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Rock Glaciers in the Central Tianshan Mountains, China

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ABSTRACT

There are hundreds of rock glaciers in the Central Tianshan Mountains (41°30′N–44°20′N, 82°10′E–88°40′E) of northwest China. West of longitude 86°E, they are mainly Alps-type rock glaciers. To the east, Colorado-type rock glaciers occur. The lobate rock glaciers which are 'frozen throughout bottom' can be divided into three layers in structure. By analysing the palaeo-snowline, it is found that the eastern rock glaciers, whose ages are 1000–180 a BP, develop gradually from lower elevation to higher elevation. The authors believe that the cold and relatively humid conditions in the west are the main reason for the differences in rock topography, lithology, glacier and geomorphological processes. The authors carried out field investigations between 1985 and 1989.

RÉSUMÉ

Des centaines de glaciers rocheux existent dans les montagnes centrales du Tianshan (41°30′N–44°20′N, 82°10′E–88°40′E) dans le nord-ouest de la Chine. A l'ouest du méridien de 86°E, existent principalement des glaciers rocheux de type alpin, tandis qu'à l'est de ce méridien les glaciers rocheux sont du type 'Colorado'. Les glaciers rocheux lobés qui sont gelés jusqu'au fond peuvent être, au point de vue de leur structure, divisés en trois couches.

En analysant la paléo-limite des neiges éternelles, les glaciers rocheux orientaux dont l'âge varie entre 180 et 1000 ans se sont développés graduellement depuis les plus basses jusqu'aux plus hautes altitudes. Les auteurs pensent que les conditions froides et relativement humides de la région occidentale expliquent les différences dans la topographie, la lithologie des glaciers rocheux et les processus glaciaires et géomorphologiques de ces régions.

KEY WORDS: rock glaciers; alpine/mountain permafrost

BACKGROUND

The Central Tianshan Mountains are situated at 41°30′N–44°20′N, 82°10′E–88°40′E. The elevations vary between 4100 and 4300 m ASL. There are more than 1000 modern glaciers with ice tongues at about 3650–3700 m in elevation. The lower boundary of permafrost is 3200–3300 m ASL, and the limit of treeline is 2600–2900 m ASL.

The Central Tianshan is a large complex mountain body mainly made of palaeozoic granites and metamorphics. It belongs to the central uplift belt of the Tianshan geosynclinal fold system.

The geology, topography, climate, and type of periglacial landforms and processes are different to the east and west of 86°E. The west is situated on the Künes synclinorium; its terrain is high and relatively flat. By contrast, the east is mainly

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situated on the Boluohuojing anticline with precipitous terrain. There are more mountains higher than 4000 m ASL in the west than in the east. There is a relatively large difference between the lower limit of permafrost and the snowline in the west, which implies a well developed periglacial landform spectrum. However, there are large deep canyons. Mass movements are relatively well developed. Although the extent of the periglacial zone in the east is not as large as that in the west, there are relatively fewer deep canyons and slopes are relatively gentle. As a consequence, the spectrum of periglacial landforms is more complete.

In climate, the topography of the west is relatively gentle and most rivers flow from east to west. This favours the entry of water vapour from the north-west. However, in the east the terrain is precipitous and most rivers flow from south to north. The east is also far from the water vapour sources. For these reasons, precipitation decreases gradually from west to east in the Central Tianshan Mountains. The greatest precipitation (>600 mm) occurs in the west.

