Bulletin of Glacier Research 7 (1989) *29—35.*

Characteristics of ice formation in the West Kunlun Mountains

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(Received December 5, 1988; Revised manuscript received January 27, 1989)

Abstract

The Chongce Ice Cap in the West Kunlun Mountains was systematically studied through snow—pit profiles and core analysis. The following sequence of ice formation zones can be seen from the terminus upward: ablation zone, infiltration—congelation zone, infiltration zone and infiltration—recrystalization zone. The summit of the ice cap is exposed to winds; subsequently the annual layer is relatively thin. There appear phenomena peculiar to infiltration ice formation. Also, some phenomena of cold—infiltration exist beneath the firn—ice layer in the infiltration zone.

1. Introduction

The major mechanism of glacier formation is "metamorphosis", by which snow changes into ice. The process is affected by glacier temperature, velocity and mass balance. Ice formation is a traditional subject of the study in glaciology in China.

Recently, some unexpected characteristics were discovered in deep drilling. Older firn layers appeared again and again under superimposed ice layers in an area where it was thought that the firn layer is not very thick.

A similar phenomenon has been discovered in Glacier No.1, Urumiqi River headwaters, Tian Shan Mts. and Dunde Glacier in the southwest Qilian Mts. This forces us to revise the lower estimate of thickness of firn—ice layers and age of ice formation for continental—type glaciers in China (Xie and Huang, 1988). In 1985 and 1987, we undertook expeditions to several glaciers centering on the Chongce Ice Cap, West Kunlun Mts., obtaining records from snow pits and more than 30m deep ice cores. This paper will describe the results of investigations in the West Kunlun Mts.

2. Measurement points and observations

In 1985 and 1987, we investigated stratigraphic profiles of more than ten snow pits and several shallow bore holes on the Chongce Ice Cap on the south side of the West Kunlun Mts. (Fig. 1). The lowest snow pit position lies on the terminus of the main flow line at 5850 m a.s.l. on the ice cap. The altitude difference between neighboring snow pits is 20 to 100 m, and the depth of the deepest snow pit is 1.60 m. The depth of the bore hole which lies on the highest elevation at 6366 m a.s.l.(B13) is 10.6 m. The deepest one (32.5m) lies at 6130 m a.s.l.(B8'). Information was obtained from the profiles of snow pits and stratigraphy of ice core at every point.

3. Structural characteristics of shallow snow (ice) pit profiles

The environment around the glaciers of West Kunlun is high mountains and plateau, desert and periglacial melting—freezing zone where the climate is dry and cool. The annual snow layers on the glacier surface are not very thick. There is no debris on the surface, and the surface is very clear.

1) Middle and lower parts of the glacier tongue

The middle and lower parts of the glacier tongue

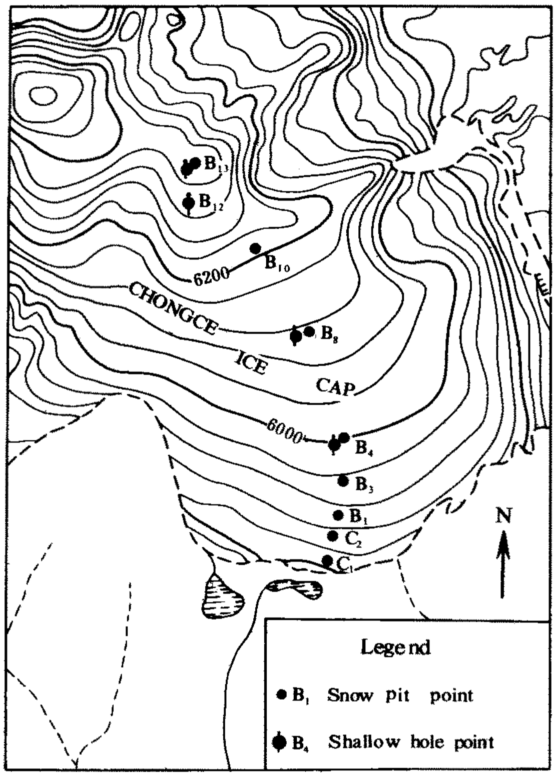

Fig. 1. Locations of pits and shallow holes on Chongce Ice Cap.

