Front. Earth Sci. China 2008, 2(3): 346–355
DOI 10.1007/s11707-008-0025-x

REVIEW ARTICLE

Progresses in the ice formation of glaciers in China

Xiangying LI (✉)[1], Shiyin LIU[1,2], Donghui SHANGGUAN[1], Aigang LU[3]

1 State Key Laboratory of Cryosphere Science/Hydrology and Ecology Laboratory of Watershed,
Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
2 Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
3 Department of Environment and Life Sciences, Weinan Teachers University, Weinan 714000, China

Abstract Glaciers, formed by snowfall and characterized by movement and size, are the most sensitive indicators to climate change. The ice formation of glaciers (the processes, mechanisms and results of transformation from snow to ice) can indicate the growth condition, the formation process and the physical characteristics of glaciers. Its spatial variation can also reflect glacier change, and further reveal climate change. Studies on ice formation of glaciers in China were initiated in 1962, when Xie and others studied the ice formation of Glacier No.1 at the Urumqi River head, Tianshan Mountain. Other researchers followed suit and did studies on ice formation of glaciers in Qilian Mountain. As time goes by, the concept of ice formation came into being in China. This paper reviews the development history of glacier zones, and the studies of ice formation of glaciers in China since the 1960s. These studies mainly focus on Qilian Mountain, Tianshan Mountain, Altay Mountain, and the western Kunlun Mountain, Himalaya Mountain, the southeastern Tibetan and Hengduan Mountains. The paper also discusses the significance of ice formation studies, the limitation and deficiency of previous studies, and the prospects and suggestions for future studies.

Keywords glacier, ice formation, glacier zone, China

1 Introduction

Glacier that grows with the metamorphism process of perennial snow cover in cold regions is a kind of natural ice body whose movement is influenced by gravity. Ice is the main component of glaciers along with air, liquid matter, and debris and trace matters derived from the release of human activity (Shi et al., 1988). Glaciers grow through different processes of transformation of snow to ice. The process of transformation of snow to firn is the key step of the transformation process of snow to ice (Kalesnik, 1982). The transformation of snow to firn occurs through three metamorphism processes: melting-freezing metamorphism process, equilibrium-temperature metamorphism process and temperature-grads metamorphism process. The melting-freezing metamorphism process can be divided into refreezing process, percolation process and percolation-freezing process based on the quantity of heat that the snow layers absorb and release. The equilibrium-temperature metamorphism process occurs in snow stratigraphy where temperature is below 0°C and temperature-grads is small; the molecules in crystal grains can move easily, and can also move through the sublimation process of water molecules on convexity and the desublimation process of water molecules on concave, Shumskii (1955) named the equilibrium-temperature metamorphism process that occur in the deeper snow stratigraphy the recrystallization process. The temperature-grads metamorphism process is characterized by temperature grads that occurs in both the surface and the interior of snow stratigraphy, and then the depth hoar formed through the metamorphism process (Shi et al., 1988).

Glaciers are one of the good indicators of climate change which influences glacier change, and vice versa—glacier change can also impact climate change. Glacier variation (glacier area, glacier length, glacier thickness and so on) is the alternative index of precipitation and temperature variations, both of which are the main climate factors that influence glacier growth. Precipitation determines glacier accumulation, and temperature determines glacier ablation. Therefore, precipitation and its annual distribution and interannual variation can influence the supply and activity of glaciers, and temperature impacts the ice formation of glaciers and glacier meltwater (Li, 2006). The transformation process of snow to ice is complex and long-playing. Glaciologists are very concerned with the following issues:

Translated from *Advances in Earth Science*, 2007, 22(4): 386–395 [译自: 地球科学进展]

E-mail: lixiangying@lzb.ac.cn

How did snow transform to ice and how long does it take? Which factors are controlled by local water-heat balance and which factors influence glacier mass balance, glacier temperature, glacier movement and the physical characteristic of glaciers? Ice formation studies can indicate the growth condition, the formation process and the physical characteristics of glaciers; ice formation of glaciers can act as a criterion for classifying glaciers, and its spatial variation can reflect glacier variation and further indicate climate change. Therefore, the ice formation of glaciers is an important part of glaciology. Study of ice formation of glaciers in China was pioneered by Xie et al. (1965), who studied the ice formation of Glacier No.1 at the Urumqi River head, Tianshan Mountain in 1962. With the development of ice formation studies in China, the concept of ice formation came into being. This paper reviews the studies of ice formation of glaciers in China since the 1960s, and presents the prospects of the development and significance of ice formation studies.

2 Methods of ice formation studies

The primary method of ice formation studies involves the following steps: first, dig a snow pit, and then depict snow stratigraphy and finally, measure physical indexes of snow layers (grain shape, grain diameter, snow density, quantity of water contained in snow layers, temperature of snow layers, grain rigidity, and so on). According to the recommendation of UNESCO, snow grain can be divided into very fine-grained firn, fine-grained firn, medium-grained firn, coarse-grained firn and very coarse-grained firn (Shi et al., 1988). Qiu (1986) also introduced detailed characteristics of different species, based on the diameter of snow grains and the extent of metamorphism. A recent glacier process investigation classifies snow grains into fresh snow, fine-grained firn (diameter < 1 mm), medium-grained firn (1 mm $<$ diameter < 2 mm) and coarse-grained firn (diameter > 2 mm) in order to unify long-term observation and standard sampling (Li et al., 2006; Wang et al., 2006). In the process of ice formation studies, snow density, snow temperature, quantity of water contained and snow rigidity should practically be measured in the field. If measuring instruments are absent, some alternative qualitative methods are available for measuring quantity of water contained and snow rigidity (Qiu, 1986). The ice shell, radiation shell, snow plank, dust layer, ice layer, icicle, ice lens and so on describe snow stratigraphy. Analysis of stable isotopes ($\delta^{18}O$ and so on), microparticle, β activity, solid electrical conductivity, radioactive matter (tritium and so forth), soluble impurity, H_2O_2, spores and so on can be used to distinguish annual snow layer (Shi et al., 1988; Qin and Ren, 2001). Furthermore, it should be noted that meltwater may occur and percolate in snow stratigraphy, where stable isotope, radioactive matter, spore and so on may be transferred into deeper snow layers. Ice formation studies should involve glacier temperature, glacier mass balance, local climate and heat balance in order to comprehensively analyze and fully understand the conditions and processes of ice formation of glaciers (Shi et al., 1988).

