Bulletin of Glacier Research 8 (1990) 61−72

The evolution of Quaternary glaciers and environmental change in the West Kunlun Mountains, Western China

ZHENG Benxing[1], JIAO Keqin[1], MA Qiuhua[1], LI Shijie[1], and Hiroji FUSHIMI[2]
1. Lanzhou Institute of Glaciology and Geocryology, Academia Sinica, Lanzhou, China
2. Lake Biwa Research Institute, Otsu, 520, Japan

(Received December 4, 1989 ; Revised manuscript received January 22, 1990)

Abstract

On the basis of field investigations in 1985 and 1987, and ^{14}C dating, minerals (including light and heavy minerals, and clay minerals), and sporo-pollen, this paper discusses problems of glaciation and palaeoenvironment during the Quaternary in the region of the West Kunlun Mountains. In the early Pleistocene, the climate was warm and semi-moist, and many large lakes might have existed. During the Yurunkax Glaciation of the middle Pleistocene, large-scale glaciers including big ice caps occupying the main Kunlun Mountains were developed. During the Last Great Interglacial period, the climate became warm and humid and there existed a large lake, 80 km long, on the south slope. The water of Gozha Lake flowed into Tianshuihai Lake via the Aksayqin broad valley. In the late stage of the middle Pleistocene, the extent of the Bulakebashi Glaciation was smaller than that of the Yurunkax Glaciation. There still existed tributary valley glaciers at the Yurunkax River, while piedmont glaciers and ice caps occurred at the headwater area of the Keriya River and on the south slope. In the Last Interglacial period, the level of Aksayqin Lake was 23 m higher than at present. The age of tills of the Last Glaciation maximum is 15,000−25,000 yr. B. P.. Sporo-pollen analysis of lacustrine deposits indicates that there were two cold periods before 18,000 yr. B. P. ; then the climate became colder and drier, leading to the disappearance of trees. Neoglaciation came to this region prior to 4,000 yr. B. P.. In the Little Ice Age, glaciers advanced again, and even today some glaciers continue to advance.

1. Introduction

Scientific studies of Quaternary glaciation of the West Kunlun Mountains and its surrounding region go back to the beginning of the twentieth century (Hedin, 1922 ; Stein, 1912 ; Sobolevski, 1919 ; Trinkler, 1930). The Comprehensive Scientific Expedition to the Qinghai-Xizang Plateau, Academia Sinica in 1976, investigated the existing glaciers and Quaternary glaciation in the regions of Quanshuigou valley and the upper reaches of the Binghsuigou valley on the south slope of the West Kunlun Mountains, and recognized three major glaciations since the middle Pleistocene, i. e. the Kunlun, Quanshuigou and Bingshuigou Glaciations (Zheng *et al.,* 1981).

The study region is located in the middle part of the West Kunlun Mountains, south of Yutian and Hotan (Xinjiang), and from the Keriya Pass in the east to Tianshuihai on the Xinjiang-Xizang Highway in the west (Fig. 1). There are three ranges of snowy mountains parallel to each other from north to south : The north snowy range is called the Karatash Mountains ; the highest peak is Muztag (6638 m a.s.l.). The altitude of the mountain ridge relative to the Tarim Basin floor is about 4000−5000 m, so that they have very steep topography. Narrow valley glaciers exist in deep gorges where streams flow rapidly so that for approaching these glaciers is very difficult. The main mountain range is wide and highest in the West Kunlun Mountains. The highest peak is Kunlun Peak

