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Rates of Periglacial Processes in the Central Tianshan, China

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ABSTRACT

The periglacial landforms of the Central Tianshan are mainly distributed above the lower boundary (3200 m ASL) of permafrost. In the eastern part of the region, there are 130 days per year when the daily average air temperature fluctuates around 0 °C. The annual precipitation is 430 mm. Thus, periglacial landform development reflects the high frost-thawing frequency. By contrast, in the western part, there are only 90 days per year when the daily average air temperature fluctuates around 0 °C; thus, periglacial landforms are those typical of areas with low frost-thawing fequencies, even though the annual precipitation reaches 827 mm. Based on observations from 1985 to 1989, schist (bedrock) cracks have a maximal dilatational value of 19 mm/a in the region, and gneiss cracks have a maximal dilatational value of 4 mm/a. The frost-heaving of diorite reaches 8–40 mm/a. The moving rate of rockfall talus is 1 m/a. On sunny slopes (195 °SW), the talus debris has amounted to as much as 31.5 cm in the past 25 years, but on semi-shady slopes (65 °NE), the debris accumulation is only 5 cm. The alluvial talus (scree) has a downward movement rate of 146 cm/a on south-facing slopes, and 73 cm/a on north-facing slopes. Block slopes have a downward movement rate of 96 mm/a on sunny or semi-sunny slopes and 72 mm/a on the shady or semi-shady slopes; the average rate is 81 mm/a in the study region. East of 86°E, the lobate rock glacier is the main type and its mean moving rate is about 6 cm/a, as deduced by debris discharge which has covered the highway over the past 25 years. Measurements from 1985 to 1986 show that the movement of lobate rock glaciers is from 1 to 49 cm/a. Rates at the higher elevation (15.5–49 cm/a) are faster than at the lower elevation. At the same elevation, the rates on the northward slopes (about 49 cm/a) are greater than on southward slopes (45 cm/a). According to lichenometry data, lobate rock glaciers formed between 3949 a BP to 180 a BP. West of 86°E, the main rock glacier type is the tongue-shaped rock glacier. The mean movement rate is 0.4 m/a. Gelifluction lobes and terraces have an average annual movement of 25 cm in the east. In the west, the average annual movement rate of gelifluction is 49 cm/a.

RÉSUMÉ

Les formes périglaciaires du Tianshan central sont distribuées principalement au dessus de la limite inférieure du pergélisol (3200 m). Dans la partie orientale de la région, la température fluctue autour de 0 °C pendant 130 jours. Les précipitations annuelles s'élèvent à 430 mm. Les formes périglaciaires reflètent cette grande fréquence d'alternances gel-dégel. Par contre dans la partie orientale, la température moyenne de l'air est voisine de 0 °C pendant seulement 90 jours par an; aussi, les formes périglaciaires y sont typiques de régions où les alternances de gel-dégel sont moins fréquentes bien que les précipitations annuelles s'élèvent dans cette zone à 827 mm. Sur la base d'observations s'étendant de 1985 à 1989, des fissures dans le bedrock schisteux auraient une valeur maximale de dilatation de 19 mm par an, tandis que dans le gneiss la valeur maximale de dilatation serait de 4 mm par an. Le soulèvement

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par le gel de la diorite atteindrait 8 à 40 mm par an. Le déplacement des débris sur les talus d'éboulis serait de 1 m par an. Sur les pentes ensoleillées (195°SW), l'accumulation de débris a atteint 31,5 cm au cours des dermières 25 années, alors que sur les pentes à demi-ombragées (65°NE), l'accumulation a seulement atteint 5 cm. Le talus alluvial montre une vitesse de déplacement moyen de 146 cm par an sur les pentes exposées au sud et de 73 cm sur les pentes exposées au nord. Les versants couverts de blocs ont un mouvement moyen vers l'aval de 96 mm par an sur les versants exposés au soleil ou semi-exposés au soleil, et de 72 mm sur les versants ombragés ou semi-ombragés. La vitesse moyenne est de 81 mm par an dans la région étudiée. A l'est de 86° de longitude est, des glaciers rocheux lobés constituent la principale forme périglaciaire et leur vitesse d'avancée moyenne est d'environ 6 cm par an si l'on en juge par la quantité de débris qui a recouvert la grand-route au cours des 25 dernières années. Des mesures de 1985 à 1986 montrent que le mouvement de ces glaciers rocheux lobés varie de 1 à 46 cm par an. Les vitesses sont plus élevées aux hautes altitudes qu'aux altitudes plus basses. A la même altitude les vitesses varient d'environ 49 cm par an sur les pentes exposées au nord à des valeurs de 45 cm par an sur les pentes exposées au sud. D'après les données obtenues par l'étude des lichens, les glaciers rocheux se sont formés il y a environ 3949 années BP (± 180 ans). A l'ouest du méridien de 86°est, les glaciers rocheux sont principalement en forme de langues avec un mouvement moyen de 0,4 mm par an. Les lobes et les terrasses de gélifluxion ont un mouvement moyen annuel de 25 cm à l'est, tandis qu'à l'ouest le mouvement annuel moyen de la gélifluction de 49 cm par an.

KEY WORDS: frost weathering; talus; block slopes; gelifluction; rates of movement

BACKGROUND

The studied region (41°31′N–44°20′N; 82°10′E–88°40′E) is located in Xinjiang Uygur Autonomous Region, China. The altitude of the mountain ridges is mainly between 4100 and 4300 m ASL. There are more than 1000 modern glaciers; the terminals of glacier tongues have altitudes of about 3650–3700 m ASL. The lower boundary of permafrost is between 3200 and 3300 m ASL, and the upper limit of the forest zone is about 2600–2900 m ASL.

The region is a mountain body which mainly consists of Palaeozoic granite and metamorphic rock. In geotectonics, it belongs to the middle section of the Tianshan geosynclinal folded system. However, on either side of 86°E, the climate and the periglacial landforms and processes are different. To the west, the Narat Mountain is situated in the Kunes synclinorium and the topographic relief is gentle in spite of its higher topography. In the east, the Kalawucheng Mountain is located in the central position of Boluohuojing anticline, so the topography is steep. In climatology, the western gentle topography is advantageous to vapour entering from the northwest. On the other hand, the eastern area has less precipitation owing to its steep topography and long distance from the moisture source.

Observational data from the Snow Deposit and Avalanche Station of Academia Sinica, situated at 1776 m ASL on the Narat Mountain, indicates that the western part has an annual average precipitation of 827 mm and a maximum of 1140 mm. At 3580 m ASL, the annual mean air temperature is −9.4 °C and the mean January air temperature is −25.5 °C. Data (1958–1980) from the Daxigou Meteorological Station, elevation 3588 m, indicate that the eastern part has an annual average precipitation of only 430 mm, an annual mean air temperature of −5.3 °C, and a mean January air temperature of −15.9 °C.

