First Results from Himalayan Glacier Boring Project in 1981–1982

Part II. Studies on internal structure and transformation process from snow to ice of Yala Glacier, Langtang Himal, Nepal

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Glaciological Expedition of Nepal, Contribution No. 87
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Abstract

Sixty-meter direct boring cores obtained in the accumulation area of Yala Glacier (Dakpatsen Glacier), Langtang Himal, Nepal were analyzed with special attention to the stratigraphy, density, grain, the air bubbles. The internal structure of the Yala Glacier was characterized by a granular snow layer 17 m deep. At this depth firn transformed into ice abruptly and the density curve showed a discontinuity. The temperature of the snow and ice measured in the borehole was 0°C throughout the entire layer.

Spouting water was found in the borehole, indicating an aquifer in the glacier. From measurement of the water level in the borehole, the rise in the water level was found to be proportional to the logarithm of the time, and the logarithm of the average recovery velocity of the water level decreased in proportion to the cumulative yield. The coefficient of permeability of this aquifer was 3.7×10^{-6} cm·sec^{-1}, or equal to that of compact silt.

From these studies, the transformation process from snow to ice in this glacier was discussed.

During the monsoon season, much meltwater and rainwater percolated into the glacier. It is considered that the aquifer was made in the glacier, due to the rapid densification of snow immersed in water. Where this transformation process from snow to ice has taken place, the discontinuity of density curve can be explained. In considering the transformation process from snow to ice in a temperate glacier, the densification of snow immersed in water is a key factor.

1. Introduction

In 1982, in the accumulation area (5,400 m above sea level) of Yala Glacier (Dakpatsen Glacier, Langtang Himal, Nepal), 60 m full depth boring to the bedrock was carried out, the first such attempt in the Himalaya. The 60 m core was analyzed paying attention to the structure of firn and ice, and the transformation process from firn to ice.

The following observations were carried out;

(i) stratigraphic observation of snow layers and glacier ice.
(ii) measurement of density profile.
(iii) measurement of grain shape and profile of grain size.
(iv) observation of elongation of air bubbles.

Due to logistic conditions, the sample core could not be brought back to our laboratory. Therefore items (i) and (ii) were immediately measured at the observation point, and items (iii) and (iv) were analyzed in Japan using the cross-polarized photographs of vertical thin section taken in the observation point. C-axis orientations by universal stage could not be measured because air temperature was high.

During this boring water was discovered spouting from about 27 m depth in the borehole. This may well be an aquifer in the glacier. This is the first time this kind of aquifer has been reported in a Himalayan glacier. We observed this aquifer.

Based on these studies, the authors intend to report the structural characteristics of Yala Glacier and the aquifer characteristics, discussing the relation between them and the transformation process from snow to ice.

2. Structural characteristics of Yala Glacier

2-1. Structure of snow cover and glacier ice

The outline of snow cover and glacier ice is shown in Fig. 1(a). It is characterized by the continuation of a thick granular snow layer from the surface to a depth of 17 m. In this layer, there are remarkable some dirt layers. Ice layer did not develop more thickly in the deeper part of the temperate granular firn as with glaciers in other regions of the Himalaya.

The boundary between firn and ice was obvious. At the depth of 17 m, firn transformed abruptly into ice. And below 30 m, the grain of the ice was larger than in the upper layers except for the hatched area in Fig. 1(a). In these hatched areas, the grain size was smaller than in the other layers, foliation was well developed and the elongation of air bubbles was conspicuous. This area can be considered to be the shear zone of this glacier.

Moreover, the temperature of the snow and ice observed in the borehole in the accumulation area was 0°C throughout the entire mass except for several meters toward the top. But last observation in 1981 showed the temperature of the ice observed in ablation area was about −1°C through the entire mass.

The photographs of vertical thin section of the core at the each depth were shown in Fig. 2.

