($K_G < 0.67$) nature of many of the sediment samples suggest multiple sources for the sand, possibly originating from a combination of fluvial, aeolian, glaciofluvial and even glacial environments. Furthermore, the variable heavy mineral assemblages in the samples suggest that the aeolian sands were derived from different source regions. Zhu et al. (1981) showed that along the northern and western margins of the Taklamakan Desert, the heavy mineral assemblages contained

$>40\%$ mica and $\sim 30\%$ metallic minerals, respectively. This contrasts sharply with the heavy mineral assemblages for samples from the Keriya River area. It shows that the western or northern adjacent regions of the Taklamakan Desert are not the sediment source for the aeolian deposits; rather the Kunlun Mountains are the more likely source for the sediment.

The underlying fluvial deposits are much finer than the dune sand. This suggests that the dune sands were not derived from the underlying fluvial sediments. The difference between samples T13_A and T13_B (see Fig. 14, Table 1) indicates that the dunes at Yaogantukelake are not simply derived by a deflation of fine materials of the underlain fluvial deposits. The course sand in the lower and middle reaches cannot be transported into the basin by the contemporary river because stronger fluvial processes are needed to bring such large quantities of coarse sand into the desert. It is probable that fluvial processes were more dominant during times of deglaciation of the upper reaches of Keriya River Basin.

The fining of aeolian sediments from the center of desert to the upper reaches of the river is probably a consequence of the dominant northerly winds. A notable exception to this trend occurs at 150 km south of Daheyan as shown by the prominent peak on Fig. 12. This is an area of desert where dune sands are being mixed with coarse fluvial sand due to concentrated deposition as the gradient of the river decreases as it flows into the desert province. Wind strength, and consequently aeolian deflation, is stronger on the desert plain than that in the active dune fields. The increase of mean grain size from the bottom to the top of a dune is a result of sorting due to the increasing wind velocity towards the crest of the dunes.

The geomorphology of the Keriya River basin is dominantly a consequence of Quaternary climatic change that has forced environmental changes in the mountains and forelands. Our study shows that there are strong links between glacial, fluvial, aeolian and lacustrine processes and landforms. The complexity is further heightened by human activity. In recent years, there has been a substantial increase in population and agriculture output that is modifying the natural environment and contributing to environmental degradation. Between 1949 and 1999, for example, the populations in the dry delta area of Daheyan and in Yutian County has increased from <300 to >1000 and from 81,000 to 202,000, respectively (Statistical Yearbooks of Xinjiang, 1986–1998). This has resulted in large areas of new land being cultivated, more than doubling the use of irrigation water. In particular, total cotton production increased from 764 tons to 9323 tons between 1986 and 1998. This has resulted in over-exploration of the water resources, and an increase in logging activities for firewood and construction in the middle reaches of the Keriya River basin. This in turn has resulted in a reduction of natural *Populus* population and has affected the desert ecosystem. As a consequence there has been serious localized land degradation including soil erosion and salinization. Much can be learned from examining and understanding the complex interaction of natural processes and environmental change along the Keriya River. This will help planners and policy makers assess the consequences and the degree to which human activity is and can alter the desert and mountain ecosystems. Our study is the first step in helping to define the nature and rates of change that will ultimately aid in sustainable development of this mountain and desert margin.

7. Conclusions

The Keriya River provides a natural laboratory to examine the relationship between environmental change and landscape evolution in mountains and desert margins of the Taklamakan Desert. In the Kunlun Mountains, glacial landforms and sediments throughout the region show that, during the last glacial cycle, the snowline was lowered by ~ 1000 to ~ 4000 m a.s.l. and the local last glacial maximum occurred at ~ 31 ka. Periglacial landforms in the mountains and foothills show that permafrost existed down to an altitude of ~ 1800 m a.s.l. with a likely temperature depression of $\sim 10°C$. It is likely that the highest fan along the Keriya River was formed at ~ 29 ka during a period of deglaciation as meltwater discharges and sediment load increased. Radiocarbon dates on sand dunes and tamarisk hills help define the age of two lower terraces to >1.5 ka and a few hundred years BP. This is broadly coincident with periods of increased precipitation during more humid times in western China at ~ 2 ka and during the Little Ice Age, respectively. The geomorphology and sedimentology show that the landforms and sediments in this region are polygenetic in origin, being transported, eroded and deposited by glacial, fluvial, aeolian and lacustrine processes. In particular, the particle size characteristics and heavy mineral concentration show that the fluvial sediments are substantially modified down-basin while in contrast the aeolian sediments are modified as they are transported from the desert towards the mountains by the dominant northerly winds. During the Late Quaternary the region has experienced changes from dominantly fluvial to dominantly aeolian processes along of the Keriya River. The landscape evolution of this desert and mountain margin is closely connected with these changes that are driven by climate change. In recent years, however, environmental changes may be occurring due to increased human activity. The effects of this have still to be fully assessed and considered in the light of the highly variable nature of the changes induced by natural climatic fluctuations.

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