The frequency of frost thaw is a main control over the forming of periglacial landforms (Figure 1). Although the source region of the Urumqi River (i.e. Daxigou area) of the eastern area is dry and cold, the time when the daily average temperature fluctuates around 0 °C in a year can reach 130 days. In the west part, the time when the daily average temperature fluctuates around 0 °C in a year is less than 90 days, so the frost-thawing frequency is lower. There are only gelifluction lobes, gelifluction terraces, rock glaciers and talus in the La-er-dun Daban area (Figure 2) (Zhu Cheng and Cui Zhijiu, 1992).

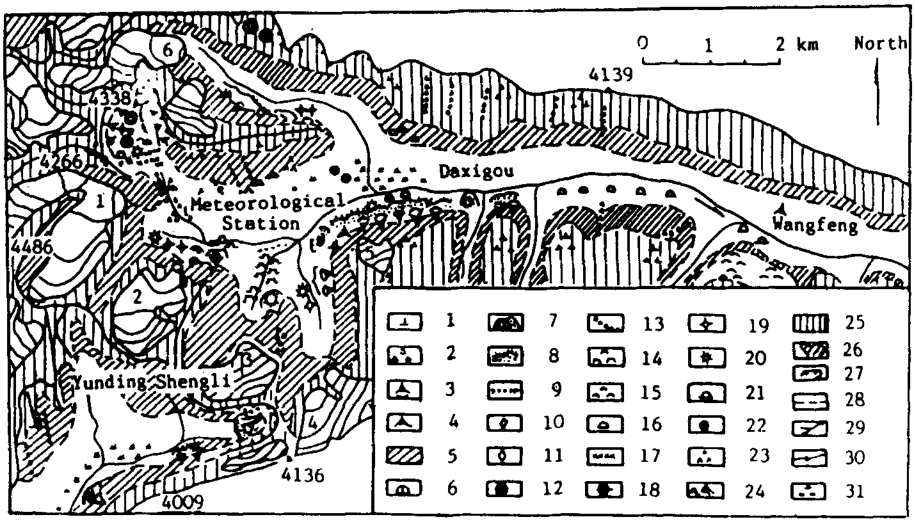
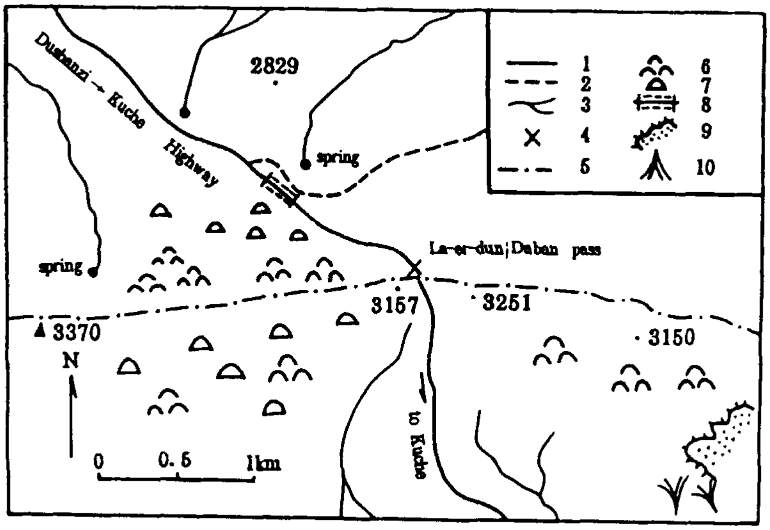


Figure 1 Sketch map showing the distribution of periglacial landforms in Daxigou area, Central Tianshan Mountains. 1 Tor; 2 rock field; 3 rock debris; 4 debris cone; 5 block slope; 6 sorted terrace; 7 rock glacier and its number; 8 cluster of rock glaciers; 9 sorted stripes; 10 sorted net; 11 sorted polygon; 12 sorted circle; 13 block stream; 14 stone spread; 15 gelifluction tongue; 16 gelifluction bench; 17 unsorted stripe; 18 unsorted net; 19 unsorted polygon; 20 unsorted circle; 21 seasonal frost mound; 22 thaw depression; 23 upheaving stone; 24 denudation from weathering; 25 rock slope; 26 modern glacier and its number; 27 cirque and nivation depression; 28 boundary line; 29 river; 30 mountain peak and ridge line; 31 swamp.



1 highway 2 path 3 river 4 pass 5 ridge
6 gelifluction lobes 7 gelifluction terrace 8 snowproof corridor 9 rock glacier
10 talus

Figure 2 Distribution of periglacial features in La-er-dun Daban region, Tianshan Mountains.

PERIGLACIAL LANDFORM PROCESSES

Frost Weathering of Bedrock

Frost weathering of bedrock is a prerequisite for periglacial landform development. In the eastern part (43°04′–43°08′N; 86°48′–87°00′E), sericite-quartz schist is easily weathered, silicalite and granite is hard but fragile, and augen gneiss has fractures and joints which are well developed. Because the swelling coefficients of the main minerals differ greatly (for example, the volumetric

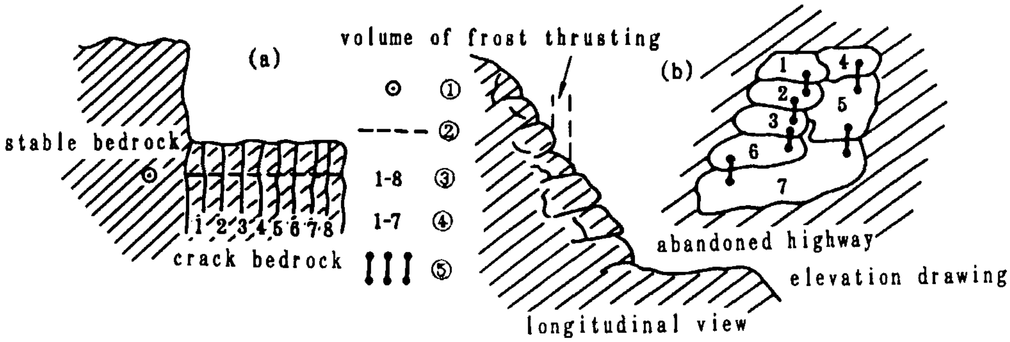


Figure 3 Sketch of (a) frost spalling and (b) frost thrusting. 1 Control point; 2 orientational traverse; 3 crack number; 4 rock-block number; 5 measuring points of frost thrusting.

expansion coefficient of quartz is 0.00031, that of feldspar 0.00017:), those minerals break easily by scalloping when air temperatures change rapidly. Water, which infiltrated the joints and cracks in the rainy season, accelerates the slaking process.

In the modern periglacial area of the Central Tianshan, frost spalling and frost wedging are the main frost-weathering processes of bedrock (Ji Zixiu, 1982). The former occurs mainly in the region where quartz schist, siliceous slate, sand-shale and phyllite occur. Most weathering debris is in the form of sheet or platy blocks with flat smooth surfaces; the latter occurs mainly in the region where gneiss, granite and all kinds of crystalline rocks are present. Their weathering debris have concavo-convex surfaces.

