# STUDIES IN GLACIER PHYSICS ON THE PENNY ICE CAP, BAFFIN ISLAND, 1953.

## Part IV: THE FLOW OF HIGHWAY GLACIER

*By* W. H. Ward

Abstract. The horizontal and vertical motions of eight points on the surface of Highway Glacier, Baffin Island are reported. The average horizontal speed below the lowest tributary glacier is 56 metres/year. The major part of this motion arises from the glacier sliding on its bed. The mean shear stress on the bed is practically constant and equal to about 0·9 bars, but it is much smaller beneath the retreating tongue. A measure of the retreat in the lower part of the glacier is obtained from the difference between the ice discharge and the net ablation.

Résumé. Cette communication décrit le mouvement, en direction horizontale et verticale, de huit points situés à la surface du "Highway Glacier" sur l'île de Baffin. La vitesse de déplacement en dessous du dernier glacier tributaire est en moyenne de 56 mètres par an. Ce mouvement est dû en grande partie au glissement du glacier sur son lit. L'effort tranchant moyen à la surface du lit du glacier est pratiquement constant et d'environ 0·9 bars, mais il est beaucoup moindre en dessous de la langue en retrait. La différence entre le débit annuel et la perte annuelle de glace donne une mesure du retrait ou de la perte en volume dans la partie inférieure du glacier.

### Introduction

Highway Glacier (see the view on p. 539, Fig. 1 of Part III of this series of articles) is one of the longest, but is typical of many, of the numerous glaciers that descend into the Pangnirtung Pass; its tongue extends farther into the Pass than any of the other glaciers and it dams a lake (Glacier Lake) at the head of the pass. It has five major tributaries arising from ice caps and several smaller ones: three of the major tributaries join at Concordia Platz, where Camp A3 was situated. At Camp A3, which was perched precariously on a tiny lateral moraine amidst crevasses and beneath a steep rock wall, there were frequent warnings of the liveliness of the ice flow quite early in the melt season and it was obvious that the ice was sliding at the rock wall. These warnings together with the success that H. Röthlisberger was having with seismic sounding of the glacier bed called for measurements of the glacier speed over as long a period as possible and estimates of the shear stress at the bed.

### Surface Speed Observations

Two sets of observations were made, 38 days apart, of the positions of eight points, A,B,C,D and $\alpha,\beta,\gamma,\delta$ on the ice surface of the glacier where it is about 1·7 km. wide and slopes between about 3 degrees and 4 degrees, see Fig. 1 (p. 593). The line $\alpha$–$\delta$ is immediately upstream of snow Stake No. 2 (see Part I of this series of articles, Vol. 2, No. 15, 1954, p. 342 of this *Journal*). Line A–D is about 0·87 km. further upstream and below the lowest tributary glacier. The seismic Cross-section IV (see Part III) lies midway between the lines $\alpha$–$\delta$ and A–D. Fig. 2 (p. 599) is a view across the glacier in mid-August from the rock wall above point A and shews a hanging glacier on the cliffs above point $\delta$. This hanging glacier has contributed only melt water to the main glacier for a long time.

The observation points on the glacier consisted of timber stakes, about 2·5 m. long, which were frozen into tight-fitting drill holes. The stakes were placed vertically and only about 0·3 m. was left exposed above the ice surface on 7 July, the snow having just disappeared. Nails driven into the tops of the stakes served as targets.

The method of survey was designed in collaboration with H. Röthlisberger to meet local conditions. The steep valley walls were almost inaccessible and so the whole survey was made from the glacier surface.

A base line B$\beta$ was first aligned by eye in the general direction of the valley. At B a subtense line, 100 ft. (30 m.) long, was measured with a tape at right angles to B$\beta$ and the angle subtended by the 100 feet line at $\beta$ was measured to 1 second of arc with a Wild T2 theodolite which was used throughout the survey.

The positions of four natural reference points on the valley walls were determined by triangulation from each end of the base line B$\beta$. The reference points were quite inaccessible and small rock joint intersections associated with some outstanding rock feature were selected.* Three reference points are theoretically sufficient, but it is not always possible to select initially three points that are visible from every glacier observation point. The survey was commenced in this case with six reference points, two being discarded in the course of initial observations.