(i) ice layer in the upper part of granular snow (at a depth of 2.5 m)

(ii) ice near the firn-ice interface (at a depth of 17 m)

(iii) shear zone (at a depth of 42 m)

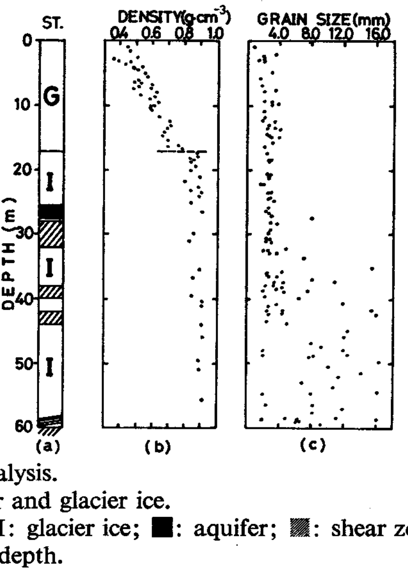

Fig. 1. The results of core analysis.
(a) The outline of snow cover and glacier ice.
G: granular snow layer; I: glacier ice; ■: aquifer; ▨: shear zone
(b) Variation of density with depth.
(c) Variation of grain size with depth.

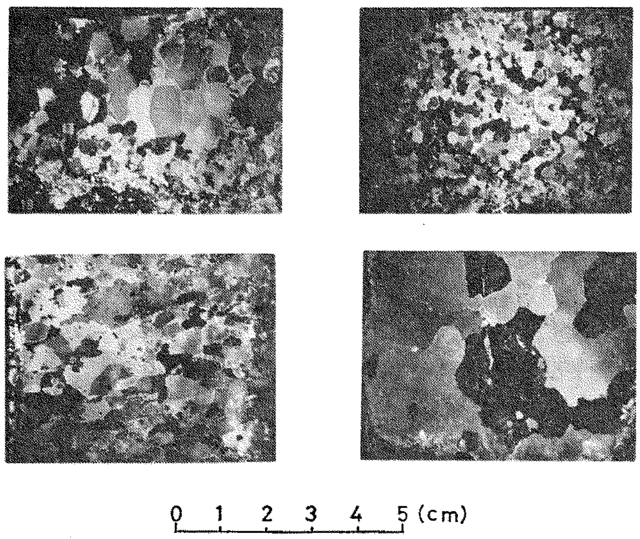

Fig. 2. The photographs of vertical thin section of the cores at the each depth.
(i) ice layer in the upper part of granular snow cover (at a depth of 2.5 m)
(ii) ice near the firn-ice interface (at a depth of 17 m)
(iii) shear zone (at a depth of 42 m)
(iv) glacier ice near the bedrock (at a depth of 55 m)

(iv) glacier ice near the bedrock (at a depth of 55 m)

2-2. Density profile

The vertical profile of average density is shown in Fig. 1(b). For the first 17 m, the density increased gradually. According to the pit studies of the upper part of snow cover, there is a seasonal cycle of density variation in the annual layer. This cycle presumably was restricted to the lower part of snow cover and gave a width of the Fig. 1(b) to the density profile.

At a depth of 17 m, firn with a density of 0.7–0.75 ($g \cdot cm^{-3}$) was suddenly transformed into ice with the density 0.85 ($g \cdot cm^{-3}$). In ice sheets in the polar region, the density curve changed gradually with breaks of slope and does not have this kind of discontinuity. To explain this, we need to consider the other kind of the transformation process from snow to ice.

2-3. Profile of grain size and elongation of air bubbles

Profiles of grain size (Fig. 1(c)) were made by photographs of vertical thin section using a particle-size analyser (CARL ZEISS, TGZ-3), and the elongation of air bubbles (Fig. 3) was measured by direct reading from core sample at the observation point.

The grain size gradually increased with depth until 30 m. At below 30 m, the grain of very large size came out. The reason is considered to be recrystallization on account of the shear following flow. But the grain size corresponding to the hatched area in Fig. 1(a) was in fact small.

The profile of elongation of air bubbles is shown in Fig. 3. M_I represents the minor axis of air bubbles and M_{II} indicates the major axis. Fig. 3(b) shows the ratio of M_{II} to M_I. The zones of much air bubble elongation are seen near depths of 30 m, 38 m and 42 m. In these zones (Fig. 1(a): hatched area) the grain size was small and foliation developed well. The