Five observation points were established in the source region of the Urumqi River to measure weathering denudation. Two kinds of weathering processes were observed from 1985 to 1989. Frost spalling was observed by the establishment of control points on stable bedrock, the numbering of cracks near the control points, and the identification of orientational traverses. Then, the change distances of the cracks were observed periodically (Figure 3a). The observation method for frost thrusting of bedrock was to establish orientational traverses on the slope, number the frost-raised rocks, and then periodically measure the elevation of the rocks (Figure 3b). Observation points 1, 3, and 5 reveal the frost-weathering characteristics of bedrock in this area.

OBSERVATION POINT 1 (3820 m ASL)

Observation point 1, located on the south-west slope of the dry cirque of Daxigou, has been used to observe the frost spalling of siliceous slate. The bedrock develops numerous vertical cracks through frost-weathering action (Figure 4). Table 1 illustrates the change values of the cracks at this observation point. Table 1 also shows that the maximal enlarging value of the cracks can reach 1.9 cm (i.e. crack 10 in 1986), and when one crack enlarges (crack 11 in 1989), others are compressed (cracks 4, 10, 12 in 1989).

OBSERVATION POINT 3 (3600 m ASL)

This point is situated 400 m west of the Daxigou Meteorological Station. The bedrock is augen gneiss and the main weathering process is frost wedging. Most of the rock surfaces are ragged and concavo-convex shaped. Certain crack widths enlarged 0.2 cm between 1985 and 1986.

OBSERVATION POINT 5 (3900 m ASL)

Observation point 5 is used to observe frost thrusting of bedrock. It is located beside an abandoned highway, which is on the west of Daxigou glacier 4. The slope gradient is 36°, and the aspect of the slope is 216°SW. The bedrock is diorite. Under long-term low temperature (mean annual air temperature < -8°C), the moisture migration within the bedrock pores is hindered by the frozen plane. By observation, rocks 1 and 6 protruded 0.8 cm and 4.0 cm respectively, while rocks 5 and 7 retracted several millimetres during 1985–1987. From 1987 to 1989, all rocks retracted 0.2 cm to 0.4 cm (Table 2).

Obviously, the annual crack changes are not simply extension and spalling. In fact, both

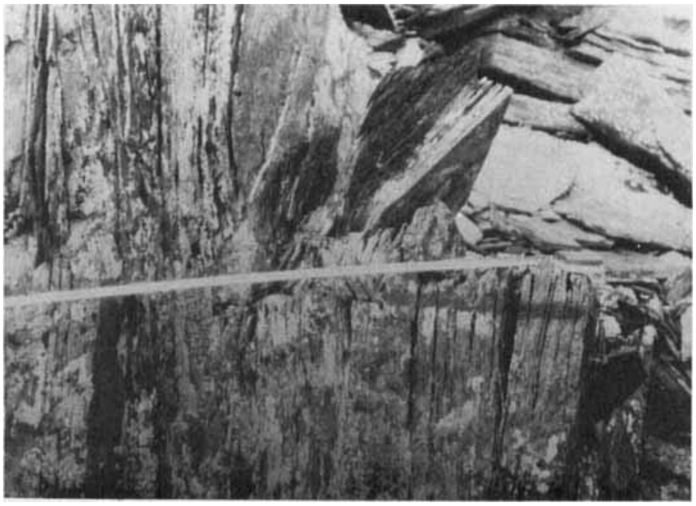


Figure 4 Observational point 1 of siliceous-slate crack change.

Table 1 Change of surveying point 1 (siliceous-slate cracks) from 1985 to 1989.

	Distances between sides of cracks and control point (cm)				
Crack	1985	1986	1987	1988	1989
1	9.4	9.6–9.8	9.5–9.9	9.7–10	9.6–9.9
2	10.8–11.0	10.9–11.1	11.0–11.2	11.0–11.2	11.0–11.2
3	11.9–12.2	11.9–12.5	12.0–12.5	12.3–12.7	12.1–12.6
4	13.6	13.7–13.8	13.9–14.1	14.0–14.2	14.2–14.2
5	15.2–43.5	15.5–43.5	15.5–43.4	15.5–42.2	15.5–43.5
6	43.9–44.0	50.5–50.7	52.7–52.9	43.5–43.9	50.0–51.0
7	44.8–44.9	52.5–52.7	55.4–55.7	50.5–51.0	52.6–52.9
8	50.0–50.9	56.6–57.0	56.6–57.1	52.7–52.9	54.8–55.0
9	52.7–53.0	58.8–59.0	58.9–59.2	56.7–57.0	56.6–57.0
10	53.2	59.7–61.6	59.8–61.6	57.8–58.8	59.1–59.3
11	53.6–53.7	61.9–62.0	61.9–62.1	59.1–59.3	59.7–61.4
12	54.2	64.3–64.4	62.5–62.7	59.8–61.7	62.0–62.2
13	54.4–54.5	64.7–64.8	64.3–64.5	61.9–62.5	62.7–62.8
14	54.7	66.6–66.7	64.7–64.8	62.6–62.8	64.5–64.7
15	54.9	67.7–67.8	66.4–66.5	64.4–64.6	65.0–65.1

extension and contraction exist. Table 1 reveals that the distance (or crack width) from each crack (two sides) to the control point actually has a certain changing annual amplitude. It is clear that cracks 1 to 4, which are near the control point, have little annual changing amplitude, while cracks which are far from the control point have a large annual changing amplitude. Hence, (1) the cracks have obvious extension-contraction and compression between themselves, and (2) the cracks dilate toward the unconstrained side.

As for the frost-weathering and denudation

Table 2 Change of surveying point at site 5 (diorite frost thrusting) from 1985 to 1989.

	Height of frost thrusting (cm)			
Thrusting status	1985	1986	1987	1989
1 higher than 2	1.0	1.6	1.8	0.5
3 higher than 2	1.0	0.8	0.9	0.7
5 higher than 3	4.0	3.9	3.9	2.4
4 higher than 5	3.5	3.9	3.7	3.5
6 higher than 7	10.0	10.4	14.0	10.1
7 higher than 5	1.0	0.7	0.8	0.4

Figure 5 Lobate rock glacier (arrow) in Daxigou Valley, Tianshan Mountains.

rates of the bedrock, Li *et al.* (1981) have obtained a value of 0.0229 $m^3/(m^2/a)$. This is deduced from the buried depths of three sections of the highway in Shengli Pass (Figure 1) during the past 20 years. The retreating rate of bedrock caused by frost weathering is 16 mm/a on sunny slopes (near 3950 m ASL), and 49 mm/a on shady slopes. It is 10 times higher than in Europe. Therefore, strong frost weathering of bedrock exists in this area, and there is abundant material (debris) for periglacial mass movement.

Movement of Talus

In the source region of the Urumqi River of the Tianshan, there are more than 40 rockfall taluses, more than 10 alluvial taluses and one protalus rampart, according to White's (1981) classification. The rockfall taluses are mainly distributed at the foot of steep northward or semi-shady slopes. The alluvial taluses are mainly at the foot of hanging glacier 5 as well as on the backwall of dry cirques, where hanging glaciers also develop. The protalus rampart is at the foot (3600 m ASL) of the glaciated scarp in the Daxigou region, yet it has evolved a typical lobate rock glacier (Figure 5) (Zhu Cheng *et al.*, 1992).