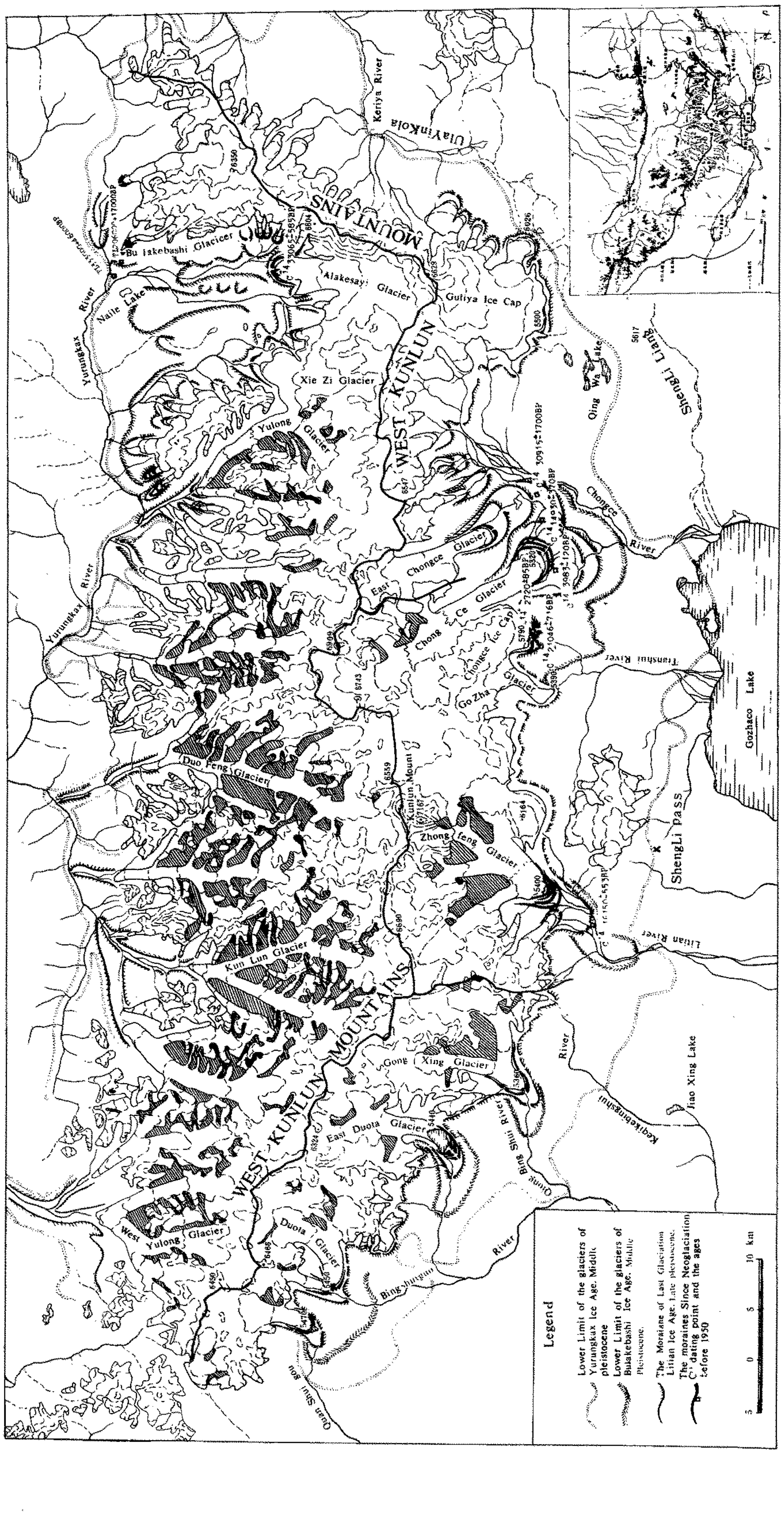

Fig. 1. Dirtribution of Quaternary glaciers of the West Kunlun Mountains.

(7167 m a.s.l.). This is the most concentrated area of existing glaciers in West Kunlun, and glaciers are 20—30 km in length. Melting water flows into the Taklimakan Desert through the Yurunkax and Keriya Rivers on the north slope ; and into Aksayqin Lake and Gozha Co Lake on the south. The south row of mountains extending up to 5500—6000 m a.s.l. is situated on the Qinghai-Xizang Plateau ; therefore relative height is smaller, and cirque glaciers and hanging glaciers exist only on a few high mountains.

During 1985 and 1987, a Sino-Japanese Joint Glaciology Expedition to the West Kunlun Mountains investigated glaciers and landforms on both south and north slopes. This paper will deal with the remaining evidence of glaciation, the classification of Quaternary glaciation, the development of lakes, the evolution of Quaternary glaciers and paleogeographical environment based on field work, ^{14}C, thermoluminescence (TL) dating, and analysis of mineral, clay mineral and sporo-pollens.

2. Evidence and identification of Quaternary glaciation

2.1 Upper reaches of Yurunkax River

The ground evidence of paleoglaciers around Bulakebashi Glacier is representative of the Quaternary glaciations. This glacier, which is 15 km in length, is located in the upper reaches of the Yurunkax River, on the northern slope of the West Kunlun Mountains, and terminates at 5060 m a.s.l.. There is a series of end moraines in front of the glacier, the outer of which is the older moraine platform. The characteristics, from younger to older moraine platform are described below (Fig. 2).

Modern end moraine : two moraine ridges are divided ; the inner one is 30—50 m above the ice surface and composed of slate and granite ; the lithological character of the outer one is similar to that of the inner one, and there are some small moraine lakes between the two moraines.

The end moraine of neoglaciation : three moraine ridges, located at an altitude above 4900 m, can be discerned. The lower two ones present hummocky relief, with some small lakes on the moraine ; the upper one is washed by later melt water and is inclined.

Arcuate end moraines of the last glaciation : A series of arcuate end moraines were accumulated on

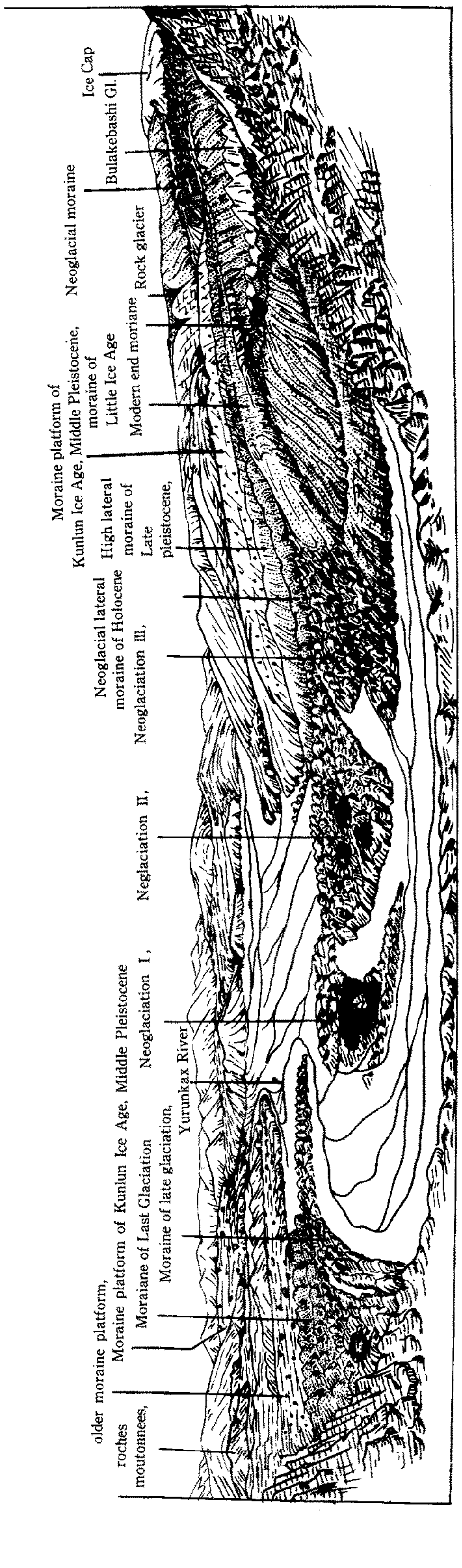

Fig. 2. The sketch of glacial geomorphology of the upper reach of Yurunkax River.

