

ZONATION IN THE ACCUMULATION AREA OF THE GLACIERS OF AXEL HEIBERG ISLAND, N.W.T., CANADA

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ABSTRACT. Mass budget studies on the glaciers of Axel Heiberg Island, Canadian Arctic Archipelago, during the summers of 1959–61, resulted in recognition of five distinct zones in the accumulation area. The 1961 data from these zones of the main glacier investigated are presented. The implication is made that the long-term changes in size, elevation and net accumulation of these zones can be utilized as climatic indicators.

RÉSUMÉ. Une étude de bilan de masse des glaciers d'île Axel Heiberg, faite durant les étés de 1959–61, a donné pour résultat la découverte de cinq zones d'accumulation distinctes. Les données de l'année 1961 pour ces zones du glacier White sont présentées. Il est proposé que les changements d'une année à l'autre, concernant les dimensions, l'altitude et le bilan d'accumulation de ces zones soient utilisées comme des indications climatiques.

ZUSAMMENFASSUNG. Massenbilanzstudien an Gletschern der Axel Heiberg Insel in der Kanadischen Arktis führten zur Unterscheidung von fünf Akkumulationszonen. Die 1961er Zahlenwerte für die Zonen des White Gletschers werden vorgelegt. Es wird darauf hingewiesen, dass das Mass der jährlichen Veränderungen der Fläche, der Höhe über Meer und der Netto-Akkumulation der verschiedenen Zonen als Klimaanzeiger dienen kann.

INTRODUCTION

The Jacobsen-McGill University Arctic Research Expedition has worked for three consecutive summers on the glaciers of the central part of western Axel Heiberg Island (lat. 79°–80° N., long. 89°–92° W.). During July and August 1959 a reconnaissance was made and preliminary work initiated. Large parties carried out a detailed and comprehensive programme in the area from early May to the beginning of September in 1960 and in 1961. Glaciers in other parts of the Queen Elizabeth Islands (Fig. 1) were also visited.

THE GLACIOLOGICAL PROGRAMME APPERTAINING TO THE PROBLEM OF ZONATION

A detailed mass balance study was made of one typical glacier, the White Glacier; for comparison, measurements were taken to obtain approximate mass balance figures for the Akaioa Ice Cap and one of its major outlet glaciers, the Thompson Glacier, as well as for a small remnant glacier, the Baby Glacier (Fig. 2).

It was decided to concentrate the glaciological studies on the White Glacier in the belief that it combines most of the features regarded as typical of the glaciers in the Queen Elizabeth Islands. It is of medium size and has a well defined accumulation basin clearly separated from the Akaioa Ice Cap and surrounded by mountains reaching up to about 1,800 m. This alpine-type valley glacier running north-south measures 14.5 km. in length, and has a width of 5 km. in the accumulation basin and 1 km. in the ablation zone. The gently sloping tongue, ending at an elevation of 65 m. a.s.l., just reaches the main valley and is 10 km. from the head of Expedition Fiord. In the region of their tongues, the White and Thompson glaciers meet but do not coalesce. The surface gradient of the White Glacier averages 10 per cent. The longitudinal profile shows three gentle steps in the accumulation area and four minor drops in the ablation zone.

For the mass balance study a total of 218 stakes was inserted in the White Glacier. In the accumulation area, to verify the measurements on the stakes, some 40 snow pits were dug at the beginning of the season and re-excavated in the middle and at the end of the summer, i.e. at the end of the budget year.

Ice temperatures, measured to a depth of 30 m. in the ablation and accumulation areas (Müller, 1961, p. 87 et seq.; Hattersley-Smith, 1960, p. 5), show that the glaciers of the Queen Elizabeth Islands are of Ahlmann's polar type. On Axel Heiberg Island, however, surface

melting occurs at the height of the summer even on the upper parts of the ice caps, therefore placing these glaciers in the sub-polar division in spite of their high latitude.

THE ZONES OF THE ACCUMULATION AREA

There is considerably more difficulty in accurately assessing the amount of accumulation than of ablation. This is partly because the accumulation area of most glaciers consists of various zones, each of which requires individual treatment in the mass budget (Fig. 3).

