ORIGIN OF DEBRIS-COVERED ICEBERGS AND MODE OF FLOW OF ICE INTO "MILLER LAKE", MARTIN RIVER GLACIER, ALASKA

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ABSTRACT. During the summer of 1963, a drift-veneered mass of ice suddenly emerged at the surface of "Miller Lake", an ice-walled lake at the terminus of the Martin River Glacier, Alaska. Subsequent fathometer traverses, together with the fact that the ice was not at the pressure melting point, revealed that it had been derived from a hole approximately 40 m. below the surface of the lake. There are numerous large debris-covered icebergs in the lake and presumably at least some are formed in this manner. Others are derived through differential ablation of projections of the glacier into the lake. Only the small icebergs are formed through calving. The interpretation of the mechanism of release of ice from the bottom of the lake, and the observation and interpretation of a rising ice-cored island in the same lake suggest that the ice on the bottom is deforming plastically and that it is undergoing compressive flow. Much of the movement may be along shear planes actually found in icebergs derived from the bottom of the lake.

RÉSUMÉ. *Origine des icebergs couverts de débris et mode d'écoulement de la glace dans le "Miller Lake", Martin River Glacier, Alaska.* Pendant l'été 1963, une masse de glace veinée de débris émergea brusquement des eaux du "Miller Lake", lac glaciaire frontal du Martin River Glacier, Alaska. Des profils bathymétriques et le fait que cette glace n'était pas à la température de fusion montra qu'elle provenait d'un trou à 40 m sous la surface du lac. Il y a de nombreux et larges icebergs couverts de débris sur le lac et probablement quelques uns sont formés de cette manière. D'autres dérivent par ablation différentielle de projections du glacier dans le lac. Seuls les petits icebergs se forment par vêlage. L'interprétation du mécanisme du décollement de la glace du fond du lac, ainsi que l'observation et l'interprétation de la naissance d'une île à noyau de glace dans le même lac suggèrent que la glace du fond est déformée plastiquement et soumise à l'écoulement de compression. La plupart du mouvement doit se faire le long de plans de cisaillement trouvés actuellement dans les icebergs provenant du fond du lac.

ZUSAMMENFASSUNG. *Der Ursprung schuttbedeckter Eisberge und die Art des Eisflusses im "Miller Lake" am Martin-River-Gletscher, Alaska.* Im Sommer 1963 tauchte plötzlich an der Oberfläche des "Miller Lake", einem ins Eis eingebetteten See am Ende des Martin-River-Gletschers in Alaska, eine mit Schutt umkleidete Eismasse auf. Aus darauffolgenden Lotungen und aus der Tatsache, dass sich das Eis nicht auf dem Druckschmelzpunkt befand, konnte geschlossen werden, dass es von einem Loch ca. 40 m unter dem Seespiegel stammte. Der See enthält viele grosse schuttbedeckte Eisberge, von denen zumindest einige auf diese Weise entstanden sein dürften. Andere entstammen der selektiven Ablation von Vorsprüngen des Gletschers in den See. Nur die kleinen Eisberge entstehen durch Kalben. Die Erklärung des Vorgangs der Eisablösung vom Seegrund sowie die Beobachtung und Erklärung des Aufsteigens einer Insel mit Eiskern im selben See lassen darauf schliessen, dass sich das Eis am Seegrund plastisch verformt und in Druckfliessen gerät. Ein Grossteil der Bewegung dürfte entlang von Scherflächen erfolgen, die in Eisbergen vom Seegrund tatsächlich zu sehen sind.

INTRODUCTION

General

Martin River Glacier is located in south-central Alaska, approximately 96 km. east of Cordova, the nearest community (Fig. 1). The glacier is an expanded valley glacier originating in the Bagley Icefields approximately 64 km. farther to the east. The terminal 6·2 km. of this glacier are covered with ablation till composed largely of cobbles, pebbles and occasional boulders up to 10 m. in diameter. In this terminal zone the ablation till averages about 0·3 m. thick and is at least 9 m. thick along part of the glacier margin. The most recent end moraine complex (Little Ice Age and younger) is still largely cored with dead ice.