In the western Tianshan, the average annual precipitation is 827 mm, the maximum reaches 1140 mm, the average annual temperature (3580 m ASL) is –9.4°C, and the coldest month (January) average temperatures reaches –24.5°C. While the average annual precipitation (1961–1980) measured by the meteorological station (3588 m ASL) in Daxigou Valley only reaches 430.2 mm (Zhu Cheng and Cui Zhijiu, 1992a), the average annual temperature is –5.4°C, and the coldest month (January) average temperature reaches –15.9°C. Thus, the climatic situation in the Central Tianshan Mountains can be obtained, i.e. the west is cold and wet, and the east is cold and dry. The cold-wet condition is good for developing glaciers, while the cold-dry condition is good for developing periglacial landforms. Thus, there are more glaciers and tongue-shaped rock glaciers in the west (Zhu Cheng and Cui Zhijiu, 1992a). However, the west lacks other kinds of periglacial landform. Only the tors, talus, block slopes, gelifluction lobes and block streams are easy to find. The development of modern glaciers in the east is not as obvious as in the west, and there are fewer tongue-shaped rock glaciers. But there are plenty of other kinds of periglacial landforms. In the Daxigou area, for example, there exist more than 20 kinds of periglacial landform, such as tors, block fields, talus, block slopes, gelifluction lobes, sorted stripes and nets, stone pavements and thermokarst settlement (Zhu Cheng and Cui Zhijiu, 1992b; Zhu Cheng, 1993).

CLASSIFICATION, SHAPE AND DISTRIBUTIVE CHARACTERISTICS

Using air photographs, hundreds of rock glaciers have been recognized in the Central Tianshan Mountains. They mainly belong to the Alps type (i.e. tongue-shaped rock glaciers). Their length is often over 1 km, their width is over hundreds of metres (ratio of length to width >1.0) and their thickness is more than 100 m. They are distributed mainly over Eren Habirgashan, Borohoro Shan and Narat Shan to the west of longitude 86 °E. Large tongue-shaped rock glaciers exist in the Azajergalang River source, Guozigou area, on the north slope of Narat Shan. Here, the mountains have knife-edge crests and horn peaks about 5300–4150 m in elevation. Traces of avalanches occur widely.

The 0 °C temperature isotherm from June to August is at about 3600 m ASL. It is as high as that of the local modern snowline. The rock glaciers in this area are developed mainly in the zone between 3600 and 3700 m ASL (Figures 1 and 2). In fact, the rock glaciers are ice-rock mixtures covered by till, with ice cores inside. They continue to creep down valleys after the glaciers have retreated and when no ice is supplied afterwards. There are many avalanche troughs at the sources and along the sides of the rock glaciers. Their cross-sections appear convex. Evidence of creeping, in the form of compressed arcs and small lakes on the rock glaciers' surfaces, can be seen clearly on air photographs. These observations suggest that ice cores occur under the coarse debris layers of the rock glaciers.

The rock glaciers exist individually or in groups. The former, for example, include No. 2 No. 3, No. 4 and No. 5 rock glaciers in the Daxigou Valley (Figure 3). The rock glacier groups appear on the southern valley wall in Daxigou Valley, the southern valley wall in Luopudaogou Valley and the south-east side of a dry cirque. They are 300–400 m wide, 30–50 m long, and 20–40 m thick. The characteristics of the individual rock glaciers are as follows: (1) in general, they are 40–70 m long, 100–150 m wide and 30–40 m thick; (2) the gradient is high (30°–41°–60°); (3) in some, an upwarping platform extends from the foot of the front slope, and troughs and ridges appear on the surface due

Figure 1 Embryonic rock glaciers, Heixionggou Valley, Kalawucheng Shan.

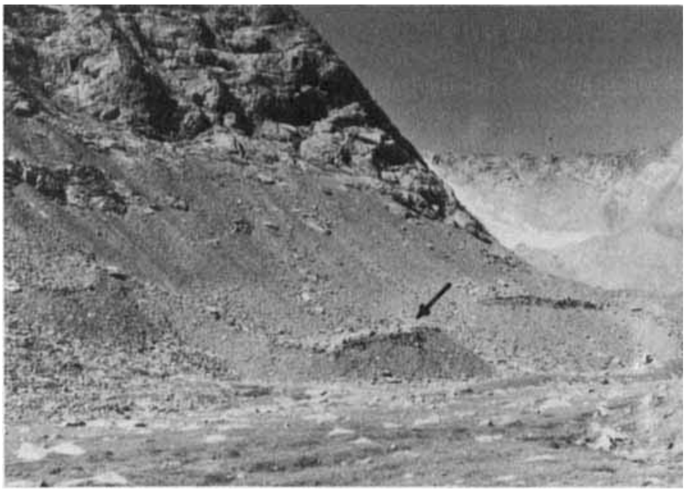


Figure 2 Rock glacier No. 2 (arrow is the hinge line on the front slope).