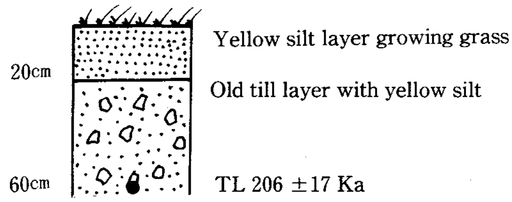

Fig. 3. Location of thermoluminescence dating sample in the old till profile of Bulakebashi Glaciation.

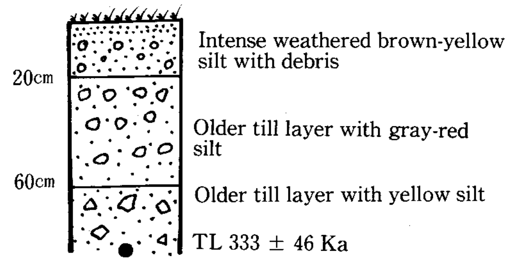

Fig. 4. Location of thermoluminescence dating sample in the older till profile of Yurunkax Glaciation.

the southwest side of the outwash apron during neoglaciation, the outer of which is 20−30 m high. The system is composed of three moraine ridges in close conjunction. The glacio-fluvial lacustrine deposits on the margin of the end moraine have been dated to be 12,025±195 yr. B. P.−18,250±625 yr. B. P. by ^{14}C datings and indicate that the arcuate end moraine appeared in the last glaciation. According to their relative shape and features, three glacial advances can be recognized by these deposits.

Old moraine Platform : The platform lies on the west of the outwash apron of Bulakebashi Glacier and has a length of 1.6 km in a N-S direction, a width of 300−600 m and a height of 30−40 m. A lot of granite porphyry erratic boulders outcrop on the ground surface, and some boulders are more than 2 m in diameter, with strong weathering and scaly weathering crusts. A brown paleosol is found less than 20 cm in depth on the moraine platform, indicating that the till was influenced by the warm moist climate of an interglacial which could be older than last glaciation. The thermoluminescence (TL) dating of the older till shows it was formed before TL 206±17 Ka (Fig. 3).

The oldest tills are on the oldest moraine platform which extends downward from the convergence to 4700 m a.s.l. of the Yurunkax and Bulakebashi Rivers spreading widely on the south bank of upper reach of Yurunkax River, some 1−3 km in width. The roche moutonnées and glaciated lake (Neile Lake) on the south side of the river are evidence of glacial erosion. The platform on which is distributed an amount of granite gneiss erratic boulders with strong weathering, has a flattish surface resulting from fluvial action over a long time. From the relative height of roche moutonnées on the southern flank, it is estimated that the thickness of the glacier was more than 200 m at that time. The thermoluminescence dating of the oldest till shows it formed before TL 333±46 Ka (Fig. 4).

The oldest moraine platform was formed by the combined action of several former piedmont glaciers from the south, and it extended 26 km down to 4700 m a.s.l. in front of the gorge. That the piedmont glacier did not flow out of the gorge to meet with the former Yurunkax Glacier is based on the characteristics of steep, cliff landforms in the gorge region.

2.2 Relics north of Gozha Co Lake on the southern slope

In 1976 and 1985, Zheng Benxing and others investigated the relics of former glaciers in the upper reaches of the Quanshuigou and Litian Rivers, and the proglacial zone of Chongce Ice Cap, and recognized three Pleistocene glaciations and neoglaciation since the middle Pleistocene in the region (Zheng, 1986 ; 1987). In 1987, we investigated glaciers to the east of Chongce Ice Cap, and also identified and discussed the relics of former glaciers in the proglacial zone of the Chongce valley glacier. Here, the names of the glaciations (Binshuigou, Quanshuigou and Kunlun) (Zheng, 1987) are renewed as Litian (last glaciation), Bulakebashi and Yurunkax (Table 1).

The end moraine series of the Little Ice Age between the 17−19 century can be distinguished into three ridges ; the outer one is 60 m high above the ground surface. The second moraine of the neoglaciation is located at the proglacial zone of the Little Ice Age moraine. Two ridges can be divided : the outer one is lower and covered with vegetation. The ^{14}C date of the till is 3,893±120 yr. B. P. (Fig. 5). The inner ridge is larger ; the ^{14}C date of the till is 3,522±117 yr. B. P.. According to these dates, the onset of neoglaciation in the West Kunlun Mountains is more than 1000 years earlier than that of the Urumqi River region in the Tien Shan Mountains and the southeastern part of Tibet (Zheng *et al.*, 1981).

End moraines of the last glaciation : two moraine ridges can be distingushed in the proglacial zone of

Table 1. Stage and date of moraines in the West Kunlun Mountains.