The positions of the remaining glacier observation points A,C,D and $\alpha,\gamma,\delta$ were determined by angle observations and interpolation relative to the four known reference points. Angles between the various glacier points were measured, where visibility permitted, for purposes of checking. The vertical distances between the theodolite, the stake target, and the glacier surface was measured at each observation point.

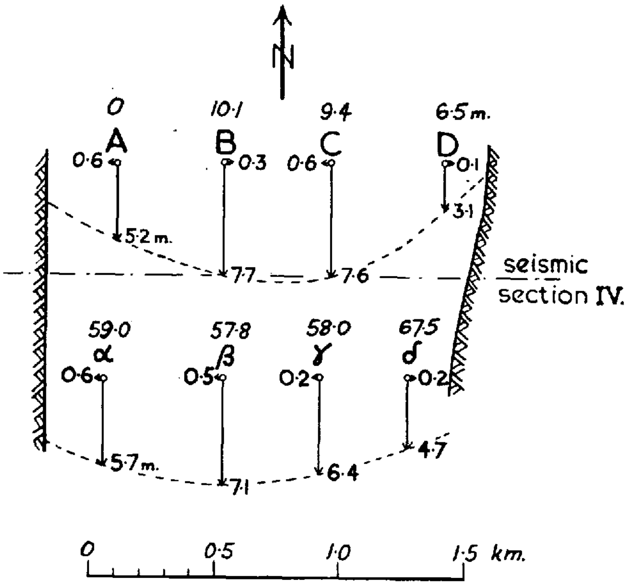

*Fig.* 1. *Plan of glacier shewing horizontal movements (metres) during 38-day period, and the amounts by which the observation points were initially below point A in metres*

A small heap of ice crystals shovelled around each foot of the tripod was found to be sufficient to prevent local melting and movement of the theodolite.

After an interval of 38 days the angles to each natural reference point were measured again from the eight glacier stakes and their new positions calculated by interpolation. The amount of ice ablation was measured.

The horizontal movements of the eight points in metres parallel and at right angles to the general line of the valley (B$\beta$) during the interval of 38 days are given in Fig. 1.† The initial levels of the eight points relative to point A, the highest point, are also given in Fig. 1.

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* It is wise to take special care in selecting a reference point. It should be selected first broadly by eye and then in detail by theodolite and the feature should not be adopted unless this process is capable of easy repetition. Accurate sketches must be made of the view by naked eye and of the theodolite view, so that the point may be recognized at a time when memory has lapsed. When taking observations from the glacier points it is best to move consistently in one direction from point to point so that the appearance of the reference point changes gradually.

† Since the preliminary results were presented to the Rome conference of the Snow and Ice Commission, calculation of the vertical displacements has been made and this has revealed some errors in the calculation of the horizontal positions. These have been corrected.

The vertical motion of the eight points and the ablation at those points during the 38-day period are given in Table 1.

The accuracy of the glacier displacements appears to be within 0·1 m. The chief sources of error are the motion of the glacier during the observations, which was erratic and therefore most noticeable amidst the crevasses at points A and D; and secondly, differences in the atmospheric refraction at the two observation times. The method of survey is simple to use in the field, but the calculations are rather laborious. The survey can be accomplished by one man, though the writer had valuable assistance from B. Bonnlander, who drilled in the stakes.

TABLE I

VERTICAL MOTION (+ UPWARDS, − DOWNWARDS) AND ABLATION OF ICE IN PERIOD OF 38 DAYS

| Point | A | B | C | D | |
|---|---|---|---|---|---|
| Vertical motion | +0·3 | −0·3 | −0·4 | +0·2 | metres |
| Ablation | 1·3 | 1·1 | 1·2 | 1·1 | m. of ice |

| Point | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | |
|---|---|---|---|---|---|
| Vertical motion | +0·0 | −0·3 | −0·0 | +0·1 | metres |
| Ablation | 1·0 | 1·2 | 1·0 | 1·2 | m. of ice |

Some details of the glacier surface features and of the rock valley in the vicinity of the movement survey are given in Fig. 3 (p. 595). Most of the moraines consist of narrow trails of single stones. By following these trails to their sources it was possible to divide the glacier into longitudinal zones labelled *a*, *b*, *c*, *d*, *e*, *f* and *g* according to the tributaries. It will be noted that tributary *c* is the main source and a comparison of the displacements in Fig. 1 does not suggest any discontinuity in the flow between adjacent zones. Moraine *m* (see Figs. 2 and 3) is unusual and will be mentioned again later. It is contained between the lateral moraines of tributary *b* and it starts and finishes abruptly in the direction of flow. Evidently it is the elongated remains of an exceptional rockfall from the impressive vertical cliff at the junction of tributary *b* and the main glacier.

