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THE NATURE AND ORIGIN OF A JÖKULHLAUP NEAR CASEY STATION, ANTARCTICA

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Abstract. A jökulhlaup event of 6 months duration occurred near Casey Station, Law Dome, Antarctica, in late March (austral autumn) 1985. This was followed by sporadic outbursts during the austral autumn and winter of 1986. The event is the first recorded outburst of water from beneath a cold ice-cap terminus on Law Dome and, to the author's knowledge, in Antarctica. From the results of oxygen-isotope and solute analysis, the water was found to have originated as basal melt water. It contained a high total solute load with a dominant enrichment in alkalis, indicting that it had been squeezed through subglacial sediments for an extensive time period. Evidence from the subglacial topography, basal ice exposures, and the sedimentology of nearby supraglacial moraines supports the presence of an ice-marginal subglacial water reservoir as the jökulhlaup source.

INTRODUCTION

The Law Dome ice margin abutting the Windmill Islands near Casey Station (Fig. 1) is characterized by the morphology of a thinning ice cap. From the seaward edge of the margin, a 2 km wide stagnant cold-ice ramp 40–150 m thick rises to an elevation of 150 m a.s.l. At this elevation, a 17 km long transverse supraglacial moraine complex, known as the Løken Moraines, is situated. These ice-cored moraines are the surface expression of emergent basal debris bands and are located on thrust planes in the ice. Their raised relief above the surrounding ice is due to differential melting. Up to four parallel moraine ridges have successively developed inland as a result of surface down-wasting and thinning of the ice sheet during the Holocene. The inland edge of the moraines locates the present boundary of the emergent active ice and the stagnant ice ramp.

In late March 1985, a sudden outburst of water or jökulhlaup erupted from a point midway down the ice ramp 2.5 km east of Casey Station (Fig. 2). The event continued for 6 months, through the austral winter period, and terminated in early October 1985. A similar event erupted from the same site in late April 1986 and continued sporadically until early September 1986.

There have been no previous jökulhlaup events observed on Law Dome and, to the author's knowledge, on the Antarctic continent.

The aim of this paper is to describe the nature of the jökulhlaup event and the results of investigations made into the origin and source of the jökulhlaup water.

THE NATURE OF THE JÖKULHLAUP

Over a period of weeks prior to the jökulhlaup, the normally crevasse-free ice ramp was fractured by a group of parallel crevasses 0.2–0.3 m wide, striking across slope. These crevasses formed on the line of vertically dipping 0.2–0.3 m wide, structural foliations which consisted of clear bubble-free ice. The fracturing was coupled to a dome-shaped uplift which elevated a $20 \times 10^3\ m^2$ area of ramp ice 4 m above the surrounding surface. Figure 3 shows the topography of the ramp affected by the uplift and Figure 4a and b shows topographic cross-sections of the uplift illustrating the dome shape. The jökulhlaup initially erupted as a 1–2 m high water spout from the major crevasse at the apex of the dome (C4). It is believed that the foliations provided a structural weakness through which the pressurized water melted a passage to the surface.