3 Glacier zones

Glacier can be divided into different zones according to the water-heat condition, which varies from glacier to glacier (Paterson, 1987; Qin and Ren, 2001). Glacier zones in polar ice sheet and the Alp Mountains have been reviewed by many scholars (Benson, 1962; Muller, 1962; Shumskiy, 1955; Paterson, 1987; Xie and Huang, 1988). The idea of glacier zone was introduced for the first time by Shumskii (1955), who divided a glacier into recrystallization zone, refreezing-recrystallization zone, cold-percolation-recrystallization zone, warm-percolation-recrystallization zone, percolation zone, percolation-freezing zone and ablation area according to the differences of ice formation of glaciers. His idea was further developed by some scholars (Kotterlongcov, 1984; Paterson, 1987; Williams et al., 1991) (Table 1).

Figure 1 shows the distribution features of glacier zones that are classified by Paterson (1987). (1) Dry-snow zone. No melting occurs here, even in summer. The boundary between this zone and percolation zone is called dry-snow line. (2) Percolation zone. Some surface melting occurs in this zone. Meltwater can percolate a certain distance into the snow at temperatures below 0°C before it refreezes. If the water encounters a relatively impermeable layer it may

Table 1 Classification of glacier zones by some scholars

Shumskii, 1955	Benson, 1959; 1961	Muller, 1962	Paterson, 1987	Williams et al., 1991
Dry-snow zone/recrystallization zone	Dry-snow facies	Dry-snow zone	Dry-snow zone	Dry-snow facies
Snow-firn zone/refreezing-recrystallization zone	Percolation facies	Percolation zone A	Percolation zone	Percolation facies
Cold-firn zone/cold-percolation-recrystallization zone				
Warm-firn zone/warm-percolation-recrystallization zone	Waterlogging facies	Percolation zone B	Wet-snow zone	Snow plasma zone, Wet-snow facies
Firn-ice zone/Percolation zone		Snow plasma zone		
Superimposed-ice zone/percolation-freezing zone	Ablation facies	Superimposed-ice zone	Superimposed-ice zone	Superimposed-ice zone
Ablation area		Ablation area	Ablation area	Ice facies

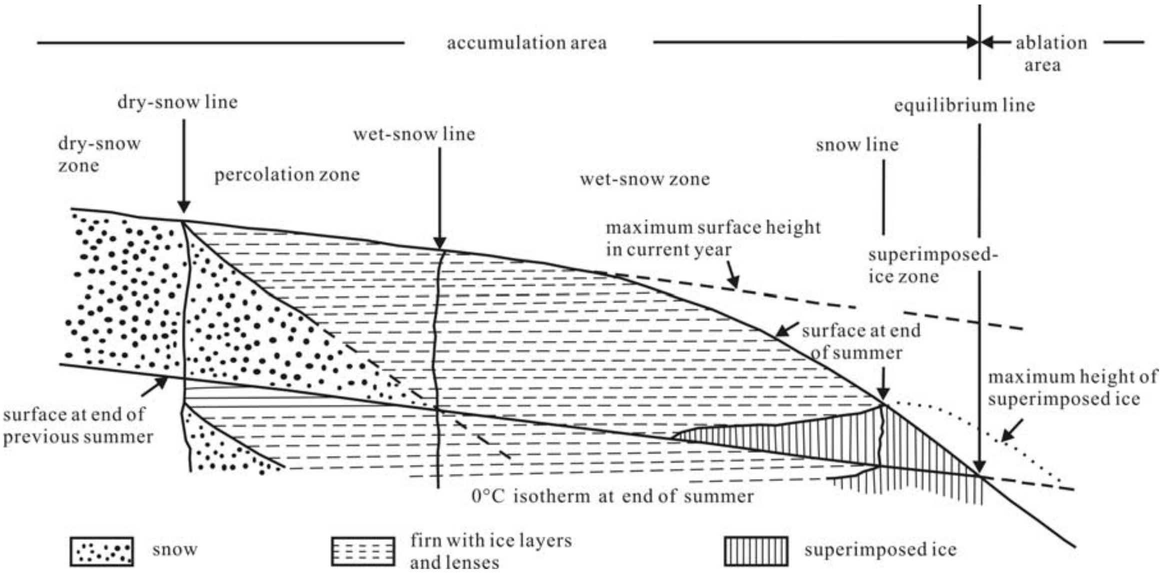

Figure 1 The distribution of glacier zones (Paterson, 1987)

spread out laterally. When it refreezes, an ice layer or an ice lens is formed. (3) Wet-snow zone. In this zone, all the snow deposited since the end of the previous summer has been raised to 0°C by the end of the following summer. Some meltwater also percolates into deeper layers deposited in previous years, though not necessarily in sufficient quantity to raise their temperature to 0°C. (4) Superimposed-ice zone. In percolation zone and wet-snow zone, the material consists of ice layers, lenses, and glands, separated by layers and patches of snow and firn. At lower elevations, so much meltwater is produced that ice layers merge to a continuous mass. This is superimposed ice. (5) Ablation area. This is the area below the equilibrium line. For different zones, the only dry-snow zones are in the interior of Greenland and Antarctica and near the summits of the highest mountains in Alaska, the Yukon, and possibly central Asia. Benson (1961) found that the dry-snow zone in Greenland roughly coincides with the region where the mean annual temperature is −25°C or less. In summer, a little melting most likely occurs even at the summits of Greenland (Langway, 1967); therefore, the whole sequence of glacier zones may be found in parts of Greenland and Antarctic.

The conception of glacier zones was firstly introduced to China in the 1960s (Shi and Xie, 1964). In the 1980s, Xie and Huang (1988) divided glaciers in China into continental glacier and oceanic glacier based on the classifications of Shumskii and Sekin (1962) and Benson (1961) and Muller (1962), and further classified glaciers in major glacier areas in detail (Table 2). The continental glacier exists in regions where climate is cold, precipitation is little and temperature is low. The typical continental glacier can be divided into ablation zone, superimposed-ice zone, percolation zone, cold-percolation zone and dry-snow zone. The oceanic glacier exists in regions where climate is mild, precipitation is enough and temperature is high. The typical oceanic glacier can be divided into ablation zone, warm-percolation zone, cold-percolation zone and dry-snow zone. The warm-percolation zone is the particular zone for the oceanic glacier where the firn is thick, and all except the glacier surface remains at melting point. In winter, when the percolation activity is strong, meltwater can percolate into the older snow layers and can not freeze completely in the firn layers. Part of the water transforms into ice through the relative movement among crystal grains, at the same time the liquid water exists in ice. The ablation zone, cold-percolation zone and dry-snow zone in oceanic glaciers are similar to that in continental glaciers, but the discrepancies still exist for other zones on both oceanic and continental glacier. In addition, some sub-zones are absent and converse on glaciers (Li, 2006).