The crevasse directions are shown in plan on Fig. 3. Except near $\gamma$, all the crevasses are limited in extent to the outer zones of the glacier and this is generally true of the main glacier. The widest crevasses are at A and D (up to 3 m. wide); just downstream of these points, where the surface profile changes from convex to concave upwards, they close up (see Fig. 3). At $\gamma$ are crevasses of quite a different character. They were forming during the late summer. In August their width was only about 2 cm. and the downstream edges were about 10 cm. *above* the upstream edges.

The horizontal displacements in Fig. 1 show that the glacier is stretching longitudinally at the margins and compressing longitudinally at the centre. At the suggestion of J. F. Nye the principle strain rate directions in the plane of the glacier surface have been determined by interpolation from those displacements. The strain rate directions normal to the principal tensile stresses[1] are generally in good agreement with the measured directions of the tensile crevasses.

## THE SHEAR STRESS AT THE GLACIER BED

The average slope of the ice surface between the eight observation points is 0·0617 radians and the mean bed shear stress $\tau$ may be estimated from the equation:[2]

$$\tau = \rho g R \alpha$$

where $\rho$ is the ice density (0·91 gm./cm.$^3$)
$g$ is the gravitational acceleration
$R$ is the ratio of area/bed perimeter of the glacier cross-section
$\alpha$ is the mean slope of the glacier surface.

The result is $\tau$=0·92 bars, a value in the midst of the range of values calculated by Nye[3] for a number of alpine glaciers, but a high value compared to most of the values Orvig[4] found for the cold Barnes Ice Cap.

From the data given in Part III (see p. 539 of this *Journal*) the mean shear stress at the glacier bed may be calculated for a number of other cross-sections. The relevant data and the results are summarized in Table II in order of decreasing altitude of the sections.

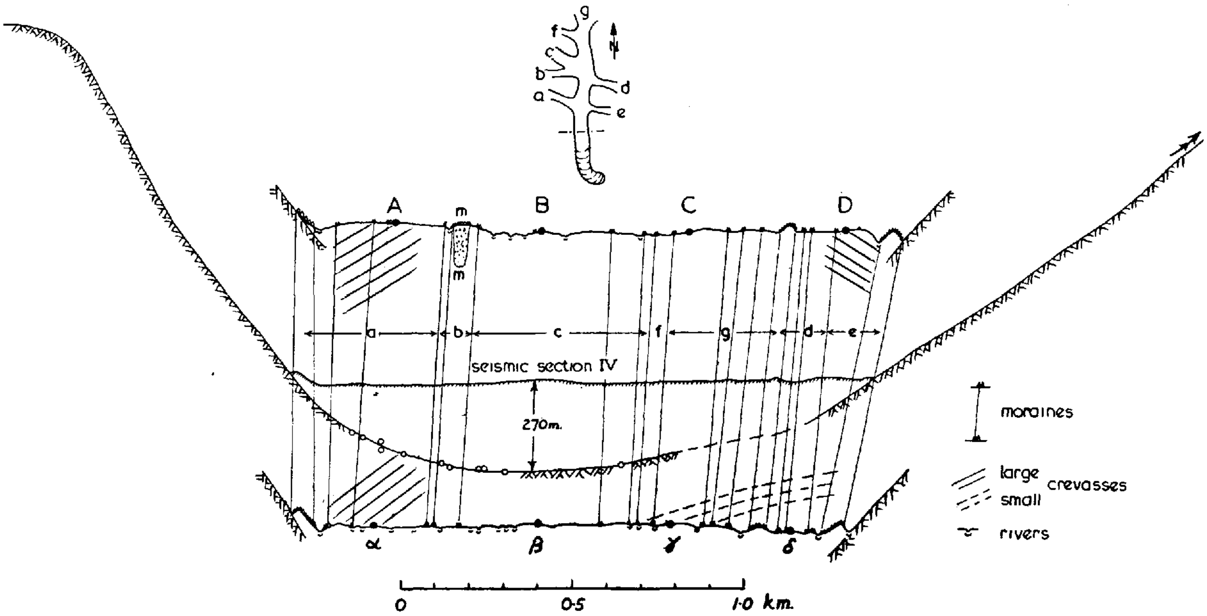

*Fig. 3. Composite drawing giving positions of medial moraines, rivers, relief, crevasses, division of glacier according to tributaries and bedrock profile in the vicinity of the movement survey. The crevasses at A, D, α and δ are shown in plan*