to compression. A fan-shaped rock glacier (3850 m ASL) which formed by an avalanche talus, with length about 600 m, front width 1 km and flow direction 260°SW (Figure 4), has been found recently on the leeward slope of Eren Habirga Shan in Yuximolegai Daban. The source ridge is a modern glacier. This topographic situation makes snow deposits form cornices on the leeward slopes of the ridge in winter, which then form avalanche-type talus and then a rock glacier. Because of this situation, the large extent of avalanches makes the mixture of ice, snow, blocks and debris form an annular zone of coarse debris in the front of the talus.

The distribution of rock glaciers in the Central Tianshan area was obtained by field investigations. Rock glaciers are distributed mainly between 3300 and 3900 m ASL. The top and the bottom of this zone have a 100 m difference from the modern snowline and the lower limit of permafrost respectively.

STRUCTURE

Results from Excavations

Using explosives, several pits were excavated on

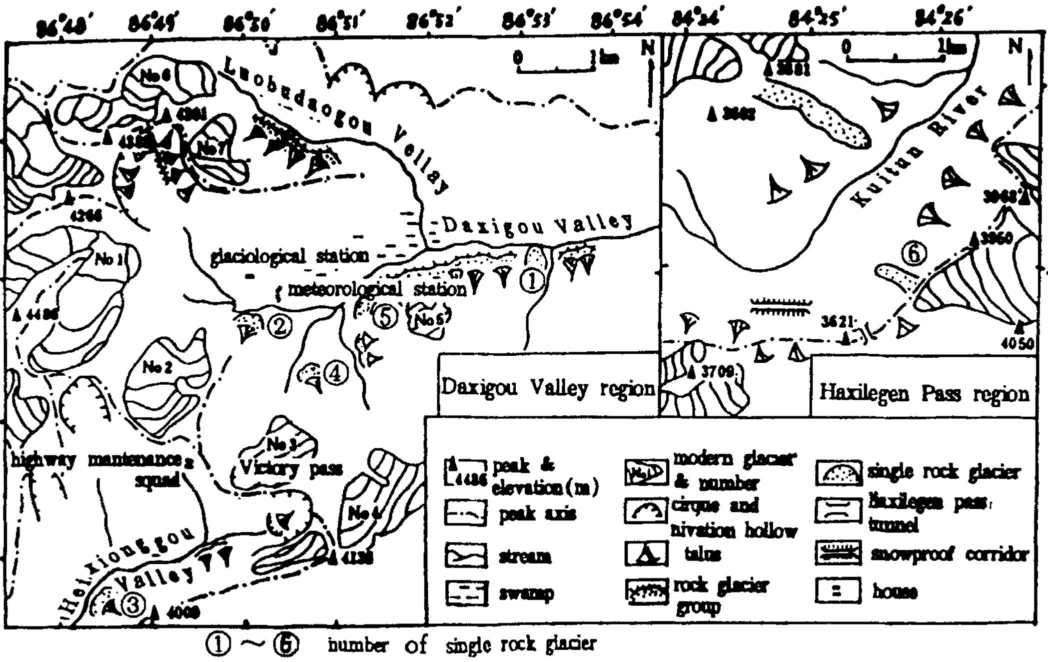


Figure 3 Distribution of main rock glaciers in study area, Tianshan Mountains, China.

Figure 4 Rock Glacier No. 6 (fan-shaped), Yuximolegai Daban.

the top of No. 3 rock glacier and No. 5 rock glacier (Figure 3) from June to July in 1986. In June, an ice lens with dimensions 20 × 15 × 8 cm was found at a depth of 1.3 m in No. 3 rock glacier. The ice was debris-free, and around it were gneiss blocks infilled between with fine debris. In No. 5 rock glacier, frozen rubble soil at a depth of 0.8 m and frozen debris with pore ice at a depth of 1.2 m were discovered. Several layers of bedded ice (thick 1–3 mm) can also be seen in fine detritus. Excavation in July gave almost the same results, the only difference being the slightly deeper depth of the frozen layer.

