MASTER

RESULTS OF STUDIES ON THE CASEMENT GLACIER, SOUTHEAST ALASKA, 1965 and 1966

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RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

ABSTRACT

An extensive glaciological study was begun in 1965 and continued in 1966 on the Casement Glacier in southeast Alaska. During these two summers, ablation data taken from 140 stakes in fourteen rows across the glacier show an annual loss ranging from 300 cm water equivalent yr^{-1} at 300 m (100 ft.) elevation along line 1 to 50 cm water equivalent yr^{-1} at 1170 m (3800 ft.) elevation at met screen 3 near the divide on the main arm of the glacier. Although an accurate determination of the snow remaining at the end of the ablation season has not yet been made, preliminary studies show that very little snow remains except high in the névé basins, and hence the Casement Glacier has a strongly negative budget.

Gravity surveys, conducted in 1965 and 1966 along ten of the rows of movement-ablation stakes to determine ice thickness, show that the maximum thickness is along line 8, a transverse line about midway up the glacier from the terminus, where the ice is 320 m thick.

Two ice tunnels were excavated along the base of the glacier to study the mechanisms of basal sliding of a temperate glacier. The first tunnel,

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dug in stagnant ice near the terminus during the 1965 season, exhibited no measurable basal slippage. However, in the 1966 tunnel and an associated natural ice cave, the ice moved over the bedrock at a rate of 2.9 cm day^{-1} , most of which can be attributed to regelation slip. A basal debris layer from 10 to 30 cm thick, which consists of alternating layers of regelation ice and debris picked up from along the bottom of the glacier, was observed at the base of the glacier. A new glaciological feature, named a "till curl", was also observed. This feature is formed when the basal debris layer becomes slowly detached from the overlying normal, clean glacier ice as the ice flows over a cavity downstream from the support of a bedrock knob.

During the two summers, a total of five meteorological stations were established. The summer of 1966 was warmer and wetter than that of 1965, so that in 1966 the firn line had retreated 3.3 km upglacier beyond its 1965 position.

A set of long-term recording meteorological instruments which record wind speed and direction, sunshine duration, barometric pressure, temperature, and relative humidity, was erected near the 1966 camp to provide meteorological information during the winter of 1966-67 for use in the heat balance study on the glacier.

An ice-dammed, self-draining lake along the west side of the Casement Glacier was observed and photographed a number of times during the two summers. It appears that, periodically, the ice buoys up the front of the ice cliff, thereby allowing the water in the lake to flow out beneath the glacier.

INTRODUCTION

The Casement Glacier ($58^{\circ}57'N$, $135^{\circ}57'W$) is located in Glacier Bay National Monument in southeast Alaska. It is a complex valley glacier formed by the merging of at least seven smaller tributaries with the main ice stream. The entire system has an area of 125 to 150 square km with névé basins at elevations between 1200 and 1700 m (4000 and 5500 ft.). The terminus is now located about 6.7 km northeast of Muir Inlet, where it once joined the Muir Glacier at the beginning of the present century (Fig. 1).

The U. S. National Park Service transported the party and its equipment and supplies from Juneau to the Casement Glacier outwash aboard the National Park Service vessel Nunatak. From the outwash the party was moved by helicopter to the selected campsite.

During the first year, 1965, only one camp was established, at an elevation of 300 m (1000 ft.). From this camp it was possible to do intensive work in the lower portion of the ablation zone of the glacier. The main camp for the 1966 season was located farther upglacier 32 km from Muir Inlet at an altitude of 1050 m so as to provide access to both the upper reaches of the ablation zone and the accumulation zone. In addition, there was a tent at the 1965 campsite and one at the location of the tunnel dug during the 1966 season. During both seasons, daily radio contact was maintained with the U. S. National Park Service at Bartlett Cove through which arrangements were made for delivery of mail and resupplies. Both field seasons were ten weeks long, with the party coming out of the field at the end of August and transported back to Juneau aboard the Nunatak.

MASS BALANCE STUDY

During the 1965 season, seven rows of movement-ablation stakes were installed in the ice in the lower portion of the ablation zone. In 1966 nine new rows of stakes were drilled into the ice and stakes from five of the seven lines from 1965 were located and redrilled. This made a total of more than 140 movement-ablation stakes in the ice (Fig. 2).

An extensive triangulation network was established during the two seasons so that all the data can be related to a single system. All the stakes were surveyed twice during the 1965 season, but five weeks of bad weather at the end of the 1966 season prevented a complete resurvey of all 140 poles; however, they will be surveyed again during the 1967 season.

