GLACIOLOGICAL STUDIES OF THE ANTLER GLACIER, ALASKA

by

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(with 12 Text-figures and 7 plates)

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Introduction

In the summer of 1964, Hokkaido University sent an expedition of six physicists, geologists and meteorologists to Alaska to collect large single crystals of ice for solid state studies and to conduct various glaciological investigations of some of the Alaskan glaciers. The large single crystals were collected from the Mendenhall Glacier. The expedition also conducted a field survey of the Mendenhall to investigate the mechanisms of ice crystal growth in a temperate glacier; studies of the beautiful ogive patterns on the Antler Glacier; and firn investigations on the upper areas of the Kaskawulsh Glacier.

The present report concerns the studies conducted on the Antler Glacier with special emphasis upon the mechanism of formation of ogives on that glacier. A peculiar disposition of dirt bands was observed on the ogives. These bands developed on the crests of the wavy ice surface, contradicting the general concept that the bands should be found in the troughs. Based upon precise observation of the textural structure of the ogive ice, as well as that of the steps in the ice fall, it was concluded that the well developed schistosities formed on the front of the ice steps by internal stress made the surface rough enough to trap the dirt particles on the crests. In addition to Nye's mechanism of wave formation in the ice at the foot of an ice fall, surface structures produced by internal, periodic stress caused by seasonal changes in velocity was also found to be important in ogive pattern formation.

General Characteristics of the Antler Glacier

The Antler Glacier is an arm of the Gilkey Glacier which arises in the northern

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part of the Juneau Ice field and flows down to Berners Bay gathering a number of branch-glaciers. The Antler Glacier flows from a small gap on the west side of the upper part of the Gilkey, at first forming an icefall approximately 1.3 km wide and 500 m high, and then continuing due west for approximetely 5.8 km with an almost constant width of 1 km, and terminating in a glacier lake (Pl. 23. Fig. 1).

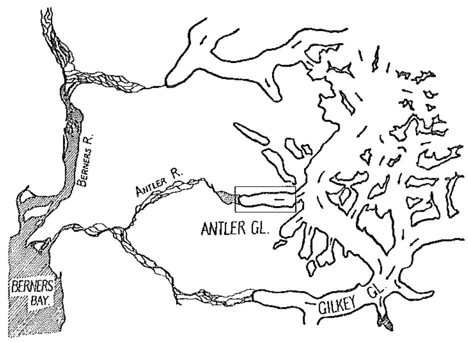

Fig. 1
Map of the Antler and Gilkey Glaciers.

There is a very clear ogive structure on the Antler, particularly from the base of the ice fall down to the middle of the glacier. The glacier also has a remarkable medial moraine on its surface. At the terminus of the glacier, this moraine lies along the central stream line. About half way back up the glacier, the moraine deviates toward the left (south) side, until, near the ice fall, it becomes a side moraine. The deviation of the moraine indicates a recent diminishing of the activity of the left side of the glacier which is divided at the top of the ice fall by a bulge in the bed rock. The primary supply to the glacier is now restricted to the right half of the ice fall, although occasional glacier avalanches from the main stream of the Gilkey may be seen in the left half. An U.S.G.S. map, based upon aerophotographs taken in 1945, shows that the ice fall was then active throughout its entire 1.7 km width, and that the median moraine on the surface was along the central stream line from the terminus up to the ice fall. At that time the glacier was about 6 km long. It is therefore assumed that during the past twenty years, thinning of the Gilkey Glacier has resulted not only in reducing the size of the Antler Glacier, but also in changing its mode of flow.

Structural Subdivision of the Antler Glacier

The structural features of the glacier below the ice fall may be divided into three categories as follows (Fig. 2):

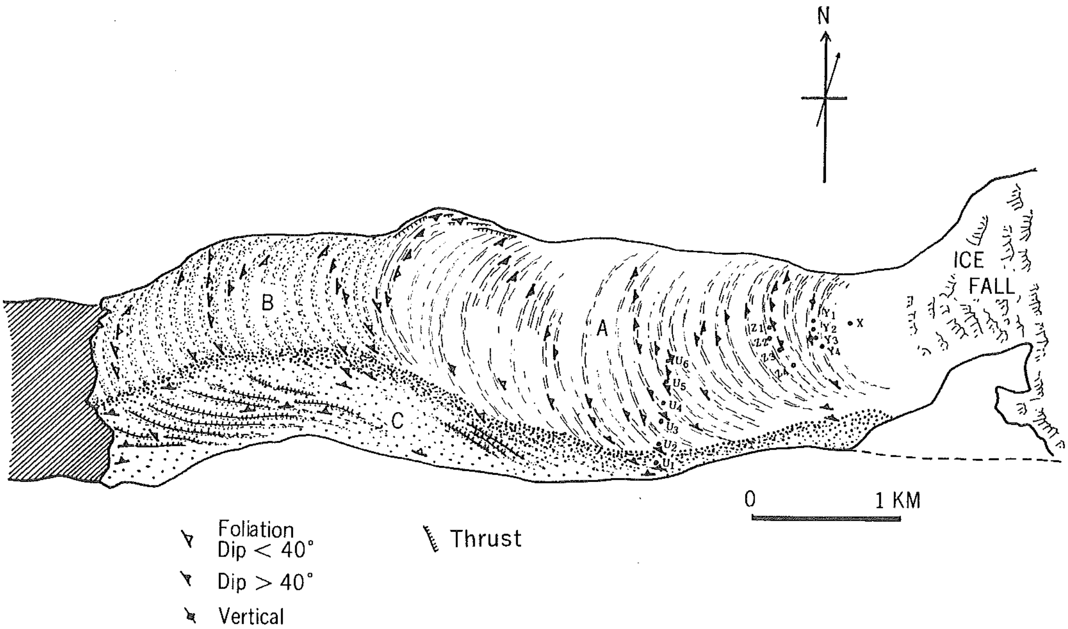

Fig. 2
Structural map of the Antler Glacier. Note subdivisions A, B and C, and stake lines U, Y and Z.

A, the ogive region, extending approximately 2 km directly downstream of the ice fall, and composing the main stream of the glacier. Both ogive and foliation structures are well developed in this region, and this part of the glacier is pushing the adjacent inactive part, toward the left.

B, the weak ogive region, immediately downstream of A. Very faint ogive patterns may be discerned, on the surface. The medial moraine, which lies close to the central stream line of the glacier, divides this part from part C. The transition zone between A and B is characterized by a complicated pattern of crevasses. Several groups of peculiar concentric, crevasses may be seen in the lower part of B.

C, the inactive region on the left side of the medial moraine. This part has lost its supply of ice from the ice fall, and its movement is greatly retarded, the only flow being that produced by the frictional drag of the adjacent, active part of the glacier. In some places, both ogive and foliation structures developed in part A penetrate this region.

In these three structural subdivisions, there are distinct differences in the texture of the glacial ice. In A, the most remarkable characteristic is the well developed foliation structure. The grains of the ice vary from 2 to 4 cm in diameter and there is a rather abrupt change in the grain size in adjacent foliation bands. In B, the grains become coarser and more uniform, especially in the lower part. The average grain diameter is approximately 5 to 6 cm. Occasionally, fairly large grains, 10 cm in diameter, are exposed on the surface. Usually, these large grains are observed in limited areas along the foliations. The coarsest and most uniform grains are in part C. Equigranular grains, averaging 10 cm in diameter, are very frequently observed, and grains 20 cm or more with polygonal boundaries are found, especially near the terminus.

Surface Flow Velocity of the Glacier

The movement of the Antler Glacier was measured with a theodolite and a system of stakes set in the glacier* (Pl. 24, fig. 2). A horizontal base line, approximately 156 m long, was established on the left bank of the glacier at the foot of the ice fall. This base line was to triangulate lines X, Y and Z in Fig. 2. Six stakes were set on a straight line in the middle of the glacier (U, Fig. 2), connecting the target on the right bank and the theodolite station on the left bank. After a certain period of time, the diviation of each stake from this center line, U, gives the surface velocity profile across the glacier. The displacement so measured is given in Table 1.

Table 1. Surface movement.

U	1	2	3	4	5	6
Displacement in 9 days (m)	0.50	0.96	1.55	1.85	2.13	2.16
Velocity (m/day)	0.06	0.11	0.17	0.21	0.24	0.24

As is shown in Fig. 2, line U crossed parts A and C in the middle of the glacier. A remarkable discontinuity of the surface velocity profile was observed in the vicinity of the medial moraine, about 230 m from the left margin of the glacier.