According to these results, we conclude the following. First, there is an active layer and a frozen layer in the lobate rock glaciers in the Daxigou Valley area. Second, the ice lens and pore ice are not continuous and have not the

Table 1 Electrical resistivities of some geological bodies in the Central Tianshan area.

Name	ρ (Ω m)	Name	ρ (Ω m)
Granite	1.0×10^{-4}–3.9×10^{-4}	Groundwater	3×10^{-2}–4.8×10^{2}
Gneiss (wet)	2.0×10^{-3}–4.5×10^{-3}	Permafrost (including frozen sand-gravel with ice)	2.7×10^{-2}–4.9×10^{4}
Siliceous slate	2.8×10^{-3}–6.3×10^{-4}	Glacial meltwater	1.7×10^{-2}–5.6×10^{2}
Gneiss (dry)	3×10^{-6}	Rock glacier meltwater	1.3×10^{-1}–1.6×10^{2}
Quartzite	10–2×10^{-8}		

flow characteristics of glacier ice. Since the rock glaciers, where ice lens and pore ice exist, are far from the modern glaciers, no moraines are found around the rock glaciers or their sources (e.g. the rock glacier No. 3), and the frozen debris has no characteristics of long-distance transportation, it is concluded that the ice is not of glacial genesis but froze locally.

Qiu Guoqin (1981) made some excavations in neoglacial moraines in the eastern area at the same elevation (3550 m ASL) as the rock glaciers studied here. They found that the permafrost table was at a depth of 2.3–2.7 m. However, at the end of July, large ice lens and pore ice blocks were found at the shallower depth of 1.4–1.9 m. This suggests that the ice belongs to the perennial frozen layer which is being degraded, rather than ice forming in the seasonally frozen zone.

Owing to their location on shady or semi-shady slopes, most lobate rock glaciers receive less heat energy from direct radiation and are deeply affected by cold in winter. As a result, snow deposits stay there longer and seasonal ablation is weaker. Relatively large amounts of ice can be preserved and the permafrost table is shallower than in other sediments with the same elevation.

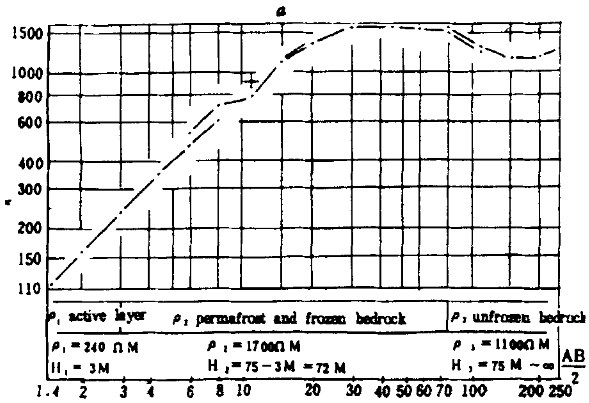
Geophysical Data

During field investigations from 1986 to 1988, the authors made electrical sounding analysis using a DDC-2A electrical autocompensator. The apparent ground resistivity method was used to interpret the internal structure of the rock glaciers, moraines and permafrost in the Daxigou Valley and Shenli Daban. Typical values of electric resistivities are given in Table 1. We also referred to the electrical sounding results of the rock glaciers in the Alps that were given by Haeberli (1985). Finally, initial curves of electrical sounding for rock glaciers and various geological bodies in the study area were obtained.

Figure 5 shows the following. First, the k-shaped ($\rho1<\rho2>\rho3$) logs of the rock glacier, moraine and frozen soil indicate that the highest resistivity is that of the frozen layer. Second, the resistivity of every layer of the rock glacier is much higher than the moraine and general permafrost. Third, the permafrost table of the rock glacier is shallower than surrounding permafrost and moraine at the same elevation. Fourth, the thickness of the seasonal thawed layer negatively correlates with elevation, i.e. the higher the elevation (the lower the temperature), the smaller is the thickness of the seasonal thawed layer.