The warm-percolation zone widely exists above the ablation zone in oceanic glaciers (Li, 1986; Xie and Huang, 1988), and yet the superimposed-ice zone also widely exists

Table 2 Classification of glacier zones in China

	Dry-snow zone Cold-percolation zone		
Continental glacier	Percolation zone Superimposed-ice zone	Warm-percolation zone	Oceanic glacier
	Ablation zone		

in continental glaciers. The superimposed-ice zone usually and widely exists in continental glaciers where the surface gradient is small, the movement velocity is slow and the annual accumulation is small (Muller, 1962). The continental glacier exists in regions where annual precipitation is small, the climate is dry and the snow cover is thin in the accumulation area. When solar radiation becomes strong and temperature increases in summer, the thin snow layer transforms into superimposed ice, particularly in the area near the equilibrium line. The oceanic glacier in China exists in areas where the climate is mild and annual precipitation is big. On the same glacier, the altitude and range of glacier zones also fluctuates due to climate fluctuation, and some subzones may disappear or appear again. The discrepancies exist between the distribution of glacier zones in continental glaciers and oceanic glaciers, as shown in Table 3 which shows a more detailed distribution of glacier zones in China (Shi, 1992). In addition, more studies of glacier zones have been done in China. Xie (1984) studied the Law Dome ice cap in Antarctic, which indicates China's contribution to ice formation studies of glaciers.

4 Ice formation of glaciers in different areas

4.1 Qilian Mountain

Most glaciers in Qilian Mountain usually exist in the interior of the Alp Mountain regions where the hypsography is small, the climate is dry and cold, the superimposed ice is widely distributed and the thickness of snow and firn layers is small. The surface of the glacier tongue is clean, the gradient of the glacier surface is small and the avalanche supply is insignificant (Liu, 1960; Dolgushin, 1961; Ren, 1963; Zheng, 1963). For example, the seasonal superimposed ice is thick in the ablation area in the Shuiguanhe glacier (Xie et al., 1985). The thickness of snow cover below the glacier tongue ranges from 20 cm to 30 cm in winter and spring. In early summer, all of the snow cover transforms into superimposed ice, the thickness of which ranges from 10 cm to 15 cm; and the ablation surface appears with more dust in late summer. The glacier surface is flat and clean in the middle part of the glacier tongue, where the thickness of snow cover ranges from 20 cm to 40 cm in winter and spring and that of the superimposed ice ranges from 10 cm to 20 cm. The snow cover and superimposed ice all melt in late summer. The thicknesses of both snow cover and superimposed ice are large and their period of existence in glaciers is long. The glacier surface is flat above the glacier tongue where the superimposed ice layers with the unconformable interface reflecting the fluctuation of snow line also exists. These phenomena were discovered in snow pits (4580 m a.s.l) in the July 1st Glacier and in glaciers in the upriver of the Beidahe. The firn layers still exist in late summer below the firn area, and its thickness ranges from 20 cm to 30 cm; the perennial superimposed ice layers (over two layers) are preserved, but the dynamical metamorphism ice is absent below the superimposed ice layers. There is a sequence of superimposed ice layers from new to old, from top to bottom. Some annual accumulation layers may disappear due to the fluctuation of the snow line. The perennial firn layers exist in the middle of the accumulation area where the maximum thickness of annual firn layer is 180 cm, and the thickness of firn layer ranges from 400 cm to 600 cm in the July 1st Glacier. The maximum thickness of the annual firn layer is 200 cm in Laohugou Glacier No.12, and that of the annual firn layer is 329 cm in avalanche pricks in Yanglonghe Glacier No.5. The thickness of firn layers is small at the top of glaciers, where the surface structure is similar to that at the bottom of the accumulation area. No meltwater occurs in the snowfield away from the uncovered rock. According to the ablation, percolation and refreezing process, the ice formation of glaciers can be divided into spring, summer, autumn and winter periods in one year (Sekin, 1962).

The glaciers in Qilian Mountain can be classified into four glacier zones: (1) Ablation zone. The quantity of heat that the glacier surface gathers in warm season can melt all seasonal snow cover and part of dynamical metamorphism ice, and can also consume part of cold reserves in active layers. According to the conservation status of superimposed ice, at the end of ablation period, the ablation zone again can be divided into: 1) Down-ablation zone. The superimposed ice derived from seasonal snow cover melts away at the end of the ablation period, and a little superimposed ice exists only in some cranny and ice cavity. 2) Up-ablation zone. At the end of the ablation period, the superimposed ice is distributed in areas where seasonal snow cover in the current year exists. (2) Percolation-freezing zone. The perennial superimposed ice exists below fresh snow at the end of the ablation period, and the obvious dust surface exists between the

Table 3 Classification of glacier zones (Sekin, 1962)

	Wet-snow zone		
	Refreezing-recrystallization zone		
	Cold-percolation zone		
Continental climate	Percolation zone	Warm-percolation zone	Oceanic climate
	Superimposed-ice zone		
	Ablation zone		

superimposed ice layers; but the metamorphism process does not obviously occur in the newly superimposed ice layers, and the dynamical metamorphism process is weak in the older superimposed ice layers. The quantity of heat that the glacier gathers in summer can melt away all snow cover and consume part of the cold reserves. However, it can not melt the dynamical metamorphism ice. Because of the runoff occurrence, the percolation-freezing zone can again be divided into: 1) Down-percolation-freezing zone. The meltwater volume is over the gaps of the residual firn, and the superfluous meltwater run off along the glacier surface. This zone lies below the accumulation area or on steep slopes which are exposed to the sun, and the superimposed ice surface explored in late summer. 2) Up-percolation-freezing zone. The meltwater transforms into ice within the gaps of the residual firn, and runoff doesn't occur. (3) Percolation zone. The perennial firn exists, and the perennial superimposed ice also exists below the activity layer. The gaps of the residual firn exceed the volume of ice that is formed annually, and the ice formation periods evidently exist in spring, summer and autumn; and the period of ice formation is over 2 years.