Ablation was measured as often as possible during both the 1965 and 1966 seasons. On line 1 at an elevation of 300 m (1000 ft.) (Fig. 2), the ablation rate is approximately 300 cm water equivalent yr^{-1} . Along line 9 at an elevation of 1075 m (3500 ft.), an average of 143 cm water equivalent was lost. This value dropped to about 50 cm water equivalent yr^{-1} at the met station 3 at an elevation of 1170 m (3800 ft.).

Snow pits (Figs. 3, 4 and 5) were dug in the accumulation zone (see Fig. 2 for location) at both the beginning and the end of the 1966 season to determine the annual accumulation of snow. The pits dug early in the season (Nos. 1-4), 23-26 June, encountered glacier ice at their bottoms. This indicates that all of the snow which had accumulated at that location during the winter of 1964-65 had melted during the 1965 ablation season, and so the snow of the 1965-66 winter fell on the exposed glacier ice. During the 1966 summer, once again all the snow melted from these locations, exposing the underlying glacier ice. The three pits dug at the end of the

summer (21, 22 and 25 August) encountered a very hard layer of firn (Fig. 5), which represents the surface at the end of the 1965 ablation season. To supplement the accumulation data from the snow pits, three snow depth profiles were made across the glacier, one in the vicinity of each of the pits (Fig. 6). It can be seen from the snow depth profiles that, even high in the névé basin, there is not much snow remaining at the end of the ablation season.

GRAVITY STUDIES

During the summers of 1965 and 1966, gravimeters were used to measure changes in acceleration due to gravity along ten lines of movement-ablation stakes. From these measurements estimates have been made of ice thickness (Figs. 7 and 8). In 1965 these measurements were made on the lower four lines using a Worden Master Geodetic model gravimeter. During the 1966 season the party used a LaCoste-Romberg gravimeter from the U. S. Army Map Service, Washington, D. C. Cross-section profiles were obtained along six additional rows of stakes (Fig. 2), but all are subject to some correction as the reduction of the survey data is completed.

In addition, a gravity survey was conducted in the Muir Inlet area at the request of the U. S. Geological Survey. Twenty-one stations were occupied around Muir, Wachussetts, and Adams Inlets (Fig. 1) and the network was tied into the U. S. Coast and Geodetic Survey gravity base station at Juneau. A full report on these studies, which are outside the scope of the present glaciological report, is being prepared for the U. S. Army Map Service and the U. S. Coast and Geodetic Survey.

VELOCITY PROFILES

It has been proposed to drill a number of holes through the glacier to obtain data on how the velocity varies with depth. This information would be valuable in assessing the mass balance of the glacier because from these velocity profiles, the through-flow of ice across a given profile can be calculated, and by coupling these velocity profiles with detailed ablation studies one can determine the mass balance of a given section of ice quite accurately.

During the 1966 season, electrical hot point drills (Fig. 9), which were constructed in the Institute's machine shop, were used to drill holes through the glacier to measure the velocity variation with depth. The two original drills burned out while drilling the first hole. With a third drill, which was sent up from Columbus in July, a hole through the glacier was completed. However, efforts to remove the drill from the hole failed as the hot point could not be moved from its position on the bottom. The several possible explanations to account for this include: (1) a large boulder from the basal load could have melted free and lodged behind the drill point; (2) because the hole was not vertical, the support cable (1/16" stainless steel aircraft cable) could have cut into the ice on the inside of the curves; (3) the hot point could have melted a cavity which was large enough to allow the drill point to fall on its side and become wedged. Whatever the reason, because the drill and cable were still in the hole, no velocity measurements could be made.

A new design for another set of hot point drills is being developed at the Institute and will be completed in time for thorough testing before the next field season in summer 1967.

ICE TUNNEL STUDIES

Basal sliding has been recognized since the late eighteenth century as one of the important mechanisms in the movement of temperate glaciers. However, due to the inherent difficulty in studying this kind of movement, most work has been speculative or theoretical in nature. Weertman (1957, 1964) postulated two major mechanisms in his theory of basal sliding: regelation slip and plastic flow. Kamb and LaChapelle (1964) verified Weertman's proposed mechanisms, but suggested that he overemphasized the role of plastic flow in relation to regelation slip as the primary agent of basal sliding.