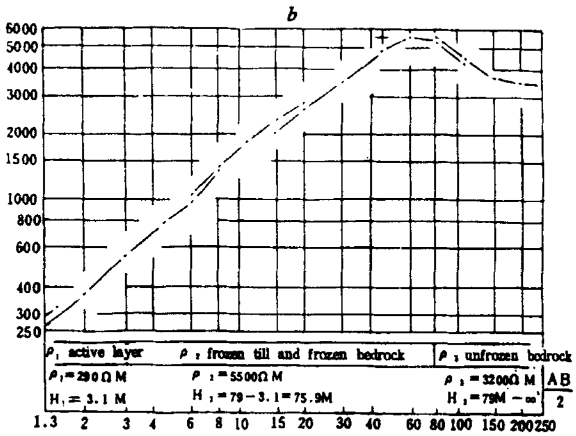
Figure 5c is representative of the structure of rock glaciers in the study area. Because most are covered by coarse debris with little fine clasts, the electrical prospecting was carried out upon rock glaciers in dry cirgues (Figure 6) and on the southern rock glacier group where the surface has finer fragments, in the Daxigou area. Three layers are identified in the lobate rock glacier in terms of electrical resistivities. The first layer, with resistivity 2500 Ω m and thickness 1.5 m, is the active layer. A second layer belongs to frozen debris and frozen bedrock, owing to the ice. Its resistivity rises to 3.7×10^4 Ω m. At a depth of over 100 metres the resistivity (0.5×10^3 to 5×10^3 Ω m) suggests that this layer must be unfrozen bedrock whose resistivity is lower than frozen debris with ice inside. At about 160 m, the resistivity rises to 7.7×10^4 Ω m again; this may be caused by a change of bedrock.

On the basis of these data, Figure 7 is obtained, in which the structure of the lobate rock glaciers (three layers) and the Alpine rock glaciers (4 layers) are shown. The lobate rock glacier lacks a layer of unfrozen sediments and has a layer of frozen bedrock. This is typical of the continental, mountainous rock glacier with a cold bottom ('frozen throughout bottom') in contrast to the oceanic rock glacier with a warm bottom (Zhu Cheng and Cui Zhijiu, 1992a).



MOVEMENT CHARACTERISTICS

The active lobate-shaped rock glaciers are near to field stations and roads. The active tongue-shaped rock glaciers are distant from field stations and measurement is inconvenient. Hence, we chose the lobate-shaped rock glaciers to measure movements. In addition, other methods were used such as painted fixed base lines whose ends are fixed at bedrock, painted-number debris, discharge and debris fabric measurements etc.



Low Movement Stable Type

Rock glacier No. 1 is more than 100 m long and 60 m wide. It is one of the few tongue-shaped rock glaciers in the area, and is 250 m away from the upper hydrographic station. We chose the bedrock on both sides of the glacier as control points, then joined the points with lines using a steel rule. After that, the debris lying on the surface was painted with numbers and a fixed line; by this method, the creep rate on the surface could be measured. Meanwhile, we chose 22 debris clasts of different sizes along the front