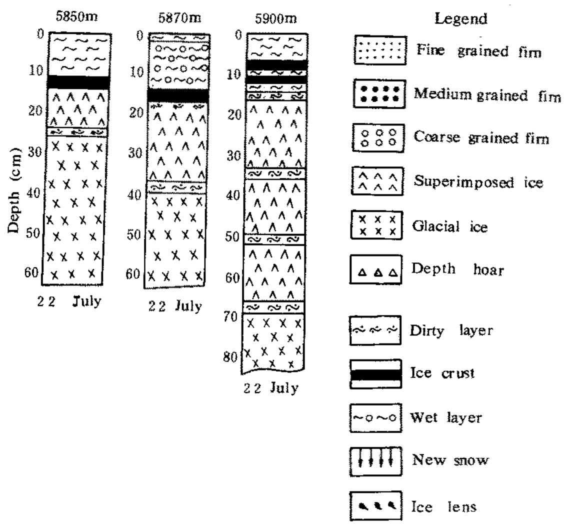

Fig. 2. Stratigraphic profile in the fluctuating snow line zone on Chongce Ice Cap.

in the valley glaciers contain many linked–base ice pyramids. The height of the ice pyramids decreases with elevation; the highest were 20 to 30 m. Occasionally, there were independent ice pyramids on the gentle termini of large valley glaciers more than 10 km long. In some places we saw thermal–solution phenomena, such as ice pillars, superglacial lakes, ice caves and snow cornices etc. Because of snow drift, the snow thickness in spring and winter was over 35 cm. In early summer it transformed to superimposed ice. The thickness of the annual layer of the superimposed ice was over 20 cm, but it melted completely by the end of July.

2) The upper part of the glacier tongue

This part has developed embryonic ice pyramids. In the vicinity of the snowline, the ice surface slope became steeper and a series of crevasses developed. Some ice–marginal crevasses developed on both sides of the ice flow. Most of them were covered with snow cover during spring and winter. The forming of embryonic ice pyramids correlated closely with crevasse development. Their tops were relatively smooth and some snow accumulated on them. The snow in this part transformed to superimposed ice in summer, but melted and flowed down along the glaciers at the end of summer. Creeping slush could be seen on the wide, smooth and continuous ice surface, where an embryonic ice pyramid formed in summer.

3) The area around the firn line

The firn line moves up and down with the fluctuation of climate. According to the observation on Chongce Ice Cap, the perpendicular firn line fluctuation was at least 50 m. In the lower part of the fluctuating firn zone, slush and spot superimposed ice were generally seen in the investigation period in July 1985 and July to August, 1987. For several years, it was covered completely with firn. However, it appeared to be wet snow in the ablation season, and slush can form in areas with steeper slope of ice surface. Generally, seasonal and perennial superimposed ice layers developed under the wet–snow layer (Fig. 2).

4) Lower part of the firn area

This part lies between 5930 and 6000 m a.s.l on the ice cap. We observed a firn layer about 40 cm thick (Fig. 3a). There were infiltration ice crusts between firn layers and depth hoar under them. Under firn layers, there were more than two layers of superimposed ice, and between them there were apparent dirty layers. The color of newer superimposed ice was white; however, the older ice was yellow.

5) Middle and upper part of the firn area

This part lies between 6000 and 6200 m a.s.l. there were firn layers more than two years old in the shal-

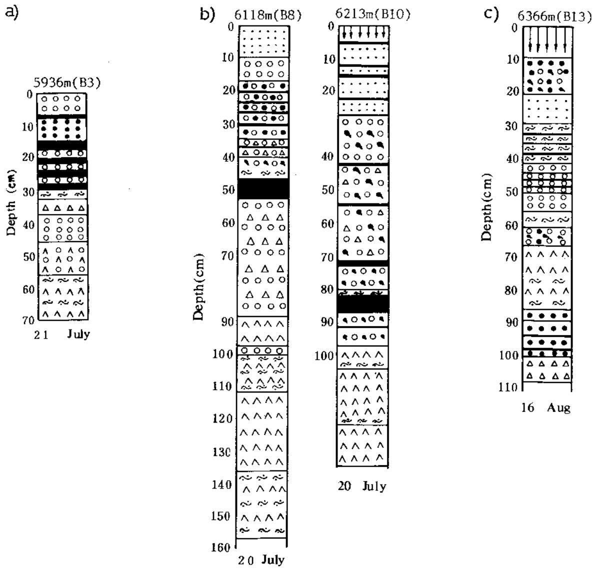

Fig. 3. Stratigraphic profiles on Chongce Ice Cap.

low snow pits (Fig. 3b). The surface snow did not metamorphose as rapidly as in the lower part. Hoar was developed below 30 cm in depth. In addition to infiltration–congelation ice crusts in the snow layers, we still saw infiltration ice lenses. Dirty and thicker congelation ice layers developed on the bottom of annual layers, and below the thicker ice layers. The firn layers mingled with hoars.