In order to more fully understand the mechanisms of basal sliding, two tunnels have been dug along the base of the Casement Glacier. Figure 2 shows the location of these tunnels, and Figure 10 shows the entrance to the 1966 tunnel. In 1965 a 60-m tunnel was dug into a nearly stagnant lobe of the glacier about 3 km from the terminus along the west side of the glacier. The tunnel was surveyed (Fig. 11) and dowels were emplaced in the walls to measure the rate of basal sliding and the strain rate along the walls of the tunnel. As the survey data now indicates the ice on the surface over the tunnel moved less than one meter the whole summer, it is not surprising that no basal sliding was observed. Thin sections of ice were examined from samples taken at 0, 0.75 and 1.5 m. Of the more than 50 sections of basal ice examined, only two had even a suggestion of a regelation layer composed of smaller crystals than the normal glacier ice. All the other sections showed normal glacier ice extending right to the bottom. There was no basal load of debris along the sole of the glacier. No further investigations were possible in this tunnel during the following

1966 season as the roof had collapsed, blocking the entrance with a large amount of debris.

A second tunnel (Fig. 12) was excavated in July 1966. The site for this tunnel was chosen on the basis of its accessibility, the sharpness of the ice-bedrock interface, and the high rate of movement. In the process of digging the tunnel, a large, natural cavity beneath the glacier was broken into. The cavity is formed as the ice flows over a bedrock protuberance. As the ice is flowing relatively fast along the bottom (2.9 cm day^{-1}) and there is not a great deal of pressure from overlying ice (which is only 5 to 20 m thick), the grooves which are produced in the sole of the glacier (Figs. 13 and 14) as the ice slides over bedrock knobs are not closed up, but rather extend downstream to form a series of cavities. In some places these cavities could be followed upglacier as much as 20 m to where the ice is in contact with the bedrock knobs which produce them.

When the cavity at the tunnel was first entered, all the surfaces were covered with a thick layer of sublimation crystals because there had been no circulation of air. Beneath these crystals, a thin layer of clear ice, usually less than 1 cm thick, can be seen. Sections of this ice examined on a Rigsby polarizing macroscope consisted of crystals which were on the order of a few millimeters in diameter compared to those in the overlying, normal glacier ice, which are 2 to 5 cm in diameter. This fine-grained ice is the regelation layer, which is produced by pressure melting on the upstream side of obstacles and refreezing on the downstream side.

The basal meter of ice (Fig. 15) as exposed in the tunnel consists mostly of normal glacier ice, but the bottom 10 to 30 cm is composed of

alternating layers of debris and regelation ice. Thus, it is suggested that the observed basal layer is a composite of layers of regelation ice and debris which accumulate on the bottom of the glacier as it passes over a series of bedrock knobs. Therefore, by a repetition of the process of sliding over a bedrock knob, producing a thin layer of regelation ice and then picking up debris from the depression between the knobs, this observed basal debris layer could be produced. Both of these processes were observed in the 1966 tunnel. Figure 14 shows two pebbles which were found frozen to the bottom of the glacier on the lee side of a bedrock knob. Presumably, this process could occur a number of times farther upglacier, producing the observed basal layering. The bedrock topography outside the tunnel has the form of roches moutonnées (Fig. 1), and this form probably continues under the glacier.

The layer of basal debris is as much as 30 cm thick on the sides and upstream from the bedrock knob pictured in Fig. 15, but thins to 10 cm where the ice flows over the bedrock knob. From three samples, the debris layer was determined to be 61 percent (by weight) mud and rock fragments, and 39 percent ice. Observations of dowels placed in the wall of the tunnel over the bedrock knob show that there is a compressive stress on the upstream side of the knob and that the basal debris layer is thinned over the top of the knob but is thickened as it flows plastically around the knob (Fig. 16) as Weertman suggests for large obstacles. As this thicker layer of debris is squeezed around the knobs and moves downglacier, out over the cavity and away from the support of the bedrock, the basal debris layer, because of its increased density, becomes detached from the overlying clean ice and falls very slowly away from the ceiling of the

cavity (or the bottom of the glacier) to produce features which have been named "till curls" (Fig. 17).