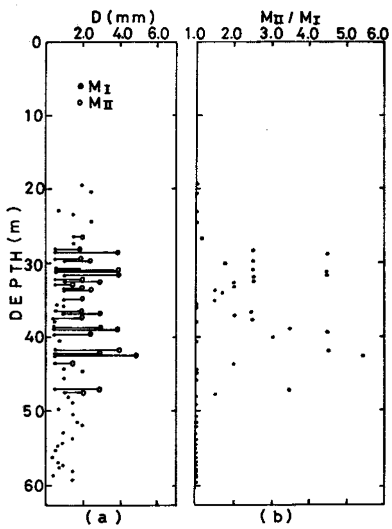

Fig. 3. Variation of elongation of air bubbles with depth.
(a) M_I represents the minor axis of air bubbles.
M_{II} represents the major axis of air bubbles.
(b) ratio of M_{II} to M_I.

present investigators suggest that this is the shear zone. The debris of the bedrock along the shear plane was taken into the glacier ice near the bedrock.

3. Observation of glacier aquifer

3-1. Borehole water level

While boring, infiltrated water gushed out in the borehole at a depth of 25.5-27.5 m, reflecting the existence of an aquifer in the glacier. The water level in the borehole rose rapidly to reach the equilibrium water level at a height of 7.8 m from the base of the borehole (Fig. 4).

The fact that the equilibrium water level in the borehole was higher than the Water Table indicated that this aquifer was a confined one. Fig. 5 shows the recovery curves of the water level inside the borehole after removal of spring water. The lines A, B and C are the observational results of the water level of Oct. 4–5, Oct. 6–7 and Oct. 7–8, 1982, respectively.

From Fig. 5 it is concluded that the rise of the water level is proportional to the logarithm of the time since pumping stopped. The lines A, B and C are given by the following equations:

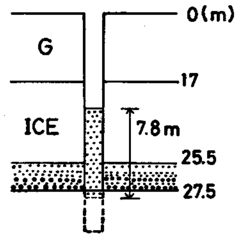

Fig. 4. The spouting water in the borehole.

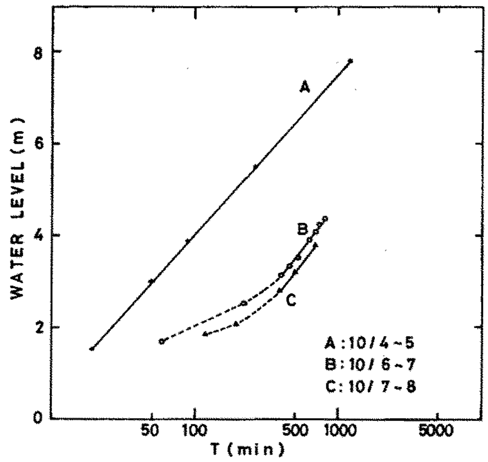

Fig. 5. Relation between water level in the borehole and the time after pumping stopped. A: Oct. 4–5; B: Oct. 6–7; C: Oct. 7–8.

$$A: L = 1.52 \ln t - 3.0$$
$$B: L = 1.85 \ln t - 8.0$$
$$C: L = 1.66 \ln t - 7.1$$

Where L is the water level and t is time since pumping stopped. The tangentials of these recovery curves (Fig. 5) are almost the same values, which means that the coefficient of permeability of each aquifer is almost the same. Also, the more water pumped up, the more the recovery velocity of the water level decreased.

In order to observe this phenomenon more closely, pumping was repeated and the recovered water level was measured from Oct. 6 through 20. In this way the relation of the cumulative yield with the average velocity of the recovered water level was measured (Fig. 6).

From Fig. 6, it can be concluded that the logarithm of the average recovery velocity of the water level decreased in proportion to the cumulative yield. And the equation of Fig. 6 is

$$V = 0.87e^{-0.006 \cdot \Sigma Q}$$

where V is the average recovery velocity of the water level in the borehole (m/h) and $\sum Q$ is the cumulative yield (liter). Having the straight line extended, it is estimated that water will almost stop when the cumulative yield reaches around 750 liters.

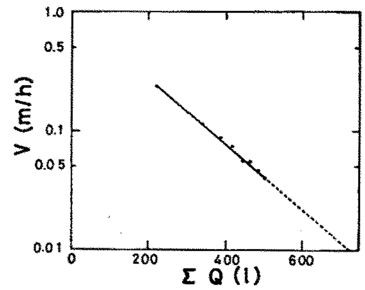

Fig. 6. Relation between the average velocity of the recovered water level (V) and cumulative yield (ΣQ).