TABLE II

CALCULATED VALUES OF THE MEAN SHEAR STRESS AT THE GLACIER BED

| *Seismic Section* | *Altitude of ice surface m.* | *Section area* $x10^4 m.^2$ | *Bed perimeter m.* | *R m.* | *Maximum ice Thickness* (D) *m.* | $\frac{R}{D}$ | *Local ice slope* ($\beta$) *rads.* | $\tau$ *bars* |
|---|---|---|---|---|---|---|---|---|
| II | 960 | 49·5 | 2020 | 245 | 410 | 0·60 | 0·0419 | 0·91 |
| — | 890 | 52 | 2100 | 250 | 356 | 0·70 | 0·0384 | ~0·86 |
| IV | 760 | 29·9 | 1790 | 167 | 270 | 0·62 | 0·0617 | 0·92 |
| V | 560 | 20 | 1700 | 118 | 150 | 0·79 | 0·0872 | ~0·92 |
| — | 400 | — | — | 104<br>144 | 130<br>180 | 0·8 | 0·0454 | ~0·42<br>~0·58 |

The values of $\tau$ at altitudes of 890, 560, and 100 m. are based on cross-sections determined by only 1 or 2 seismic soundings. Except at 400 m., the values of $\tau$ vary very little and the general uniformity of the surface features of the glacier between 960 and 560 m. is in agreement with this result. The bed shear stress remains practically constant despite the entry of tributary glaciers.

However at 400 m. the glacier changes; it turns a corner and assumes the character of a retreating tongue. The medial moraines are no longer trails of single stones, they widen and become thicker, and evidently the glacier is slowing down rapidly. Wide lateral moraines cover dead ice on both sides and, in the absence of detailed movement observations, the width of the moving ice is unknown.

In order to obtain some estimate of $\tau$ at 400 m., $R/D$ is assumed to be 0·8 and the depths to rock and to the basal layer are used. The resulting values of $\tau$ (see Table II) are much less than higher up the glacier, and it does not seem possible for $\tau$ to be larger than about 0·5 anywhere in the region of the tongue.

Nye[2] obtained a similar result in his analysis of the Unteraar Glacier. He assumed a constant shear stress on the bed throughout the glacier and obtained a greater thickness of ice at the tongue than existed.

Nye has pointed out to the writer that the mean longitudinal stress between the two transverse lines of Fig. 1 is of the same order as the mean bed shear stress. The mean longitudinal compressive strain rate in the central zone of the glacier is about $1{\cdot}0 \times 10^{-2}$ years$^{-1}$ and the mean longitudinal tensile strain rate at the margins is $1{\cdot}2 \times 10^{-2}$ years$^{-1}$. These values correspond, on the basis of Glen's equation (see below), to longitudinal compressive and tensile stresses of 0·89 and 0·93 bars respectively.

## Estimation of the Ice Flow and comparison with Surface Speed

The flow within the ice at the site of the glacier speed measurements may be estimated approximately from the results of laboratory creep tests on compression specimens of polycrystalline ice reported by Glen[5]. The rate of strain depends on the temperature, and the vertical distribution of temperature is not known in Highway Glacier. Observations near the glacier surface shewed that the steady temperatures of the ice were about −5·5 and −6·0° C. at elevations of 440 and 1010 m. respectively. The temperature at the rock-bed is likely to be below the ice melting point because no water issued from beneath the tongue. In fact all the melt water flowed on or near the glacier surface and two eskers about 1 km. long existed on the surface of the tongue.