The quantity of heat that a glacier gathers in summer can only melt part of the snow cover and consume part of the cold reserves in activity layers, where the temperature of ice is below 0°C. According to the occurrence and structure of the runoff, the percolation zone can again be divided into: (1) Down-percolation zone. One annual firn layer exists. Fresh annual accumulation layer is composed of the firn and superimposed ice in late summer. The period of ice formation is 2 years. The volume of meltwater is larger than that of ice formed annually and part of meltwater run off. The firn layer freezes from the top down and the thick superimposed ice is formed. (2) Middle-percolation zone. The annual firn layer is over 2 layers, the percolation ice dominates in this zone and the percolation-freezing ice exists on the ice surface below the firn layers. This zone is usually distributed in the middle of the firn basin and at the bottom of the back cliff. (3) Up-percolation zone. The thickness of firn layer is thin, the age of firn layer is less than 1 year, the ice formation time is 1 year and runoff does not occur. This zone is usually distributed above the accumulation area, and appears with the up-percolation-freezing zone in turn. (4) Cold-percolation-recrystallization zone. The perennial snow-firn layers exist and the meltwater cannot percolate through all annual snow layers. The minus temperature dominates throughout the whole year. The percolation-freezing ice does not exist. The ice formation period does not exist in summer nor does the runoff occur. The percolation process occurs, and the recrystallization process also occurs by snow compaction process. The period of ice formation is over 5 years, and the quantity of heat that the glacier gathered in summer can not melt all annual accumulation layers. The temperature below the activity layers is very low, and is close to mean annual temperature. This zone is distributed in the middle and at the top of the accumulation area of the western Qilian Mountain (5100 m a.s. l–5200 m a.s.l). The cold-percolation-recrystallization zone only exists near several high peaks of Alp Mountain due to the limitation of altitude. On the same glacier, the location and range of glacier zones change, and the sub-zones may also disappear or appear again due to climate fluctuation (The collected publication of Lanzhou Institute of Glaciology and Cryopedology, 1988). In addition, the cold-percolation-recrystallization zone is absent in the July 1st Glacier and Yanglonghe Glacier No.5, and the up-ablation zone and the up-percolation-freezing zone are absent in the Shuiguanhe Glacier No.4 (Xie et al., 1985). Glacier zones of Laohugou Glacier No.12 can be divided into ablation zone (down-ablation zone and up-ablation zone), superimposed-ice zone (down-superimposed ice zone and up-superimposed-ice zone), percolation zone (down-percolation zone, middle-percolation zone and up-percolation zone) and cold-percolation zone (over 5100 m a.s.l or 5200 m a.s.l) (Shi, 1992).

4.2 Tianshan Mountain

The vertical fall of altitude of glaciers is large, the accumulation difference is also big, the ice formation types are various, and glacier zones are intact in Tianshan Mountain (Shumskii, 1955). The recrystallization zone may exist in the southern slope (over 5 900 m a.s.l) of the Tuomuer peaks (Wang and Zhang, 1985), and is mainly distributed in the middle of Tianshan Mountain. The maximum fall of altitude of glaciers can reach up to 2000 m (Liu and Ding, 1988). The recrystallization zone may also exist in the peaks (over 5400 m a.s.l) of the southern and interior Tianshan Mountain, Bogeda Mountain and so on except the central Tianshan Mountain (Liu et al., 1996). The recrystallization-refreezing zone usually exists below the recrystallization zone. Here, the positive temperature exists on the glacier surface in the warmest time of day when weak melting occurs, and then the refreezing ice layers are formed. However, most snow layers have very low temperatures throughout the whole year, thus the recrystallization process still dominates here. The lowest boundary of this zone ranges from 4800 m a.s.l to 5000 m a.s.l, the vertical fall of this zone ranges from 400 m to 500 m, and the recrystallization-refreezing zone may exist in the peaks (over 4800 m a.s.l or 5000 m a.s.l) of the Tianshan Mountain. The cold-percolation-recrystallization zone exists widely below the recrystallization-refreezing zone, the strong melting occurs on the snow surface, and meltwater percolates into the snow layers and transforms into the percolation ice layers. In the process of meltwater percolation, the snow crystal turns into the firn soon, but meltwater cannot fill the gaps of the annual accumulation layer. Here meltwater refreezes and transforms into the percolation ice in snow layers that accumulated annually. When strong melting occurs, part of the meltwater can percolate into the older snow layers that accumulated annually, but the whole firn layer holds negative temperature and the runoff does not occur. The lowest boundary of this zone ranges from 4000 m a.s.l to 4200 m a.s.l, and its vertical fall is 1000 m. The cold-percolation zone is mainly distributed in the middle of the firn basin of the glaciers in Tianshan Mountain. The maximum accumulation also occurs in this area. The recrystallization process mainly forms the ice in the cold-percolation recrystallization zone, and the period of ice formation time is longer. This zone is only distributed in the margins (3700 m a.s.l–4200 m a.s.l) of the most western Alp Mountains. In general, the percolation-freezing zone exists mainly below the cold-percolation-recrystallization zone. Here the perennial firn layer is absent in snow stratigraphy, and the period of ice formation ranges from 1 to 2 years. According to the growth of superimposed ice and the occurrence of runoff, the percolation-freezing zone can be further divided into up-percolation-freezing zone and down-percolation-freezing zone. The up-percolation-freezing zone is usually distributed in areas near a flat watershed above the percolation zone (Wang et al., 1985). The inversion or interleaving of glacier zones is pervading in Tianshan Mountain. The vertical fall of the percolation-freezing zone depends upon the proportion between precipitation and temperature, and the depth increases in regions where snowfall is small and temperature is low. The vertical fall ranges from 10 m to 100 m in the eastern Tianshan Mountain, and is over 300 m on the southern slope of glaciers in the Tuomuer peaks (Wang and Zhang, 1985).