Results of measurements on the lines X (this was practically one point), Y and Z are tabulated in Table 2 with those of calculations of velocity and change of stake intervals. The results showed a general tendency for the velocity, of the lower part of the glacier to be smaller than that of the upper part. Since the width of the glacier is almost constant (apprx. 1 km), this tendency suggests that, given fairly constant thickness, the mode of flow of the Antler Glacier is compressive. Compressive flow is also indicated by strain measurements taken near the foot of the ice fall. These measurements are given in the next section.

* Bamboo stakes were set in holes, drilled 50 cm deep. The ice surface near the stakes was covered with thin aluminum foil to retard ablation. Since surface ablation was approximately 10 cm/day, the stakes were reset every few days.

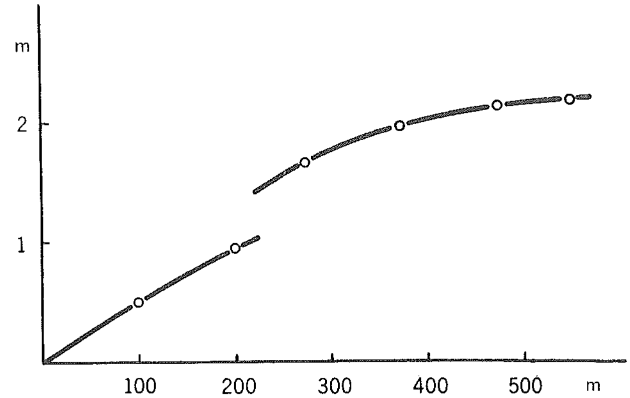

Fig. 3
Surface flow velocity distribution along stake line U, across the glacier.

Strain Measurements

A method using stakes set in squares was adopted for the glacier ice strain measurements. These systems were established at both Y_2 and Z_3 which were selected as the center of each square or the intersection of two diagonals of the

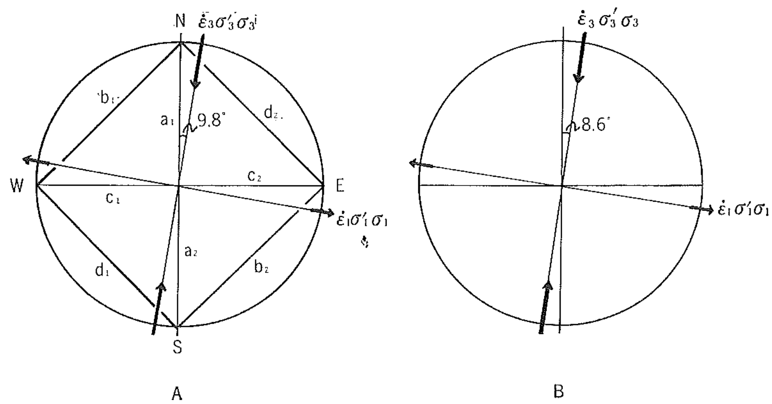

Fig. 4
Stress and strain rates, measured from deformation of square stake system.

square (Fig. 2 and Fig. 4). The direction of one of the diagonals (E-W line) was established parallel to the strike of the foliation. Five days after the squares were established, their deformation was measured by taping (Table 2).

Table 2.

Stake		Displacement in 7 days (m)		Displacement per day (m) Horizontal	Direction of horizontal displacement	Stake intervals (m)		Relative displacement between adjacent two stakes (m)
Group	No.	Hori-zontal	Vertical			Original	7 days later	
X	1	7.91	−2.90	1.13	S 57°37′W			
Y	1	5.86	−1.24	0.84	S 71°30′W	→ 53.08	53.01	−0.07
	2	5.70	−0.75	0.81	S 71°35′W	→ 45.17	45.51	0.34
	3	5.50	−0.98	0.79	S 68°22′W	→ 48.25	48.55	0.30
	4	5.56	−1.15	0.79	S 64°55′W			
Z	1	3.94	−0.70	0.56	N 75°29′W	→ 51.06	51.36	0.30
	2	3.83	−0.65	0.55	N 79°35′W	→ 60.80	60.41	−0.39
	3	4.16	−0.86	0.59	N 76°27′W	→ 99.40	100.50	1.10
	4	3.61	−0.70	0.52	N 88°26′W			

Table 3. Deformation of the squares.

		a_1	a_2	b_1	b_2	c_1	c_2	d_1	d_2
Y_2	l_1	10.00	10.00	14.18	14.06	10.00	10.00	14.16	14.13
	l_2	9.98	10.00	14.11	14.07	10.00	10.02	14.17	14.08
Z_3	l_1	10.00	10.00	14.14	14.14	10.00	10.03	14.13	14.14
	l_2	9.91	9.99	14.10	14.11	9.97	10.05	14.10	14.14

1 : Span length of original square.
2 : Span length 5 days later
see Fig. 5 for explanation of signs a, b etc.

The strain rate of the glacier at Y_2 and Z_3 was calculated by a standard procedure developed by NYE (1959A). In the following equations the principal strain rates $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ are given in (yr^{-1}), the principal stress deviations σ'_1, σ'_2, σ'_3 in bars, and the principal stress σ_1, σ_2, σ_3 in bars.

At Y_2 (Fig. 4A),
$\dot{\varepsilon}_1 = +0.0159\ (yr^{-1})$,
$\dot{\varepsilon}_2 = +0.1620\ (yr^{-1})$, and
$\dot{\varepsilon}_3 = -0.1779\ (yr^{-1})$.

Using GLEN's empirical formula for the flow law of ice, and the plasticity equation,

$$\sigma'_1 = (\tau/\dot{e})\,\dot{\varepsilon}_1 = 6.070\times(+0.0159) = +0.0965 \text{ bars},$$
$$\sigma'_2 = (\tau/\dot{e})\,\dot{\varepsilon}_2 = 6.070\times(+0.1620) = +0.9833 \text{ bars, and}$$
$$\sigma'_3 = (\tau/\dot{e})\,\dot{\varepsilon}_3 = 6.070\times(-0.1779) = -1.0799 \text{ bars.}$$

$\sigma_1 = 2\sigma'_1+\sigma'_3 = -0.887$ bars,
$\sigma_2 = 0$,
$\sigma_3 = \sigma'_1+2\sigma'_3 = -2.0635$ bars, and
$\sigma = \frac{1}{3}(\sigma_1+\sigma_2+\sigma_3) = -0.9845$ bars.
At Z_3, (Fig. 4B),
$\dot{\varepsilon}_1 = +0.004$ (yr^{-1}),
$\dot{\varepsilon}_2 = +0.412$ (yr^{-1}), and
$\dot{\varepsilon}_3 = -0.426$ (yr^{-1}).
$\sigma'_1 = 3.054\times(+0.004) = +0.0122$ bars,
$\sigma'_2 = 3.054\times(+0.412) = +1.2639$ bars, and
$\sigma'_3 = 3.054\times(-0.426) = -1.3011$ bars.
$\sigma_1 = -1.277$ bars,
$\sigma_2 = 0$,
$\sigma_3 = -2.59$ bars, and
$\sigma = -1.29$ bars.

The calculations, showed that the diagonals of the square (both Y_2 and Z_3) had been orientated along the principal axes of strain, and therefore, perpendicular and parallel to the foliation. Results of calculations were shown by vectors in Fig. 4 and this indicate that the glacier was in compression in the direction perpendicular to the foliation, and in tension in the direction parallel to it. Since the results show that the longitudinal compression is more than ten times that of the lateral extension, the glacier surface must be rising, because of the incompressibility of ice.

Crevasses

Although in general, the Antler Glacier is less crevassed than many other glaciers in this district, several kinds of crevasses were observed (Pl. 23, Fig. 1 and Pl. 27, Fig. 1, 2).

a) Radial crevasses

Near the foot of the ice fall, there were radial crevasses running perpendicular to the ogive structure. These crevasses were wider at the crest of the ogives than at the troughs. In the middle of the glacier, these crevasses merge in broad grooves and curve outward.

b) En echelon crevasses

En echelon crevasses were observed in the boundary region between parts A and C. This type of crevasse may be formed by shear fracture produced by strong differential movement of the two adjacent parts of the glacier.

c) Concentric circular crevasses

Near the terminus of the glacier there were several sets of concentric, circular crevasses.

Ogives

Ogives are sets of concentrically arched glacial structures which are formed directly downstream of an ice fall. They are alternating series of crests and troughs and of broad black and white bands. Generally, the surface pattern is characterized by conforming foliation. Some of the characteristic features of the ogives are given below.