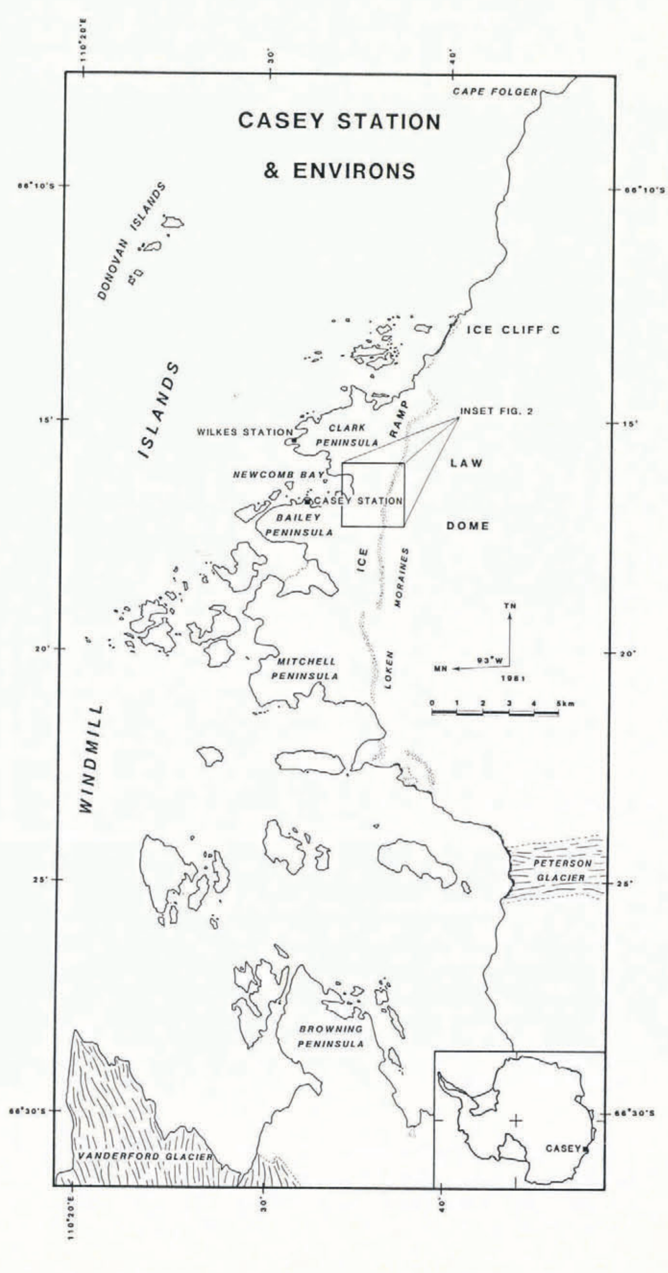

Fig. 1. The Law Dome ice margin abutting the Windmill Islands, near Casey Station.

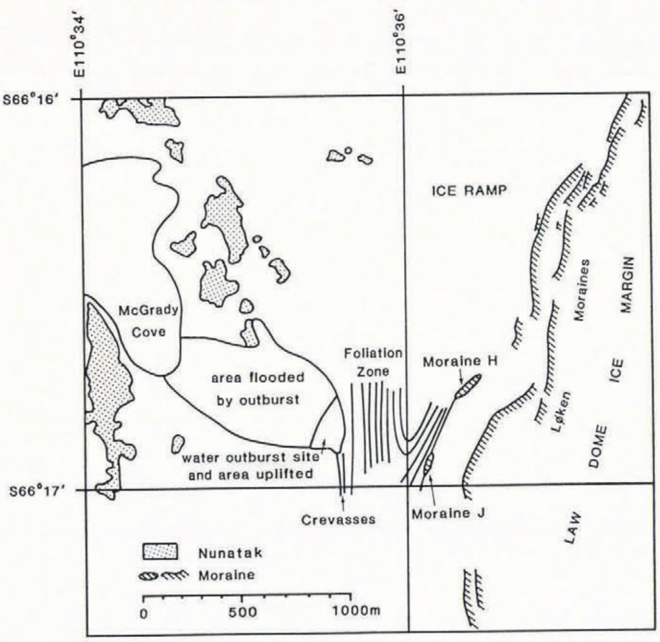

Fig. 2. The morphology of the Law Dome ice margin adjacent to the jökulhlaup site, showing the Løken Moraines, the foliation zone, the outburst site and uplift area, and the ice-ramp area flooded by the outburst.