In the summer of 1985, the author drove three rods, 0.5 m long, into the sediment at the foot of a rockfall talus on the abandoned highway on the southward slope (aspect 195°SW, gradient 36°) of the Shengli Pass. By the summer of 1986, the front of the talus had overstepped the rods by 100 cm. Obviously, talus movement is rapid.

In 1986, Xiong (Xinjiang Geography Institute, 1990) used bedrock control points, thin steel rods and painted orientational traverses to observe movement of the alluvial taluses on the backwall (with aspect of 38°NE and gradient of 36°) of the dry cirque, and on the northward slope (shady slope with aspect of 15°NE and gradient of 35°) of the Shengli Pass. After several months, he found that the alluvial talus has a moving rate of 0.4 cm/d (maximum 1.4 cm/d, minimum 0.1 cm/d) on the southward slopes and 0.2 cm/d (maximum 0.4 cm/d, minimum 0.04 cm/d) on the northward slope. Annually, the rates of the two taluses are 146 cm/a and 73 cm/a respectively.

On the abandoned highway, which is located to the west of glacier 4, the debris of recent rockfall taluses was observed. On a semi-shady slope (aspect 65°NE), the frequency of the daily

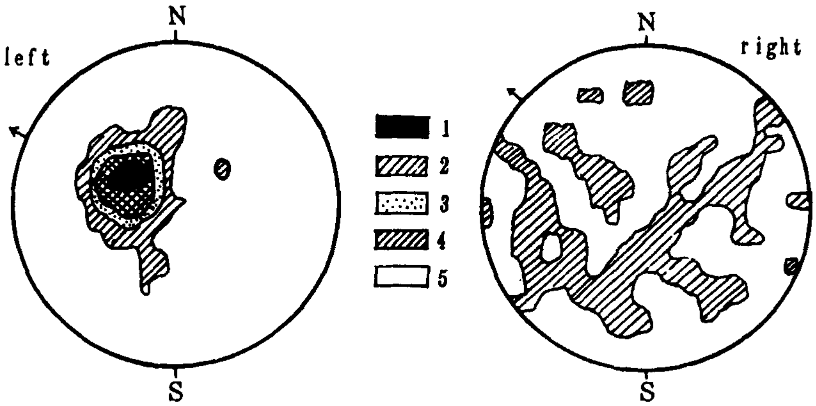


Figure 6 Debris fabric of A-axis of rockfall type (left) and alluvial type (right) talus. Left, rockfall talus: accumulated thickness 0–2.00 m, maximum degree 26%, sedimental-plane aspect 295°; sedimental-plane gradient 35°. Right, alluvial talus: accumulated thickness 0–1.35 m, maximum degree 5%, sedimental-plane aspect 310°, sedimental-plane gradient 37°. 1, 8–14%; 2, 6–8%; 3, 4–6%; 4, 2–4%; 5, 0–2%. Arrow: sedimental-plane aspect.

average air temperature fluctuation around 0°C is lower, so frost weathering is weaker and the weathering debris is less than that of the sunny slope. Debris accumulation at the retaining wall (semi-shady slope) of the abandoned highway is only 5 cm thick, while debris on the sunny slope (aspect 195°SW) is 31.5 cm. It is clear that the talus debris from the sunny slope is about five times greater than from the semi-shady slope.

During the period from 1985 to 1986, the two kinds of talus described above (rockfall and alluvial) moved faster than in other areas in the world. For example, the moving rate of talus is 22 cm/a in the north of Norway (Washburn, 1979) and 8–10 cm/a (White, 1981) in the Front Ranges of Colorado.

Fabric analysis is an important method in inferring the transportation and deposition mechanism for coarse sediments. It was undertaken on the northward and southward slopes of the Daxigou Valley (3600 m ASL). One hundred gravel pebbles were measured at both localities. The fabrics show that each talus has a uniformity between AB plane dip and depositional surface. For the rockfall type the difference between dip and aspect is within 30°, while for the alluvial type the difference is 30–40°. This indicates that the two kinds of talus are both formed mainly by gravitational action. That the rockfall talus has a more dominant dip of the AB planes indicates that gravitational control in the transportation and deposition of the rockfall is more obvious.

There is a difference of A-axis dip between the two kinds of talus (Figure 6). The A-axis dip of the rockfall type is uniform with its depositional plane aspect. However, the A-axis dip of the alluvial talus is dispersed. There is a difference of 100° to 200° between the A-axis dip and the sedimental plane aspect. Since the debris of the two types is angular and subangular respectively, the genesis of the two talus is also different.

Block Slope Movement

Block slopes are well developed in the region, especially on gentle bedrock slopes (30°–60°) on the sunny side. They often extend from mountain ridge to valley bottom (Figure 7). When the block slopes extend downslope with a narrow shape, they often evolve into block streams. When the slope is gentle, they often evolve into block fields (such as on the top of the Shengli Pass).

Ten observation points for the movement of block slopes were established in the Daxigou area. By establishing control points on stable bedrock situated on two sides of a block slope and setting up painting profile lines with different colours between the control points every year, the periodic changes in these profile lines and the displacements of the painted debris were measured. Table 3 shows the annual moving rate and change of the block slopes. Because the slope of the observation point MM4–1 is larger than 45°, the moving rate of the block slope is affected by gravity. Using the data of the other nine points, the average downglide rate for the sunny slope (or semi-sunny slope) is 10.6 cm/a

Figure 7 Active block slope on the south slope of Shengli Daban, Tianshan Mountains.

Table 3 Moving rates of block slopes.

Number	Altitude (m)	Aspect	Gradient	Length of cross profile (m)	Downglide rate (cm) Year	Max.	Min.	Mean	Remarks
MM1	3620	62°NE	35°–40°	25.50	1986 1987	30 34	2.0 3.5	8.0 11.6	Boulder 7 disappeared by rolldown to foot of slope
MM2-1	3840	62°NE	30°	1.60	1986 1987	60 84	2.2 2.0	19.7 23.0	Upper
MM2-2	3837	62°NE	44°	1.64	1986 1987	3 10	2.0 4.0	2.6 7.3	Middle
MM2-3	3832	62°NE	17°	1.64	1986 1987	4 5	1.0 2.0	2.6 3.6	Lower
MM3-1	3800	142°SE	11.5°	11.20	1986	21	2.0	9.4	Near drainage ditch
MM3-2	3800	142°SE	19°	17.65	1986	12	3.0	6.0	Far away from drainage ditch
MM4-1	3950	89°NE	>45°	5.70	1986	169	104.0	124.0	Upper
MM4-2	3950	89°NE	35°	5.70	1986	40	9.0	20.5	Lower
MM5	3950	216°SW	36°	9.60	1986 1987 1988	15 20 115	1.0 2.0 1.0	7.2 10.8 19.5	
MM6	3400	44°NE	35°	61.95	1986	2	0.5	1.4	Located at front of rock glacier

(maximum 115 cm/a, minimum 1 cm/a) and the rate for the shady slope (or semi-slope) is 8.9 cm/a (maximum 84 cm/a, minimum 0.5 cm/a). The average rate for all the block slopes is 9.5 cm/a.