Glen expressed the results of his ice tests in the form $\dot{\epsilon}=B\sigma^n$, where a uniaxial compression stress $\sigma$ bars produces a compressive strain rate $\dot{\epsilon}$ years$^{-1}$. The value of $n$ is about 3·3 and $B$ depends on the temperature with values of about 0·02 and 0·01 years$^{-1}$bars$^{-3\cdot 3}$ at −1·5 and −6·7° C. respectively. Hence for Highway Glacier a value of $B$ equal to 0·015 seems to be reasonable. In terms of simple shear the above relation becomes[6]:

$$\dot{\gamma}=\sqrt{3}\sqrt{3}^{3\cdot 3}B\tau^{3\cdot 3}$$

$$\text{or}\qquad \dot{\gamma}=0{\cdot}16\tau^{3\cdot 3},$$

where a general shear stress $\tau$ bars produces a shear strain rate of $\dot{\gamma}$ years$^{-1}$.

Integration of the above equation over the depth ($D$ metres) of the glacier leads[1] to the following expression for the surface speed of the glacier ($u_0$ metres/year) due to distortion of the ice alone:

$$u_0=0{\cdot}037\tau^{3\cdot 3}D.$$

The calculated values of $u_0$ at the glacier sections considered in Table II are given in Table III below.

Table III

Calculated Values of the Central Glacier Speed Due to Distortion Within the Ice

| *Altitude* *m.* | D *m.* | $\tau$ *bars* | *Speed* $u_0$ *m./year* |
|---|---|---|---|
| 960 | 410 | 0·9 | 11 |
| 890 | 356 | | 9 |
| 760 | 270 | | 7 |
| 560 | 150 | | 4 |
| 400 | 130 | 0·42 | 0·3 |
| | 180 | 0·58 | 0·1 |

One may question whether the speeds measured at Section IV (altitude 760 m.) over a period of 38 days are representative of the average speeds over a longer period. In July 1948, almost exactly 5 years before the present survey was made, the Royal Canadian Air Force took an oblique aerial photograph pointing due west and with its principal point very close to observation point A, see Fig. 2. By a fortunate coincidence the unusual moraine *m* lies between the points A and B. The protection afforded to the ice by this moraine is such that it is expected to move at the same speed as the underlying ice. The change in the position of the lower end of moraine *m* between 1948 and 1953 was easily measured on the ground relative to features on the west rock wall of the valley that were recognized in the aerial photograph. The moraine had moved about 300 m. or at an average speed of 60 m./year. This value compares well with the equivalent annual speeds of 50 and 74 m./year measured at points A and B respectively that lie on either side of the moraine. Hence the 38-day speed measurements appear to be representative of long-period values.

The maximum measured surface speed is about 74 m./year and the average horizontal surface speeds at both lines A–D and $\alpha$–$\delta$ (see Fig. 1) are about 56 m./year. These values are considerably greater than the calculated speeds due to displacements within the ice and it is concluded that the major contribution to flow of the glacier arises from sliding at its bed. This was the result found by Nye[1] for some temperate glaciers. Extrapolations of the measured surface speeds to the valley walls (see Fig. 1) also suggest sliding at those points, except possibly at the edge near point D.

It is not known what determines the velocity with which a glacier slides at its bed, but the evidence suggests that it is a vital problem in glacier physics and one in urgent need of attention. It seems possible from the meagre evidence at present available that a glacier only slides at its bed when $\tau$ (at the bed) approaches 1 bar and that the actual bed velocity is determined, in a steady glacier, by the ablation. In this condition the differential motion within the ice is of little importance to the glacier regime.

## Local Vertical Movements of the Surface

The differential vertical movements across the two transverse lines A–D and $\alpha$–$\delta$ appear to follow a pattern and require comment. If the glacier flow is laminar the surface would fall at least as fast as the bed slope, but there is a definite tendency for the ice to rise near the edges of the glacier. This observation is confirmed by the slightly concave upwards shape of the transverse profiles, see Fig. 3. The greatest upward speeds are at A and D where the crevasses are widest, but this observation does not necessarily conflict with current views[7] on the motion of crevasses.* The ice flow is presumably not entirely laminar. Perhaps there is a circulation of ice downwards at the centre of the glacier cross-section and upwards at the margins.

## The Retreat of the Glacier

The annual discharge of ice through Section IV at the site of the speed measurements is disposed of by melting and evaporation from the surface of the moving glacier below that section together with an increase or decrease in the volume of the moving ice. The budget of the lower part of the glacier may be estimated on this basis.