The western Qiongtailan Glacier can be divided into five glacier zones on the eastern slope of the Tuomuer peaks: (1) Ablation zone (3150 m a.s.l–4500 m a.s.l). The superimposed ice exists at the top and middle of this zone in early summer. (2) Superimposed ice zone (4500 m a.s.l–4800 m a.s.l). The ice formation quantity accounts for 20% to 50% of the total accumulation. (3) Percolation zone (4800 m a.s.l–5200 m a.s.l). The period of ice formation ranges from 2 years to 5 years. The ice formation quantity accounts for over 50% of the total accumulation. (4) Cold-percolation zone (above 5 200 m a.s.l). The thickness of the snow layers that accumulated annually ranges from 250 cm to 300 cm, and the annual accumulation ranges from 1300 mm to 1550 mm. (5) Dry-snow zone (above 5900 m a.s.l) (Wang and Zhang, 1985). The perennial low temperature dominates (summer mean temperature is below -9.5°), and no melting occurs in this zone (Wang and Zhang, 1985). In 1962, Xie et al. (1965) divided Glacier No.1 at the Urumqi River head into ablation zone, percolation-freezing zone and percolation zone (the thickness of snow layers ranges from 1 m to 5 m and the ice formation time ranges from 3 years to 5 years) and cold-percolation-recrystallization zone. In 1981, Wang and Zhang (1982) found that the thickness of firn layers is over 7 m in the percolation zone at the west branch on Glacier No.1; and the period of ice formation is over 10 years. The cold-percolation-recrystallization zone was replaced by the percolation zone due to the warming of the climate (Wang et al., 1988), and Liu and Gyuregainov (1989) divided the glacier into ablation zone (the highest boundaries of down-ablation zone is 3880 and 3980 m a.s.l at east and west branch respectively; the vertical fall of up-ablation zone is 50 m and 60 m at east and west branch respectively), percolation-freezing zone (at altitudes of 3925 m a.s.l–4075 m a.s.l and 4036 m a.s.l–4130 m a.s.l at the east and west branch, respectively; at altitudes of over 4200 m a.s.l and 4450 m a.s.l respectively, and near the head of east and west branch) and percolation zone (the vertical fall are 125 m and 320 m at east and west branch, respectively). Recently, Li et al. (2006) found that glacier zones and the snow stratigraphy of Glacier No.1 have transformed from cold to warm. The firn (fine-grained firn and coarse-grained firn) dominates snow stratigraphy. The depth hoar, ice layer and ice lens have decreased in snow stratigraphy of the percolation zone. The percolation-freezing process becomes more severe than before, and the number of dust layers decreases and its color darkens. The period of ice formation ranges from about 41 months to 47 months (You et al., 2006). The glacier zones can be divided into ablation zone (below 4066 m a.s.l at the east branch, and the local area on the summit of the east branch; below 4089 m a.s.l at the west branch), percolation-freezing zone (at altitude of 4066 m a.s.l–4098 m a.s.l and area between the highest boundary of percolation zone and the lowest boundary of local ablation area on the summit at the east branch; at altitude of 4089 m a.s.l–4136 m a.s.l and the local area on the summit at west branch) and percolation zone (area between 4098 m a.s.l and the lowest boundary of percolation-freezing zone above firn basin at the east branch; area between 4136 m a.s.l and the lowest boundary of the local percolation-freezing zone on the summit at the west branch). It is obvious that the local area on the summit at the east branch has turned into the local ablation area with strong ablation features (Li, 2005).

The temperature of Sigonghe Glacier No.4 on the northern slope of the Bogeda peaks is lower than that of Glacier No.1 at the Urumqi River head. There is more precipitation, the equilibrium line is low, and the thickness of firn layer is bigger in Sigonghe Glacier No.4. The distribution features of glacier zones are: the cold-percolation zone is absent, and the vertical fall of superimposed-ice zone is about 100 m. The ablation zone can be divided into up-ablation zone and down-ablation zone. The up-ablation zone is narrow and long, and is characterized by the spot-state area of superimposed ice. The highest boundary of the accumulation area of Sigonghe Glacier No.5 is high and the cold-percolation zone may exist (Xie et al., 1983). The superimposed-ice zone is thick on Heigou Glacier No.8 of the southern slope of the Bogeda peaks, and its vertical fall ranges from 150 m to

200 m (Wang et al., 1986). Glacier ice explores directly at altitudes of about 4253 m a.s.l and below 4253 m a.s.l on Miaoergou Flat-Topped Glacier. The snow stratigraphy is composed of fine-grained firn and coarse-grained firn at an altitude of 4343 m a.s.l, and is composed of fresh snow, fine-grained firn and coarse-grained firn at altitudes of 4453 m a.s.l to 4513 m a.s.l. Glacier zones are composed of ablation zone and percolation-freezing zone. The vertical fall of percolation-freezing zone is about 60 m or more (Li et al., 2007). The snow stratigraphy in the accumulation area (3680 m a.s.l) on Haxilegen Glacier No.51 at Kuitun River is composed of fine-grained firn and coarse-grained firn. The coarse-grained firn is thick and similar to that of the west branch of Glacier No.1, and the number of dust layers is bigger. Glacier zones are composed of ablation zone, percolation-freezing zone and percolation zone. The vertical fall of the percolation-freezing zone is about 70 m (Li et al., 2007).

4.3 Altay Mountain and western Kunlun Mountain

The Kanasi Glacier on the southern slope of the Youyi peaks in Altay Mountain can be divided into four glacier zones: (1) Ablation zone. (2) Superimposed-ice zone. The ice stream at the left branch is located at an altitude of 3150 m a.s.l to 3200 m a.s.l, and at the right branch it is located at an altitude of 3240 m a.s.l to 3280 m a.s.l. The thickness of the ice stream ranges from 40 m to 50 m, and the thickness of superimposed ice ranges from 6 cm to 19 cm. (3) Percolation zone. The ice stream at the left branch is located at an altitude of 3200 m a.s.l to 3400 m a.s.l, and at the right branch it is located at an altitude of 3 280 m a.s.l to 3 480 m a.s.l. The thickness of the ice stream can reach 200 m. (4) Cold-percolation zone. This zone may exist in the middle and top of the accumulation area above the percolation zone (the vertical fall is about 1000 m) (Wang et al., 1983). The equilibrium line on Chongce Flat-Topped Glacier of the western Kunlun Mountain is close to an altitude of 6000 m a.s.l. The net accumulation in glaciers ranges from 200 mm to 400 mm, and the superimposed-ice zone exists between 6000 m a.s.l and 6300 m a.s.l. The cold-percolation zone exists at an altitude of 6 300 m a.s.l, where the thickness of firn layers is over 20 m (Shi et al., 1988).