Stage	Shape feature	Surface feature	Place Contacted relations of stratra	Dating	Name of ice age
1	fresh moraine with well shape.	undeveloping soil, drift uncovered.	close to existing glacier.	17−19 century	Late Holocene, modern Little Ice Age Q_{4-3}^{gL}.
2	moraine well, but ridge flated.	week soil developing	1-2km from existing valley glacier less than 1km from ice-cap.	^{14}C 4,000−1,000 yr. B.P.	Late Holocene, Neoglaciciti Q_{4-3}^{gL}.
3	moraine with weak washed, but shape keep with completed.	loess covered, developing soil.	in lower U-shaped valley.	^{14}C 30,000−10,000 BP ^{14}C 40,000−30,000 BP TL 66,700±3,300 BP	The late stage of late Pleistocene, Last Glaciation Q_{3-3}^{gL}.
4	moraine stronge washed.	loess covered, developing, brown-yellow soil.	in outer side of lower U-shaped valley.	TL 206±17 Ka.	Bulakebashi glaciation of the early late pleistolene. Q_{3-1}^{gL}.
5	moraine into the high terrace by washed and planated.	moraine with stronge weathering developing drab paleosol.	developed high-terrace or high-platform in the upper U-shaped valley.	TL 333±46 Ka.	Yurunkax Glaciation of middle pleistocene. Q_2^{gL}

Chongce Glacier. The inner one is about 5 km from the margin of the glacier. There is an outcrop of lacustrine deposits 5 m thick near the inner end moraines of the Chongce Glacier ; the upper layer has the age of 14,930±3,700 yr. B. P.. Another lacustrine deposit lying under the outer end moraines has a ^{14}C date of 30,915±1,700 yr. B. P. (Fig. 6).

The moraine platform is located between the inner and outer Chongce Rivers outside the last glaciation moraine. The northern part of the moraine platform is characterized by moraine hill relief as the result of melt water washing. It is estimated that the glacier, 8 km longer than at present, had a broad terminal lobe at that time and it can be compared with Bulakebashi Glaciation in the late stage of middle Pleistocene.

The older moraine platform was formed by the largest glaciation in the region. From the view of the distribution characteristics of moraine relics, these glaciers were linked into a big ice sheet with Chongce Ice Cap and Guliya Ice Cap, and the ice mass flowed as far as the north part of Gozha Co Lake (Fig. 1). The small island was virtually formed by glacial deposits. Then, as the lake level fluctuated, three moraine benches were formed by wave attack.

2.3 Problems of relative dating of various moraines

The ages of moraines in the region were determined by the stratum correlation, landform positions and weathering features, and by ^{14}C and thermoluminescence datings. The scintillation counter is one method of ^{14}C dating available for age determination of both the organic-carbon in lacustrine deposits and inorgniccarbon in old tills. Due to the arid and cold climate, the dissolution and illuviation had occupied mainly the formational mechanism of carbonate in West Kunlun glacial deposits in early period and became weaker in late, therefore the inorganic dating data may reflect well the real ages of West Kunlun glacial deposits.

The thermoluminescence dating is based on the dose rate of U, Th and K in dated samples determined with the neutron activation analysis. The samples were obtained from the confining systems which is 60−80 cm under the surface, so their dose rate and dating data is reliable.

2.4 Mineralogical features of tills different glacial periods

Tills of different glacial ages have different conbinations of light-heavy minerals in each river drainage basin. They are controlled not only by the lithology of debris sources but also by reforming of minerals by recent weathering. The headwater of Yurunkax River and the drainage basin of Chongce River can be used as an example in the study of the mineralogy. The results are listed in the following tables (Tables 2 and 3). Stable Limonite content is zero in modern till from the headwaters of the Yurunkax River, 0.25%−0.5% in till of the Little Ice Age, 1.2% in the neoglaciation, 3.25% in the last glaciation ; and 6.5% in the Bulakebashi Glaciation. The older the till, the higher the limonite content.

From the view of clay and mineral content of till, the Hydromica content also increases with the age of the tills. For example, Hydromica is 60−67% in

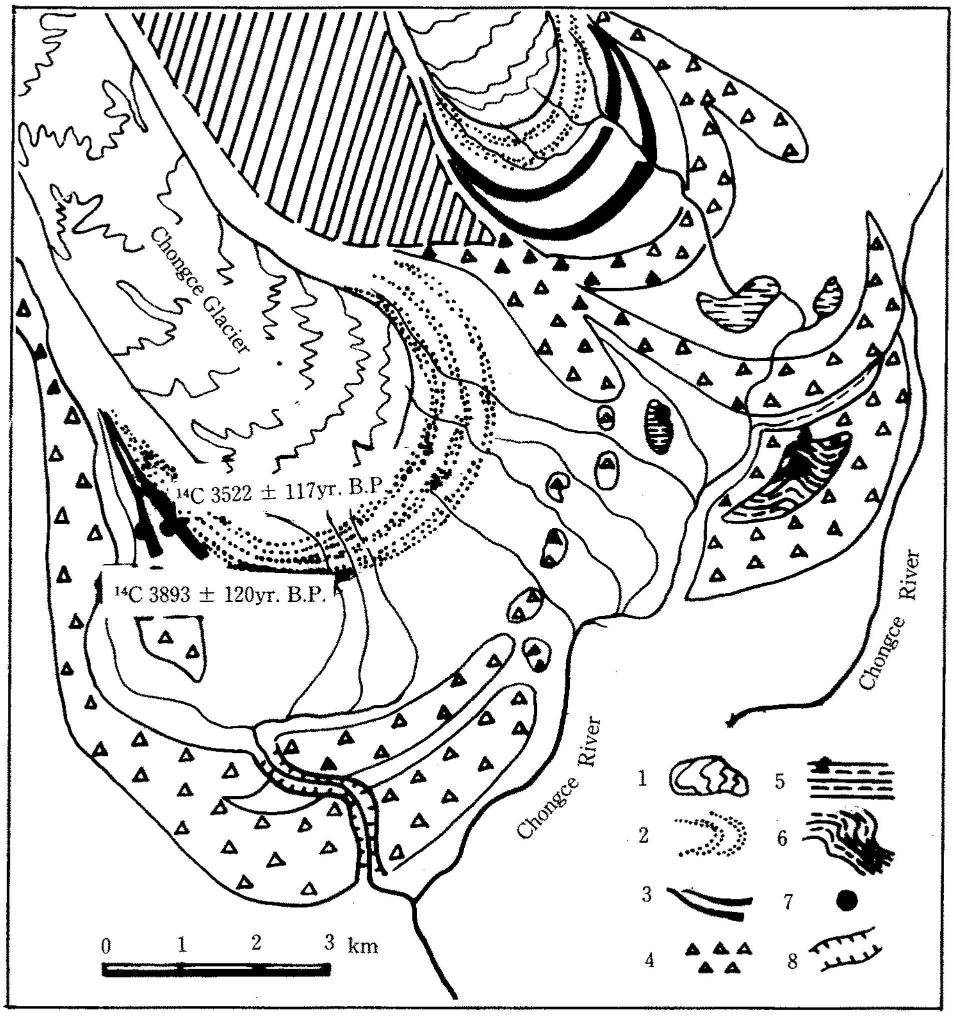

Fig. 5. The sedimentary geomorphological map of Chongce Glacier (35°15'N, 81°11'E) on south slope of West Kunlun Mountains.