The author believes that the movement of block slopes is affected by three factors, as follows.

SLOPE GRADIENT

Block slope MM2 illustrates this control since three profiles are located on the same slope, but their gradients are different. The gradient of the upper one is 30°, of the middle one is 44° and of the lower one is 17°. Their average downglide rates are 21.4 cm/a, 5 cm/a and 3.1 cm/a respectively. The movement of the upper profile, which is near the top of the slope, is affected by the impacting force of the frost-weathered debris falling from the free face above, so its rate is highest. However, over the whole longitudinal profile, it is clear that the downglide rate of the block slope is controlled by the slope gradient when other conditions (e.g. debris size, thickness of active layer and moisture) are the same.

MOISTURE

Block slope MM3 consists of two profiles and is located in the outlet of the dry cirque in Daxigou region. The profile MM3-1 (slope gradient 11.5°) is near a drainage ditch, while profile MM3-2 (gradient 19°) is further away. Their mean downglide rates are 9.4 cm/a and 6 cm/a respectively. Furthermore, the displacement debris of the former is more than the latter. Table 3 shows that the downglide rate of the profile MM3-1 is more than twice that of MM2-3 although the slope gradient is 5°–6° lower than MM2-3. These data tell us that the movement of block slopes in an area whose slopes have almost the same gradients are controlled by moisture. For example, when the rate in a dry place is 0.9–2.9 cm/a, the rate in a humid place can reach 3.4–3.7 cm/a.

ASPECT OF SLOPE AND FROST-THAWING FREQUENCY

The moving rates of MM5 (on the semi-sunny slope) and MM3 (on the sunny slope) are 5–15 times faster than that of MM6 (on the shady slope) (Table 3). This is explained by the frost-thawing frequencies and moisture differences on the different slope aspects. Based on the data of 1985, for instance, an annual precipitation of 293 mm, and 126 days per year when the daily average air temperature fluctuates around 0 °C, were measured at the meteorological station on the southward slope in the Daxigou Valley. However, an annual precipitation of only 179 mm, and 101 days in a year when the daily temperature fluctuates around 0 °C, were measured at the Total Control Hydrometric Station, near control point MM6. This explains why the moving rate of the block slope and its debris accumulates faster on MM5 and MM3 than on MM6. It is also one of the reasons why asymmetrical valleys exist in the area with gentle southward slopes and steep northward slopes.

Movement of Rock Glaciers

The author (Zhu Cheng *et al.*, 1992) has discussed the distribution and genesis of the rock glaciers in the region. Large active rock glaciers to the west of longitude 86°E belong to the tongue-shaped rock glacier, whereas the small, less active rock glaciers to the east of 86°E mainly belong to the lobate-shaped category. Based on the debris discharge which has covered the abandoned highway surface during the past 25 years, the mean moving rate of lobate rock glaciers is 6 cm/a. The rock glaciers also move in an irregular fashion. An instrument survey during 1985–1986 shows that their velocities varied between 1 and 49 cm/a.

Based on annual data, the flow velocities (15.5–49 cm/a) of the rock glaciers at higher elevations are faster than those at lower elevations (1 cm/a). At the same elevation, the rate (49 cm/a) of the rock glacier on the northward slope is faster than that on the southward slope (45 cm/a).

The tongue-shaped rock glaciers in the west are mainly situated in steep canyons and field observation is difficult. However, the author has observed a tongue-shaped rock glacier, about 200 m long and 40 m wide, whose slope aspect is 330°NW and whose slope is 17° (Figure 8). It occurs adjacent to the Dushanzi-Kuqa Highway (at 112 km) to the north (about 400 m) of the Haxilegen Daban Tunnel in Eren Habirga Sham. To the rear of the rock glacier, marks of road building can be seen. Therefore, it should be classified as an artifical-origin rock glacier according to the classification of Corte (1988).

A theodolite was used to measure the movement of 10 pieces of detritus at the front of the rock glacier surface in July 1988 and July 1989. Of the ten points, nine moved forward and one moved backward. In one year, the horizontal and vertical displacement averaged 1.93 m and 0.4 m respectively (Figure 9). Obviously, the movement of tongue-shaped rock glaciers is much faster than that of lobate rock glaciers. However, reliable average annual movement velocities remain to be observed, at least for several years.

In addition, a rock glacier about 3 km long, 200 m wide and 120 m high was observed to the south of the Dushanzi-Kuqa Highway. The front slope is 37°. This tongue-shaped rock glacier, composed of moraine, is fast moving, since stones often fall down the front sope.

Lichenometry is one of the six main methods

Figure 8 A tongue-shaped rock glacier (arrow) of artificial origin on the side of Haxilegen Daban peak.

of Holocene dating (e.g. Beschel, 1973). The *Xanthoria elegans* is a kind of effective cosmopolitan species of dating. There are numerous round *Xanthoria elegans* on the front of rock glacier 2. The shape of 50 lichens growing on boulders were measured. The lichens have a mean long-axis diameter of 81.5 mm and a short-axis diameter of 62.9 mm. Based on growing curves (Figure 10) of *Xanthoria elegans* in the Daxigou region derived from measurement of lichens in Houxia cemetery, the age of these lichens was deduced to be about 150 a BP.

Movement of Gelifluction Lobes (Terraces)

Gelifluction lobes and solifluction terraces occur mainly in the lower boundary (2900–3350 m ASL) of the permafrost. In order to obtain their movement characteristics, five observation points were established. The control points were set up on the bedrock. Using a theodolite and plane table, the movements of the gelifluction lobes and solifluction terraces were repeatedly measured.

The solifluction lobes in Wangfeng and La-er-dun Daban and the solifluction terraces in Daxigou Valley are typical. Lying at an elevation of 3350 m ASL, the Wangfeng lobe, whose aspect of slope is 50°NE and gradient is 21°, was observed in 1985 and 1986. Fifteen piles were used, among which thirteen moved forward and the other two moved backward within one year. Pile 6 moved fastest with a horizontal velocity of 0.7 m/a and a vertical velocity of 0.22 mm/a. The mean horizontal and vertical velocity of the fifteen piles was 0.25 mm/a and 0.09 m/a respectively (Figure 11). The fabric measurement of the gravels at 0–1 m depth shows both the *AB* plane dip and the *A*-axis dip are reverse to the main flow direction and the *AB* plane dips concentrate closely.

The gelifluction lobes in La-er-dun Danban (3080 m ASL) develop mainly on the north slope (Figure 12). In order to reveal their interior structure, temperature and water content, the author undertook excavation of a gelifluction lobe. Its slope was 29°, its length was 19.8 m, and it varied in width between 17.7 m at the back border, 15.9 m at the middle and 6.5 m at the front. The raised height at the front was 1.4 m. The following four layers were revealed: (1) dark brown alpine meadow humic soil (0.15 cm); (2) dark brown rubble-bearing alpine meadow soil (15–97 cm); (3) dark brown gravel-bearing sandy soil (97–170 cm); (4) gray brown granular-shaped ice-bearing frozen ground (1.7–2.0 m).