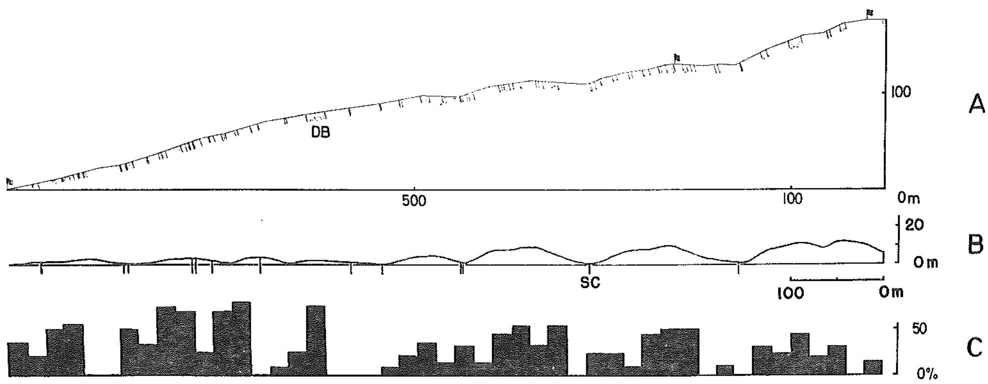

Fig. 5
A) Longitudinal profile down the central flow line of the glacier. Flags indicate locations of stake systems, Y (upper), Z (middle) and U (lower). Shaded portions as was indicated by DB are dirt bands.
B) Ogive waves are magnified by using constant level for troughs.
C) Concentration of dirt bands at 20 m interval.

a) Crests and troughs

There are ten or eleven ice steps and steep ice cliffs which cross the ice fall. In the upper region of the ice fall, the ice steps are fairly straight, but they arch downstream in the lower region. This arched shape is the prototype of the ogive.

In the region of gentler slope, directly below the ice fall, the ice steps change to broad arched banks crossing the glacier (Pl. 24, Fig. 1). These banks, and the lower parts between them, are the crests and troughs which compose the ogives in Part A. The width of one unit of the ogives, or the wave length of the ogives, was approximately 150 m. If the crests are numbered in series, beginning directly below the ice fall, stake lines Y and Z were set on the third and fifth crests of the ogives. The ogive relief is very faint in lower part of A probably because of active ablation.

The longitudinal profile of the glacier surface is illustrated in Fig. 5A. This profile was obtained by taping and angle measurement. Distribution of the dirt bands on the glacier is also shown in this figure. Snow-filled crevasses of which locations are shown by lines denoted SC on Fig. 5B appear at the troughs in the upper part and at the crests in the lower part. Since such snow-filled crevasses were considered to be formed by a separation of ice masses on the ice fall due to the seasonal change of flow velocity, these can be credible indices of period of original ogive waves.

Results of the measurements of wave length and wave height of every individual ogive numbered as above stated are tabulated in Table 4. As are shown in the table and Fig. 5A, B, the major crests often consist of two minor crests separated by a small depression, but, only major crests and troughs are considered as ogive units.

Table 4.

Crest	Width (m)	Height (m)	
		Major	Minor
3	170	10	10
4	160	10	6.5
5	140	10	7.5
6	95	5	
7	105	1	
8	70	2.5	
9	115	3	
10	90	2	

b) Banding

The ogives are characterized by dirt bands which are very clearly visible from the air, but which are less easily identified from the glacier. From the glacier, the dirt bands may be recognized as areas covered with streaks of dirty ice which are 1 to 15 m wide. In the center of the glacier stream, in Part A, there is an area about 100 m wide which is heavily streaked with dirt. The distribution of the streaks is shown in Fig. 5C.

In general, the crests of the ogives are more heavily streaked with dirt than are the troughs, and in the lower part where the superficial ogive relief is indistinct, there are more dark areas than light ones (Pl. 23, Fig. 1, Pl. 27, Fig. 2 and Fig. 5C). In the upper portion, the crests and the dirt bands are in the same phase, but this changes gradually until, in the lower portion, the relation is reversed. This change may be caused by the decreasing relief and by the reversal of the height because of more severe ablation associated with the dirt.

c) Foliation and schistosity

Foliation is a glacial structure of layers of white, bubble-filled, ice alternating with clear bubble-free ice. It has been proven that the mechanism of formation of foliation is the internal shearing produced by glacier flow.

Schistosity is here defined as another, distinctly planar structure, which accompanies foliation. It generally parallels the foliation and occurs as very thin layers of granulated ice grains or aggregations of bubbles which are assumed to be formed by strong, local slip. It is therefore, a substructure of the foliation and is rather distinct over an area which was strongly sheared.

Some differences were found in the textures of the foliations and schistosity in the dirt and white bands. Schistosity is frequently observed along the foliation in dirt bands, but rarely, in white bands. Although the schistosity plane is generally continuous in the glacier ice, parallel to the foliation, it was observed here folded and slightly oblique to the foliation near the boundary between the dirt and white bands (Pl. 28, Fig. 2)

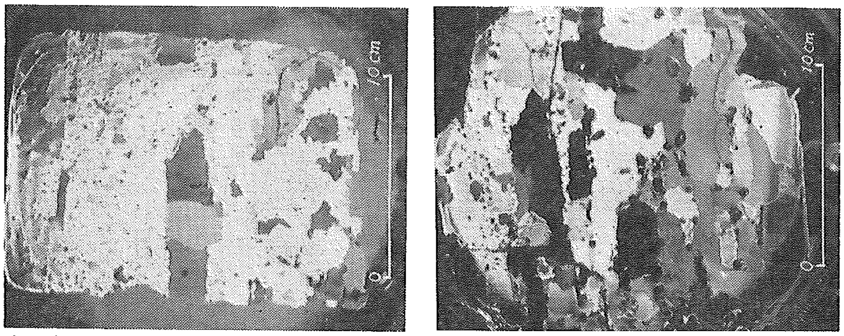

Fig. 6
Texture of dirt band ice
left: sample No. 1, right: sample No. 5.
Note foliations and distinct schistosity. Seams of fine-grained ice aggregate are trace of shearing plane.

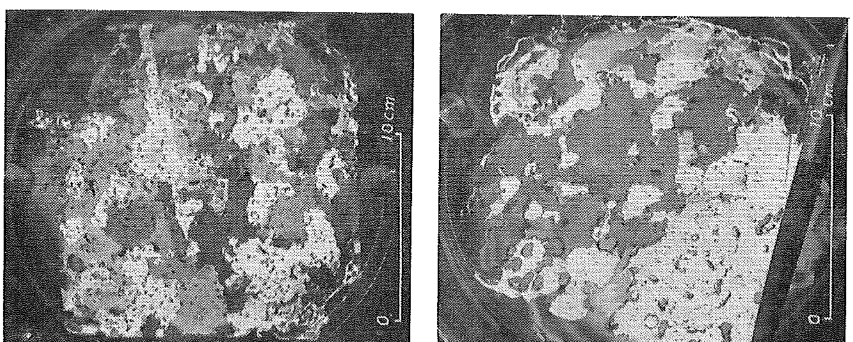

Fig. 7
Typical texture of white band ice
left: sample No. 2, note bubbly ice grains with irregular boundaries.
right: sample No. 2, note ice grains in clear ice band almost free from air bubbles, and interlocking boundaries.

The ice under the dirt bands was primarily composed of clear elongated grains with simple boundaries. The grains were fine (long axis, apprx. 5 cm). On the ice surface, the schistosity planes had been selectively melted by solar radiation. Eventually, these melted areas became narrow, dirt retaining, grooves. This accumulation of dirt in the ice under the dirt bands accelerated the melting of the ice surface in this area. In the white bands, on the other hand, there was no schistosity, and foliation generally consisted of alternating sheets of bubble-filled and clear ice 2 to 10 cm thick with occasional lenticular, bubble-filled layers embeded in the clear ice (Pl. 29, Fig. 1). The grain shapes in the white band ice were extremely complicated and the boundaries were sutured. There was occasional crystal interlocking and poikiloblastic texture indicating that melting was less accerelated in these areas than in these where schistosity was involved.