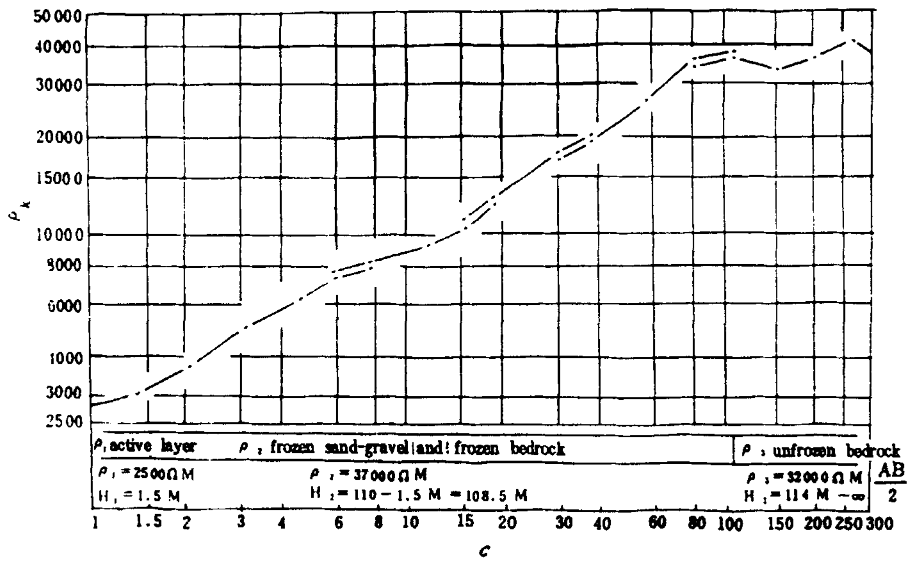


Figure 5, (a) (b) (c). See p. 75 for detailed caption

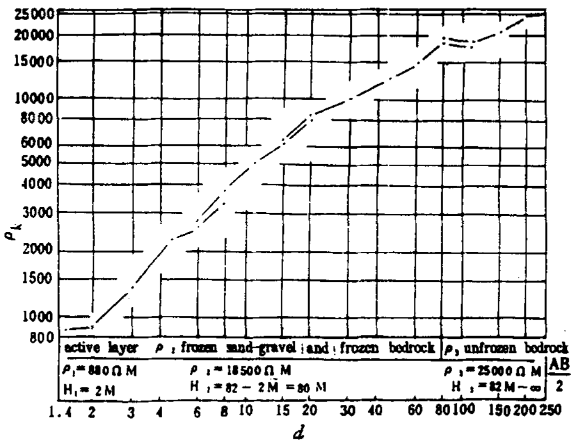
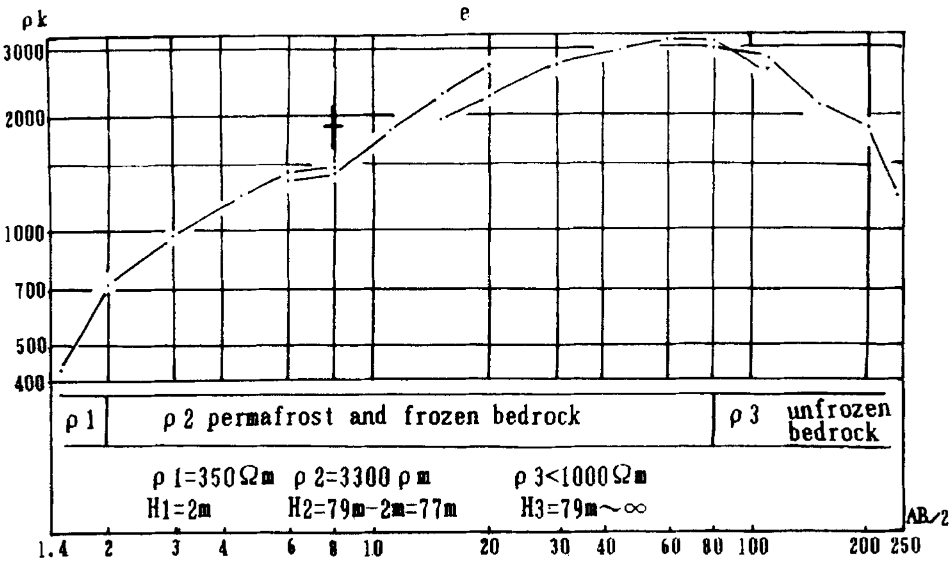
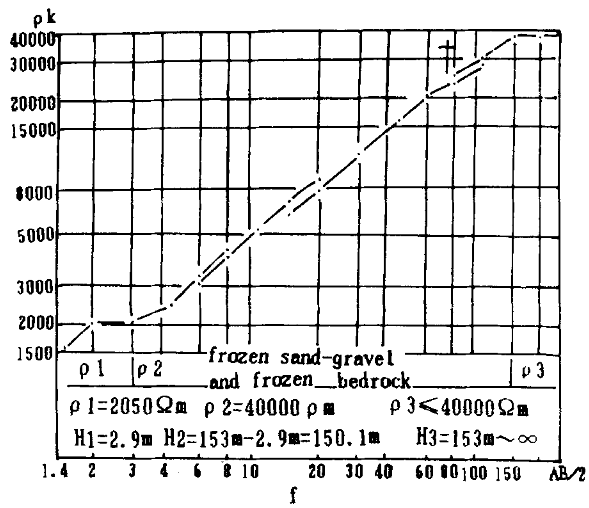