Legend 1. Existing glacier 2. Modern moraines 3. Neoglacial lateral moraines
4. Moraines of Last Glaciation
5. Lacustrine clay (^{14}C date ; 14,930±3,700 yr. B. P.)
6. Deformed lacustrine deposit (^{14}C date ; 30,915−1,700 yr. B. P.)
7. Spots of sample 8. Step of terrace

modern till, increasing to 75.5% in the Yurunkax Glaciation of the middle Pleistocene. In addition, cryolite content decreases with age, from 25% down to 17.5% (See Table 4).

3. Interglacial deposits

The interglacial deposits of the region are mainly a series of paleolacustrine deposits and paleosols on the southern slopes of the West Kunlun Mountains. Based on morphological evidence from Akesayqin Lake as well as widespread and thick lacustrine deposits of the former Tianshuihai Lake, it was concluded that the former Tianshuihai lake existed in the early Pleistocene (Zheng, 1987).

The lacustrine profile is 15 km southeast of the Tianshuihai, it is 3.8 m thick, 4900 m a.s.l.. Its strata dip 5−10° southwestward and may be divided into six layers, the total number of sporo-pollen in these layers

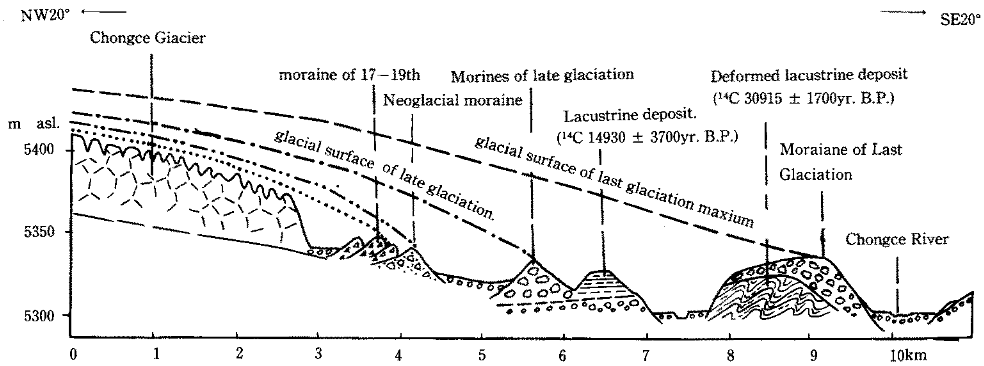

Fig. 6. The geomorphological profile near the terminus of Chongce Glacier on south slope of the West Kunlun Mountains.

Table 2. Content light-heavy mineral of various tills at the riverhead of the Yurunkax River on the northern slope of the West Kunlun Mountains.

Age	Heavy mineral				Light mineral	
	Un-stable	Sub-stable	Stable	Well-stable	Quartz	Feldspar
Present time	2.25	4.75	16.75	76.25	40.00	49.75
Little Ice Age	5.00	4.25	22.75	66.50	42.50	48.00
	4.50	3.50	25.75	66.25	45.50	42.25
Neoglaciation	2.75	8.25	18.25	70.75	38.25	45.25
Last glaciation	5.75	2.25	28.75	68.25	38.25	53.50
Bulakebashi	18.75	8.75	17.50	55.00	43.75	40.00
glaciation	0	0.5	26.25	73.25	26.5	46.5
	6.50	1.00	20.50	72.00	45.00	
Yurunkax	2.50	0.25	21.75	75.50	35.00	76.75
glaciation	7.75	2.75	20.00	69.75	37.5	38.50

Table 3. The content of light-heavy minerals of various tills in Chongce River on the southern slope of the West Kunlun Mountains.

Age	Type of deposits	Heavy mineral				Light mineral	
		Un stable	Sub stable	Stable	Well stable	Quartz	Feldspar
Present time	end moraine	10.75	7.75	17.25	64.25	36.00	32.75
Little Ice Age	Lateral moraine	4.75	2.75	43.0	49.50	34.00	32.50
Neglaciation	Till	6.00	4.60	23.40	66.00	42.50	38.75
Last glaciation	Till	7.25	3.25	43.25	46.25	33.50	38.75
Blakebashi glaciation	Till	18.25	7.0	24.5	48.17	35.50	33
Yurunkax glaciation	Till	19.75	7.5	29.00	43.75	32.00	27.6

is from 60−339. The arbor occupy 2.8−18.3% : mainly *Pinus* and *Betula*, and secondarily *Abies*, *Picea*, *Artemisia*, Chenopodiaceae and *Ephedra* as the principal grasses. According to the investigation and sporo-pollen analyses of old lacustrine deposits, there was a warm climate in the Tianshuihai region. However, a high cold desert environment occupies this region at present.