3-2. Coefficient of glacier ice permeability

Although it has been considered that glacier ice has no permeability, the contrary was proved by Wakahama et al. (1973), who observed that water percolated into ice in the ablation area of the Alaskan Glacier. Nye and Mae (1972), having conducted various thermodynamical research on the crystal boundary inside ice, proved that at the ice melting point, water could flow along the place where three grains meet. They also confirmed the same experimentally.

This time it was confirmed that the ice of an accumulation area at Yala Glacier has permeability. The study was enlarged to compare the water inside the pore space of the glacier ice to the groundwater inside the pore space of soil particles. Efforts were made to obtain the coefficient of permeability, that is, the hydrologic constant which is the key to the quantitative evaluation of the groundwater aquifer. The recovery method (Theis, 1935) was employed to obtain the coefficient of permeability in which recovery of the water level is measured by a pumping test. The water level in the borehole rapidly recovered when pumping was stopped. Supposing that the quantity of the recovery water is the same with that of the pumped-up water, the coefficient of transmissibility T is given by the following equation,

$$T = 0.183Q/S' \cdot \log t/t' \qquad (1)$$

where Q is the volume of pumped-up water since the pumping was started, t is the time since the pumping was started, t' is the time since the pumping was stopped, and S' is the residual draw-down (i.e., the difference of the initial water level in the borehole and the water level during the recovery period).

It is assumed that $\log t/t'$ is one cycle, and that, $\Delta S'$ is the water level difference during this one cycle.

Eq. (1) can be rewritten as

$$T = 0.183Q/\Delta S' \qquad (2)$$

then let m be the thickness of the aquifer.

The coefficient of permeability K is given by

$$T = Km \qquad (3)$$

This method was used to obtain the coefficient of permeability on the basis of the water level data from the observation of Oct. 6 p.m. 4:15–Oct. 7 a.m. 10:30:

$$K = 3.7 \times 10^{-6}\ \mathrm{cm \cdot s^{-1}}$$

This value, which is the value of compact silt in case of soil, means that the above-mentioned aquifer is considered aquiclude (with slight permeability). This value virtually agrees with the value ($K = 6.0 \times 10^{-6}$ cm·s^{-1}) which Takahashi et al. (1970) obtained from their winter observation at an ablation area of an Alaskan glacier.

4. Discussion

4-1. Aquifer

It is reported that most of the annual accumulation in a Nepal Himalaya Glacier is brought about by monsoon precipitation in summer. Also, ablation arises in summer, so this glacier is said to have a mass balance of "one-season dependent type" (Ageta, 1983).

Yala Glacier is not an exception, and it is also considered to undergo most accumulation and ablation during the monsoon season. Therefore, in considering the origin of water of an aquifer, it is necessary to measure the liquid precipitation and ablation during the monsoon season. But this difficult kind of observation has not been done at Yala Glacier. Thus, for a rough estimation of these quantities, Ageta's (1983) estimation formula was used.

First, air temperature data of Kathmandu was compared with those of Lhajung (Khumbu region): 0.57°C/100 m was found to be the lapse rate.

From this Kathmandu air temperature data, the mean air temperature was obtained each month at different heights on the Yala Glacier. At the Boring Site, air temperatures were as follows:

June, −0.19°C; July, 0.86°C; August, 0.53°C; and September, −0.77°C.

According to Ageta's formula for estimation, ablation (a_s: cm water) during the monsoon season (supposing Ts is the mean air temperature (°C)) is given by

$$a_s = -(Ts+3.2)^{3.2}$$

Using this formula, the ablation is calculated at the Boring Site during the monsoon season (June–September) as −46 (cm water). Next, the probability of occurrence of solid precipitation S(%) to total precipitation is given by Ageta (1983) as follows:

$$S = -23Ts+80 \quad (-0.8<Ts<3.4)$$

According to this formula, the probability of occurrence of solid precipitation at the Boring Site during the monsoon season (June–September) S is 77.5(%) and 22.5(%) is liquid precipitation.

Next, solid precipitation was estimated to be 97 cm water by annual accumulation as estimated by boring core and presumed ablation. This result gave us the estimated liquid precipitation at Yala Glacier during the monsoon season (June–September); the value is 28 cm water, and much liquid precipitation was the distinctive feature.