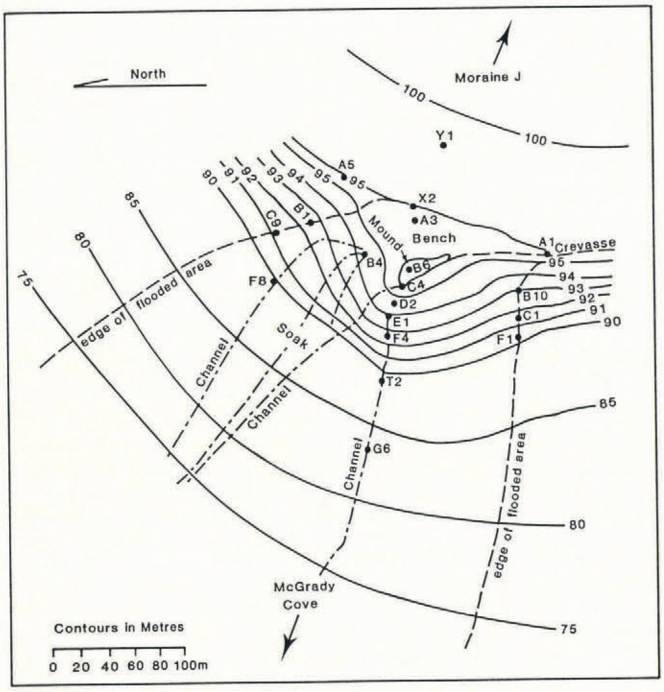

Fig. 3. The morphology of the jökulhlaup site, showing the major crevasse and original point of issue C4, and the uplift zone delineated by the 90 m and 95 m contours. Also shown are the location of the major conduits B4 and E1, and their associated channels together with the radial flow boundaries of the upper ice-ramp area flooded by the outburst. The locations of the profiles shown in Figure 4 are also shown.

As the outburst proceeded, the water issued with fluctuating pressure from a series of springs near C4. This saturated the new bench area between C4 and X2 to a maximum depth of 0.4 m. Most of the surface springs froze over when the air temperature fell below −15°C, and 1–5 m diameter heaving mounds formed as a result of the volume expansion of the freezing spring water. The development of these mounds blocked the outflow of water directly as springs forcing the water through a network of veins and conduits, to emerge primarily as sheet flow and secondarily in two major channels 0.3 m × 0.3 m below the bench areas. The water flowed radially from the apex down the ramp following the surface slope to the crevassed ice cliffs abutting McGrady Cove (Fig. 5). This flooded a triangular-shaped area 0.3 km^2 to an average depth of 0.25 m, creating a surface water storage of 75 × 10^3 m^3. The water outburst at its estimated peak flow was discharging at approximately 1 m/s from conduits at B4, C4, and E1. The major channel at B4 was exposed to the air throughout the winter period, forming a soak 50 m wide down the ramp. Numerous oxbow lakes occupied local depressions in the slope. In June (winter) 1985, the measured temperature of the water issuing from a spring near C4 was 0.0°C with an air temperature of −20.5°C.

The difference between air and jökulhlaup water temperatures resulted in a remarkably strong heat shimmer over the flooded surface. The majority of the flooded area excepting the three major channels was covered by a 5–10 mm thick refrozen ice sheet which was criss-crossed by a maze of thermal fractures and heaving mounds. These features are commonly found on melt lakes throughout the winter. Characteristic of the refrozen jökulhlaup water was its olive-green color, which contrasted sharply with the surrounding blue of the glacial ramp ice.

An estimate of total water discharge was impossible to make due to the rapidly changing morphology of the outburst site and the unpredictable opening and closure of both the springs and internal veins and conduits. Towards the end of the 1985 event the points of issue were observed to migrate down-slope from C4 to a point near T2 as the upper conduits closed, following an abrupt decrease in water pressure. It is probable that the decrease in water pressure resulted from a lowering in the ice cap's reservoir level.

CHEMICAL COMPOSITION AND ORIGIN OF THE WATER

To determine the origin of the water, oxygen-isotope and solute analyses were carried out on water samples collected on 17 June 1985 (winter) (sample JA) and 7 October 1985 (spring) (sample JB) from the jökulhlaup springs.

Oxygen-isotope analysis of the water produced a $\delta^{18}O$ value of −23.8‰. Surface melt waters on the ramp have an oxygen-isotope value of −15‰ to −16‰ as a result of the mixing of melt water derived from emergent glacier ice and locally precipitated snow. Consequently, the relatively cold −23.8‰ value for the jökulhlaup water suggests that it is derived entirely from glacial ice. Furthermore, the −23.8‰ value when compared to an oxygen-isotope depth profile for the BHC2 core drilled at Cape Folger (Fig. 6), 20 km north of the jökulhlaup site, corresponds to glacial ice at 300 m depth. Morgan and McCray (1985) estimated that the age of ice at this depth in the Cape Folger core is 14 000 years, which pre-dates the last glacial maximum ice.