The study of Martin River Glacier was carried out by faculty and student members of the Department of Geology, The University of North Dakota, under sponsorship of a grant from the National Science Foundation (G-22016, Dr. W. M. Laird, Principal Investigator). Although the main purpose of the investigation was to correlate dead ice features with related fauna and flora, it was only natural that the degree of activity of this glacier be considered

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important. Much of the information presented in this paper came from observations at the "Miller Lake" camp in 1963.

"Miller Lake"

A large lake 2·8 km. long, 800 m. wide and up to 70 m. deep has formed between the active ice front and the dead ice-cored moraine complex at the terminus of Martin River Glacier (Fig. 1). This lake has been unofficially named "Miller Lake" after the late Dr. Don Miller of the U.S. Geological Survey. "Miller Lake" is an ice-walled lake formed by the coalescence of several ice sink holes which are common features in the terminal zone of Martin River Glacier (Reid and Clayton, 1963; Clayton, 1964). A large part of the lake

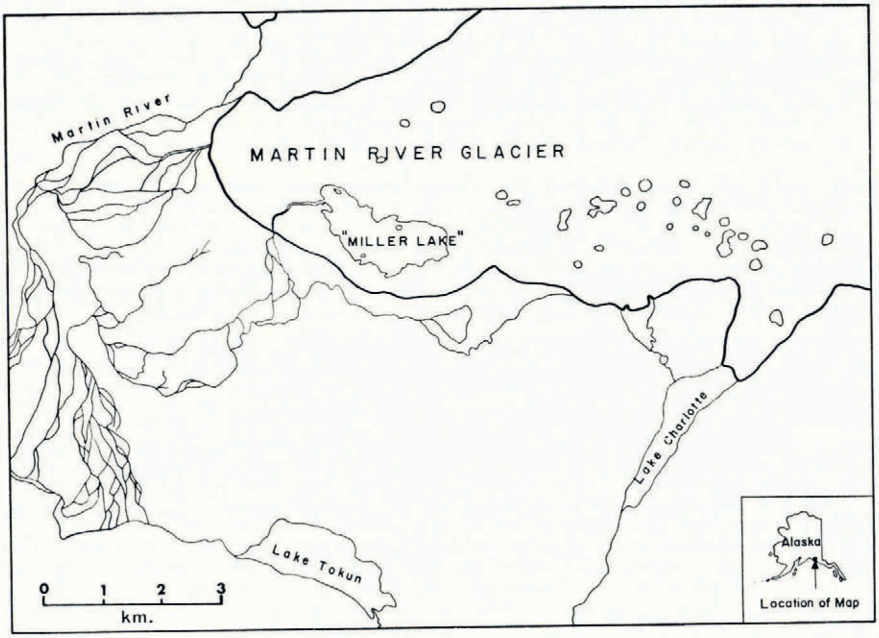

Fig. 1. Map of the lower part of Martin River Glacier, showing the location of "Miller Lake"

basin is underlain by ice located only a short distance beneath the surface. This is inferred from thermal data which show very cold water (0·1° C.) near the bottom of the lake. The bottom of "Miller Lake" is quite irregular and is characterized by steep-sided depressions and hills which in turn contain smaller similar negative and positive features. The northern two-thirds of the basin is characterized by several elongate depressions, many of which contain steep-sided hills commonly rising 20 m. above the basin floor. The south-western part of the basin exhibits a fairly extensive gently sloping littoral shelf. The present sub-circular outline of the lake has evolved from a more irregular outline characteristic of compound sink holes. The shoreline has been partly modified by wave action and calving of ice.