As is described above, the remarkable difference in the texture of the glacier ice of the white and dirt bands seems to be the reason for the concentration of dirt on the crests of the ogives of the Antler Glacier. Concentration of dirt in most glaciers generally occurs in the troughs of ogives because of the stability of sand particles blown on the ice surface. The present case contradicts the general concept, if there is no particular reason why the ice on the crests should differ in its ability to trap sand particles on the surface. For this reason, the formation of band structures under the ice fall alternating schistosity-poor and rich portions should be clarified. Putting aside the mechanism of formation, the difference in the mode of deformation of these two portions will be described using the general

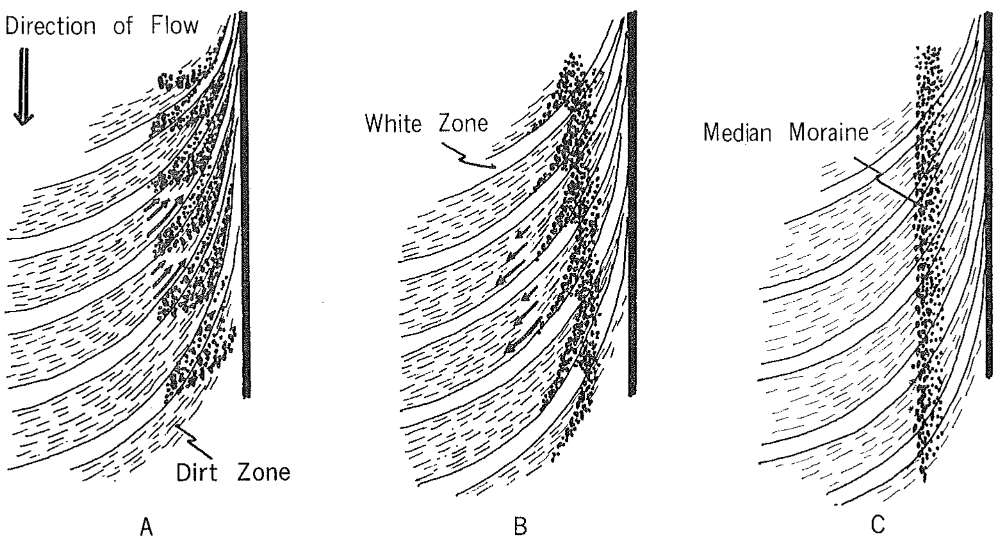

Fig. 8
Deformation of medial moraine.
A) Extensive flow, B: Compressive flow, C: Original state.

features of the glacier flow. The saw-shaped outline of the medial moraine of the glacier indicates inequality of lateral motion along different bands (Pl. 26, Fig. 1).

The mechanisms of formation of the two types of saw-toothed medial moraines shown in Fig. 8, A, B and C may be explained as follows. At first we must consider the behavior, in lateral expansion, of alternating dirt and white bands which contact a stagnant ice mass along a straight boundary of a medial moraine (Fig. 8, C). The glacier ice under the dirt bands is more easily deformable under shearing stress than that of the white bands because of slipping along the schistosity. Therefore, when the glacier is undergoing lateral expansion, there would be more outward expansion of the straight margin of the medial moraine at the dirt bands than at the white bands. If the glacier flow produces lateral extension, the straight outline of the medial moraine becomes irregular, as is shown in Fig. 8A. If the flow is laterally compressive, the straight margin of the medial moraine would be changed to the different saw tooth-shape shown in Fig. 8B. Deformation of the medial moraine in the former manner was observed, in part A, and of the latter type, in the middle of the glacier. They both conform to the stress conditions described above if they are considered with respect to the shape of the valley.

Thrust

Well developed thrusts were observed in the Antler Glacier. Since thrust seemed to us to play an important role in the formation of the alternating bands of the schistose and non schistose under the ice fall, every effort was made to observe the thrust near the ice fall despite the avalanche danger. However, from the results of the observations on a whole area of the glacier, various modes of occurrence of the thrust can be stated as follows.

1) Near the foot of the ice fall, minor thrusts were formed oblique to the general trend of the ogive waves and were accompanied by the formation of the small arches in the foliations. However, the driving force for the formation of these thrusts near the ice fall may be the block motion of ice steps on the ice fall.

2) In part A of the glacier, thrust-like structures were observed along the boundaries of the white and dirt bands. This kind of thrust may be caused by the differential lateral motion which was revealed by the saw-toothed deformation of the medial moraine.

3) A similar type of thrust was observed to develop in part C of the glacier. Some foliation and schistosity was observed on the extension of the ogive line especially along the dirt bands. Alternation of such foliated and foliation-free bands in this area gradually narrowed and eventually tended to thrusts dipping NE with angles as low as 40 to 50°.

4) Another remarkable series of thrusts was observed in the terminus region

of part C at intervals of 20 to 100 m. A heavily schistosed band had been formed on the hanging wall of each thrust. The thrust plane itself appeared as a vein of clear ice (Pl. 25, Fig. 2 and Fig. 3, Pl. 27, Fig. 1).

As was stated in the section on structural subdivisions, there are remarkable discontinuities in the velocity of the glacial flow in parts A, B and C. The mode of deformation of ice in these parts is also very different. Foliation and schistosity are the major mechanisms of deformation in parts A and B, and thrust formation in part C. The difference in mechanisms may be caused by a difference in grain size and ice uniformity.

Ice Petrofabbic Analysis

As has been previously described, a remarkable differential movement of ice was observed along the foliation of the ogives. The direction of shear movement was nearly perpendicular to the general stream line. The principal direction of the flow is along the axis of the ogives and this movement is superimposed. Superimposition of lateral movement on the longitudinal compressive strain in the glacier would result in a complicated stress distribution in the ice. Petrofabric analysis was performed to obtain some information about the stress acting upon the ice at various sites on the glacier.

The samples for fabric analysis were collected in various places in parts A, B and C. The dimension of each ice sample was approximately $25 \times 25 \times 50$ cm. The orientations of each sample and of the foliation were recorded with respect to the surface and geographical direction. Analysis was performed in the cold room laboratory at Hokkaido University, using normal procedures of analysis with a Rigsby stage (Rigsby, 1960 and Kamb, 1959). The poles of the c-axes of the ice crystals were projected on a Schmidt net from the upper hemisphere.

Ice-sample No. 1

This ice was taken from a dirt band zone on the crest of the ogive near the foot of the ice fall, where the concentration of dirt streak was not yet striking. Here, the dirt band was composed of streaks of dirt, most of which had been trapped in narrow grooves left behind by melted schistosities. A thin section of this ice revealed the following characteristics when viewed under crossed polaroids. The disposition of grains of the same extinction orientation was unrelated to the orientation of the foliation or of the schistosity. The long axes of elongated grains were at oblique angles to foliation. The grain boundaries were irregular and complicated, even in the clear ice sheets, and this may indicate that these ice grains are far from equilibrium. The fabric patterns of the clear ice, the bubbly ice, and composite diagrams for both are shown in Fig. 9, A, B and C.

Each diagram in Fig. 9 shows a complicated, polymaximum distritution which is hard to interpret. However, it may be said that the fabric of the bubbly

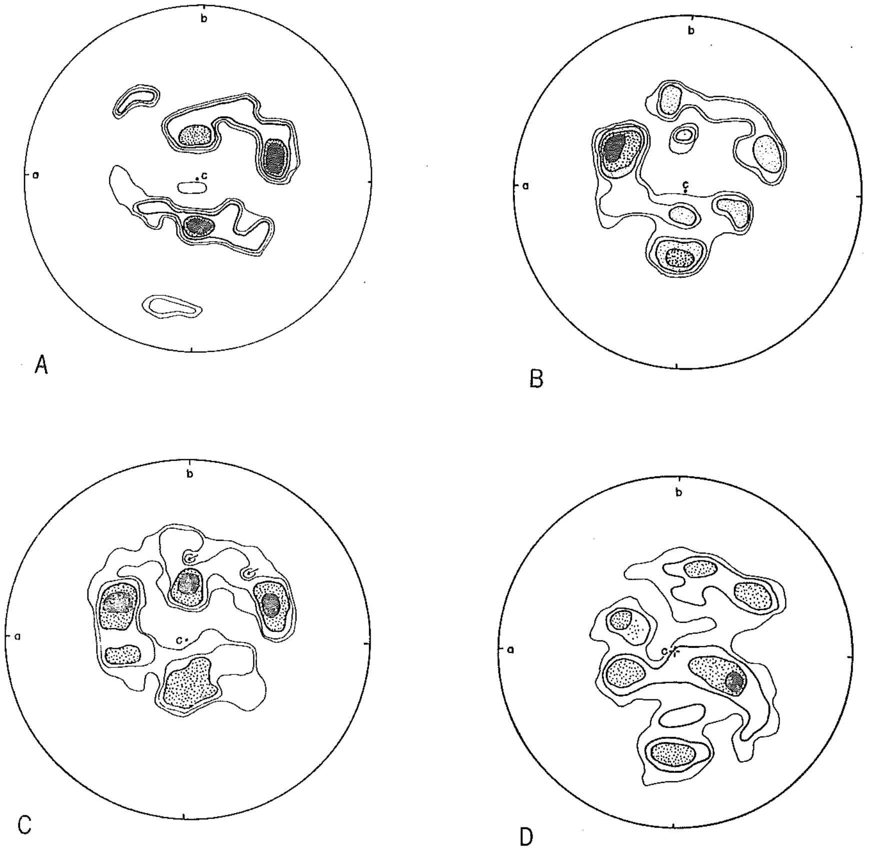

Fig. 9
Fabric diagrams for ice sample No. 1 and 2.
A) Bubbly ice. Contours 15-10-5-3-1%, Max. 21%, 150 grains.
B) The clear ice. Contours 15-10-5-3-1%, Max. 26%, 250 grains.
C) Composite diagram for both of the dirt band ice. Contours 10-5-3-1%, Max. 15%, 400 grains.
D) The diagram for the bubbly ice at white band. Contours 10-5-3-1%, Max. 10.3%, 659 grains.