In the main part of the excavated tunnel (Fig. 12), which starts at the ice-bedrock contact at the head of one of the large grooves, dowels were placed above the bedrock (Fig. 15) to determine the rate of basal sliding over the bedrock. In the period from 5-28 August 1966, there was no measurable differential movement of the dowels from 10 to 150 cm above the bedrock. All of them moved with a rate of 2.9 cm day^{-1} , which therefore represents the velocity of the basal sliding. This indicates a plug-type of flow, which is different from that observed by Kamb and LaChapelle (1964) who observed a gradual increase in velocity with height above the tunnel floor. However, the Casement results may reflect only a local condition; the ice was only 12 m thick at the point where the observations were made, and this may not be sufficient overburden to produce enough friction along the bottom to retard the basal sliding and thus to produce a change in velocity with height above the bedrock.

The 1966 tunnel will be extended under thicker ice during the 1967 season in an attempt to investigate basal sliding where a greater overburden exists. Perhaps under these conditions, a differential flow will be observed in the wall of the tunnel. Plans are now being made to implant instrumented artificial obstacles on the bedrock knobs and allow them to be overrun by the glacier ice. These can be instrumented to feed back such valuable information as the differential temperatures on the up- and downstream sides of obstacles, and the shear stress at the bottom of the glacier. Knowing these parameters will aid greatly in understanding the mechanics of basal sliding.

METEOROLOGICAL RESULTS

During the two field seasons of 1965 and 1966, five meteorological stations were erected and maintained, two during the first season and three during the second season (see Fig. 2 for location). During the 1965 season the lower two stations were established; the upper three stations were in operation during the 1966 field season. Table 1 gives the instrumentation, setting, and period of operation of the stations.

The summary of results of the 1965 season was prepared by Loewe (1966), and that of the 1966 season by the writer (Figs. 18, 19 and 20). A typical instrument set-up is shown in Figure 21. The meteorological results will be used in making the final analysis of the mass balance of the glacier. The relative importance of radiation, sensible heat, and latent heat in supplying energy at the glacier surface will be calculated for the ablation period.

A. Sunshine and Cloudiness.

The weather during the 1966 season was the opposite from that which prevailed in the summer of 1965. The best weather in 1966 came during the first half of the summer, with increased cloudiness and precipitation prevalent during the second half of the season. The observations are summarized in Table 2.

TABLE 1. Meteorological shelters, locations, instrumentation, and dates of operation.
See Figure 3 for location.

Year	Station	Elevation	Terrain-surface material	Instrumentation	Period of Operation
1965	1	300 m (1000 ft.)	Ice	Barograph Hygrothermograph Pyrheliograph Recording anemometer Campbell-Stokes sunshine recorder Assmann psychrometer Precipitation totalizer Max and min thermometers	30 June - 25 August 1965 with three times daily observations at 0700, 1200, and 2100 hrs. Cloud cover in 10's noted at time of observations.
	2	100 m (325 ft.)	Outwash gravel	Hygrothermograph Pyrheliograph Recording anemometer Precipitation totalizer	1 July - 25 August 1965
1966	1, base camp	1050 m (3400 ft.)	Moraine	Barograph Thermograph Assmann psychrometer Rain gauge and totalizer Hand anemometer Max and min thermometers Campbell-Stokes sunshine recorder	23 June - 26 August 1966 with three times daily observations at 0700, 1300, and 2100 hrs. Cloud cover in 10's noted at time of observations.

cont.

Table 1, continued

Year	Station	Elevation	Terrain-surface material	Instrumentation	Period of Operation
1966	2	1030 m (3350 ft.)	Snow/ice	Hygrothermograph Pyrheliograph Max and min thermometers Precipitation totalizer Recording anemometer	22 June - 22 August 1966
	3	1170 m (3800 ft.)	Snow	Hygrothermograph Pyrheliograph Max and min thermometers Precipitation totalizer	4 July - 22 August 1966

TABLE 2. Total sunshine in hours per day and mean cloud cover.

	22-30 June	1-15 July	16-31 July	1-15 Aug.	16-26 Aug.
Maximum possible hours of sunshine per day	18.25	17.75	17.00	16.00	15.00
Mean daily sunshine, 1965	--	5.5	4.5	-- 6.4 --	
Mean daily sunshine, 1966	4.9	5.8	5.1	3.6	1.3
Mean cloud cover, 1965	--	70%	70%	63%	42%
Mean cloud cover, 1966	88%	65%	71%	76%	90%

TABLE 3. Total radiation in calories per square centimeter per day.