Figure 5 Curves of geoelectrical prospecting for different kinds of geological bodies: (a) permafrost in front of meteorological station (3558 m ASL); (b) moraine behind meteorological station (3558 m ASL); (c) rock glacier group, Daxigou Valley (3550 m ASL), probe orientation SE; (d) rock glacier in dry cirgue, Daxigou Valley (3850 m ASL); (e) permafrost to the west of meteorological station (3650 m ASL); (f) rock glacier group, Daxigou Valley (3550 m ASL), probe orientation NW. Resistivities: (a), (b), (c) are k-types where $\rho_1 < \rho_2 > \rho_3$; (d) is A-type where $\rho_1 < \rho_2 < \rho_3$.





slope and numbered them. After one year, fourteen clasts on the control line had been displaced, although the movement velocities are very slow (maximum 2.5 cm/a, minimum 0.5 cm/a, average 0.96 cm/a). Compared to other rock glaciers, velocities are insignificant. This results from the low frequency of frost thawing which restrains the movement velocity of rock glacier No. 1. It is the lowest rock glacier (3350 m ASL) in the area, near to the lower limit of permafrost, and the average annual temperature is 2 °C higher than at rock glaciers No. 2, No. 3 and No. 5 (discussed below). The number of days that temperature fluctuates at 0 °C is 25 less than at the meteorological station situated at rock glaciers No. 2 and No. 5, at least in 1985.

Figure 6 Tongue-shaped rock glacier in dry cirgue, Daxigou Valley.

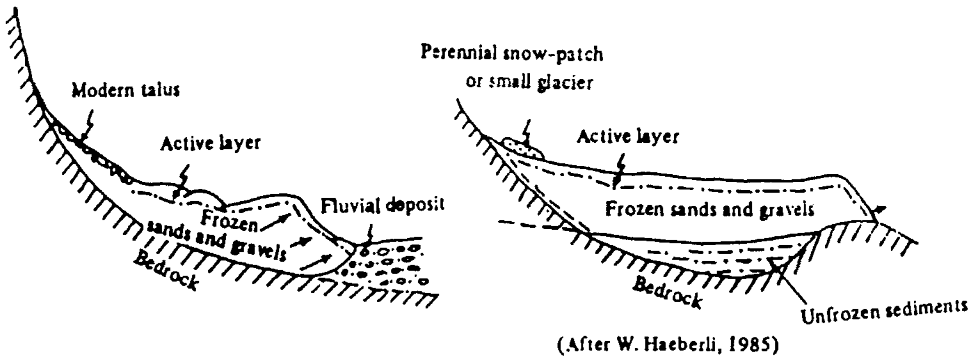


Figure 7 Comparison of structure of rock glaciers of the Tianshan type (left) and the Alps type (right).

Relative Active Type

Examples of this type are rock glaciers No. 2, No. 3, No. 4 and No. 5.