6) Top of the firn basin

The surface was flat at the top of the firn area on Chongce Ice Cap. Under the new snow we saw the infiltration ice layer mingled with ice lenses, and thicker infiltration–congelation ice layer was discovered too above the last annual layers at the top of the ice cap, 6366 m a.s.l.(Fig. 3c). An infiltration–congelation ice layer 20 cm thick developed 70 cm deep. Under the infiltration–congelation ice layer, the firn layers appeared. Depth–hoar was seen below 1 m.

4. Structural characteristics of ice cores from the shallow borehole

During the expedition, several boreholes were drilled at different elevations in the accumulation area of the Chongce Ice Cap. We saw that the ice forming processes had apparent structural characteristics. A complete description of the ice cores is given by Han *et al.* (1989). This paper will describe briefly some representative profiles.

1) Lower part of the firn area

The column structure of ice core at B4 (5974 m) showed that firn and infiltration ice layers mingled with ice lenses from the surface to 70 cm depth. Below it, 95% profiles (depth proportion, the same below) were the superimposed ice layers mingled with dirty layers (Fig. 4a). The remnant firn wrapped with superimposed ice was still separate at depths of 1.65 to 1.80 m, 2.45 to 2.60 m and 2.85 m. Two thicker dirty layers appeared respectively at 0.90 m and 2.00 m; and their estimated formation years were possibly 1984 and 1980.

2) Middle part of the firn area

The surface snow stratigraphy at 6130 m (B8') was the same as in Fig. 3b. From 0.80 m to 9.20 m, perennial superimposed ice mingled with dirty layers. Downward to 26.30 m, the proportion of infiltration superimposed ice decreased (about 73%) (Fig. 4b).

3) Upper part of the firn area

The borehole depth at B12 (6327 m a.s.l) was 23.1 m, and the ice core showed a stratigraphic structure that was mostly infiltration firn, infiltration ice layers and ice lenses (Fig. 4c). Though a thicker infiltration ice layer appeared, the total proportion was only about 28% of the whole ice core, which showed that the intensities of ablation and infiltration were apparently weak.

4) Top of the firn area

Stratigraphical characteristics of ice core at B13 (6366 m a.s.l) on top of Chongce Ice Cap (Fig. 4d) were apparently different from those at B12 (Fig. 4c), and the same as B8' (Fig. 4b). In addition to the surface firn layer, the stratigraphic profile with thickness of 4.00 m showed mostly infiltration–congelation ice (over 90%) within the ice core profile from 4.00 to 10.60 m. Downward, the firn structure, infiltration ice layer crusts and lenses mingled with each other apparently strengthened, but the proportion of infiltration–congelation ice was still 58% of the whole layer.

5. Main characteristics of ice formation

5.1 Mechanism and calculation of amount of ice formation in summer

In summary, the shallow firn layer was very thin; however, the superimposed ice layer was thick in the West Kunlun Mts., which shows that the amount of ice formation in summer in this area is more than that of