The total surface area of the glacier exposed to ablation below Section IV is about $11 \times 10^6$ m.$^2$. The areas thickly covered with moraine are excluded as their contribution to ablation is negligible. The annual loss of water from the glacier surface for the 1953 season was found to be 2·22 m. and 1·06 m. at elevations of 440 and 750 m. respectively (see Part I of this series of articles). Therefore the average loss of ice thickness from the glacier below Section IV is about 1·8 m., and the annual volume of ice lost by ablation is $1{\cdot}8 \times 11 \times 10^6$ or about $20 \times 10^6$ m.$^3$.

On the other hand the annual discharge of ice through Section IV cannot be more than the

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* The maximum tensile strain rate at the surface is about $5 \times 10^{-2}$ years$^{-1}$ and the crevasse depth on the basis of Nye's recent equation is 18 m. The depths were not measured, but the result is not unreasonable.

product of the annual surface speed and the cross-sectional area, that is $56 \times 29{\cdot}9 \times 10^4$ or about $17 \times 10^6$ m.$^3$.

The difference between the above volumes indicates that the glacier is retreating, and probably that the area of moving ice is less than the total area exposed to ablation. In fact the discharge of ice is balanced by ablation from an area that extends only as far as an elevation of about 400 m. It is at this elevation that the bed shear stress becomes small, see Table II, and that is probably the limit of the glacier motion at its bed. Just above this level and rather below Section V, where $\tau$ is still about 0·9 bars, overthrusting and a series of thin curved bands (visible only in an aerial photograph) commence. Therefore it is reasonable to suggest that the sliding at the bed is finally transferred through the ice in the form of a series of overthrusts. However this is a suggestion requiring further study and observation in much greater detail.

### ACKNOWLEDGEMENTS

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# FRANZ JOSEF GLACIER, NEW ZEALAND
## SPEED OF FLOW

From information given by Mr. H. Ayres, a local guide, Professor N. E. Odell has sent details of the movement of an aircraft which crashed on this glacier in March 1950 at a point opposite Hende Ridge. Between that date and January 1955 the wreck had travelled to a point opposite Lemmer Peak, a distance of approximately two miles, which is roughly equivalent to 5 to 6 ft. (1·52–1·83 m.) per day.

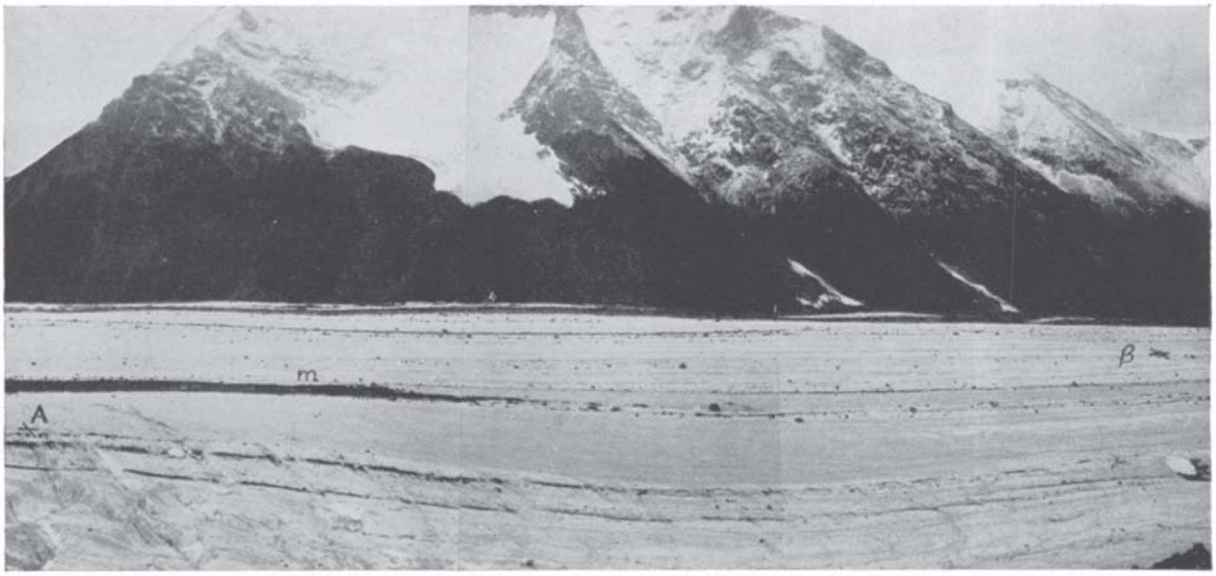

*Fig. 2. View across Highway Glacier from the west wall above point A, shewing the small medial moraines and the unusual moraine* m *(See pages 592 and 597)*