Thermally, "Miller Lake" is a sub-polar lake according to the classification proposed by Yoshimura (Hutchinson, 1957, p. 437). Although the mean summer surface temperature is nearly 6° C., the deeper waters are much colder, dropping to 2° C. at −10 m. and 0·1° C. at −30 m. The thermal gradient is small and the thermocline is poorly developed; temporary cooling at various times throughout the summer generally allows fairly frequent mixing of the lake waters, thereby destroying any thermal stratification.

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Icebergs

General

Perhaps the most striking feature of "Miller Lake" is the icebergs. Most of these icebergs are typically veneered with ablation till of varying lithology, particle size and abundance. Observation of the active ice cliff along the north-eastern, eastern and south-eastern margin of the lake, however, reveals that the characteristic tumbling action of calving ice allows only a trace of debris to be retained on the resultant floating ice masses. Furthermore, floating ice masses formed this way are normally only of growler size and are less than one-tenth the size of the largest icebergs on the lake which are the typical till-veneered icebergs. This mode of formation for the debris-covered icebergs was therefore deemed insufficient to account for the abundance and size of these ice masses in "Miller Lake". Another explanation was therefore sought.

Grounded iceberg origin

The suggestion that clean icebergs are blown against the ablating ice cliff, thereby receiving the ablation debris from above by mass wasting, was rejected because it assumed too much of a coincidence to justify the abundance of this type of iceberg. Furthermore, the strong storm winds were always observed to blow the icebergs away from the active cliffs, not towards them.

Differential ablation origin

Another explanation is that promontories of the irregular ice cliff become detached from the rest of the glacier through differential ablation, perhaps along incipient crevasses (Fig. 2). Eventually, the mass becomes a separate unit and is buoyed up as a "dirty" iceberg, the till veneer being the original ablation till of the terminal zone of the glacier. Examination of

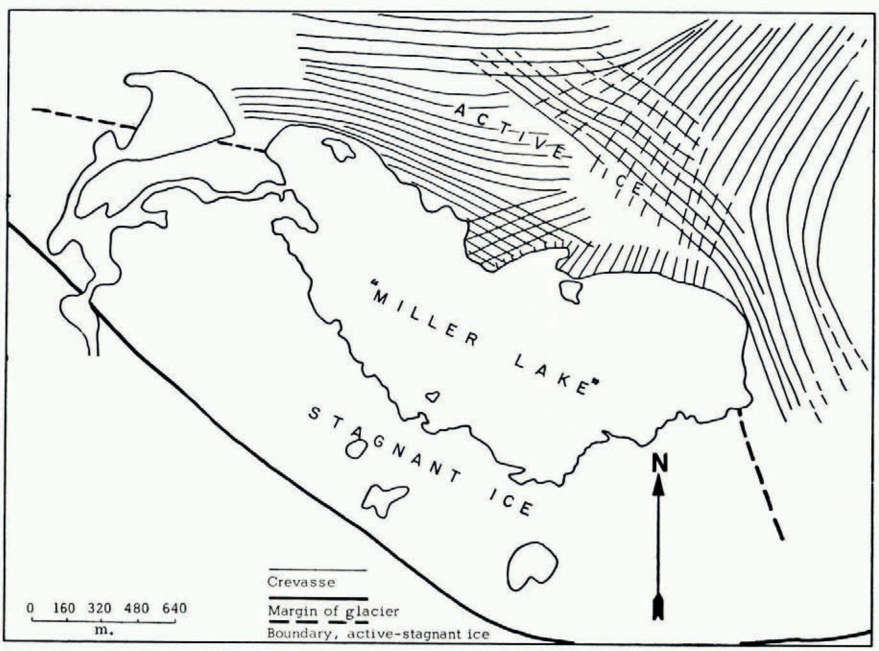

Fig. 2. Crevasse pattern and condition of the ice surrounding "Miller Lake"

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aerial photographs taken in 1950, 1957, 1959 and 1963 (Fig. 3) shows numerous such projections that have since disappeared, presumably as icebergs of this type.