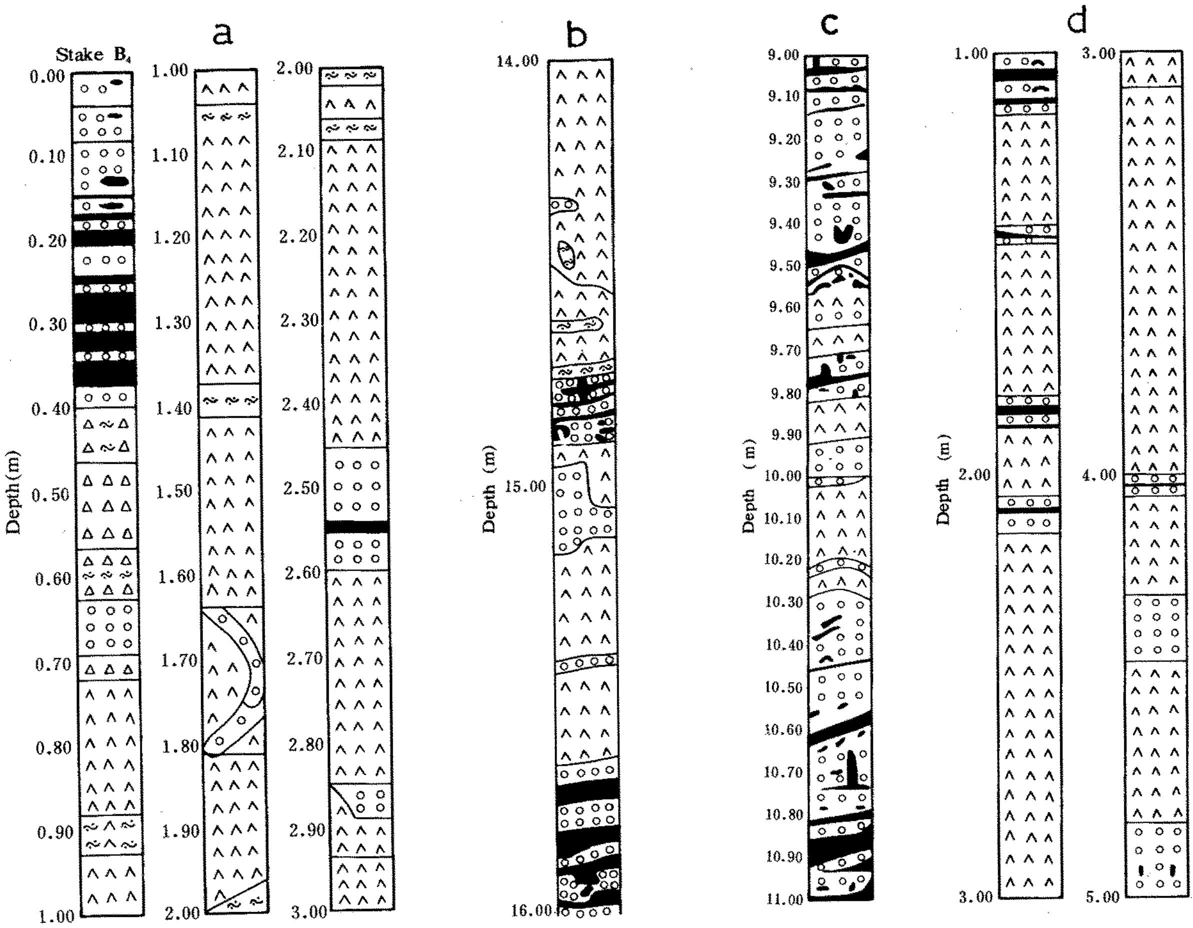

Fig. 4. Stratigraphic structure of ice cores on Chongce Ice Cap.
a. lower firn area (B4, 5974 m a.s.l.)
b. middle part of the firn area (B8', 6130 m a.s.l.)
c. upper part of the firn area (B12, 6327 m a.s.l.)
d. top of the ice cap (B13, 6366 m a.s.l.)

other glaciers of continental type such as Tian Shan Mts. and Qilian Mts.

The intensity of ice formation in summer is dominated by these factors : the amount of cold storage in glaciers, the thickness of remnant firn, the frequency of melting and refreezing, the length of the ablation period and the ice surface slope. When the amount of cold storage in glaciers is large, the firn layer is thinner, melting and refreezing is frequent, infiltration–congelation is complete and superimposed ice develops continuously. The mean slope of the larger glaciers on the West Kunlun Mts. is generally about 5–10 %; that of Chongce Ice Cap is 10%. Such a gentle glacial morphology retains melting water which freezes to form new superimposed ice layers; the proportion of lost melting water as run–off is small. According to observations during the expedition, at B4(5974 m a.s.l.) on the Chongce Ice Cap, the mean lowest diurnal air temperature appeared at 7:00 a.m. Beijing Standard Time (B.S.T.), and the highest at 7:00 p.m. B.S.T.. At the beginning of July, the mean lowest air temperature was −4.4℃ and the highest 2.8℃. In August, the mean lowest was −5.3℃, the highest 1.7℃ and the mean diurnal difference was about 7℃.