ice (Fig. 9, A) is that of an earlier phase of glacier ice which would be changed during the process of the development of ogives. The fabric pattern of the bubbly ice may be referred to as a sort of 3 maximum pattern in which two maxima are interconnected. One of the interconnected maxima and one isolated one seem to be on the ac-plane of the projection sphere. Similar characteristics may also be observed in the fabric pattern of the clear ice, although the maxima are in different locations.

Ice-sample No. 2

This ice was taken from a white band adjacent to the dirt band from which sample No. 1 was obtained. It has a layered structure composed of bubbly ice interposed by thin, lenticular layers of clear ice. The grain texture is coarse, 2 to 4 cm in diameter, with very irregular boundaries which interlock with adjacent grains. Occasional poikiloblastic development of large crystals (up to 10 cm in diameter) was observed, especially within non-schistose foliations. Often, the bands of bubbles which make up the foliation are cut by the grain boundaries. Faint delineation of micro-bubbles of an orientation different from that of the foliation is frequently observed, especially in the clear ices.

The fabric pattern of sample No. 2, (as shown in Fig. 9D) is much more complicated than that of sample No. 1. This polymaximum type of the fabric, in conjunction with complicated interlocking of adjacent grains, and the formation of poikiloblasts, suggests that very active recrystallization is taking place in the ice in the white bands.

Ice-sample No. 3

This sample was taken from typical dirt band ice in the middle stream region of part A. Texturally, there is remarkable schistosity and well developed foliation, with parallel arrangement of tabular, clear, ice crystals from 5 to 10 cm long (Pl. 28. Fig. 2). Equigranular grains of clear, tabular ice are disposed along the foliation, however, the grains sometime develop across the schistosity. Small grains, 1 cm in diameter, of the same extinction orientation were also observed, occurring in this region. The fabric pattern of sample No. 3, shown in Fig. 10A, is a typical three maximum type, two of which, seem to be in the ac-plane of the fabric axes in which the direction of motion lies. This characteristic is almost the same as that in sample No. 1, and it may be concluded therefore, that this 3-maximum type appear in relatively stable ice crystals in dirt band zone.

Ice-sample No. 4

This sample was taken from the white band adjacent to the dirt band from which sample No. 3 was taken (Pl. 28, Fig. 1). Though some schistosity and foliation can be recognized, most of the ice grains have irregular boundaries which intersect relict layers of bubbles on the foliation and schistosity. The average diameter of the grains is roughly 3 cm, with some as large as 10 cm.

The fabric pattern of sample No. 4 is apparently a four maximum type, but it probably should be considered a two maximum type, fundamentally the same as the three maxima of samples 1 and 3. The distribution of the poles of the very coarse-grained crystals is scattered, as is shown by the small circle in the diagram (Fig. 10B).

Ice sample No. 5

This sample was taken from dirt band ice in part B, near the terminus of the glacier. It is primarily composed of clear ice with well developed schistosity.

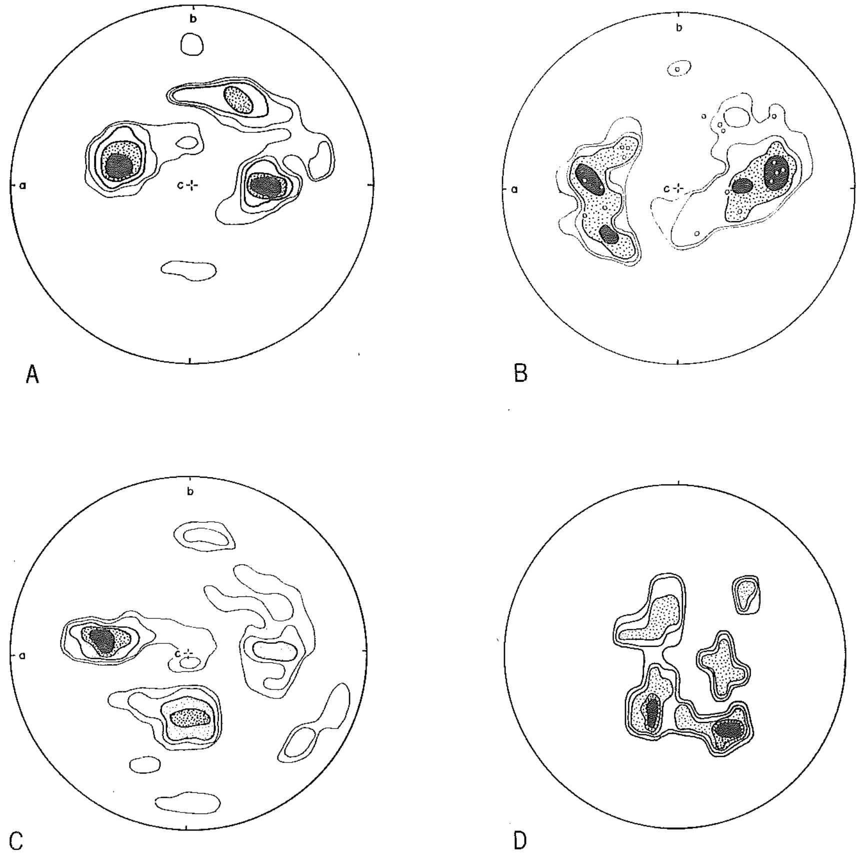

Fig. 10
Fabric diagrams for ice sample No. 3 (A), 4(B), 5(C) and 6(D).
A) Contours 15-10-5-3-1%, Max. 13%, 201 grains.
C) Contours 15-10-5-3-1%, Max. 17%, 221 grains.
D) Contours 15-10-5-3-1%, Max. 18%, 176 grains.

The grains are elongated in tabular shapes, along the schistosity, and there is mosaic structure of fine grained ice among them. Partial sheets of irregular, elongated ice grains, up to 15 cm long, are imposed, parallel to the foliation.

The fabric pattern is primarily a variation of the three maximum type (Fig. 10C), with two maxima on the ac-plane. There is relatively poorer definition of poles than in any other ice from part A. Under crossed polaroids, there is a strain shadow in some grains.

Ice sample No. 6

This sample was taken from stagnant glacier ice in part C. Foliation and schistosity were very rare near the sampling site. The sample is composed of coarse-grained clear ice crystals of uniform size, approximetely 10 cm in diameter (Pl. 29, Fig. 2). The fabric diagram has three maxima pattern with some additional maxima (Fig. 10D). It was difficult to determine the fabric axis because there was no marked structural characteristic, however, the projection plane of the figure could be considered to coincide with the foliation plane in the area.

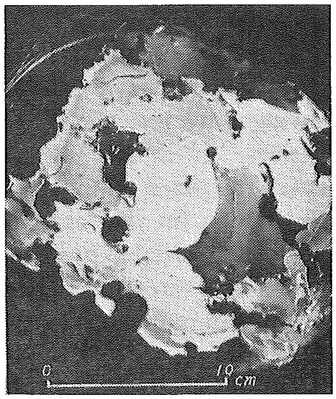

Fig. 11
Thin section photograph of ice sample No. 6 (stagnant ice) under crossed polaroids.

Based upon the polyhedral grain texture shown in Fig. 11, it may be concluded that there was no remaining active deformation of the glacier ice in this region, and that the fabric pattern is simply the result of recrystallization.