4.4 Himalaya Mountain

The snowfall is platy crystal during March to April on the northern slope (below 5800 m a.s.l) of the Xixiabangma peaks, and is also probably platy crystal in summer (below 6000 m a.s.l). The columnar crystal snowfall may occur on the summit in winter or summer. Snow stratigraphy structure belongs to the cold metamorphism process before the middle ten days of April. The thickness of snow cover ranges from 35 cm to 70 cm on the shaded slope of the second lateral moraine (5820 m a.s.l) in late March. Most snow is coarse-grained firn in snow stratigraphy, the depth hoar and surface fresh snow exist, and fine-grained firn also exists in some regions. Snow cover is thick on glaciers. The thickness of snow cover ranges from 50 cm to 100 cm on the top of ice pyramids, and most snow cover has transformed into depth hoar. The snow shell exists below surface fresh snow and its thickness ranges from 5 cm to 7 cm. Snow cover near the snow line (5900 m a.s.l) did not melt in early May and depth hoar still exists in the snow stratigraphy. The snow stratigraphy structure is similar to that of Glacier No.1 at the Urumqi River head, but surface snow cover melted earlier than Glacier No.1, and depth hoar still exists until the first ten days of May on the ice tongue of Glacier No.1. The percolation-freezing zone is widely distributed in regions near the glacier snow line, and the typical glacier is Nakeduola Glacier No.7 (Xie, 1982). Nakeduola Glacier No.7 is located on the flat roof of the palaeo-moraines (Shi and J, 1982). The highest site and the terminal are located at altitudes of 6170 m a.s.l and 5700 m a.s.l, respectively, and one or two glacier zones exist. When the equilibrium line is located at an altitude of over 6150 m a.s.l, the ablation zone dominates the whole glacier. When the equilibrium line is located at an altitude of 5950 m a.s.l, the superimposed-ice zone dominates above the equilibrium line and the ablation zone also dominates below the equilibrium line. Both the perennial equilibrium line and the equilibrium line in 1991 are near an altitude of 5950 m a.s.l, the superimposed-ice zone dominates above the equilibrium line, and the ablation area dominates below the equilibrium line. When the equilibrium line is located at an altitude of 6150 m a.s.l or over 6150 m a.s.l on the summit, the ablation area dominates the whole glacier. The thickness of superimposed ice ranges from 5 cm to 10 cm at the lower part of the glacier. The strong dust surface (ablation area) is composed of macadam and granular aggregate clay and exists below the superimposed ice. The ice formation mechanism belongs to the percolation-freezing process in superimposed-ice zone, the diameter of ice grain formed vertically is bigger than that formed horizontally. The ice density can reach or exceed 830 kg/m^3 (Shi, 1992).

The thickness of surface snow and firn ranges from 30 cm to 50 cm in the Nakeduola Glacier No.6. The superimposed ice is widely distributed, and the percolation-freezing zone dominates the accumulation area. The distribution of snow cover is non-homogeneous in the Yebokangjiale Glacier, the ice explores on the top of ice pyramids, the maximum thickness of snow cover can reach 220 cm in the depressions among the ice pyramids in late April, and snow cover in non-glacial areas is only distributed on the shade or leeward slope. Surface snow begins to melt on the ice tongue in late April, and meltwater percolates into the deeper snow layers, depth hoar and other snow rapidly transforms into the firn, most meltwater freezes and transforms into ice layers in low temperature. The wide distribution of freezing ice on the ice tongue, the growth of the drumlins in Nakeduola river valley, and the distribution of periglacial phenomena all indicate that the freezing zone exists widely on the northern slope of the Xixiabangma peaks. Its vertical fall can reach or exceed 1000 m. The superimposed ice is distributed discontinuously above the ice pyramids (5900 m a.s.l–6000 m a.s.l), and the strong dust layer exists below the superimposed ice. This zone is distributed at an altitude of 5 950 m a.s.l to 6100 m a.s.l on Nakeduola Glacier No.2, and the superimposed ice is distributed mostly below the slope with a gradient of 10 degrees. The percolation-freezing zone is distributed at an altitude of 6000 m a.s.l to 6 100 m a.s.l on both Yebokangjiale Glacier and Nakeduola Glacier No.2. The firn basin on Yebokangjiale Glacier is distributed at an altitude of 6000 m a.s.l to 7350 m a.s.l, and the firn is widely distributed in the firn basin. The firn is thick and the glacier depends mainly on the firn supply. However, Nakeduola Glacier No.7 depends mainly on the ice supply. But the thickness of firn layers fluctuates strongly, the firn layer is very thin on the slope (only a few dozen centimeters), and the superimposed ice surface is sometimes explored. The fluctuation of glacier surface topography near the snow line influences the distribution of snow cover. The superimposed ice is discontinuous and is only distributed in areas where snow cover is thick. Therefore, a single line cannot denote the snow line on these glaciers, and actually the snow line is a zone. In this zone, the accumulation area and ablation area are interlaced. The vertical fall of this zone is 100 m (5900 m a.s.l–6000 m a.s.l) on Yebokangjiale Glacier, and is 150 m (5950 m a.s.l–6100 m a.s.l) on Nakeduola Glacier No.2 (Xie, 1982). Glacier zones on both Yebokangjiale Glacier and Rongbu Glacier can be divided into ablation zone, superimposed-ice zone (superimposed ice exists until altitude of 7450 m a.s.l), percolation zone and cold-percolation zone (Xie and Wang, 1975; Zhang and Xie, 1981; Xie et al., 1982; Xie, 1982). Xie (1982) doubted that the dry-snow zone exists on the highest peaks of Himalaya Mountain.

The firn exists on the glacier surface, the percolation ice (percolation-freezing ice) explores in some areas, and the melting-refreezing process generally occurs. The recrystallization zone and the refreezing-recrystallization zone do not exist in the highest areas of the Xixiabangma peaks. Glacier zones on the northern slope of the Xixiabangma peaks can be divided into ablation zone (the lowest boundary located at altitude of 5000 m a.s.l), percolation-freezing zone (the vertical highness ranges from 100 m to 200 m), percolation zone and cold-percolation-recrystallization zone. Based on data that climbers supplied and observation data on the northern slope of the Xixiabangma peaks, the recrystallization zone and refreezing-recrystallization zone do not exist in Everest, but they exist in central Antarctic (Xie, 1982). Li (1986) showed that the superimposed-ice zone exists widely in the accumulation area on Qiangyong Glacier near the eastern Yangzhuoyongcuo. The annual thick snow cover did not result from the avalanches or the wind. Drifting snow indicates that the glacier is located at the edge of a continental glacier where precipitation is abundant. In recent years, researchers found that the refreezing-recrystallization process (refreezing-recrystallization zone) exists on the large platform (7000 m a.s.l) of Dasuopu Glacier on the northern slope of the Xixiabangma peaks, thereby a new ice formation type was found in China (Yao et al., 1998). The refreezing-recrystallization process is dominant in the eastern Dasuopu Glacier on the northern slope of Everest. The ice formation of the eastern Dasuopu Glacier also fluctuates frequently due to variation of water and heat condition year after year (Kang et al., 2005).