Such frequent intensive air temperature fluctuations were favorable for frequent melting–freezing. According to the analysis of stratigraphy of snow pits and bore holes the annual accumulation rate in the accumulation area did not vary with increase of height in the past ten years. The accumulation was 300−350 mm (water equivalent). Considering the mass loss caused by drift snow and possible run−off in summer on the ice cap, the annual accumulation could not exceed 500 mm, which is less than the accumulation rate of the glaciers in the Tian Shan, Qilian Mts. and the Himalayas. For example, the annual accumulations on Qiyi Glacier and Laohugo Glacier No. 12 of the Qilian Mts. were respectively 577 mm and 644 mm, which were the smallest values (Xie, 1980). The thinner annual firn layers became filled with melt water and formed superimposed ice. According to measurements and calculation of glacier temperature on Chongce Ice Cap, the temperature of active layer (16 m) in the accumulation area varied between −9.8°C and −13.0°C (Shao and Liu, 1989). They are the lowest glacier temperatures observed up to now, and because most of the material in the active layers has the dense superimposed ice, the cold storage in active layers must be the greatest of all known Chinese glaciers (Table 1).

Only thinking of summer, the amount of ice formation can be calculated using the equation below according to the variation of cold storage in the unpermeable active layer (Chikin, 1962).

$$M_{-pf}=\frac{r_i\rho_i}{80}\int_{h_1}^{h_2}\Delta t(h)\,dh. \qquad (1)$$

M_{-pf} Amount of ice formed in summer (g/cm)
r_i Specific heat of ice (0.5 cal/g°C)
ρ_i Density of ice (0.9 g/cm^3)
80 Latent heat of ice melting (cal/g)
h_1 Depth at bottom of firn layer (cm)
h_2 Depth of bottom of active layer (cm)
$\Delta t(h)$ Variable value of the ice temperature with depth in the active layer in the period of measurement.

From glacier temperature observations (Shao and Liu, 1989) on Chongce Ice Cap from July 22 to August 26 in 1987, the amount of cold storage in the active layer above 10 m (5977 m a.s.l.) is −9358 cal/cm^3. If the ice layer thickness is 10 m, equation (1) simplifies to:

$$M_{-pf}=56\overline{\Delta t}. \qquad (2)$$

Δt The mean variable temperatures in the upper 10 m in the period of observation

From equation (2), 11 cm thickness of infiltration ice could form in the accumulation area near B4(5974 m a.s.l.) in the observation period (July 22 to August 26). At B4, 13.5 cm of ice formed in summer before August 1987, which agrees with the value calculated. From temperature observation (Xie *et al.,* 1985) on the Qiyi Glacier during July to August 26, 1975, the amount of cold storage in the active layer (6 m thick) could form a 6.0 cm−thick infiltration−congelation ice layer. So the glaciers in the West Kunlun Mts. are colder than any other glaciers in China yet studied.

5.2 Spatial distribution of ice formation

The glaciers in Qilian Mts. are considered by Chinese glaciologists as typical continental−type. Ice formation zones of those are divided into ablation, infiltration−congelation, infiltration, cold infiltration−recrystallization and other subzones (Xie *et al.*, 1985). Based on the model above and stratigraphic characteristics of snow layers and ice cores, the authors divide the ice formation zones in the West

Table 1. Comparison of cold storage in ice layers above 10m in several glaciers, China.

Glacier name	Elevation of snow line (m)	Elevation of observed points (m)	Date of observation	Amount of cold storage (cal. cm^3)
Chongce Ice Cap in West Kunlun Mts.	5920	5977	22July to 26 Aug 1987	−9358
Laohu Glacier No.12 in Qilian Mts.	4700	4650	20 to 31 July 1975	−4050
Qiyi Glacier in Qilian Mts.	4600	4573	18 Aug 1975	−3595
Yanglong River Glacier No.5 in Qilian Mts.	4600	4648	26 June to 19 July 1977	−3835
Xiqiong Tailan Glacier in Mt. Tomur. Tian Shan	4500	4050	30 June 1978	−1185