Solute analysis of the water samples involved the measurement of the major ions Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, NH_4^-, and HCO_3^- (total alkalinity) together with pH and conductivity. The results for samples JA and JB are listed in Table I. For purposes of comparative analysis, the solute compositions of: (1) glacier ice from 300 m depth in the Cape Folger core (Johnson and Chamberlain, 1981); (2) bubble-free regelation ice (C1) from a basal sequence shown in Table II cropping out in a nearby cliff; and (3) the bulk melt waters of two Antarctic glaciers, Lower Taylor and Lower Wright Glaciers (Keller and Reesman, 1963) are also shown. The chemical concentration in the Cape Folger glacier ice at 300 m depth is in the order of parts per billion (ppb) for the major ions Na, K, Ca, and Mg. The concentration of Na is dominant by a factor of 10. Murozumi and others (1978) found these characteristics to be indicative of Antarctic precipitation and its marine origin. By comparison, analysis of the jökulhlaup water, which is suggested to have been derived from glacier ice of the same precipitation age, shows a massive solute enrichment, which is a factor of 1000 greater than the glacier-ice concentrations. The total solute load Σ^+ for the jökulhlaup water is 7 meq l^{-1} which is over twice the maximum Σ^+ value for glacial melt waters, reported by

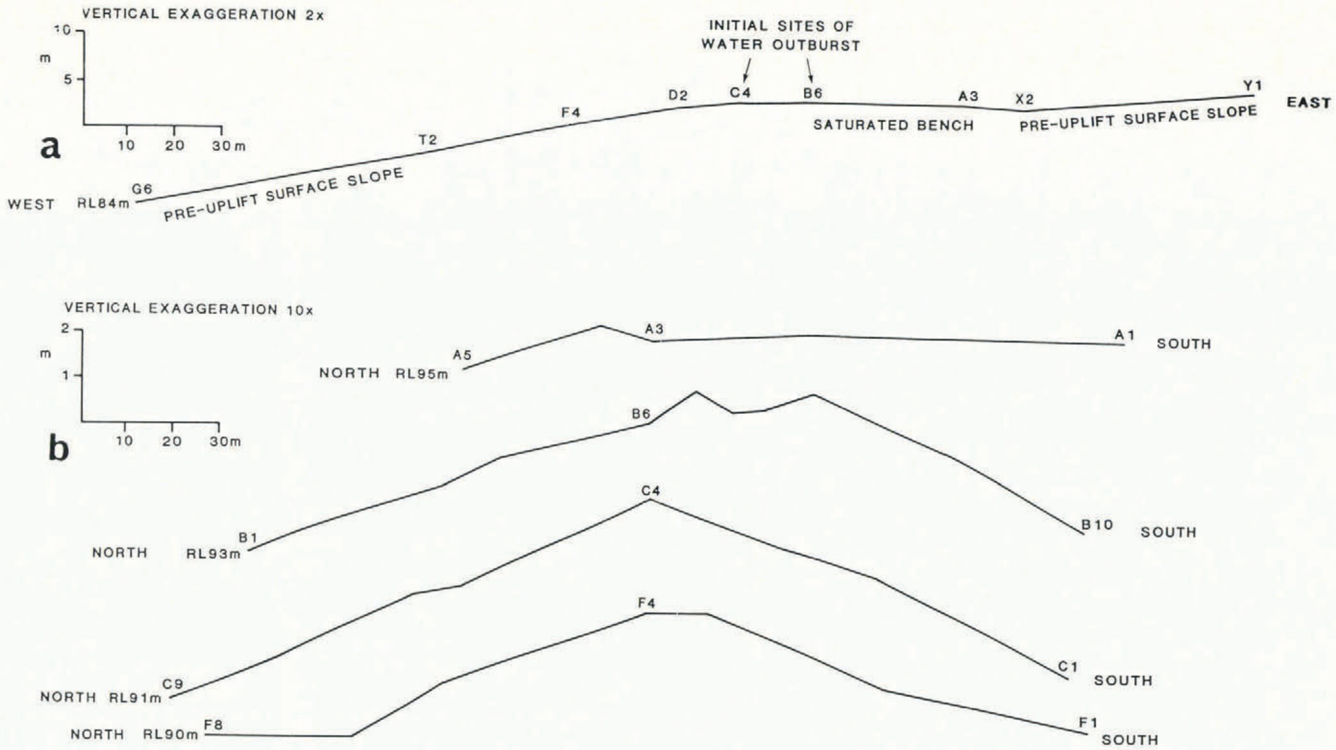

Fig. 4. a. Longitudinal ice-surface profile of the uplift zone showing the dome shape between T2 and X2, with the apex at C4. b. Transverse ice-surface profiles of the uplift zone.