Concluding Remarks

Since an earlier study of the formation of ogives was reported by J. D. FORBES, there have been a number of investigations of the subject. F. B. LEIGHTON (1951) proposed the periodical extrusive flow of a glacier at the foot of an ice fall, as an origin of ogives, and R. STREIFF-BECKER (1952) extended the pressure wave theory. J. F. NYE (1959B) gave a simpler explanation of the formation of ogives; a combination of the seasonal change of glacier flow rate at an ice fall and the amount of ablation from the data obtained from Austerdalsbre Glacier by the Cambridge University Expedition. NYE interpreted the mechanism of formation of the crest and the trough of an ogive, but no that of the pattern of arched bands of dirt and white ice. KING and LEWIS (1961) pointed out importance of the dirt-holding property of coarse-grained ice crystals, though they did not use this concept for their interpretation of dirt bands formation. As was stated in P. 245, b), the concentration of dirt on the crests of the upper part of the ogives is a very characteristic feature of the Antler Glacier. This contradicts the general theory about the disposition of dirt on ogives and raises a very important problem.

The fact that the texture of the ice is so very different in the dirt and the white bands in the upper part of the ogives, indicated that the concentration of dirt depends upon the texture of the ice. Since the texture is the cumulative result of the deformation that the ice has undergone, the possibility of a difference in the deformation modes of the ice should be considered. If there is no such difference, the sand particles blown from nunataks and cliffs and originally uniformly deposited, can only be separated in bands by having been washed down to the troughs. This washing-down and/or the blowing down mechanism, has been a generally accepted theory for the dirt bands on ogives. If the dirt bands on the crests are assumed to have been formed by the surface roughness produced by the texture of the glacier ice, there should be some explanation for the formation of such periodic textures in glacier ice. In other words, the surficial expression of the internal structure of the glacier, which is produced by the stress distribution in the ice, plays an important role in the formation of banding in the ogives.

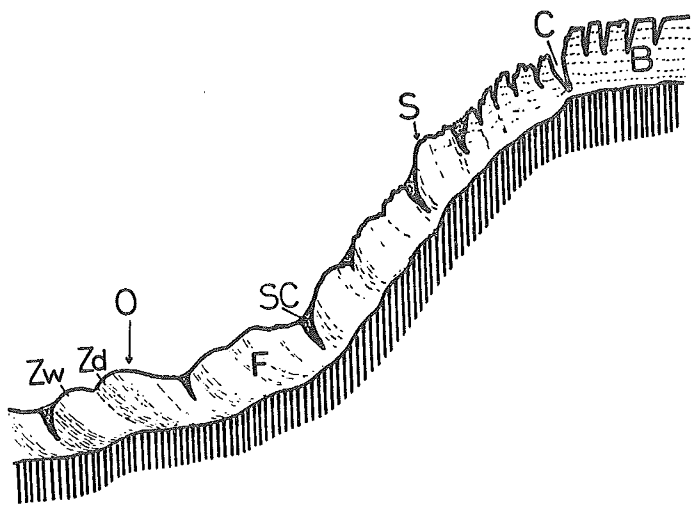

Fig. 12
The Antler ice fall and mode of formation of ogives.
B: Sedimentary bedding, C: Crevasses,
S: Ice steps, SC: Snow-filled crevasse,
F: Foliation and schistosity, ZD: Dirt band,
ZW: White band, O: Ogive crest.

As was stated in P. 245, c), ice which has much schistosity and many foliations can trap more dirt in the grooves formed on its surface than can be trapped by the surface of ice lacking such structures. Schistosity and foliation are both related to the actively deformed zone of glacier ice. Therefore, the question is, why the periodic changes in the deformation activity of ice, in and below an ice fall?

As is well known, glacier flow velocity is greater in summer than winter. Early in the winter, large scale crevasses form at the kink line, just below the outlet of the ice fall, because of the marked difference in velocity above and in the ice fall. A large ice mass, separated from the following ice by a large crevasse, is the origin of an ice step on an ice fall, and of the wavy relief of the glacier surface below the ice fall. In winter these large crevasses are filled with snow or avalanche ice and such snow-filled crevasses act as indices of seasonal boundaries marking the transition from summer to winter. They were so used to confirm the fact that one wave length coincides with the movement of ice in one year. This observation is also supported by the measured longitudinal velocity.

The crests of the each wave, where the ice is largely influenced by stress, coincides with the faces of the individual ice steps or ice masses. If stress distribution in the ice mass is considered, it should occur on the faces because of the relatively large forces pushing the mass through the ice fall. The fact that the minor thrust arches were initiated by separate movements of ice blocks on the faces of ice steps near the foot of ice fall is another proof of the stress concentration on the front face of individual ogive crest.

It is obvious that the mode of glacier flow is extremely compressive at the foot of an ice fall, and this compressive stress results in lateral extension and warping of the ice. Strain measurements taken near the base of the ice fall have proven the existence of both warping and lateral extension. Warping occurs at the area where the stress is concentrated and the thrust is resulted. Lateral expansion also occurs at the same area and foliations and schistosities are formed by lateral shear motion of glacier ice in this area. It may be therefore concluded that the zone of high stress concentration appears to be located periodically on the front faces of ogive crests and that surface structures formed on the zone can cause the dirt bands exist on the crests.

In the middle, or down stream region of the glacier, where the superficial relief of the ogive crests disappeared, thrust-like discordances were occasionally observed along the boundaries between the white and dirt bands. Although no actual thrust motion was observed, the structure may be the trace of that active thrust which occurred when this boundary was just below the ice fall. Broadening of the dirt bands and reversal of the phase relation between the dirt bands and the crests in the lower part of the glacier, may result from surface ablation as has been previously stated. This assumption is supported by the marks of snow-filled crevasses.

Based upon examination of aerophotographs of ogives on other Alaskan Glaciers, the writers feel that ogive formation mechanisms may differ in different glaciers, depending upon such factors as scale, rate of flow and ice fall height.

Further study of ogive formation may require observation of the movement of ice in and below the ice fall for long periods of time and more detailed investigation of the structure of ice and the changes which occur in it.

Acknowledgement

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(Manuscript received September 10, 1965)

PLATE AND EXPLANATION 23

Explanation of Plate 23

Fig. 1. General aerial view of the Antler Glacier.