With these estimations, the total melt and rain water at Yala Glacier Boring Site during monsoon season was 74 cm water. By percolation of much melt and rain water into the glacier, the transformation from fine-grained snow to coarser-grained snow took place in this way, and thereby the percolation was more accelerated. With this positive feedback, we consider, thick granular snow layer up to 17 m in depth has been formed. Still more, the percolated water forms an unconfined aquifer at the firn-ice interface, where the Water Table is formed during monsoon season. This aquifer is considered to have water percolation to

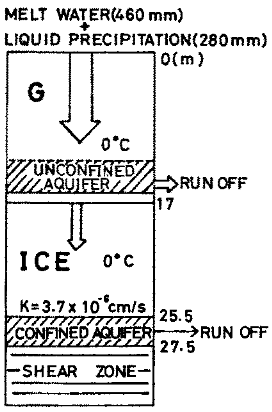

Fig. 7. Schematic diagram of aquifer in Yala Glacier.

permeable ice, in addition to the run-off in the inclimated direction. Percolated water forms an aquifer inside the ice with the holding plane for infiltrated water near the shear zone. There is the possibility that during the monsoon season, the upper and lower aquifers are connected, but at the time of observation, only the lower aquifer was considered to remain. The model of Yala Glacier Aquifer is shown in Fig. 7.

4-2. Transformation process from snow to ice in Yala Glacier

Two steps have conventionally been considered to be involved in the transformation process from snow to ice in a temperate glacier.

(i) Transformation by densification.

(ii) Formation of superimposed ice by invasion and accumulation during a winter coldwave and refreezing of percolated melt water.

However, in the case of Yala Glacier, if we take the process (i) only, the densification was gradual, so the discontinuity of density curve at 17 m in depth can not be made clear. Also in the case of (ii), it is hard to consider that a winter coldwave could reach the snow—ice interface with 17 m-thick granular snow layer as an adiabator. Lliboutry (1971) confirmed that winter cold does not penetrate deeper than 15 m from his observation of the firn at 3,550 m on Mont Blanc in the French Alps. At Yala Glacier, only the ice layer of the upper part of the snow layer was seen to increase by refreezing of melt water. At Yala Glacier, it is necessary to take other transformation processes into consideration.

Then here is the alternative process: densification of snow immersed in water of 0°C. According to Wakahama (1965) and Tsushima (1978), the immersion of snow in water leads to a rapid increase of compression strength. Thereupon, they immersed snow in 0°C water and applied a compressive stress of approximately 100 g-wt/cm^2; the compressed snow transformed into ice in one week.

Takikawa (1983) also experimented with compression tests under constant load of water-saturated snow. When water-saturated snow was loaded with a compressive stress 177 g-wt/cm^2, he found that the density soon increased, reaching 0.82 g/cm^3 after about 100 hours. From observation of a thin ice section, crystals of even-grained globular form were observed. He also obtained the coefficient of compressive viscosity, which is defined by the formula $\eta = \sigma/\dot{\varepsilon}$ (σ: compactive stress; $\dot{\varepsilon}$: strain rate), with the conclusion that in the case of water-saturated snow, the value of the compressive viscosity coefficient (η) was four orders smaller than that of antarctic snow analyzed by Kojima (1964). The load of 100–200 g-wt/cm^2 equals 2–4 m depth of snow with the density 0.5 g/cm^3. Therefore, an aquifer was obviously made at the snow-ice interface at a depth of 17 m in Yala Glacier, where there occured rapid densification of snow immersed in water of 0°C.

If the above-mentioned transformation of snow to ice has taken place, the discontinuity of density curve which was mentioned previously would be explained. The photograph of a thin section of the ice at the depth of 17 m showed even-grained crystals of sphere form just as in the experimental results.

On the basis of these data, at the transformation of snow to ice of Yala Glacier, densification of snow immersed in water is considered to be important. Not only in Yala Glacier, but also in other Himalayan glaciers around 5,000–6,000 m, with the condition of comparatively gentle slope with much ablation and liquid precipitation, the same transformation process is supposed to take place.

Recently, a Water Table was found by Vallon et al. (1976) and Schommer (1976) in an

Alpine glacier. Also, in Japan, the same transformation process of snow to ice is considered to take place in perennial snow patches. When considering the transformation of snow to ice in a temperate glacier, the densification of snow immersed in water is a key factor.

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