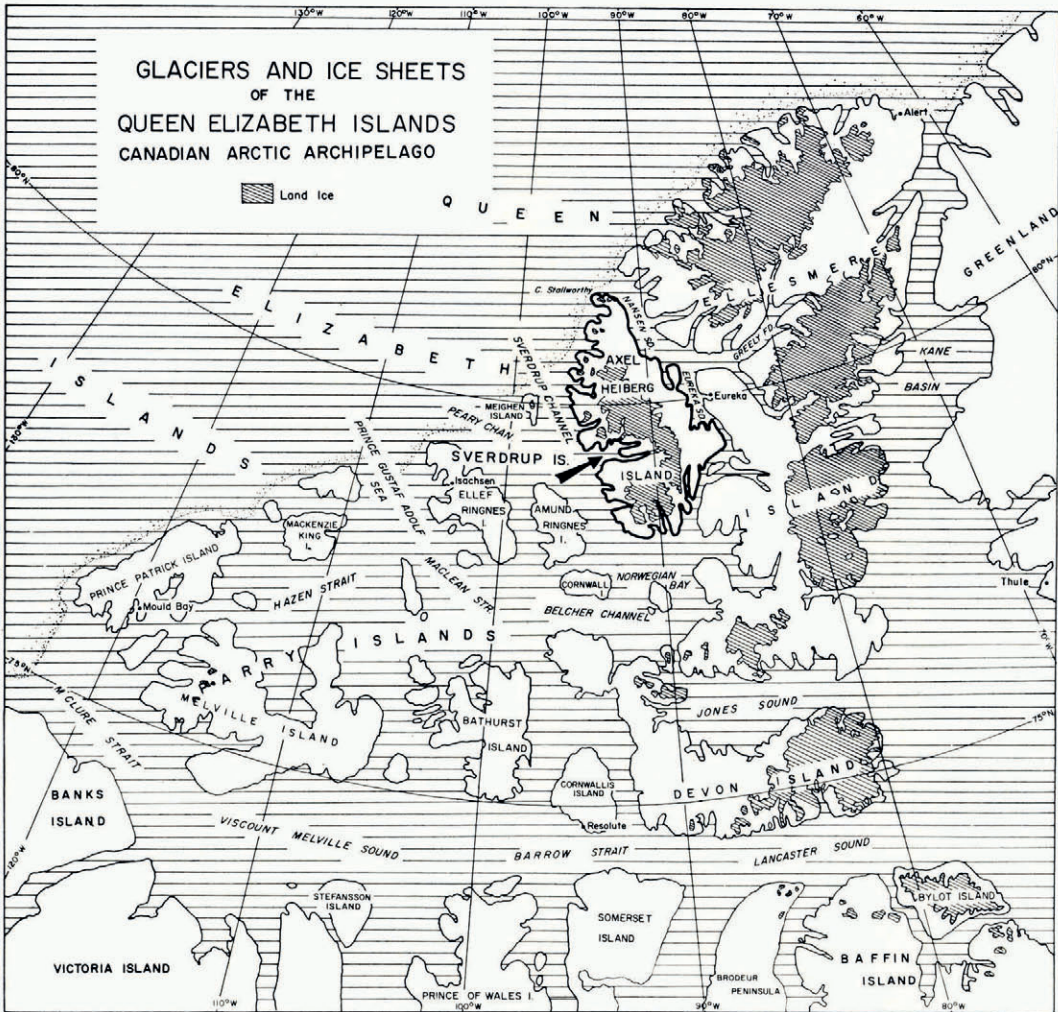


Fig. 1. Location map

As others have already noted, the annual snow line, sometimes erroneously called "firn limit" or "firn line", is often not identical with the equilibrium line which separates areas of net ablation and net accumulation. The zone of net accumulation by superimposed ice, which is situated between the annual snow line and the equilibrium line, was of considerable size in each of the three years the Axel Heiberg glaciers were studied. Many of the lowland ice

masses, even one of the most northerly on the island, have no net gain of snow and firn. In fact, for all those glaciers which do not reach higher than 900 to 1,100 m. a.s.l., net increment by superimposed ice is the only method of nourishment.