Plate 23

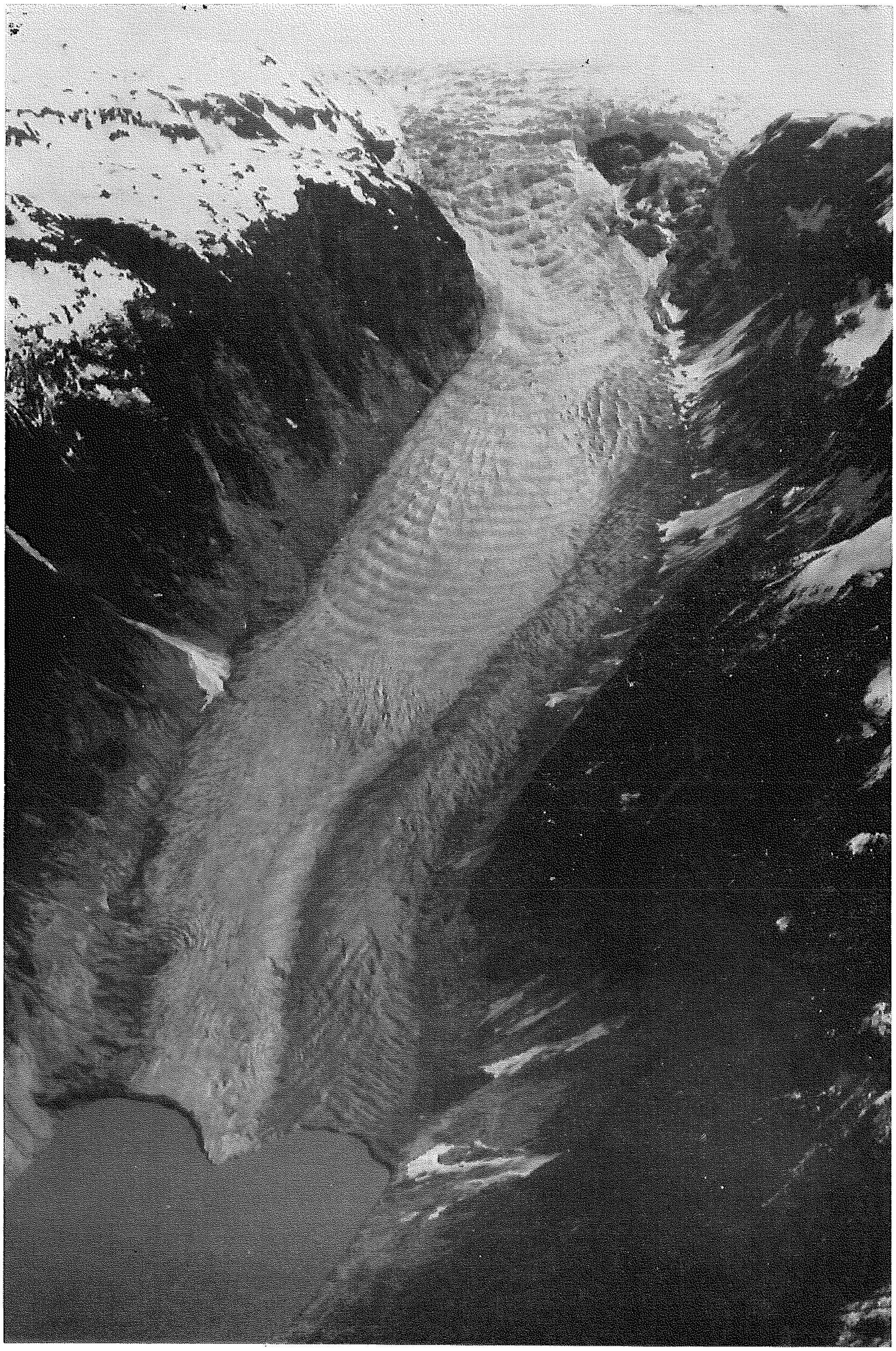


PLATE AND EXPLANATION 24

Explanation of Plate 24

Fig. 1. Ogive structure near foot of the ice fall.
Note lack of dirt band development, upper part A.

Fig. 2. Stake system on line Y, on a crest of ogive, upper part A.

Fig. 3. A minor arch of thrust near foot of the ice fall.
Vertical stripes are foliations.

Plate 24

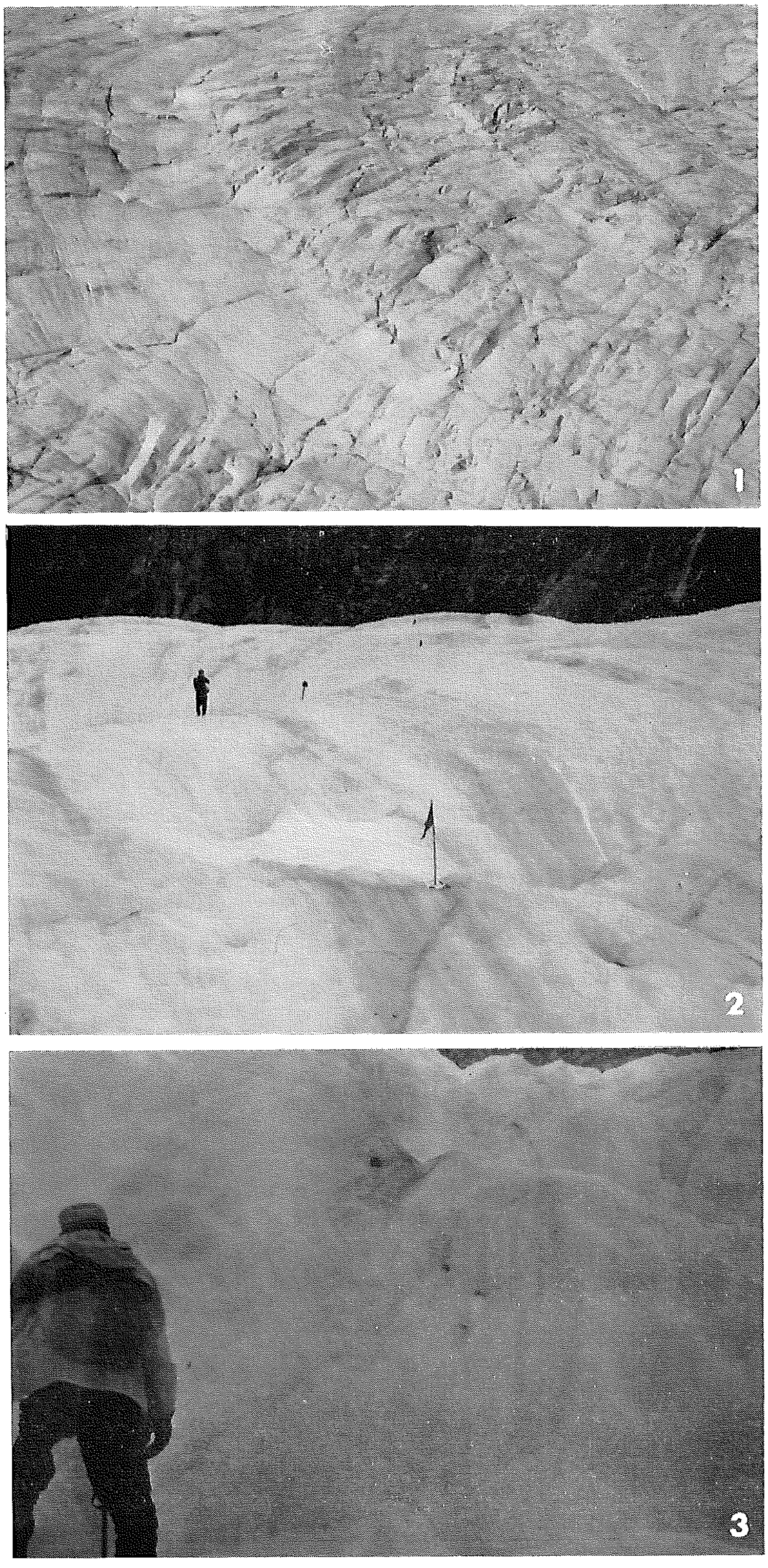


PLATE AND EXPLANATION 25

Explanation of Plate 25

Fig. 1. Glacial structure, part B, near the terminus.
Note coarse-grained ice, with prominent schistosity and foliation.

Fig. 2. Thrust in part C.
Note low angle thrust planes in center accompanying foliation or schistosity.

Fig. 3. Superficial structure, part C.
Note homogeneous, coarse-grained ice and open crack left side, indicating thrust.

Plate 25

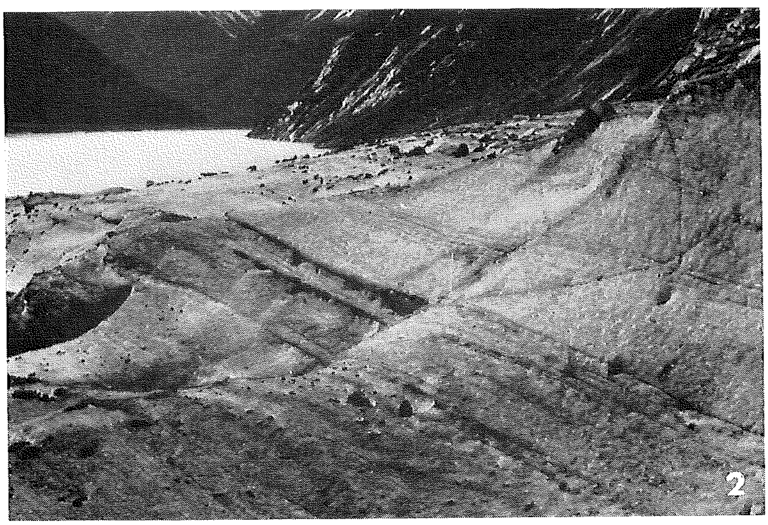


PLATE AND EXPLANATION 26

Explanation of Plate 26

Fig. 1. Saw-toothed deformation of medial moraine.
Note lateral extension of glaciers in upper stream, compression toward axial direction in mid-stream.