Talus apron origin

A third possibility is directly related to ablation till deposited along the base of the ice cliff as talus aprons or "cones" which then inhibit further ablation of the underlying ice. Throughout the 1963 summer season several such features formed, expanded and finally became ice-cored islands when the rest of the ice cliff melted back far enough (Fig. 4). Because

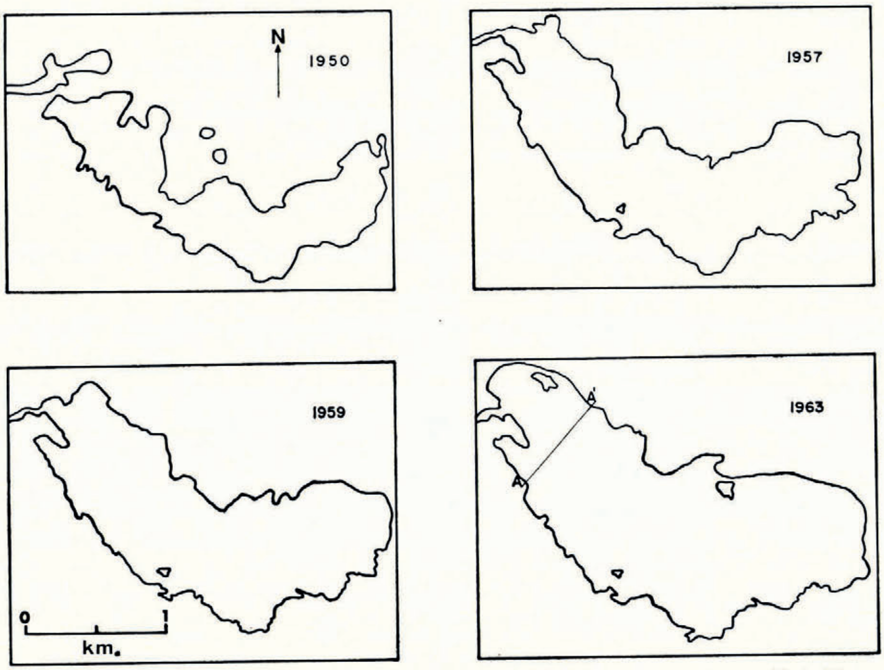

Fig. 3. Outline of "Miller Lake" in 1950, 1957, 1959 and 1963. The location of the bathymetric profile in Figure 4 is shown on the 1963 outline

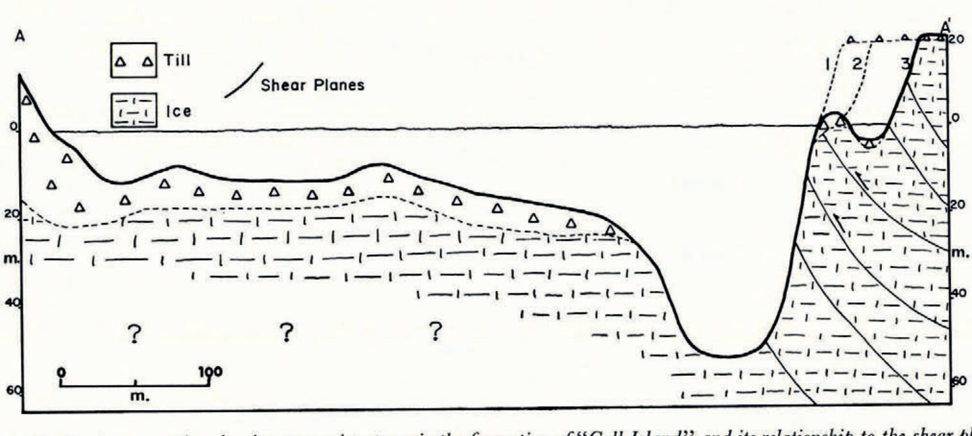

Fig. 4. Idealized cross-section showing successive stages in the formation of "Gull Island" and its relationship to the shear planes. The depression represents the site from which the iceberg emerged. The vertical scale is three times the horizontal scale

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these debris-covered islands became submerged during rising lake levels, they were concluded to be still attached to the bottom. Since most of the ablation debris from the active ice is ultimately deposited on the bottom of the lake, it was surmised that complete detachment of sub-lake ice masses and/or debris-covered islands from the active ice front might be responsible for the large ablation till-covered icebergs.