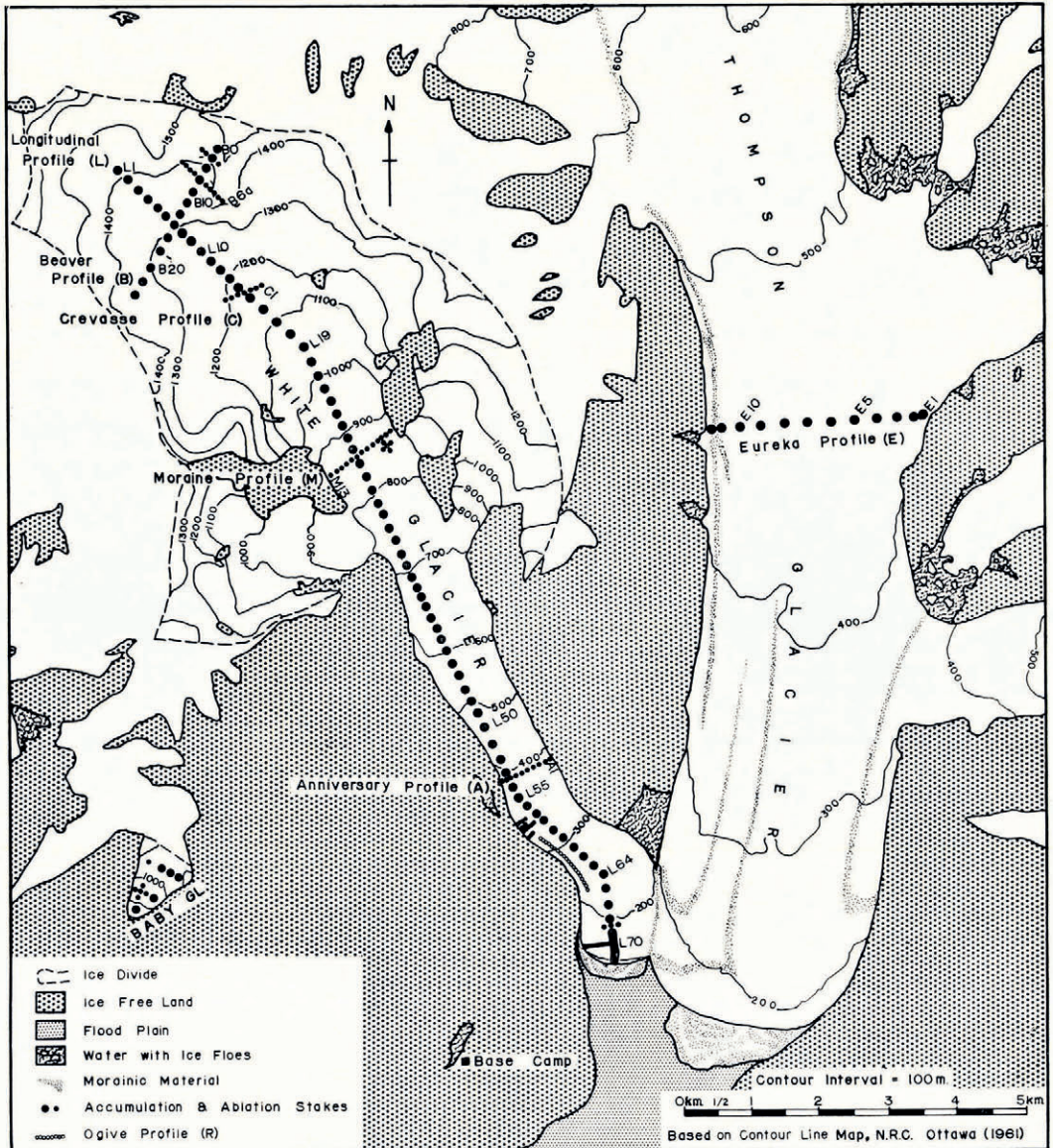


Fig. 2. Pattern of stakes in southern part of expedition area, Axel Heiberg Island, N.W.T.