In order to reveal the movement characteristics of the gelifluction terraces in La-er-dun Daban, an observation point was established on the top of a snow-proof corridor which is made of reinforced concrete. This site was used to survey a gelifluction terrace which is 20-–40 m above the corridor. The observational data obtained between 1988 and 1989 (Table 4) show that all eleven rods glided downslope. The average horizontal displacement was 0.49 m and the largest (rod 2) was 1.06 m. The average vertical

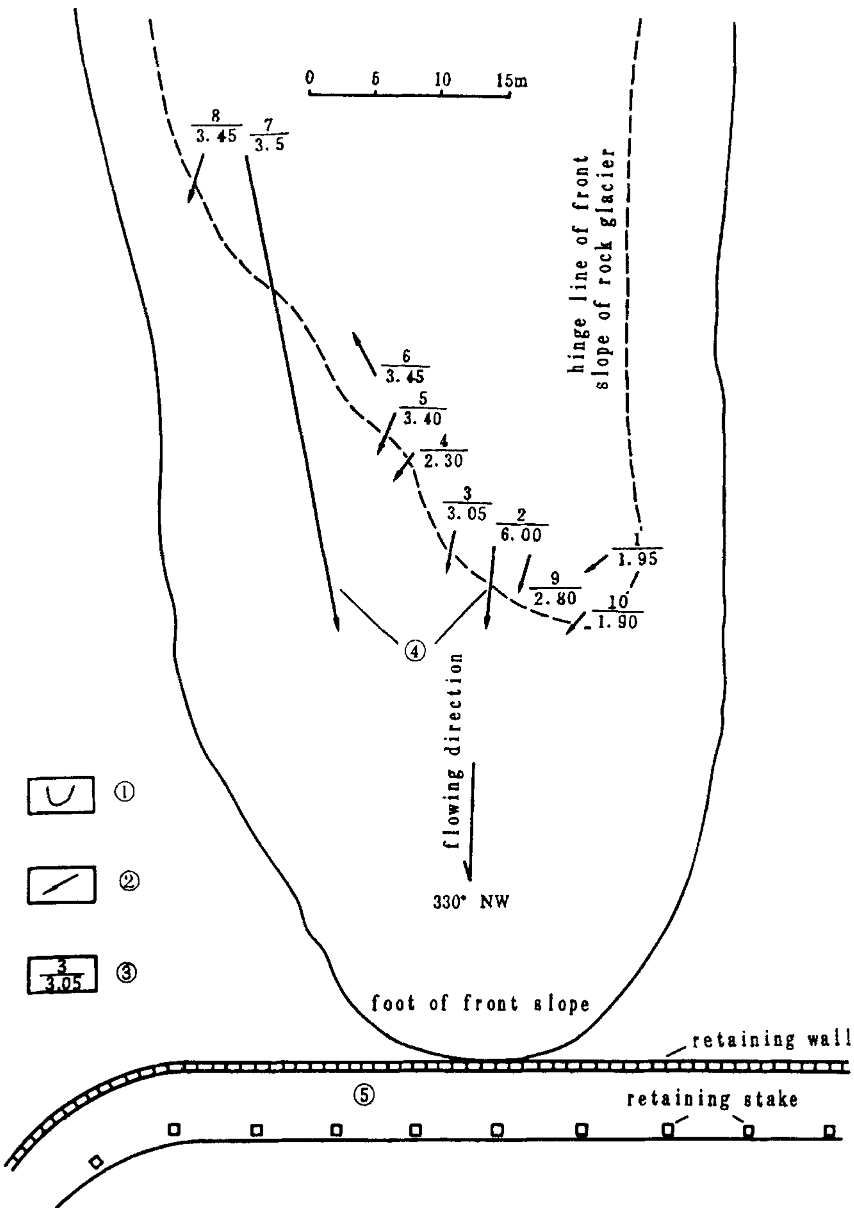


Figure 9 Moving direction and rates of creep on the Haxilegen Daban rock glacier, 1988 to 1989. 1 Rock glacier boundary; 2 moving direction of surveying points; 3 numerator is survey point number, denominator is flow velocity (m/a); 4 gravity roll-down for points 2 and 7, reversed movement for point 6; 5 surface of Dushanzi-Kuqa Highway.

displacement was 0.12 m and the largest (rod 9) was 0.27 m. Obviously, the horizontal moving rate of the La-er-dun Daban gelifluction terrace is 0.24 m/a faster than that of the Wangfeng gelifluction lobe and the vertical rate of the former is 0.03 m/a faster than that of the latter. We believe this can be explained by the higher gradient of the La-er-dun Daban gelifluction terrace and the higher precipitation which makes the active layer water-saturated. Table 5 compares the creep rates of the gelifluction lobes and gelifluction terraces of the Central Tianshan with other polar and subpolar areas. It shows that the creep rate of the gelifluction lobes (terraces) is 2–4 times faster than on Spitsbergen which is the highest of all the other regions. We believe this is because of the long frost-thawing period and deep thawing depth in the Central Tianshan in

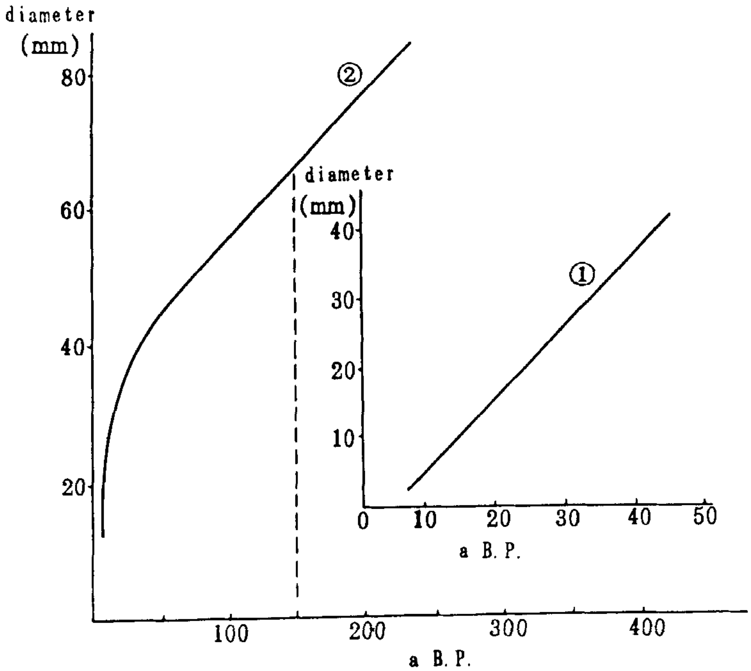


Figure 10 Growing curves of *Xanthoria elegans* in Daxigou region and Houxia. 1 Growing curves of *Xanthoria elegans* in Houxia cemetery; 2 growing curves of *Xanthoria elegans* at Tianshan Glaciological Station.

addition to the steep slopes (Cui Zhijiu and Zhu Cheng, 1989; Zhu Cheng *et al.*, 1991).