		June	1-15 July	16-31 July	1-15 Aug.	16-21 Aug.
Sta. 1	1965 Mean for month	--	420		400	
	Mean for sunny days	--	700-750		550	
	Mean for cloudy days	--	100		65	
Sta. 2	1966 Mean for all days	600	620	495	320	225
	Mean for sunny days	770	690	715	555	no clear days
	Mean for cloudy days	510	495	290	155	225
Sta. 3	1966 Mean for all days	--	690	510	420	345
	Mean for sunny days	--	800	690	595	no clear days
	Mean for cloudy days	--	600	345	300	345

TABLE 4. Mean temperatures and mean extremes (°F).

	Time	30 June - 18 July		19-31 July	1-25 Aug.	
Station 1, 1965	0700	41.9		42.1	43.5	
	1200	42.3		42.8	44.6	
	2100	42.6		43.2	44.8	
	Max.	50.2		49.8	51.4	
	Min.	40.1		39.9	39.4	
	Time	23-30 June	1-15 July	16-31 July	1-15 Aug.	16-26 Aug.
Station 1, 1966	0700	38.5	39.9	46.3	42.8	40.2
	1300	45.0	42.7	50.9	43.0	42.4
	2100	38.5	41.8	47.3	42.6	42.0
	Max.	54.1	52.3	55.2	48.8	45.5
	Min.	32.1	33.4	39.7	36.2	34.5
Sta. 2 1966	Max.	46.7	48.7	48.5	43.0	39.8
	Min.	29.6	32.4	35.0	32.2	32.0
Sta. 3 1966	Max.	--	47	44	39	40
	Min.	--	28	30	30	30

B. Total Radiation.

In 1965 the recorded values of radiation at stations 1 and 2 were very similar, as the same meteorological conditions almost always prevailed at both locations. However, in 1966 the instruments were located in different micro-environments, and hence it was not uncommon to have different meteorological conditions at the two met screens. Thus, there is a difference in the radiation values recorded at the two stations. Radiation measurements are summarized in Table 3.

C. Temperatures.

In addition to the recorded temperature data, each season observations were made three times daily, including readings of current temperature and of the maximum and minimum thermometers. During the 1965 season, these observations were made at 0700, 1200, and 2100 hours. During the 1966 season the schedule was altered to 0700, 1300, and 2100 hours, Alaska Standard Time. This is one hour behind true solar time at the location, so that, for example, 0700 AST is equal to 0800 true solar time. The mean temperatures and extremes are given in Table 4.

D. Relative Humidity.

The mean relative humidities as determined each year with an Assmann psychrometer at the base station are given in Table 5.

TABLE 5. Mean relative humidities, 1965 and 1966.

	Time	July		August		
1965	0700	72%		82%		
	1200	80%		81%		
	2100	78%		79%		
	Time	23-30 June	1-15 July	16-31 July	1-15 Aug.	16-26 Aug.
1966	0700	49%	59%	66%	79%	86%
	1300	59%	55%	69%	80%	89%
	2100	53%	54%	70%	82%	80%

E. Precipitation.

Rainfall observations are available for the terminus station for the 1965 season. During the 1966 season, precipitation measurements were made at all three stations. The precipitation data are presented in Table 6. Of the total precipitation at stations 1 and 2 in 1966, only a few centimeters fell as snow; the rest fell as rain. However, at station 3 a higher percentage fell as snow, but the ratio of rain to snow was not determined. As can be seen from the table, 1966 was a wetter year than 1965.

TABLE 6. Precipitation data, 1965-1966

Year	Station	Precipitation (cm water equiv.)	Period of observ.	No. of days	No. of days w/ measurable precipitation
1965	2	20	15 June-25 Aug.	69	30
1966	1	29.8	9 July-27 Aug.	49	33
	2	27.4	9 July-22 Aug.	44	30
	3	25.8	4 July-22 Aug.	49	32

Sumner Recorders.

At the end of the 1965 field season, on 27 August, a Sumner meteorological recording system (Fig. 22), which is designed to record wind speed and direction, sunshine duration, barometric pressure, temperature, and relative humidity for one year, was erected on morainal material adjacent to the glacier at an elevation of 1100 m (3600 ft.). The instruments could not be set up any sooner, because they were delayed in their delivery from the manufacturer in Australia. Consequently, there was no opportunity to check that all the elements were functioning properly before the party left the field.

On 19 June 1966, at the beginning of the second field season, it was found that only two of the six instruments, the wind direction and the sunshine duration, had worked over the winter and the record for those was not complete. During the next weeks, the instruments were examined, adjusted, and put in working order so that by August 1966 all the elements were working satisfactorily. Thus, a complete record of the meteorological conditions in the accumulation zone over the winter of 1966-67 should be available for study and use in the heat balance analysis of the glacier.