In delimiting the higher zones of the accumulation area, Benson's cross-section of the diagenetic facies in the annual layer of snow on the Greenland Ice Sheet was very useful (Benson, 1959, p. 20 et seq.). It was, however, necessary to subdivide his soaked facies into a slush zone and a percolation zone B, the two being separated by a line for which the name slush limit is suggested (cf. *Abflussgrenze* in Kasser, 1959, p. 4). The slush zone loses some of its

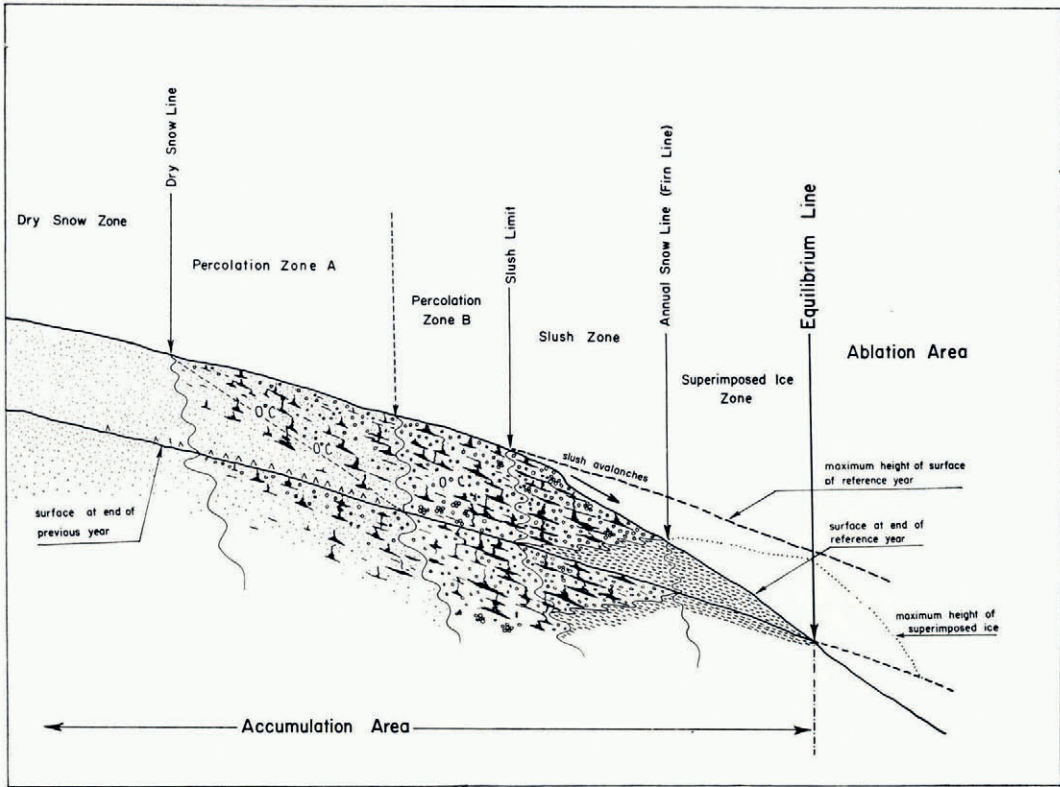


Fig. 3. Schematic zonation of the accumulation area



Fig. 4. Typical slush avalanche in the lower part of the accumulation area of the White Glacier, 20 August 1960. Photograph by F. Müller

yearly increment by run-off. Very frequently this loss of material occurs as slush avalanches (Fig. 4). Ice layers within or often at the bottom of the snow-cover of the reference year form an impervious layer (cf. Fig. 5) on top of which the snow during the course of the summer gradually becomes saturated. In consequence slush lakes form on level surfaces and a gradient of only 3° – 4° is sufficient to initiate slush avalanches which quite frequently carry down-glacier most of the reference year's accumulation and deposit the solid part of it in the ablation area, thus forming accumulation outliers. This process is so common and of such relative importance for the Axel Heiberg Island glaciers that it has to be considered in the mass budget. The slush limit can be ascertained more readily in the field than the annual snow line and certainly is much more obvious than the equilibrium line. Variations in this upper limit of the occurrence of slush avalanches, if recorded by taking aerial photographs at the height of the ablation season in consecutive years, could be utilized to obtain approximate values for the annual changes in the mass budgets of the glaciers in the Queen Elizabeth Islands.