*Fig. 1. Aerial view of Ruapehu crater lake at commencement of eruption, March 1945; note emerging and steaming lava plug (See page 602)*

*R.N.Z.A.F. photograph*

*Fig. 2. Ice cave at tunnel entrance and outlet of Ruapehu crater lake from the Pyramid; note old water level (dotted line) about 26 ft. (8 m.) above present water surface and 50 ft. (15 m.) dam of ice and ash (mainly fallen material)*

*Photograph by L. O. Krenek*

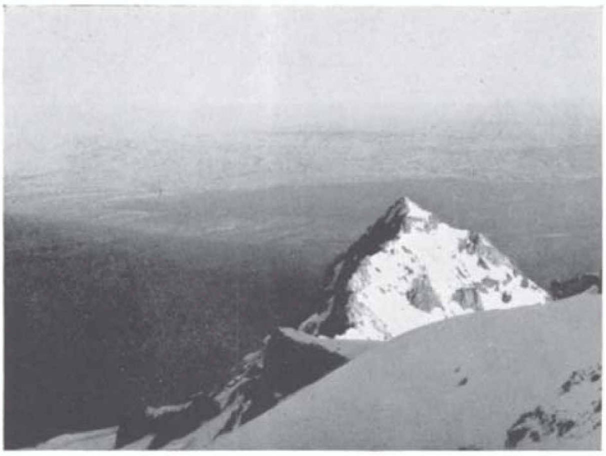

*Fig. 3. Looking due south from the top of Tahurangi (Ruapehu): Whangaehu River (which flooded) in shadow on left: Tangiwai lies between the top left-hand corner and Girdlestone Peak (8760 ft. 2670 m.) in foreground*

*Fig. 4. Whakapapa Glacier, Ruapehu, lower portion, taken at about 7000 ft. (2130 m.)*

*Fig. 5. Ruapehu crater lake with Tahurangi in background (highest point): at lake level directly below it is the ice tunnel outlet. Taken from the Dome in late afternoon 13 May, 1954*

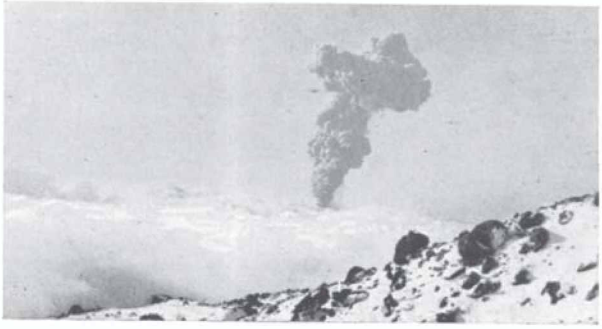

*Fig. 6. Ngaurohoe in eruption (13 May, 1954) from the Upper Whakapapa Glacier*

*Photographs Figs. 3–6 by N. E. Odell*

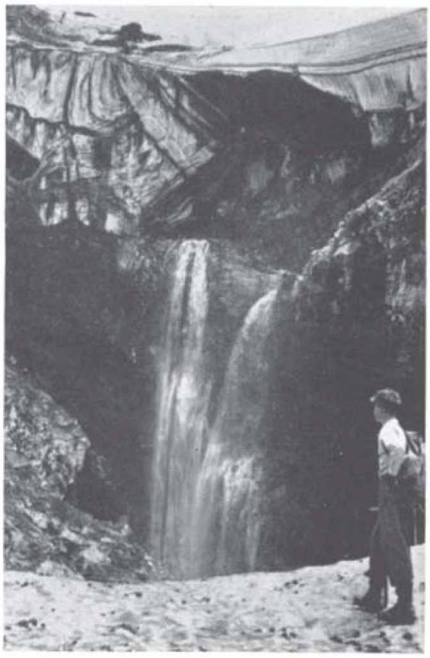

*Fig. 7. Tunnel outlet of drainage from crater lake into chasm, head of Whangaehu Glacier*

*Photograph by L. O. Krenek*