HYDROLOGY

Discharge Studies.

During the 1966 season an attempt was made, using the saline-dispersal technique, to measure the meltwater discharge from the glacier at a time when most of the surface water was flowing in one channel through bedrock. The discharge was so great that the salt solution was diluted beyond the

detecting capacity of the instrument, so that no value for the discharge was obtained. Later, when another attempt was to be made to measure the discharge, the stream had altered its course and had formed a distributary pattern across the outwash, which rendered any measurement impossible.

However, even if the discharge through this system of streams could be measured, the measured discharge value would very probably be in great error as much of the discharge percolates into the permeable outwash. This part of the discharge is extremely difficult to measure. Further complicating the problem of accurately measuring the discharge is that one should have an estimate of the rainfall in the whole drainage basin to subtract the runoff due to precipitation from the measured discharge, to determine the amount due to the melting of snow and ice. Such an estimate is not possible with the precipitation data available.

The principal investigator feels that although discharge measurements made under good conditions, such as with a single discharge stream flowing through a bedrock channel and a smaller glacier with more precipitation data, can be valuable in assessing the mass balance of a glacier, continued attempts to measure the discharge of the Casement Glacier will not yield any results of value. Therefore, it is intended that this part of the study be discontinued so that more time may be devoted to aspects of the study which have already proven to be more fruitful.

Self-draining Lake.

A small self-draining lake exists on the west side of the Casement Glacier at an elevation of 550 m (1800 ft.). Daily observations were made by Lindsay (1966) on the level of the lake during the 1965 season. He has calculated that on the night of 8-9 July 1965, the lake discharged approximately $6.88 \times 10^6 \text{ m}^3$ of water and that another smaller discharge of $1.49 \times 10^6 \text{ m}^3$

occurred on 4-7 August.

During the 1966 season, additional observations were made on the level of the water in the lake. Because the main camp for the 1966 work was 20 km from the lake, observations were made only at irregular intervals. On June 1966, when the writer flew over the glacier on a reconnaissance flight, the lake was full with the top of the water above the edge of the ice cliff and spreading out onto the adjacent glacier ice (Fig. 23 top). The lake was still full on 19 June, but on 27 June it was only half full. During July the lake level varied, but not greatly from the 27 June level. However, on 10 August (Fig. 23 middle), the lake was empty and several sets of terraces had been developed in the sediment on the lake bottom, indicating that the lake had been drained for a number of days. Only a few stranded blocks of ice remained in the valley in sharp contrast to the situation in 1965, when a large number of icebergs were stranded by the drainage of the lake on 7 August 1965. On 26 August 1966, the lake was observed to be filling up again, and by 28 August it was about two-thirds full with very few icebergs (Fig. 23 bottom).

The mechanism for the drainage of such a lake is not clearly understood. Glen (1954) has suggested that the water in the lake builds up a hydrostatic pressure that enlarges openings and could open a drainage outlet. Thorarinsson (1939) suggests that the water might actually float the ice cliff sufficiently to allow the lake to drain through a sub-glacial stream which could be kept open by abrasion after the cliff was let back down. Then, when the lake was completely empty in August 1966, there was no longer sufficient water flowing through the sub-glacial channel to keep it open and it was closed by the same kind of plastic flow that limits the depth of

crevasses. As August 1966 was a wet month, and the sub-glacial channel had closed, the lake began to fill again and by 28 August it had reached the level shown in Figure 23 (bottom). It is possible that the lake continued to fill and then drained again before winter.

The observations from the 1966 season favor Thorarinsson's floatation theory on the drainage of this kind of ice-dammed lake. The water, being up over the edge of the cliff, certainly was deep enough to allow for floatation of the ice cliff. This theory works out very nicely for the observations made in 1966, but it cannot explain the second sudden discharge in 1965, when the lake was only about half full. This still needs an explanation.

During the summer of 1967, it is proposed to put a microbarograph on the ice cliff to see if there is any lifting of the ice cliff front when the lake drains. In addition, a pressure recorder to record water depth as a function of pressure may be lowered to the bottom of the lake to give a continuous record of water level. This information may lead to the solution of the problem of how ice-dammed lakes are drained.