For the percolation zone B the condition is made that the 0° C. isotherm penetrates at the height of the summer to the surface of the previous year's snow pack. Benson (1959, p. 20) calls the highest altitude at which this occurs the saturation line and refers to the snow below it as soaked, but as snow and firn at 0° C. are not necessarily saturated or soaked these terms could not be adopted. For present purposes it was decided not to use another name for this division. This seemed justified as there were no distinct surface differences between the percolation zones A and B. From the point of view of mass budget studies, however, there is a need to make a distinction between these two zones. Percolation zone B loses some of the accumulation of the reference year to the underlying layers of the previous years, where ice glands and ice lenses are formed. In percolation zone A the melt water would usually refreeze within the snow pack of the reference year (Fig. 5). However, investigation of the various deep pits dug in the upper part of the White Glacier and in the Akaioa Ice Cap showed that occasionally in the percolation zone A a considerable amount of water seeps down into the layers of the previous years. This occurs particularly when warm air masses cause so much water to accumulate from rain and melting that surface lakes develop. This phenomenon was observed three times during the summer 1961 (13–14, 19, and 27 July) on the Akaioa Ice Cap where hundreds of such lakes developed within a few hours. The largest one, with a diameter of 400 m., was at an elevation of 1,600 m. Many of these lakes drained within 24 hours without developing surface streams. Some of this water certainly percolated into the firn layers of previous years. To assess the amount of this loss it is necessary to have measurements of the specific gravity at both the beginning and the end of the summer for the firn of preceding years.

There is no dry snow zone on the Axel Heiberg glaciers unless one small ice cap at the northern end of the island, which unfortunately has not yet been investigated, reaches into this zone. There is also the possibility that during a year with a continuously cold summer the highest parts of the ice caps and the highest mountains would retain the dry snow of the previous winter.

DEPTH HOAR OF THE VARIOUS ZONES

In the accumulation basins of the Axel Heiberg Island glaciers the passage from summer to winter snow is marked by a layer of depth hoar. This phenomenon provides the most reliable means of distinguishing between the snow of the reference year and that of the preceding year. To prevent ambiguity it was decided to include the layer of depth hoar, with its cup-shaped crystals, bars and plates of up to 12 mm. diameter, in the accumulation of the reference year. In this context it is particularly noteworthy that the appearance of the depth hoar at the end of the budget year differs considerably from one zone to the next (cf. Fig. 5).