Lake bottom origin

On 14 July a new iceberg estimated to weigh between 170 and 200 tons suddenly emerged from the bottom of the lake approximately 250 m. from the active ice front. The iceberg was 30 m. wide and 350 m. long; it floated with its surface as much as 8 m. above water level. One entire side of the iceberg was covered with assorted lake sediments and glacial debris, indicating that it had rotated only slightly upon emerging from the bottom. It was surprising that so much sediment remained on the surface as washing during emergence undoubtedly removed much of what had covered the ice. Subsequent fathometer traverses revealed a hole 20 m. deep, 360 m. long, 60 m. wide, and near the site where the iceberg first emerged (Fig. 4). The violent wave action produced by the emergence of the iceberg undoubtedly forced it away from the cliff because the hole is about 100 m. closer to the ice cliff than the place where the iceberg was first measured. Although this mechanism of formation of debris-covered icebergs in "Miller Lake" is probably not as important as that of differential ablation, there is little doubt that other icebergs in the lake originated in this manner. Similar observations were made by Russell (1891, p. 101–02), who postulated an ice toe projecting 1,000 ft. (305 m.) in front of the ice cliffs. The resulting icebergs from beneath the water were sometimes 200 and 300 ft. (61 and 91 m.) in diameter and, as in the case of the "Miller Lake" icebergs, they were much larger than those produced by calving of the ice cliff. Tarr (1909, p. 31) supported the existence of such an ice projection and listed three conditions that favored the formation of the projection: "(1) The warmer water at the surface . . . causing undercutting of the ice; (2) the crevassed, weathered, and thereby weakened upper portion of the glacier; (3) the attack of waves, especially those generated by the iceberg falls." Nowhere in the literature, however, have icebergs been reported as emerging from the bottom of an ice-walled lake.

The reason for the emergence of the "Miller Lake" iceberg was puzzling. The easiest explanation would be that part of the terminus was floating and that it was, in fact, a projection which broke free and rose to the surface. However, the fathometer traverses discounted the presence of any floating projection. The second suggestion was that the ice mass became an isolated remnant as a result of differential ablation along the bottom and finally broke free. But the fathograms showed that the ice mass came from a *hole*. Had it been a remnant, the chances are that it would have been a subdued projection on the bottom prior to its separation from the bottom. This hypothesis, however, was not completely rejected.

A third suggestion was that the ice mass became separated along crevasses that were present in the ice on the bottom of the lake. It was believed that the bottom ice was not sufficiently brittle to contain crevasses. The explanation, therefore, was not immediately known. The explanation took on an added importance when a rising island was observed in the same lake.

Rising Island

General

As has been previously stated, when debris from the surface of the glacier falls into the lake, a cone or apron of talus frequently accumulates near the water line. This deposit inhibits the ablation of the underlying ice and, as the rest of the ice cliff retreats through continued ablation, the deposit may be left as an ablation till-veneered island (Fig. 4). One such island, informally called "Gull Island", had already formed by the beginning of the 1963 summer

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season. It had an area of about 60 m.^{2} above water level during this early part of the season and it attracted frequent attention because of gulls nesting there.

On 4 July 1963 the lake suddenly rose 1·35 m. This rise was presumed to be due to the draining of one of the numerous supraglacial lakes above the terminus (Reid and Clayton, 1963; Clayton, 1964). The rise of the water almost inundated "Gull Island" and definitely revealed that the island was not floating. When the large iceberg, discussed above, emerged from the bottom ten days later, "Gull Island" appeared to have risen. Although no direct measurements had been made, further rise substantiated this conclusion. The rise appeared to be steady despite additional rises of the lake level during and subsequent to periods of heavy precipitation. By the end of the summer season the island had risen approximately 4–5 m. above the level it had been 10 weeks earlier. It had also increased its surface area by as much as 200 m.^{2} even after taking into consideration lake-level changes since the beginning of the season.