Fig. 5. Part of the flooded ice ramp, during the jökulhlaup in the 1985 austral winter. The surface is covered by a 10 mm thick ice crust consisting of refrozen jökulhlaup water. McGrady Cove is in the background.

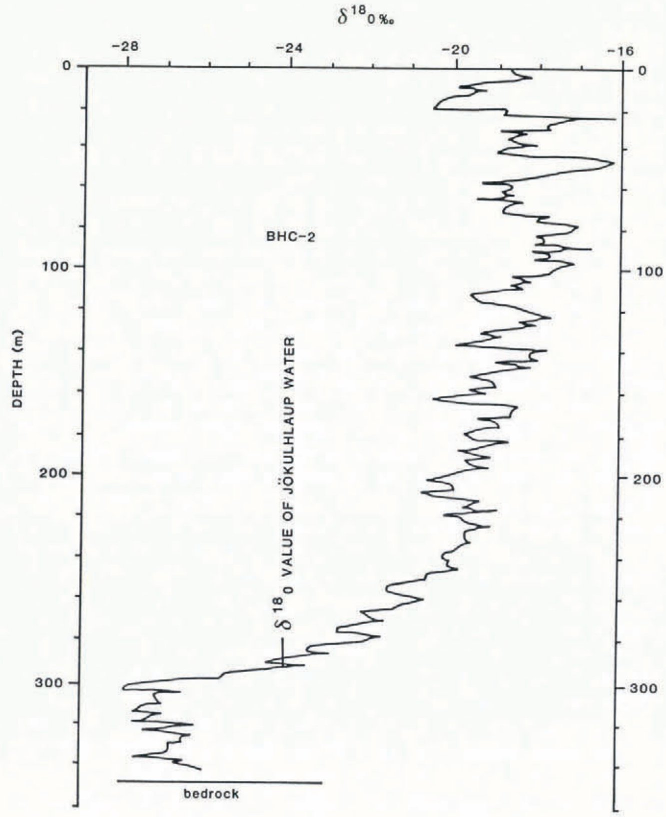

Fig. 6. Oxygen-isotope–depth profile for the Cape Folger (BHC-2) core, showing the $\delta^{18}O$ of the jökulhlaup water.

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TABLE I. SOLUTE AND PHYSICAL ANALYSIS OF JÖKULHLAUP WATER AND ANTARCTIC COMPARISONS

Composition		*JA*	*JB*	*C1*	*Cape Folger core*	*Lower Taylor Glacier*	*Lower Wright Glacier*
Na	mg l^{-1}	151.0	148.0	1.00	0.10	6.90	2.14
K	mg l^{-1}	8.0	8.1	0.12	0.01	1.14	0.40
Ca	mg l^{-1}	1.83	1.87	0.23	0.01	17.90	0.00
Mg	mg l^{-1}	1.95	2.14	0.09	0.02	0.94	0.09
NH_4	mg l^{-1}	0.01	<0.01	<0.01			
SO_4	mg l^{-1}	25.0	26.4	0.43			
NO_3	mg l^{-1}	<0.01	<0.01	<0.01			
Cl	mg l^{-1}	77.7	74.4	1.07			
HCO_3^-	meq l^{-1}	3.52	3.45	0.02			
pH		8.37	8.50	6.19			
Conductivity	μS cm^{-1}	565	590	6.0			
Σ^+ meq l^{-1}		7.03	6.91	0.07	0.01	1.30	0.11
(Na + K)/(Ca + Mg) meq l^{-1}		26.88	24.61	2.47			

TABLE II. ICE CLIFF C BASAL DEBRIS/ICE SEQUENCE

Layer	*Depth*	*Description*
C1	0.0–0.9 m	Clear bubble-free regelation ice
C2	0.9–2.2 m	Alternating sorted clay–sand-sized debris bands with clear bubble-free regelation ice
C3	2.2–2.7 m	Solid sediment with interstitial ice lenses and dominant fine fractions surrounding lodgement boulders and pebbles

Raiswell (1984) following his analysis of 40 melt-water systems. This exceptionally high solute load is indicated further by a high pH of 8.5, a total alkalinity of 3.5 meq l^{-1} and a conductivity of 580 μS cm^{-1}. This is thought to be responsible for the olive-green color of the refrozen water. The type and concentration of chemical species found in the jökulhlaup water suggest that the source of the enrichment is the weathering of geological materials (Lyons and Mayewski, 1984).