TYPICAL SNOW PROFILES

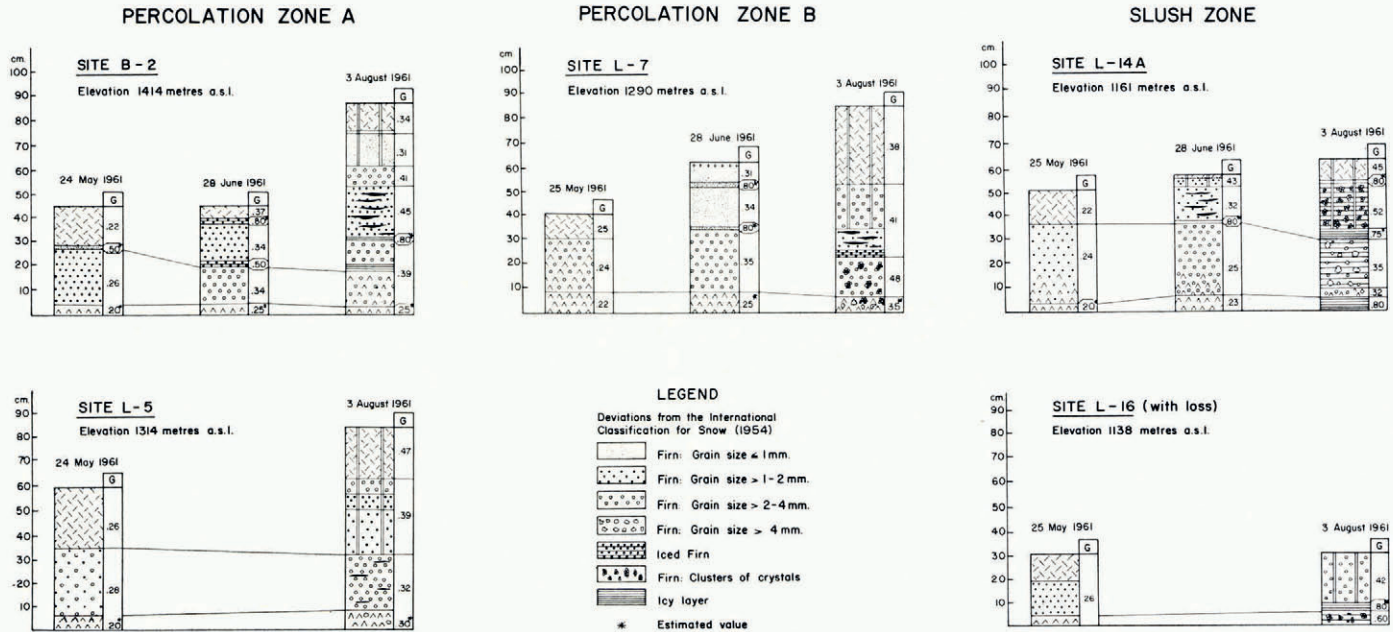


Fig. 5. Typical examples of snow profile sequences from the accumulation area of the White Glacier, summer 1961

In percolation zone A the depth hoar layer usually shows very little change in character during the summer; there are some exceptions, however, as when very local melt water penetrates to this depth (cf. Fig. 5, site L-5). On the other hand, throughout the percolation zone B to the slush limit a gradually increasing number of cup-shaped crystals are replaced by large rounded ones, thus raising the specific gravity of this layer. By the end of the season the depth hoar in the slush zone has almost entirely been replaced by clusters of irregular massive crystals or even icy layers. This transformation is due mainly to the percolation and re-freezing of melt water. The derivatives from the former depth hoar have frequently the character of superimposed ice.

THE ACCUMULATION DATA FOR THE WHITE GLACIER, 1960-61

The summer 1961 accumulation measurements from the upper 38 sites of the longitudinal profile are compiled in Figure 6. Based on these data and information from additional sites the elevation of the various zones and their net accumulation have been determined (Table I).

TABLE I. ELEVATIONS AND NET ACCUMULATION FOR THE ZONES OF THE WHITE GLACIER, BUDGET YEAR 1960-61

	Elevation m. a.s.l.	Area km. ²	Mean water equivalent mm.	Volume × 10 ⁶ m. ³	Volume per cent of total
----- <i>Dry snow line</i> -----	not present				
Percolation zone A		11.54	306	3.53	45
<i>Division between</i>					
----- <i>percolation</i> -----	1301				
----- <i>zones A and B</i> -----					
Percolation zone B		5.72	306	1.75	22
----- <i>Slush limit</i> -----	1213				
Slush zone		8.72	240	2.10	27
----- <i>Annual snow line</i> -----	1010				
Superimposed ice zone		2.39	172	0.42	5
Sporadic superimposed ice		0.39	235	0.09	1
----- <i>Equilibrium line</i> -----	915				
Accumulation area (total)		28.76	274*	7.89	100

* Calculated from total volume and area of accumulation.

These results give, naturally, a slightly more complicated picture than the schematic generalization (Fig. 3). The accumulation outlier at stake L-34 occupies a shallow basin. This morphological irregularity accounts for the increased local accumulation and is also responsible for this being the terminal place of descending slush avalanches. On inspection at the end of the summer it was found that most of the material of this outlier had the character of superimposed ice and is therefore in Table I included under the heading "sporadic superimposed ice". Two small ablation outliers due to crevasses at stakes L-21 and L-18 have been omitted as they were of extremely local nature. They have been replaced by values which were estimated by averaging data from neighbouring sites.

THE SIGNIFICANCE OF THE ZONING OF THE ACCUMULATION AREA

In the past great emphasis has been placed on studies of the variations in the amount of ablation and accumulation, and of the vicissitudes of the annual snow line as important features in the reaction of glaciers to climate. The division of the accumulation area into several zones each of which is individually assessed and related to the whole elaborates this

MASS BUDGET ASSESSMENT 1960-61
CENTRAL PART OF WHITE GLACIER
AXEL HEIBERG ISLAND, N.W.T.