4.5 The southeastern Tibetan and Hengduan Mountain

Warm-percolation zone exists on Ruoguo Glacier, Lagu Glacier, and so on in southeastern Tibetan. The highest boundary of this zone may be located at an altitude of 6000 m a.s.l at least, and dry-snow zone is distributed at an altitude of over 7000 m a.s.l. The highest boundary of most glaciers is not over 6000 m a.s.l in southeastern Tibetan except in some areas of the southern Jiabawa peaks. Percolation-freezing process occurs on some glaciers and parts of the glacier. Many pulse ice, depth hoar, percolation ice layer and ice lens formed in autumn, winter and spring (Li, 1986). Oceanic glaciers dominate in Hengduan Mountain (The exploration team of Tibetan Plateau, 1996); warm-percolation zone is widely distributed in the accumulation area of glaciers in Gongga Mountain and Yulong Mountain, and ice formation depth ranges from 10 m to 20 m or 30 m (Xie et al., 1982; Su et al., 1987). Thereinto, snow line on the Hailuogou Glacier ranges from 4700 m a.s.l to 5200 m a.s.l. Warm-percolation zone exists widely in the accumulation area. Ice formation depth ranges from 10 m to 20 m or 30 m (Xie et al., 1982; Li et al., 1983). Snow layers in the accumulation area of Hailuogou Glacier were formed from snow accumulated in the current year. Superimposed-ice zone exists widely in most areas above the equilibrium line. The period of ice formation is one year. The vertical fall of this zone is about 400 m. The highest boundary is over an altitude of 5 300 m a.s.l (Shi, 1992).

5 Summary

The ice formation of glaciers controlled by local water-heat condition influences glacier mass balance, glacier temperature, glacier movement and so on, and it is one of the bases of glacier classification. Ice formation studies can indicate the growth condition, the formation process and the physical characteristics of glaciers, and can be regarded as a gist for glacier classification. Its spatial variation can reflect glacier variations and further indicate climate changes. Ice formation studies mainly focused in periods from 1960s to 1980s in China, where main study areas focused in Qilian Mountain, Tianshan Mountain, Altay Mountain, western Kunlun Mountain, Himalaya Mountain, the southeastern Tibetan and Hengduan Mountain, and so forth. So far, relevant studies have been very productive. However, researchers cannot reach study areas by themselves due to poor working conditions, the complex topography in the glacier area and extreme weather conditions. As a result, ice formation studies are subject to limitations and uncertainties due to the fact that these researchers are limited to observation data supplied by climbers and the deduction and estimation for some glaciers based on observation of other neighboring glaciers. In recent years, under the influence of climate warming, glaciers melted strongly, the ice formation of glaciers changed enormously in different glacier areas. Therefore, it is important for us to study ice formation of glaciers and to explore the response of ice formation of glaciers to climate changes. Furthermore, for studies of the ice formation of glaciers, it is suggested that researchers should dig snow pits, observe snow stratigraphy by themselves, and measure physical indexes (grain shape, grain diameter, snow density, quantity of water contained in snow layers, and temperature and rigidity of snow layers and so on) of snow layers by apparatuses in order to improve the precision of ice formation studies, overcome the deficiency of previous studies, and further its advancement.

Acknowledgements This study was supported by the National Natural Science Foundation of China (40571034; 40601022), the Knowledge Innovation Project of Chinese Academy of Sciences (KZCX2-YW-301) and the Special Program for Key Basic Research of the Ministry of Science and Technology (2006FY110200).

References

Benson C S (1959). Physical investigations on the snow and firn of northwest Greenland 1952, 1953 and 1954. Snow, Ice and Permafrost Research Establishment (SIPRE). Research report 26

Benson C S (1961). Stratigraphic studies in the snow and firn of the Greenland ice sheet. Folia Geographica Donica, 9: 13–37

Benson C S (1962). Stratigraphic studies in the snow and firn of the Greenland ice sheet. SIPPE research report 70

Dolgushin L D (1961). Main particularities of glaciations of central Asia. AHS. No.54

Han T D, Liu S Y, Ding Y J, et al (2005). A characteristic mass balance of Glacier No.1 at the Urumqi River head, Tianshan Mountain. Advances in Earth Science, 20(3): 298–303 (in Chinese with English abstract)

Kalesnik C U (1982). An introduction to glaciology. Lanzhou: Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences, 13–40

Kang S C, Qin D H, Ren J W, et al (2005). New knowledge of transformation of snow to ice in the eastern Rongbu Glacier, the northern slope of Mount Qomolangma (Everest). Scientia Geographica Sinica, 25(4): 415–419 (in Chinese with English abstract)

Kotterlongcov V M (1984). Glacidogy dictionary. Leningrad: Hydrology and Meteorology Press, 144–147 (in Russian)

Langway C C (1967). Stratigraphic analysis of a deep ice core from Greenland. CRREL research report, 77

Li J J (1986). The distribution and characters of modern glaciers. Tibetan plateau exploration team, Chinese Academy of Sciences. Tibetan glaciers. Beijing: Science Press, 6–36 (in Chinese)

Li J J, et al (1983). The investigation of glaciers in Gongga Mountain. The exploration team of Tibetan plateau, Academia Sinica. Research on Tibetan plateau, special volume of Hengduan Mountain. Kunming: Yunnan People Press, 140–153 (in Chinese)

Li X Y (2006). The present environmental processes of snow-ice on Glacier No.1 at the Urumqi River head, Tianshan Mountain: a. Ice formation zones and stratigraphy profiles; b. Seasonal variations and elution processes of pH and electrical conductivity: [Dissertation]. Lanzhou: Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (in Chinese with English abstract)

Li X Y, Ding Y J, Liu S Y, et al (2007). Primary studies of stratigraphy profiles of pH and electrical conductivity in snow pits on Miaoergou glacier, Hami and Glacier No.51 at Haxilegen of the Kuytun River, Tianshan Mountain. Journal of Glaciology and Geocryology, 29(5): 710–716 (in Chinese with English abstract)

Li X Y, Li Z Q, You X N, et al (2006). Studies of the ice formation zones and stratigraphy profiles of snow pits on Glacier No.1 at the Urumqi River head, Tianshan Mountain. Journal of Glaciology and Geocryology, 27(1): 37–44 (in Chinese with English abstract)

Li Z Q (2005). A glacier meltwater pool was discovered at summit of east branch of Glacier No.1 at the Urumqi River head, Tianshan Mountain, Xinjiang. Journal of Glaciology and Geocryology, 27(1): 150–152 (in Chinese with English abstract)

Liu C H, Ding L F (1988). A primary calculation of temperature and precipitation in Tianshan Mountain, China. Journal of Glaciology and Geocryology, 10(2): 151–159 (in Chinese with English abstract)

Liu C H, Xie Z C, Gyuregainov M B, et al (1996). Glacial action in Tianshan Mountain. Beijing: Science Press, 96–115 (in Chinese)

Liu C H, Gyuregainov M B (1989). Study on processes of mass balance of Glacier No.1 at the Urumqi River head, Tianshan Mountain. Annual Report of Tianshan Glaciological Station, 8: 1–23 (in Chinese with English abstract)