The fossilized plants of the old lacustrine shows that there was a warm-humid climate at that time, it

Table 4. Contents of clay mineral of tills on the southern slope of the West Kunlun Mountains

Name	Coll. No.	Content of clay mineral			Light mineral	
		Hydromica	Chlorite	Kaolinite	Quartz	Feldspar
Till of Little Ice Age	44	67.9	25	7.1	Less	Less
	45	66.7	25.6	7.7	Little	Little
	46	69.8	23.8	6.2		
Till of Neoglactiation	46	74	20.1	5.9	Little	Little
	47	71.8	20.1	8		
Till of Last glaciation	43	71.4	19.7	8.9	Little	Less
Old moraine platform	49	75.5	17.5	7	Little	Little
Basal till of Exsiting glacier	72.5	72.5	22.3	5.2	More	Little
Meltout till of Exsiting glacicr	19	76	19.5	4.5	More	Little
Profiles of end moraine of last glaciation	Top. 29	78	16.8	5.2	Little	Little
	Hidd. 28	75	19.2	5.8	More	Little
	Botto. 27	72.8	20.2	7.0	Little	Little
Till of late stage Middle pleistocenene	17	73.1	16.7	10.2	Trace	Trace
	20	72.5	16.3	11.2	Little	Little

may be called Yurunkax-Bulakebashi interglaciation. The *Betula, Pinus,* etc. formed a forest steppe landscape on the piedmont plain in Tianshuihai region, on the slope there was a temperate coniferous forest zone growing *Picea* and *Abies,* and similar to the plant zone at the same latitude, 2500−3000 m a.s.l.. On the southern slope of Xiqingshan mountain in south Gansu today, in that region, the *Pinus tabulaeformis* grows below 1600 m a.s.l., *Picea neiveitchii* and *Pinus armandii* grow at 1600−2500 m a.s.l. and *Picea* forest zone lies 2100−2600 m a.s.l. and the *Abies faxaniana* is growing 2500−3900 m a.s.l. (Natural Division Committee of Academia Sinica, 1960). The mean annual temperature difference between the southern slope of Xiqingshan and the Tianshuihai region is about 18°C, and the annual precipitation difference is about 1000−1500 mm (Shen *et al.,* 1986). Some red-brown paleosols developed on upper till of Yurunkax Glaciation also show that it had undergone a long weathering under moist and hot climatic period.

The lacustrine deposit did not developed enough during the last interglaciation, when the Ashishan volcanic episodes, based on the data of K-Ar dating of Ashikule Volcanoes, occurred 120,000 years ago (Liu and Mai, 1989) and the brown paleosol developed on the old till of the Bulakebashi Glaciation.

The climate of the last glaciation fluctuated between cold and warm. Paleolacustrine deposits outcrops to a thickness of 2.7 m on the east bank of Aksayqin Lake, and the deposits have ^{14}C dates of 25, 260±280 yr. B. P., 21,500±120 yr. B. P. and 16,235±120 yr. B. P. (Table 5). The clay layers of 20−100 cm and 210−250 cm depth contained rich and abundant sporo-pollen grains of arbor and scrub in their profiles. The grey clay layer below 270 cm depth was mainly scrub with a uniform lithology and the grey clay on the middle part of the northern bank of the lake has an age of 34,735±820 yr. B. P.. Thus, we can consider that the second glacial stage of the last glaciation from 30,000 to 15,000 yr. B. P. underwent three cold and two warm stages. After 18,000−15,000 yr. B. P., the climate became dry and cold, and the arbor trees disappeared gradually in the area of Aksayqin Lake. The Hypsithermal period of the Holocene had a dry and hot environment,. The Ca-precipitated layer lies in upper part of the palaeolacustrine deposits of Tianshuihai ; its ^{14}C date is 9,767±135 yr. B. P., when the climate became warm and dry, and the Tianshuihai Lake was very small. Some soil had developed on the surface of last glacial moraine. The ^{14}C age of the soil is estimated as 4,621±92 yr. B. P..

Table 5. Lacustrine deposits profile including the sporo-pollen statistics at the east Aksayqin Lake

No. of sample	Depth (cm)	Sediments	^{14}C dating yr.B.P.	Content of sporo-pollen(grains)												
				Arbor	Shrub & herb	*Pinaceae*	*Abies*	*Pinus*	*Betula*	*Polygonoceae*	*Caryophy Haceoe*	*Compositae*	*Artemisie*	*Chenopol iocene*	*Ephedra*	*Polyoiolio*
A1	0-10	Subsilt; Containing sand	16235±120	0	0											
A2	10-20	Silt		0	0	0	0	0	0	0	0	0	0	0	0	0
A3	20-100	Grey yellowsh clay with fossil plants leaves		3	16			3						8	8	
A4	100	Clay		46	213		2	40	4		1		17	160	36	
A5	100-150	Grey clay	25260±280	15	38			15					2	23	13	
A6	150-185	Clay fossil plant leaves alternating		0	1										1	1
A7	185-210	Fossil plant leaves layer		2	7			2			1		1	4	1	
A8	210-240	Grey-yellow clay		11	163			10	1	1			34	107	21	
A9	240-250	Aquatic plant leaves layer		5	32	1		3	1			2	10	16	4	
A10	250-270	Grey-yellow clay		4	1				4					1		
A11	270 blow	Grey clay with fossil leaves		0	0											

4. Evolution of Quaternary glaciers and change of paleoenvironment

The West Kunlun Mountains are an important centre of glacier development in the northwestern part of Qinghai-Xizang plateau. Its history has not only a similarity with the whole of Qinghai-Xizang Plateau, but also a specific and individual development. Thus, both areas must be considered when studying the evolution of Quaternary glaciers and the changes in paleogeographical environment in the area. Based on the study data of this region and on comparisons with neighbouring regions, the paleogeographical environment since the Pliocene can be described briefly as follows (Table 6).

4.1 Pliocene paleogeographical environment

The *Hipparion tibetansis* fauna, that was discovered on the southern slope of Tanggula Mountain (Ji *et al.*, 1981) suggests that the Tibetan Plateau had low altitude in the early Pliocene. Therefore, it can be concluded that elevation of the West Kunlun Mountains was only 500−1000 m a.s.l., with a landform type of hills and low mountains with basins.