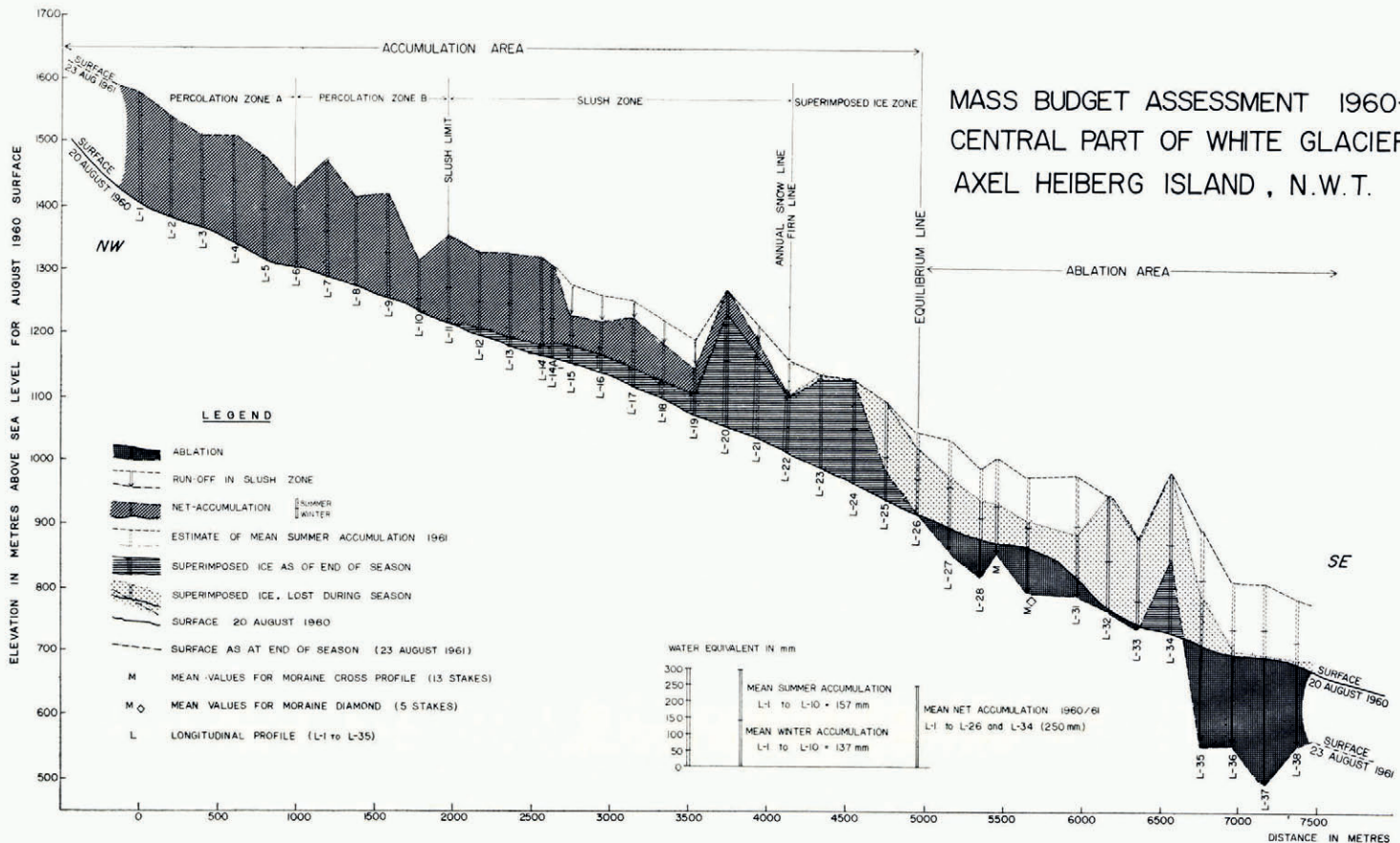


Fig. 6. Accumulation and ablation values in the longitudinal profile of the White Glacier

study. If over a period of years the elevation, the absolute and relative size, and the yearly net accumulation of each zone were compiled, as in Table I, and correlated with the contemporaneous meteorological records, further detail of the relationship between glaciers and climate might be revealed.

ACKNOWLEDGEMENTS

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DISCUSSION OF DR. F. MÜLLER'S PAPER

DR. W. H. WARD: I am very interested in Dr. Müller's account of the transition zone between ablation and accumulation. The point he made about where the superimposed ice disappears to when you get off the solid ice of the ablation zone is exactly comparable with the picture I had in the Penny Ice Cap. I would like to ask him whether the layers of superimposed ice finger out in a peculiar manner when you get further in towards the percolation area. You have got to get some sort of separation of different years, and I think that, somehow or other, this mass of superimposed ice, which starts as one continuous layer, probably separates out. What bothers me slightly is that you have obviously got more firn underneath somewhere, and I am not sure what is happening down below.