OBSERVATIONS ON "ICE WORMS"

During the 1966 field season, a large number of the oligochaete, Mesenchytraeus, commonly known as ice worms, were observed on the snow and ice of the Casement Glacier. Ice worms have been reported by a number of investigators, but no research has been done on them. Consequently, when time permitted, observations were made on these animals.

The ice worm is a reddish-brown to black annelid as much as 2 cm in length. They apparently have the ability to burrow in the snow and ice,

because they were very rarely seen on the surface during the morning. They were most abundant in the late afternoon of sunny days, but on cloudy days it was difficult to find any ice worms. This suggests that their feeding habits are related to production of food on this type of day. It was previously thought that perhaps the ice worm's diet consisted primarily of the algae which exist on the surface of the glacier, but in a personal communication from Tynen it was learned that no enchytraeid which has been studied thus far possesses the necessary cellulases to digest algae. Thus, their diet must be restricted to material such as bacteria with which there would be no cellulose problem.

CONCLUSIONS

The two main objectives of this study are a mass balance assessment of the Casement Glacier and a study of the basal sliding mechanisms of a temperate glacier. With two of the proposed three summers of field work completed, it is possible to draw some preliminary conclusions concerning these objectives.

The budget of the Casement is strongly negative, which is attributed to the high surface loss due to ablation during the summer. Snow pit and snow-depth probe studies in the accumulation basins of the tributaries, which collectively form the Casement Glacier, reveal that near the end of the ablation season, the average snow depth is only about 1 m. Since the area of the ablation zone is much larger than that of the accumulation zone, the annual net loss is quite large.

The investigation of the basal sliding mechanisms proved to be very

interesting as new features were observed at the base of the glacier. There is a distinct layer of basal ice which is composed of alternating layers of regelation ice and debris. This layer appears to have been produced by alternation of the process of regelation sliding over obstacles and of picking up of debris from the cavities which exist on the downglacier side of bedrock protuberances. Regelation is thought to play the major role in the basal slip process, but evidence of plastic flow around large obstacles was observed.

This study has shown that attempts to measure the discharge of a large glacier that is not confined to a bedrock channel are pointless; the values have little significance because there are too many variables which affect the measured discharge.

At this time the calculation of the trajectory of a given layer through the glacier has not been completed. The necessary survey data of ice velocities have been recorded, and the calculation of the rate of burial and date of exposure of such a layer are continuing during the coming months. The calculations and results will be included in the final report which is to be written after the third summer's work.

ACKNOWLEDGMENTS

This research was conducted during the summers of 1965 and 1966 by the Institute of Polar Studies through the financial support of the U. S. Atomic Energy Commission (Contract No. AT(11-1)-1473) administered through the Ohio State University Research Foundation. The generous logistical support provided by the U. S. National Park Service at Juneau and Bartlett

Cove aided the project in many ways, particularly with transportation and communications.

I appreciate the help of my field assistants who were, during the 1965 season, John Lindsay, Peter Darvall, Mark Owens, Paul Hooge, and David Saarela, and during the 1966 season, Gerald Holdsworth, Fred Erdmann, Mikkel Mandt, Jim Carroll, and Tom Sanders.

I wish to acknowledge the many hours of discussion with Garry McKenzie and the other members of the Institute of Polar Studies, which greatly aided in the research. I also wish to thank Dr. Colin Bull and Dr. Richard P. Goldthwait whose aid and suggestions throughout the study have proven invaluable. Thanks also are due to Dr. Bull and Dr. Arthur Mirsky for their helpful suggestions during the preparation of this report.

REFERENCES CITED

- Glen, J. W. (1954) The stability of ice-dammed lakes and other water-filled holes in glaciers: Journal of Glaciology, Vol. 2, No. 15, p. 316-318.
- Kamb, W. B. and LaChapelle, E. R. (1964) Direct observation of the mechanism of glacier sliding over bedrock: Journal of Glaciology, Vol. 5, No. 38, p. 159-172.
- Lindsay, J. F. (1966) Observations on the level of a self-draining lake on the Casement Glacier, Alaska: Journal of Glaciology, Vol. 6, No. 45, p. 443-445.
- Loewe, F. (1966) Climate, p. 19-28 in R. P. Goldthwait et al., Soil development and ecological succession in a deglaciated area of Muir Inlet, southeast Alaska: Ohio State Univ., Inst. Polar Stud., Rept. 20, 167 p.
- Thorarinsson, S. (1939) The ice dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations: Geografiska Annaler, Årg. 21, Heft 3-4, p. 216-242.
- Weertman, J. (1957) On the sliding of glaciers: Journal of Glaciology, Vol. 3, No. 12, p. 33-38.
- , (1964) The theory of glacier sliding: Journal of Glaciology, Vol. 5, No. 39, p. 287-303.