Character of the bottom ice

Because it appeared that consideration of the character of the bottom ice would be of great importance in evaluating the cause of the rising island and the emerging iceberg, several caculations were made. With an average depth of about 40 m. (the bottom of the hole from which the iceberg emerged) and an average water temperature of 1° C., the hydrostatic stress (σ) on the bottom was equal to 56·9 lb./in.^{2} ($3 \cdot 87 \times 10^6$ dyne/cm.^{2}). By dividing by $\sqrt{3}$ (Nye, 1953), the resulting shear stress (τ) there was equal to $2 \cdot 24 \times 10^6$ dyne/cm.^{2}. This value of shear stress is considerably more than the 1×10^4 dyne/cm.^{2} used by Butkovich and Landauer (1960, fig. 3), and with which they measured appreciable rates of creep. Furthermore, their results were based on lower temperatures than the "Miller Lake" ice which, because of an ice-water interface, was at the melting point and therefore capable of even greater rates of creep.

Another aspect of ice that is brought from depths is the sudden change in the relationship of the temperature to the pressure-melting point. Since ice at a depth of 40 m. is under a pressure of 3·87 atmospheres, the melting point is lowered by approximately 0·04° C. Furthermore, because the ice at the bottom is in direct contact with water, it must be at the pressure-melting point. If this ice were to be suddenly brought to the surface, as occurred when the iceberg was formed, the melting point would be raised above the temperature of the ice and it would therefore freeze harder due to the release of water pressure. When the iceberg was investigated the morning following its emergence, the canvas raft that was used to reach the iceberg froze to the surface of the ice even though the air temperature had never dropped below 7·2° C. that night. This freezing confirmed the supposition.

Mode of Ice Flow

In a system in which a glacier terminates in water, the forward advance of the terminus is determined largely by calving, and melting by direct and indirect radiation. Where the terminus is not floating, calving may still occur. The rate of this calving will be determined by the abundance and distribution of crevasses as well as by the rate of undercutting at the water line. The ice below the water line will ablate at the same rate as the rest of the ice cliff only if the water temperature is high enough. Such is not the case for "Miller Lake"; the water temperature is rarely above 1° C. except for the upper few centimeters on warm calm days when the surface temperature may locally reach 15° C.

The result of these two factors is a more rapid ablation of the upper ice cliff by both surface melting and calving due to undercutting by the relatively warm surface waters in the lake. The end result may give the erroneous impression that the ice beneath the water is flowing faster than the rest of the ice cliff, a condition which might be interpreted as extrusion flow

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(Demorest, 1943, p. 364–73). A more reasonable interpretation is that the ice is undergoing compressive flow (Nye, 1952), though no sub-glacier profiles have yet been determined to confirm, for example, the presence of a rising bedrock floor. The terminal boundary of the active ice must exist somewhere between the ice cliff and the other side of the lake where only ablation till-veneered dead ice is found. Obstruction to normal flow should cause shearing of the active ice over the inactive ice, similar to shearing of the terminus of the Greenland Ice Sheet at TUTO (Bishop, 1957).

Examination of the iceberg a few hours after it had emerged from the bottom of the lake showed numerous shear planes which indicate that flow by shearing must have occurred sometime during the recent history of that ice. Since differential flow and related recrystallization would rapidly destroy or distort these planes of shear, they must have formed near the zone in which they were observed. They therefore support the idea that shearing by compressive flow is actively taking place near or along the bottom of "Miller Lake" (Fig. 4).

It is by this mechanism that separation of the mass of ice from the bottom was initiated, and it is by this mechanism that a vertical component forced the ice island to rise. Whether or not the entire lake is bottomed by ice is not known, but this mode of flow implies its presence throughout.

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