Plate 26

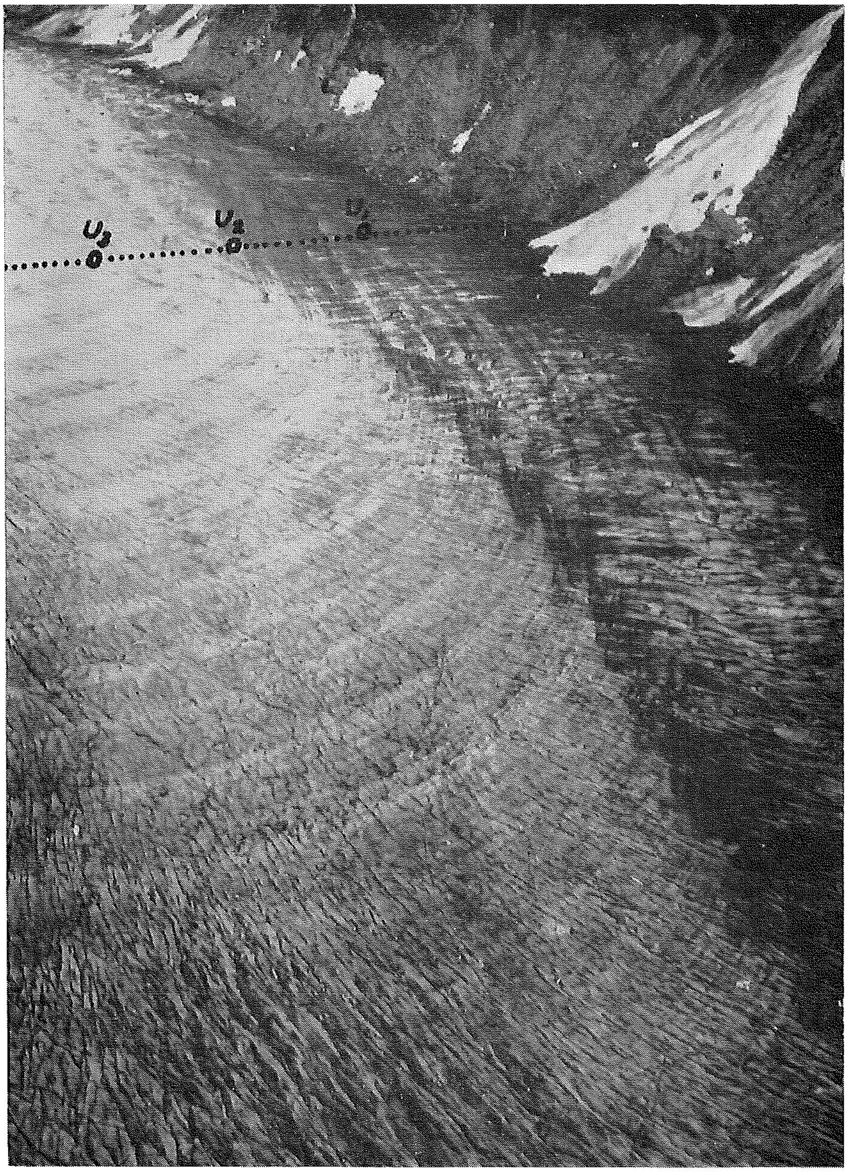


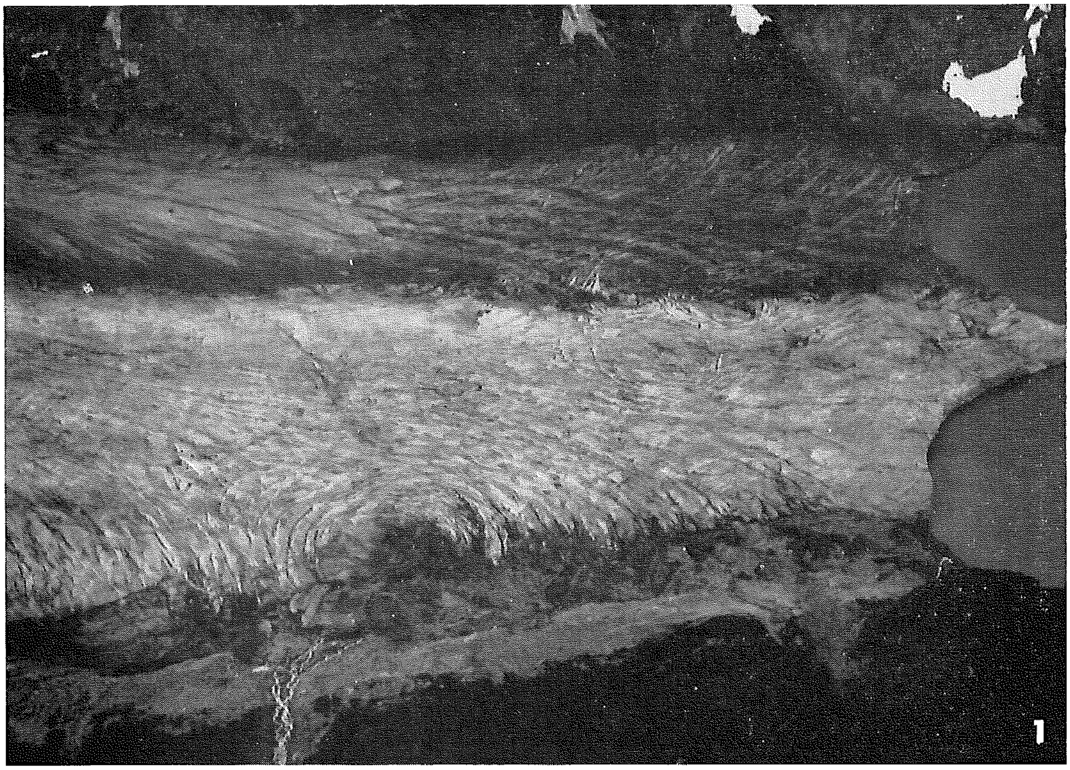
PLATE AND EXPLANATION 27

Explanation of Plate 27

Fig. 1. Terminus of the Antler Glacier.
Note medial moraine on central stream line. Part covered with morainic materials on the opposite side of the medial moraine comprises part C. Note concentric circular crevasses in part B and thrust planes indicated by dark, parallel bands in C.

Fig. 2. Ogive patterns in the mid-glacier region.
Note prominent dirt zones, downstream, A.

Plate 27



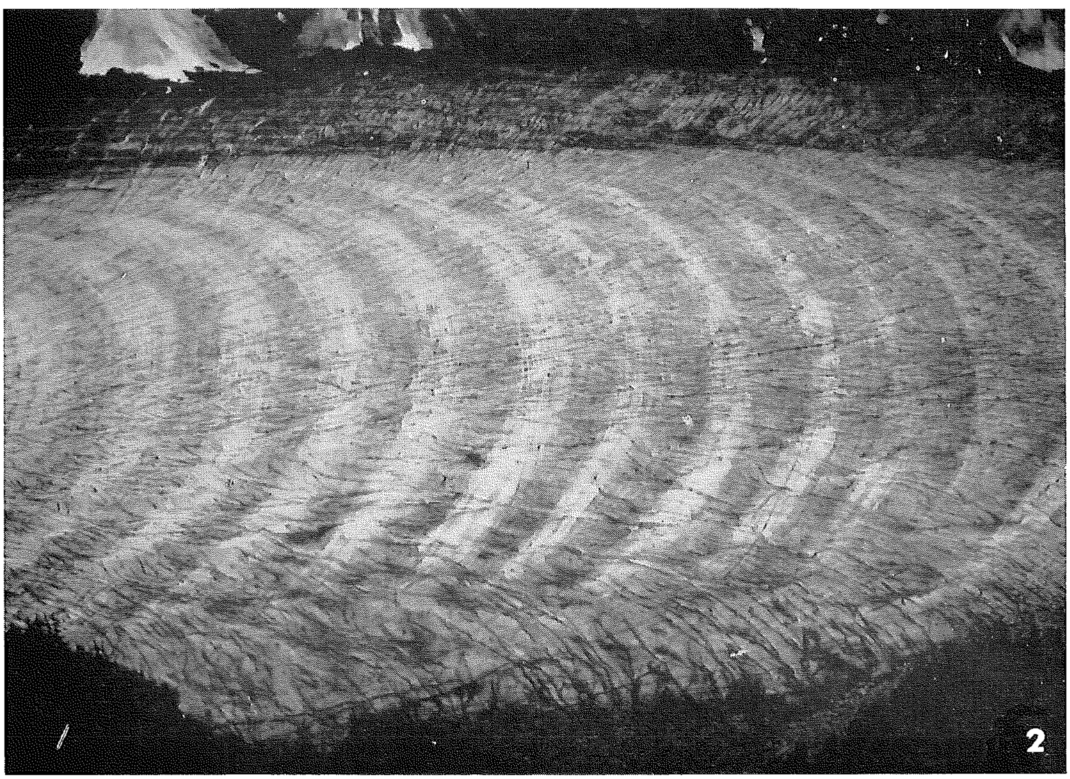


PLATE AND EXPLANATION 28

Explanation of Plate 28

Fig. 1. Superficial features of white ice band, middle stream region, A.
Fig. 2. Dirt band ice, same region as above.

Plate 28

1

2

PLATE AND EXPLANATION 29

Explanation of Plate 29

Fig. 1. Foliations in white band, mid-stream, A.
Note alternation of bubbly ice layers and clear ice.

Fig. 2. Texture of stagnant ice at terminus of part C.
Note polygonal crystal boundaries.

Plate 29