Figure 1. Map of Muir Inlet area showing the retreat of the ice front of the Muir, Casement and associated glaciers by decades since 1880. The location of gravity stations occupied in the Muir Inlet area are shown by solid triangles.

Figure 2. Map of the Casement Glacier showing the location of the camps, the survey stations, the rows of movement states, the met stations, and the ice tunnels.

CASEMENT GLACIER, ALASKA

Figure 3. Profile of snow pits 1 and 2, Casement Glacier, Alaska, 1966.

CASEMENT GLACIER, ALASKA

Figure 4. Profile of snow pits 3 and 4, Casement Glacier, Alaska, 1966.

CASEMENT GLACIER, ALASKA

Figure 5. Profiles of snow pits 5, 6, and 7, Casement Glacier, Alaska, 1966.

Figure 6. Transverse snow-depth profiles along lines A, B, and C through respectively pits 7, 5, and 6, Casement Glacier, Alaska. See Figure 5 for pits profiles.

Figure 7. Valley profiles along lines 1-4 based on 1965 gravity data, Casement Glacier, Alaska.

Figure 8. Valley profiles along lines 8-13 based on 1966 gravity data, Casement Glacier, Alaska.

Figure 9. Hot point drilling operation at flag 11 on line 10, Casement Glacier, Alaska.

Figure 10. Entrance to 1965 tunnel in upper Casement Glacier, showing position along ice-bedrock contact. Note roches moutonnées topography.

PLAN OF TUNNEL, CASEMENT GLACIER 1965

Figure 11. Plan of 1965 tunnel near lower camp, Casement Glacier, Alaska.

Figure 12. Plan and cross-sections of 1966 tunnel and associated ice-cave, Casement Glacier, Alaska.

Figure 13. View of ice-cave roof showing part of a large groove that is produced in the ice at the bottom of the Casement Glacier where it flows over a bedrock knob. The flow is towards the viewer. The material in left foreground is bedrock with a thin veneer of debris. Width of view is about 2.5 m.

Figure 14. View of ice-cave roof showing rocks frozen onto the ceiling (i.e. the bottom of the Casement Glacier) on the downstream side of a bedrock knob (behind viewer). The large rocks in the center are about 7.5 cm and 5 cm in width.

Figure 15. Ice-bedrock contact about 25 m inside 1966 tunnel in Casement Glacier showing the debris-laden layer in the basal ice, and ice velocities as determined by emplacing dowels in the glacier. Note how the debris layer thins as it passes over the bed-rock knob.

Figure 16. Feature in ice-cave wall about 20 m inside Casement Glacier, showing "turbulent flow" of the basal ice layer as it is squeezed around the side of a bedrock knob. Flow is from right to left. The shiney appearance of the wall is a result of the camera flash reflecting off a thin layer of clear regelation ice.

Figure 17. "Till curl" about 15 m inside ice-cave in Casement Glacier.
Flow is from right to left.

Figure 18. Temperature, sky cover, and sunshine duration at met station 1, Casement Glacier, Alaska, 1966.

Figure 20. Maximum-minimum temperature and radiation at met station 3, Casement Glacier, Alaska, 1966.

Figure 21. Typical met station set-up, station 3, Casement Glacier. Hygrothermograph and maximum-minimum thermometers inside shelter, pyrheliograph on top of shelter, and totalizing rain gauge to left rear of shelter.

Figure 22. Summer recorders set up in upper Casement Glacier. From left to right, the instrumentation shown are 1) Anemometer, 2) Wind direction vane and recorder for wind speed and direction, 3) temperature and relative humidity sensing elements and recorder, 4) Barometric pressure element and recorder for barometric pressure and sunshine duration, and 5) Sunshine sensing head.

Figure 23. Different stages in the "life" of the self-draining lake along the side of the lower Casement Glacier. Upper photo, taken on 12 June, 1966 from top of glacier, shows lake filled up and overlapping the edge of the ice cliff. Middle photo, taken on 12 August, 1966, shows the lake drained and terraces cut in deltaic sediments on the lake bed; the stranded icebergs are up to 20 m long. Bottom photo taken on 28 August, 1966, shows the lake 2/3 full.