Based on the sporo-pollen analysis of Pliocene lacustrine deposits in the basin of the Quanzhenhu Lake on the south slope of the Kunlun Mountains, this stage had only the *Picea-Pinus-Cedrus* group, and the distribution of vegetation on the south slope at that time was the mountain coniferous forest with *Picea* sp., *Pinus* sp. and *Cedrus* sp., also containing some species of subtropical mountain forest such as *Tsuga* sp., and fewer species of thermophilous plants such as *Podolarpus* sp., *Corylosis* sp., *Castauopsis* sp. and so on. In the upper part of the lacustrine profile, the sporopollen combination of *Quercus, Betula, Pinus* and Chenopodialeae is dominant with some appearance of the less dry pollen of *Nifraria L.*, showing the climatic change to dry and cold environments, an indicator of the beginning of the Quaternary glaciation (Huang and Liang, 1983a).

4.2 Paleogeographical environment of the early Pleistocene

In the beginning of the Pleistocene, the Himalayas were uplifted due to the Indian Plate drifting northward again, with many high mountains rising up above the height of the snow line during Xixabangma Glaciation, and a small ice-cap was developing on the

Table 6. The Paleogeographical environment in the West Kunlun Mountians since Pliocene

Age	Glacial and interglaciation	Glacial landforms and deposits	Natural Environment	Type of glacier	Elevation of the south slope (m.a.s.l.)	Episode of volcanic eruption (Ma)	Development history of piedmont landforms
Holocene	Present time	Many glaciers length exceed 20km developed, elevation of snowline in 5800–5900 m.a.s.l.	Cold desert steppe, dry-cold	Valley glacier, Ice-cap.	5000	Modern volcanism on May 27, 1951	Fluvial deposits, modern alluvial fan.
	Little Ice Age between 17–19 century	Modern moraine	Same above	Same above		Late period of episode of Ashkule. <0.005Ma.	Eolian sand on the top of middle terrace ^{14}C:4550±230 yr.B.P. Lower terrace. Lower plluvial-alluvial fan, river down cutting.
	Neoglaciation	Chongce Ice Cap Neoglaciation ^{14}C:2720±85B.P. Chongce glacier: ^{14}C:3522±117B.P. ^{14}C:3983±120B.P.	Bush-steppe, warm cool, semi-arid.	Glacier advanced			
	Hypsithermal epoche	Ca-precipitated film of Hypsithermal period on till	Cold desert steppe changed into warm, sami-arid.	Glacier retreated slowly.			
Late Pleistocene	Last glaciation (Litian Glaciation)	Terminal moraine ^{14}C:18250 yr.B.P. in Bulakebashi. ^{14}C:22904±950 yr.B.P. in Alakesayi	Cold desert steppe. Cold-dry.	Vally glaciers and piedmont glaciers.	4500	0.20–0.12 Ma episode of Uruke.	Eolian sand on the gravel layer of middle terrace. ^{14}C:31000±1500 yr.B.P. 66700±3300 yr.B.P. Middle terrace. Sand-gravel layer.
	Last interglaciation	High terrace of Aksayqin Lake	Steppe, warm semi-moist.		4000		
Middle Plecistocene	Blakebashi Glaciation	Older moraine platform at 4900m .a.s.l. in the upper reach of Yurunkax River, TL 206±17 Ka (206,000±17,000 yr.B.P.)	Steppe, cold and semimoist.	Big valley glaciers, middle piedmont glaciers.			
	Large interglaciation	Upper part of paleolacustrine sediments of Tan Shuihai, brown-yellow paleosol on high moraine platform	Coniferous and broad-leaved mixed forest, Brown-yellow soil, warm and moist.	Glacier disappeared	2500~3000	0.44–0.28 Ma episode of Yueya Shan.	High terrace
	Yurunkax Glaciation	High moraine platform in the upper reach of Yurunkax River. TL 333±46 Ka. High moraine platform in the north side of Guozha Lake	Steppe, cold-wet	Large piedmont glacier and ice caps.		Episode of Hei-long Shan 0.67–0.50 Ma.	
Early Pleistocene		Lower paleolacustrine sediments of Tanshuihai	Coniferous forest zone, warm and moist climate, steppe zone. cold-wet (nearby Kunlun pass).		2000	Kansulake lava 1.21–1.43 Ma; episode of Mati Shan 1.63 Ma.	Highest platform of piedmont fluvial fan.
Pliocene	Preglacial period	High plain and high planation surface with flattish relief	Forest and steppe, with Hipparion faunas		500-1000	Episode of Xi Shan 2.8 Ma.	Red sand and conglomerate formed anticline.

northern slope and wide shallow valley glaciers were developing on the southern slope. However, the Kunlun Mountains did not rise up to the height of the snow line, so that no glacier developed in the region and there were only many lakes on the southern slope. In the lacustrine deposits of early Pleistocene from Maergou and Maerge lakes in the northern Tibetan Plateau, the sporo-pollen combination was *picea-Pinus-Betula,* accompanied with the species of *Ulmus* and *Quercus.* The natural environment was characterized by temperate mountain coniferous and broad-leaved mixed forest, with a dominance of coniferous forest. The climate was warm and semi-moist (Huang and Liang, 1983b).

Based on the sporo-pollen assemblage of the Changtang formation of the early Pleistocene from Kunlun pass, Qinghai province, the vegetation was coniferous forest, and aquatic plant species of *Sparganium, potamogeton, Typha, Nelumbo* and *Pediastrum boryanum Menehini* were also present. According to the description of 20 known species of *Sparganium,* the plants generally flourished below 2,000 m a.s.l. (Kong and Liu, 1981). Therefore, the elevation of basins on the southern slope of the West Kunlun Mountains was then less than 2,000 m a.s.l..