DR. MÜLLER: In this area we tried to look for this in several places, and we always found that there was an almost completely icy layer, but that you could see the individual grains. We have some grain-size measurements for these zones; it does not appear to be real firn any more, we always called it an icy layer (not an ice layer), and then you have superimposed ice sitting on top of it, with a quite different crystal structure.

DR. WARD: What is its density?

DR. MÜLLER: Always in the range from 0.45 to 0.85 g./cm.³.

DR. V. SCHYTT: We collected some information on this problem from Nordaustlandet during the I.G.Y., but I have not so far worked out all the data. We have exactly the same conditions, as it is at lat. 80° N. We have taken about ten 5 m.-long cores from the ablation area through the transition zone about every quarter mile (400 m.), then at about every km. when we have come up into the actual firn area. When we left the superimposed ice we could follow it for quite a long way going down getting deeper and deeper, and then we drilled through several years of firn, and could even recognize the annual layers in this firn lying on top of the superimposed ice, and we could see how some of these old firn layers gradually got soaked with water so that more was added to the superimposed ice bounding it underneath.

This "superimposed ice" was formed way below. Higher up we got cores that went through firn at first and then solid ice for one or two metres and then through maybe 10 or 20 cm. of coarse firn and then into solid ice again, because of extreme years with lots of accumulation, so that the firn had been buried under an impenetrable layer and had never been soaked. We even found that condition at the highest point of the ice cap Vestfonna of Nordaustlandet, not very far from the central station of the Oxford University Expedition of 1936. There I had a pit which was about 7 m. deep, and found that from 5 to 5.6 m. there was a layer of solid ice, and under that was ordinary coarse firn again, very easily dug with a shovel. I think it would be very interesting to do such a study on your glacier, it is rather easily done if you take long cores.

DR. MÜLLER: Taking cores has the difficulty that you cannot allow for local differences, I therefore trust pits much more, even though they involve much harder work. We dug a small number of pits, and just took a few cores in the surroundings.

DR. SCHYTT: Suppose you have 2 m. of firn and then solid ice. You cannot go on digging a pit through that ice! Therefore you cannot tell how it is tapering out and how the solid ice goes over into thick ice layers and thinner ice layers and then they disappear.

DR. MÜLLER: I have one advantage on Axel Heiberg Island. There is a very small amount of annual precipitation. It varies from 50 mm. water equivalent to 280 mm. of water equivalent in an exceptional year such as 1961, but in the two previous years the amount was more in the range of 200 mm. and below; so you see we do not need to dig too far.

MR. J. T. HOLLIN: We have similar circumstances at "Wilkes Station", at lat. 66° S., and we have followed up the suggestion of Dr. Schytt, who worked at Thule on a somewhat similar situation, that some of these firn layers just above the superimposed ice zone might get carried down beneath the superimposed ice zone, but not have enough time to consolidate into ice before they came out again in the ablation zone. We found that ice cliffs at the edge of the ice sheet had areas where layers of firn seemed to be trapped underneath a considerable thickness of superimposed ice. They had not consolidated into solid ice, even though they had been buried to a depth of tens of metres.

We also worked on superimposed ice stratigraphy. We were interested in the idea that, if an ice layer forms in the autumn, it is then exposed to autumn radiation, and Tyndall melt figures will form near the surface. These will refreeze to form the vapour figures described by Nakaya, and so you should have in each layer of such material a concentration of these vapour figures in the surface. We did not get very convincing results, but I think people might bear this in mind as a possible help in establishing some sort of stratigraphy.

DR. WARD: Did you in fact get down into solid ice in the accumulation area on the ice cap?

DR. MÜLLER: Yes. We dug one snow pit on the top of the ice cap down to 150 ft. (46 m.), so that we have the whole profile there up to a density of 0.78 g./cm.³.

DR. WARD: On the Penny Ice Cap it went solid much more rapidly, I think in about 40–50 ft. (12–15 m.).

DR. MÜLLER: But that was in the percolation zone. It was only at 2,000 ft. (600 m.) a.s.l. in the percolation zone that you could see the water percolating through up to five or six years' accumulation—more usually through one or two years'—and then spreading out to make huge layers and lenses sometimes up to 15 cm. thick.