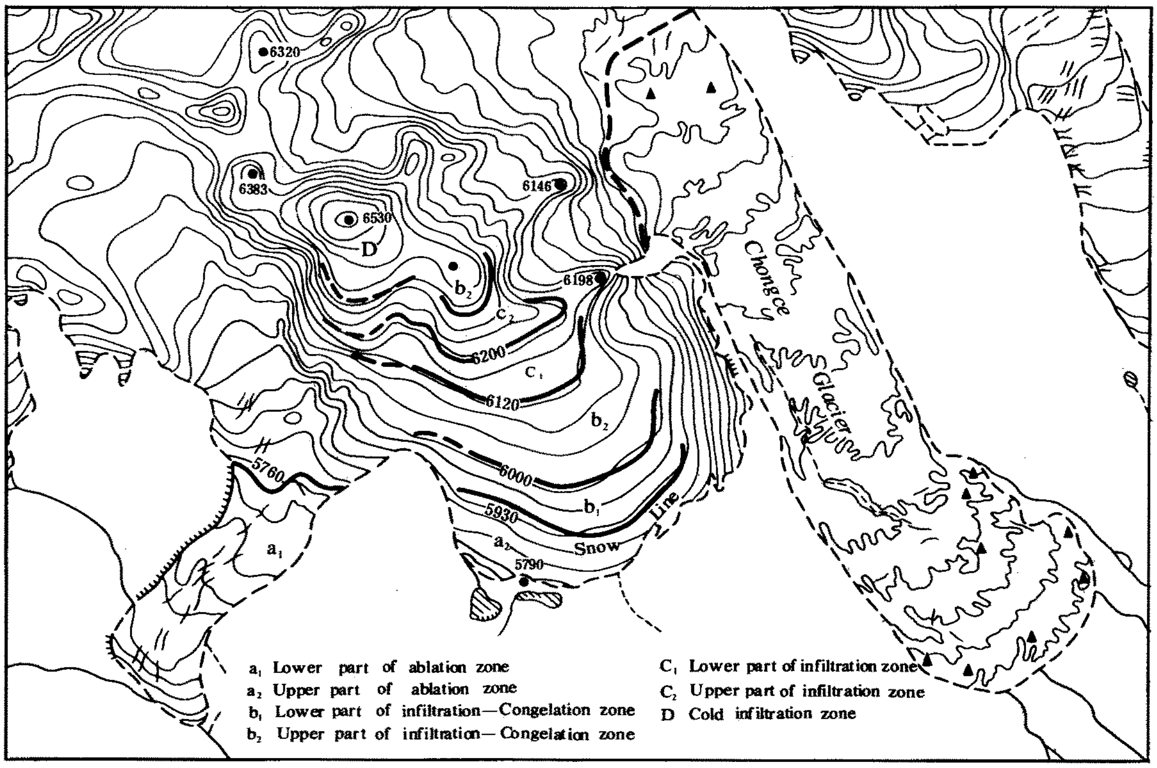

Fig. 5. Distribution of ice formation zones on Chongce Ice Cap.

Kunlun Mts. into: lower part of ablation zone, upper part of ablation zone, lower part of infiltration–congelation zone, upper part of infiltration–congelation zone, lower part of infiltration zone, upper part of infiltration zone and cold infiltration zone (Fig. 5).

1) Lower part of ablation zone

Lies principally in middle and lower parts of the ablation area in valley glaciers. At the end of the ablation period, superimposed ice formed from drifted snow and seasonal snow melted completely, but there may be a small amount of congelation ice in crevasses and shady spots against the glacial staircase and ice cave. There was no such zone on the ice cap.

2) Upper part of ablation zone

Lies principally in the upper part of the ablation area in valley glaciers and the terminal ridge of ice cap. In summer, it appeared mainly to be covered with wet snow. There was no apparent run–off, water moving mainly through slush flow and slow percolation in the firn. The water refroze to become superimposed ice at night. At the end of summer and the beginning of autumn, ablation ended. Though there was sporadic firn cover, the mass balance was negative.

3) Lower part of infiltration–congelation zone

Lies in the lower accumulation area, occasionally on steeper slopes toward the sunshine. In the period of strongest ablation, it showed spotted superimposed ice; run–off was mainly slush flowing downward. But on steep slopes the infiltration of melting water into firn increased.

4) Upper part of infiltration–congelation zone

The melt water was completely formed into ice in pores in the remnant firn, and no run–off was produced.

5) Lower part of infiltration zone

Lies relatively higher than in Qilian Mts. The firn layer was not thick and consisted of firn and superimposed ice. Some of the melt water penetrated slowly.

6) Upper part of infiltration zone

The firn layer was thinner, all melt water froze to ice in the firn layer, the amount of melt water was still small and no run–off was produced. This zone lies mainly in the middle and upper parts of the accumulation area.

7) Cold infiltration zone

This is a cold infiltration – recrystallization zone. Its existence showed that melt water could not percolate through the whole annual layer. Unmelted snow remained under the annual layer. There was no infiltration–congelation ice, so this zone belongs completely to the accumulation zone. This zone exists above 6300 m a.s.l.

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