Liu Z C (1960). The modern glaciers in Qilian Mountain. Florilegium of papers in national geographical meeting (physiognomy). Beijing: Science Press (in Chinese)

Muller F (1962). Zonation in the accumulation area of glaciers of Axel Heiberg Island, N.W.T., Canada. Journal of Glaciology, 4: 302–313

Paterson W S B (1987). The physics of glaciers. Second edition. Oxford, etc., Elsevier

Qin D H, Ren J W (2001). Antarctic glaciology. Beijing: Science Press, 61–69 (in Chinese)

Qiu J Q (1986). Expression and meanings of routine terms of snow-an introduction to terms and classes in avalanches charts. Journal of Glaciology and Geocryology, 8(1): 89–96 (in Chinese with English abstract)

Ren B H (1963). The ablation, accumulation and ice formation of modern glaciers in Qilian Mountain. Study data of glaciology and cryopedology (in Chinese)

Sekin Y P (1962). Mass income in firn basin of glaciers. Moscow: Science Press, No. 8 (in Russian)

Shi A P (1992). General features of Nakeduola Glacier No.7 in the northern slope of Xixiabangma Mountain and Hailuogou Glacier in Gongga Mountain: [Dissertation]. Lanzhou: Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences (in Chinese with English abstract)

Shi Y F, Huang M H, Ren B H, et al (1988). An introduction to glaciers in China. Beijing: Science Press, 55–57 (in Chinese)

Shi Y F, Ji Z X (1982). The distribution and types of modern glaciers in Xixiabangma area. Exploration reports of Xixiabangma area. Beijing: Science Press, 24–39 (in Chinese)

Shi Y F, Xie Z C (1964). General features of modern glaciers in China. Acta Geographical Sinica, 30(3): 83–208 (in Chinese with English abstract)

Shumskii P A (1955). Principles of structura glaciology. Moscow: Science Press, 401–464 (in Russian)

Shumskii P A, Sekin Y P (1962). Regional problems of glaciology, glaciology research, protection and discussion data, Moscow, (in Russian)

Su Z, Wang L L, Pu J C, et al (1987). The primary study of basic characteristics of modern glaciers in Hengduan Mountain. Collected publication of glaciology meeting (glaciology). Lanzhou: Gansu People Press, 96–103 (in Chinese)

The exploration teams of Tibetan plateau, Academia Sinica(1996). Hengduan Mountain glaciers. Beijing: Science Press, 1–26 (in Chinese)

The utilization and variations of glaciers in Qilian Mountain (1985). The collected publication of Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica (No.5). Beijing: Science Press, 1–40 (in Chinese)

Wang F T, Li Z Q, You X N, et al (2006). Study of ice formation process of surface snow layer in accumulation area of Glacier No.1 at the Urumqi River head, Tianshan Mountain. Journal of Glaciology and Geocryology, 27(1): 45–53 (in Chinese with English abstract)

Wang L L, Liu C H, Kang X C, et al (1983). Fundamental features of modern glaciers in Altay Mountain. Journal of Glaciology and Geocryology, 5(4): 27–38 (in Chinese with English abstract)

Wang L L, Zhang W J (1985). The modern glaciers in the Tuomuer peaks, meteorology and glaciers in the Tuomuer peaks. Urumqi: Xinjiang People Press, 43–49 (in Chinese)

Wang X J, Wang Z X, Xie Z C (1988). A change trend of recent climate in Tianshan Mountain regions from the change of the past 28 years of Glacier No.1 at the Urumqi River head, Tianshan Mountain. Chinese Science Bulletin, 9: 693–696

Wang X J, Zhang J H (1982). The observations on accumulation and stratigraphy profiles on Glacier No.1 at the Urumqi River head. Annual Report of Tianshan Glaciological Station, 1: 11–21 (in Chinese)

Wang Z T, Shao W Z and Zhang J H (1986). The characteristics of Heigou Glacier No.8 in the southern slope of Bogeda Mountain

Williams R S Jr, Hall D K, Benson C S (1991). Analysis of glacier facies using satellite techniques. Journal of Glaciology, 37(125): 120–128

Xie Z C (1982). Snow and ice formation in the northern slope of the Xixiabangma peaks. Exploration reports of the Xixiabangma area. Beijing: Science Press, 45–59 (in Chinese)

Xie Z C (1984). Studies of ice formation and ice fabric on the Law Dome, Antarctica. Journal of Glaciology and Geocryology, 6(1): 1–23 (in Chinese)

Xie Z C, Huang M H (1988). The ice formation of glaciers in China. In: Shi et al, eds.The overview of glaciers in China. Beijing: Science Press, 55–68 (in Chinese)

Xie Z C, Huang M H, Mi A L, et al (1965). An evolution of the snow-firn layer and ice formation on Glacier No.1 at the Urumqi river head, Tianshan Mountain. Studies of glaciology and hydrology in the Urumqi river, Tianshan Mountain. Beijing: Science Press, 1–14 (in Chinese)

Xie Z C, Wang L L, Wu G H, et al (1985). The ice formation of glaciers in Qilian Mountain. Collected publication of Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica, 5: 27–40

Xie Z C, Wang Z T (1975). Ice formation of glaciers in the northern slope of Everest area. Exploration report of Everest area (1966–1968). Beijing: Science Press, 8–25 (in Chinese)

Xie Z C, Wu G H, Wang Z X, et al (1983). The ice formation of the northern slope of the Bogeda peaks, Tianshan Mountain. Journal of Glaciology and Geocryology, 5(3): 37–46 (in Chinese with English abstract)

Xie Z C, Zheng B X, Li J J, et al (1982). The variations, characteristics and distribution of glaciers in China. Collected publication of glaciology and geocryology meeting (glaciology). Beijing: Science Press, 1–13 (in Chinese)

Yao T D, Pu J C, Wang N L, et al (1998). A new type of glacier zones found in the Himalayas. Chinese Science Bulletin, 43(1): 94–97

You X N, Li Z Q, Wang F T (2005). Study on time scale of snow-ice transformation through snow layer tracing method-take Glacier No.1 at the Urumqi River head as an example. Journal of Glaciology and Geocryology, 27(6): 853–860 (in Chinese with English abstract)

Zhang W J, Xie Z C (1981). New data and variations of some glaciers in the southern Tibetan. Journal of Glaciology and Geocryology, 3(4): 61–64 (in Chinese with English abstract)

Zheng B X (1963). The distribution and characteristics of modern glaciers in Qilian Mountain. Study data of glaciology and cryopedology (in Chinese)