Rock glacier No. 2, located on the south side of Daxigou Valley (3600 m ASL, Figure 2), is more than 70 m long and 119 m wide, and has a slope of 34°. Using the same method as that of rock glacier No. 1, control points on bedrock on both sides of the rock glacier were set up. A total of 37 clasts were plotted on lines that joined the control points on the top of the front of the rock glacier. Thirteen clasts moved forward in one year; the distance was 11.23 cm on average. In particular, one block (quartz schist, with dimensions 70 × 60 × 45 cm) rolled forward 1.58 m, and the painted part of the top turned 90° in angle. However, two large clasts moved backward 4.5 cm and 1 cm respectively. Of 100 clasts that were plotted on the front slope, 36 moved. The fastest moving debris was on the middle of the front slope; the average vertical displacement was 2.0–4 m, and the average horizontal displacement was 1.5–3 m. Yet, there was no movement for the 20 clasts at the top, and only 2 clasts moved at the foot.

The movements of rock glaciers No. 3, No. 4 and No. 5 were also measured. Rock glacier No. 3 is about 60 m long, 150 m wide, and 30 m high on the front, and is located in Heixionggou Valley on the south of Victory Pass. A total of 32 painted survey points were monitored. We found that 29 survey points were displaced in a year. The horizontal and vertical movement of these points averaged 45 cm/a and 14 cm/a respectively. Rock glacier No. 4 is located at the foot of the north slope of Victory Pass (Figure 3). The horizontal and vertical movement velocities of 15 plots were 15.5 cm/a forward and 16.5 cm/a downward.

Active Type

The movement of the large tongue-shaped rock glaciers in the west cannot be observed closely because of the high and precipitous mountains and gorges. However, a tongue-shaped rock glacier about 200 m long and 40 m wide, with 330°NW aspect of slope and a 17° sediment slope (No. 7 rock glacier), exists beside the Dushanzi–Kuqa Highway (at 112 km) to the north (about 400 m) of the Haxilegen Daban Tunnel in Eren Habirga Shan. Some marks of road building can be seen, though not very distinct, at the back of the rock glacier surface. Therefore, it is an artificial rock glacier according to Corte's classification (Giardino *et al.*, 1987). A theodolite was used to measure repeatedly the movement velocities of ten clasts at the front of the rock glacier surface in July 1988 and July 1989. Of the ten points, nine moved forward. The horizontal and vertical displacement ranges average 1.93 m and 0.4 m respectively.

In addition, there is a rock glacier about 3 km long, 120 m high and 200 m wide on the south of Dushanzi–Kuqa Highway (at 108 km, Figure 3). The front slope is 37°. This Alpine-type (tongue-shaped) rock glacier is composed of moraine due to deglaciation. It is a fast-moving rock glacier since stones often fall down the front slope.

CONCLUSIONS

Barsch (1971) and Haeberli (1985) found that there is a 400–500 m difference between the maximal elevation of rock glaciers and relevant snowline in different periods. For example, in Switzerland, most modern snowlines are about 3100 m ASL, whereas the maximal elevation of rock glaciers is 2600 m ASL. Cui Zhijiu (1985) found that the terminals of rock glaciers are 468–518 m lower than the snowline (5150–5200 m ASL) in the Kunlun Mountain area. Wang Jingtai (1981) calculated the elevation of snowlines in different periods when glaciers advanced in the source area of Urumqi River. He obtained the elevations of snowlines to be 3880±25 m in the Little Ice Age, 3800±30 m in the Neoglaciation (3500–2900 a BP) and 3630±40 m at the end of Upper Wanfeng Stage (9500–10,000 a BP, i.e. the age between the Pleistocene and the Holocene).

In the Tianshan the elevation disparity between the rock glaciers and the snowline is smaller than that in the Alps and the Kunlun Mountains. For example, the modern active rock glacier group (3900 m) with the maximal elevation is about 150 m lower than the modern snowline; the elevation of rock glacier No. 2 (3600 m), formed in the Little Ice Age, is 280 ± 25 m lower than the snowline at that time. It can be calculated that rock glaciers No. 3, No. 4 and No. 5 (3500–3550 m ASL), which are lower than rock glacier No. 2, are older. It can also be concluded that rock glacier No. 1 may have been formed in the Upper Wanfeng Stage; its elevation is 330±40 m lower than the snowline at the end of the Upper Wangfeng Stage (i.e. 9500–10,000 a BP, the stage between the Pleistocene and the Holocene).

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