Washburn (1979), French (1976) and Jahn (1975) have all observed varying velocities at depth in Greenland, Arctic Canada, and Spitsbergen. However, the difference between surface movement and the lower debris has never been observed carefully. They found the relative moving difference only by the different rates of rods with different depths. To obtain the relative moving differences, we measured the front dip angles of the measuring rods in Daxigou Valley, Tianshan.

Figure 13 shows the changes of the front dip angles of six measuring rods which were established on gelifluction terrace MM7 near the Total Control Hydrometric Station at the outlet of the Luopudaogou in Daxigou Valley. The elevation of the gelifluction terrace is 3300 m ASL. Its aspect is 310°NW, the gradient is 25° and the width is about 100 m. It can be divided into two parts: the upper terrace and the lower terrace. Two measuring rods were established on the upper terrace, which is about 19 m long, and four rods were established on the lower terrace, which is about 12 m long. All the rods (1 m in length) were inserted about 0.5 m into the terrace. Using a geological compass, the front dip angles were measured in August of 1985 and 1986. During the year, the front dip angles all increased by 1–17° (Figure 13, II).

The mechanism of the different creep rates at different points in the active layer of the gelifluction lobes and terraces is shown in Figure 13.

The relative moving difference between the surface debris and the middle material of the active layer can be deduced by the rule of similar triangles (Figure 13, III). We can suppose an inactive apex exists on the ground surface. The end of the measuring rod is an active point. Thus, a right-angled triangle (OPQ) is obtained. Then the following general formula is obtained:

$$x = r \cos \alpha$$

The length of r (0.5 m) and the change of α are known, so the displacement of point P in one year can be calculated by the formula:

$$\Delta x = x_1 - x_2 = r_1 \cos \alpha_1 - r_2 \cos \alpha_2$$

According to the calculation method, the average relative displacement of point P to point O of the six measuring rods is 4.7 cm; the maximum (rod 5) is 14.8 cm and the minimum (rod 3) is 0.8 cm.

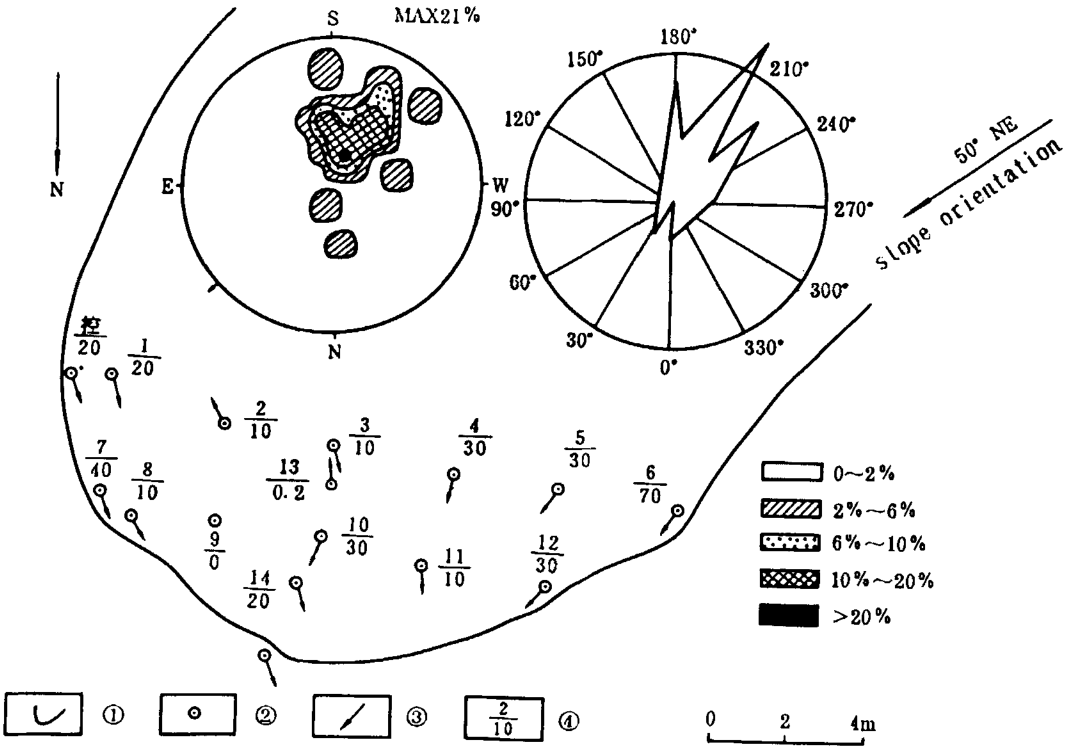


Figure 11 Flow velocity and surface debris fabric of Wangfeng gelifluction lobe, 1986 to 1989. 1 Boundary of gelifluction lobes; 2 position of survey point; 3 moving direction; 4 numerator is survey point number, denominator is flow velocity (cm/a).

Figure 12 Gelifluction lobes, La-er-dun Daban, Tianshan Mountains.

Table 4 Observational data from survey rods on gelifluction terraces in La-er-dun Daban, 1988 to 1989.

Survey marker	Slant range (m) 1988	Slant range (m) 1989	Vertical angle 1988	Vertical angle 1989	Horizontal separation (m) 1988	Horizontal separation (m) 1989	Elevation (m) 1988	Elevation (m) 1989
1	24.4	24.4	17°12′	18°32′	22.3	21.93	6.89	6.84
2	21.0	20.12	14°10′	15°43′	19.7	18.64	4.98	4.81
3	19.7	19.8	9°23′	11°00′	19.2	19.08	3.17	3.15
4	21.5	21.9	8°47′	10°16′	22.0	21.20	3.39	3.32
5	24.0	23.9	8°18′	9°40′	23.5	23.23	3.42	3.30
6	27.0	27.0	6°02′	8°08′	26.7	26.46	2.71	2.58
7	30.4	–	5°50′	–	30.1	–	3.06	–
8	34.0	–	6°19′	–	33.6	–	3.72	–
9	37.8	33.8	7°50′	8°55′	37.1	36.31	5.23	4.96
10	39.7	37.0	7°42′	8°04′	39.0	38.27	5.26	5.04
11	36.0	36.2	13°52′	14°50′	34.0	33.83	8.38	8.34
12	34.2	34.0	13°09′	13°58′	32.5	32.02	7.57	7.47
13	31.2	–	12°10′	–	29.9	–	6.43	–
14	29.5	29.3	11°05′	12°13′	28.4	27.99	5.56	5.47

Instrument heights were 1.48 m in 1988, 1.53 m in 1989.
Surveying markers 7, 8 and 13 were moved by artificial activity; therefore the markers were not measured.

Table 5 Creep rates of gelifluction lobes (terraces) in Tianshan Mountains and other polar, subpolar and alpine regions.