In the West Kunlun Mountains, volcanic eruptions occured in the early Pleistocene, such as the Xishan volcano, the Matishan volcano (Ashikule lake basin), and a lava flow layer in the Kangulake area of the Keriya River (Liu and Mai, 1989). In these areas, there was no glacier development during the Early Pleistocene.

Although Norin (1932) reported that the oldest moraine extended to the piedoment plain at 1200–1500 m a.s.l. in the Douwa valley of the Tarim basin, however sediments were considered not to be of glacialgenetic origin(the Comprehensive Scientific Expedition of Xinghiang, 1978).

4.3 Environment of the glacial and interglacial periods of the middle Pleistocene

In the beginning of the middle Pleistocene, the West Kunlun Mountains underwent strong uplift with the volcanic eruptions of Heilongshan, continuing since the end of the early Pleistocene (Liu and Mai, 1989). Then the climate entered the cold stage and the largest glaciation period, the Yurunkax glaciation began. Valley glaciers of huge tributary complex developed upstream of Yurunkax River, on the north slope of the main mountain range, and large ice-caps in the West Kunlun and Keriya Pass regions extended down to the basin. The glacier from Mt. Kunlun extended down to the mouth of the Litian River valley. In the Gozha Co region, the Chongce Ice Cap and Guliya Ice Cap joined and flowed down to the northern part of Gozha Co. The meltwater, flowing from Gozha Co Lake via Aksayqin valley to the Tianshuihaı region, formed a big fluvial lake 80 km in length and 10 km wide in Tianshuighai.

The Kulapu River on the north slope of the Karatash Mountains, developed a large valley glacier, which did not extend to the piedmont plain. The melt water of the glacier formed the higher bedrock terrace with alluvial deposits and a higher flat plain with telescoped structure in the highest pluvial fan.

During the last great interglacial, the Yurunkax-Bulakebashi interglacial, the climate was warm and wet, and glaciers disappeared, leaving many lakes on the southern slope of the Kunlun Mountains. The climatic conditions were warmer and wetter than that of the first interglacial, and coniferous and broadleaved mixed forest grew on the slopes and broadleaved forest on the shores of the lakes. The volcano in the Ashkule basin erupted again in 0.28-0.31 Ma, and formed the Yueyashan lava (Liu and Mai, 1989). On the north slope the river cut down due to the moist climate and greater precipitation, and the outwash apron was dissected into the high terrace.

During the Bulakebashi Glaciation in the late stages of the middle Pleistocene, precipitation was less than that of the middle stage, and valley glaciers developed on the northern slope of the main mountain range, with a small piedmont glacier and ice cap developing on the southern slope. Valley glaciers still existed on the northern slopes of the Karatash Mountains, but the dimensions was less than that of Yurunkax Glaciation.

4.4 Last interglacial and last glacial environment of the late Pleistocene

In the begining of the last interglacial, the level of Aksayqin Lake was higher than that of today, and the river cut down to form the medium terrace on the piedmont of the Kunlun Mountains near Pulu in the Keriya River basin. In this time before 120,000 year, the Ashishan volcano had been erupted (Liu and Mai, 1989).

During the last glaciation the length of glaciers was several kilometres longer than that of existing glaciers. The glaciation can be divided into two stages. Most of the glaciers were large in the late stage. All of ^{14}C dates from moraines of the last glaciation were younger than 30,000 yr. B. P. and the maximum period of the last stage was at 15,000-25,000 yr. B. P. in this area. At that time, the length of Litian glacier was 29.4 km, Chongce Glacier was 35.7 km, Yulong Glacier stretched for 37 km down to the main valley, and Bulakebashi Glacier was 16.2 km long. On the north slope of Karatash Mountains, the Kulapu Glacier was 13.1 km long, reaching the main valley, 7 km longer than the existing glacier today.

After 18,000 yr. B. P. the climate became arid and cold. Arbor trees disappeared from the shore of Aksayqin Lake.

4.5 Paleogeographical environment of the Holocene

After 10,000 yr. B. P. the climate began to warm up and entered into postglacial period. Glaciers on the northern slope of Karatash Mountains, which is near the Tarim basin, retreated greatly and the snow line rose more than 1000 m. There are many cirques on the mountain. But the glaciers near the main range retreated less, because of the great altitude and plentiful moisture and snow. Thus, even in the Hypsithermal period, the glacier had a considerable dimension. When the climate became dry and warm, Ca-film was precipitated on the boulder of the last glaciation. The beginning of neoglaciation in 4,000 yr. B. P. was 1,000 yr. earlier than that of the Tien Shan Mountains and the southeastern part of Tibet (Zheng and Li, 1981 ; Zheng *et al.*, 1981). During this period, glaciers advanced and deposited at least two moraines, one thousand to several hundred metres far from termini of existing glaciers today. In the Little Ice Age of the 17-19 th century, glaciers were slightly larger than the present glaciers.

Some advancing glaciers have overrun the moraines of the Little Ice Age, such as the Yake Glacier in the upper Yurungkax river where the cliff-like front of the glacier pushed the debris material to just short of the modern moraine. Some existing glaciers are advancing, but the most of the glaciers have been retreating, such as Chongce Glacier and Alakesayi Glacier.

Acknowledgments

The authors are grateful to Mr. Ma Zhenghai for identification of mineralogy, Mrs. Wang Rui for sporo-pollen analysis, Mr. Qu Rongkang for the clay mineral analysis, Mr. Gu Gongshu and Xu Qizhi for ^{14}C dating, Mrs. Zhang Jinzhao for TL dating and Mrs. Yin Shichong for drawing. We are many thanks to Prof. E. Derbyshire for his approving the paper, and also thanks to Dr. S. Iwata for that he took part in our field Work, and suggested some good idea when reapproving the paper.

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