Region	Place	Dip (°)	Rate (cm/a)	Source
Tianshan	La-er-dun Daban	29	49	Zhu Cheng, 1992
	Wangfeng Platform	21	25	
Other	Banks Is.	14–22	0.9–2.7, 0.4–1.9	Quoted in French 1976; Washburn 1979; Jahn 1975
	Mesters Vig	10–14	0.9–3.7	
	Spitsbergen	11–15	1.5–12	
	Lapland	15	2	
	Norra Storfjäll	5	0.9–3.8	
	Okstindan	4–17	6	
	Karkonosze Mt	8–39	9.3–2.1	
	Grytviken	21	3–5	

The above calculation tells us that the creep rates of the middle active layer (at least at depth 0.5 cm or so) are faster than at the surface in the Central Tianshan. This conclusion is not identical with other colleagues' conclusions that the creep of gelifluction decreases as depth increases.

CONCLUSION

In the periglacial area of the Central Tianshan, frost spalling and frost wedging are the main frost-weathering processes of bedrock. The former occurs mainly in the region where quartz schist, siliceous slate, sandshale and phyllite occur. The maximal enlarging value of the cracks in bedrock reach 19 mm/a. When a crack enlarges, others are compressed. The latter occur mainly in the region where gneiss, granite and all kinds of crystalline rocks occur. The maximal compressing value of the cracks in gneiss can reach 21 mm/a and the maximal enlarging value can reach 4 mm/a. In addition, the frost thrusting of diorite protrudes 8–40 mm.

The moving rate of rockfall talus reaches 1 mm/a on sunny slopes (195°SW). The thickness of debris discharge of talus exceeded 31.0 cm in the past 25 years; on semi-shady slopes (65°NE),

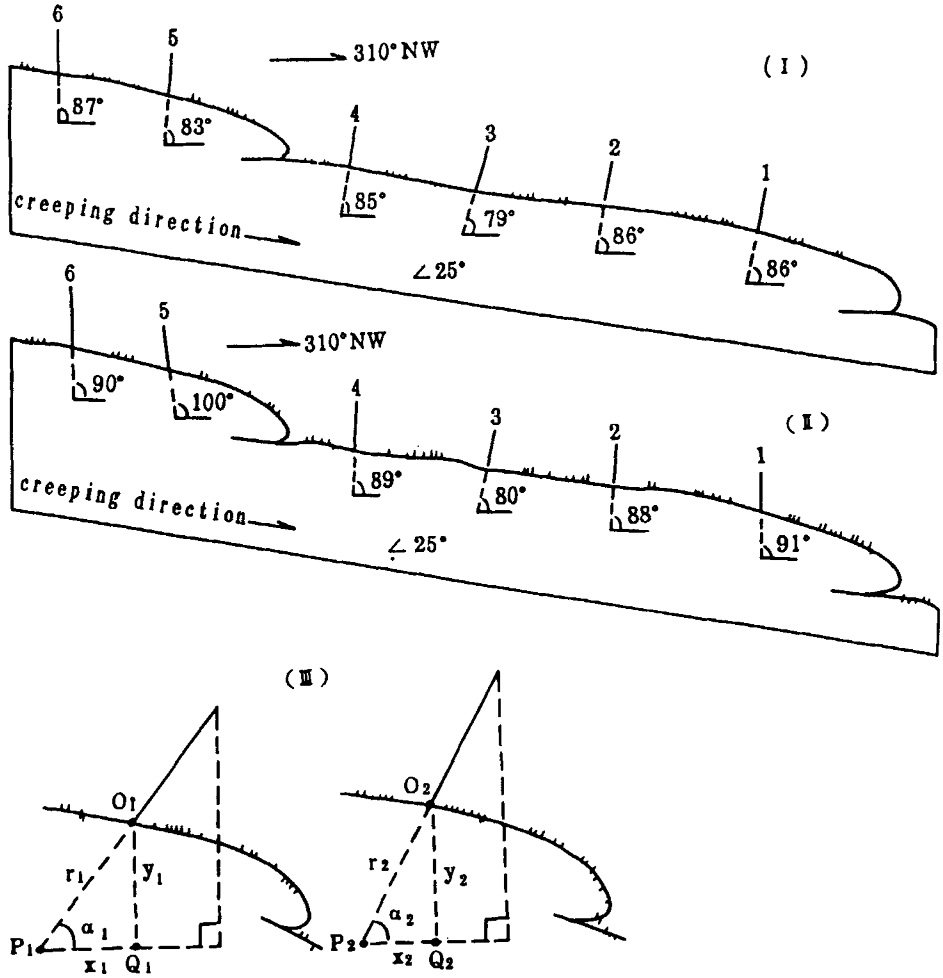


Figure 13 Change of dip of survey rod and displacement among the different layers of gelifluction terrace MM7, Tianshan Mountains 1985 (I) to 1986 (II). O_1O_2 apex; P_1P_2 active point; r_1r_2 hypotenuse; x_1x_2 adjacent side; y_1y_2 opposite side; a_1a_2 frost dip angle of survey rods.

the debris discharge has only been 5 cm. Alluvial talus (scree) has a downward rate of 146 cm/a on southward slopes and 73 cm/a on northward slopes.

Block slopes are widely distributed on gentle bedrock slopes (30°–36°). The block slopes have a downward rate of 96 mm/a on the sunny or semi-sunny slopes and 72 mm/a on the shady or semi-shady slopes. The average rate is 81 mm/a for the whole studied region. The development of block slopes is controlled by slope gradient, moisture, aspect of slope and frost-thawing frequency (Zhu Cheng, 1993).

To the west of longitude 86°E there are mainly lobate rock glaciers, while to the east there are mainly tongue-shaped rock glaciers. The lobate rock glacier has a mean moving rate of about 6 cm/a, as deduced by the debris discharge which covered the highway in the past 25 years. The instrument survey from 1985 to 1986 shows that the moving rates of the lobate rock glaciers are from 1 to 49 cm/a; the rates (15.5–49 cm/a) at the higher elevations are faster than at the lower elevations. At the same elevation, the rates (about 49 cm/a) on the northward slopes are faster than on the southward slopes (45 cm/a). According to the data of lichenometry, lobate rock glaciers formed from 3949 a BP to 180 a BP. To the west of 86°E, tongue-shaped rock glaciers have a mean moving rate of 1.93 m/a and a mean descending rate of 0.4 m/a. Because the movement of rock glaciers is irregular, reliable moving rates remain to be established by observations for at least several years.

Gelifluction lobes and solifluction terraces are mainly distributed in the lower boundary (2900–3350 m ASL) of the permafrost. In the east part of the region, gelifluction lobes (or gelifluction terraces) have an average annual movement of 25 cm, and a descending rate of 9 cm/a. In the west, the average annual moving rate of the gelifluction terrace is 49 cm/a and its descending rate is about 12 cm/a. The difference is attributed to the higher gradients and higher precipitation in the western regions. According to the annual changes of the frost dip angles of six measuring rods, creep rate of the middle part of the active layer is faster than at the surface. How the creep rate actually changes as the depth increases needs further observation and research.

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