These analyses suggest that the jökulhlaup water originated as basal melt water active in the chemical erosion of the subglacial terrain. To investigate the character of the subglacial terrain and the processes controlling the solute enrichment of the jökulhlaup water, the ratio between alkali (Na + K) and alkaline-earth (Ca + Mg) content has been calculated for each of the Law Dome samples together with those for Lower Taylor and Lower Wright Glaciers.

The (Na + K)/(Ca + Mg) ratio value of the solute-rich jökulhlaup samples JA and JB are 12 times higher than the values for the Cape Folger glacier ice and basal regelation ice C1 and are twice the relatively high value for Lower Wright Glacier and a factor of 80 higher than Lower Taylor Glacier. Souchez and Tison (1981) attributed such an increase in ratio values to the advanced monovalent/diavalent separation of cationic species, as interstitial water is squeezed through fine-grained subglacial sediments with a significant clay-size fraction. This process of ion exchange allows the water to exchange diavalent ions (Ca^{2+}, Mg^{2+}) for monovalent ions (Na^+, K^+) with the clay minerals, thus increasing the Na^+ and K^+ content of the melt water.

Stratigraphic observations made on basal ice exposures in ice cliffs along the Law Dome margin recorded debris/ice layer sequences similar to that shown in Table II for ice cliff C. These exposures are extensive both in the ice cliffs and as supraglacial moraine formations. Analysis of the (Na + K)/(Ca + Mg) ratio for the jökulhlaup water suggests that the water has been squeezed through the interstitial pore spaces of a solid sediment layer similar to layer C3 shown in Table II. The extremely high ratio value and total solute load for the jökulhlaup water indicate its extensive contact with clay-sized sediment layers and long residence time in the subglacial drainage system. This implies that a saturated sediment layer may exist over a large area beneath Law Dome. The dilute solute load and location of the 0.9 m thick regelation ice layer C1 overlying the saturated sediment layer C3 suggest that basal melt water may be discharged beneath Law Dome by both regelation and water-squeezing processes if the solid sediment layer is oversaturated.

SUBGLACIAL MORPHOLOGY AND THE POSSIBLE JÖKULHLAUP SOURCE

A preliminary topographic and gravity survey was carried out during 1985 to investigate the subglacial morphology for a possible source of the jökulhlaup water. These surveys extended earlier ice-margin surveys carried out in 1958 and 1962. Ice thicknesses calculated from the gravity surveys have a relative accuracy of ±5 m and an estimated absolute accuracy of ±10 m. A broad representation of the subglacial morphology is given in Figure 7. The subglacial morphology is dominated by three

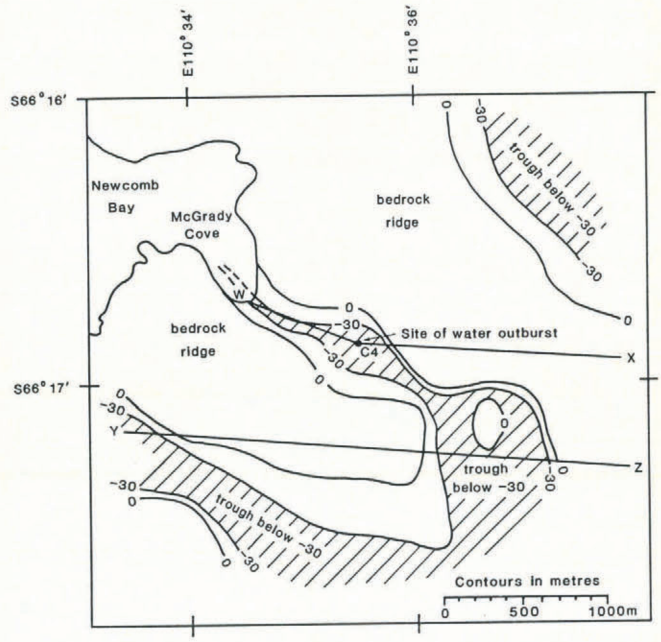

Fig. 7. The subglacial morphology of the Law Dome ice margin, showing the three troughs beneath the ice ramp and the location of the −30 m contour indicating the possible extent of a subglacial water reservoir below this level. Also shown are the locations of subglacial bedrock profiles WX *and* YZ *illustrated in Figure 8.*

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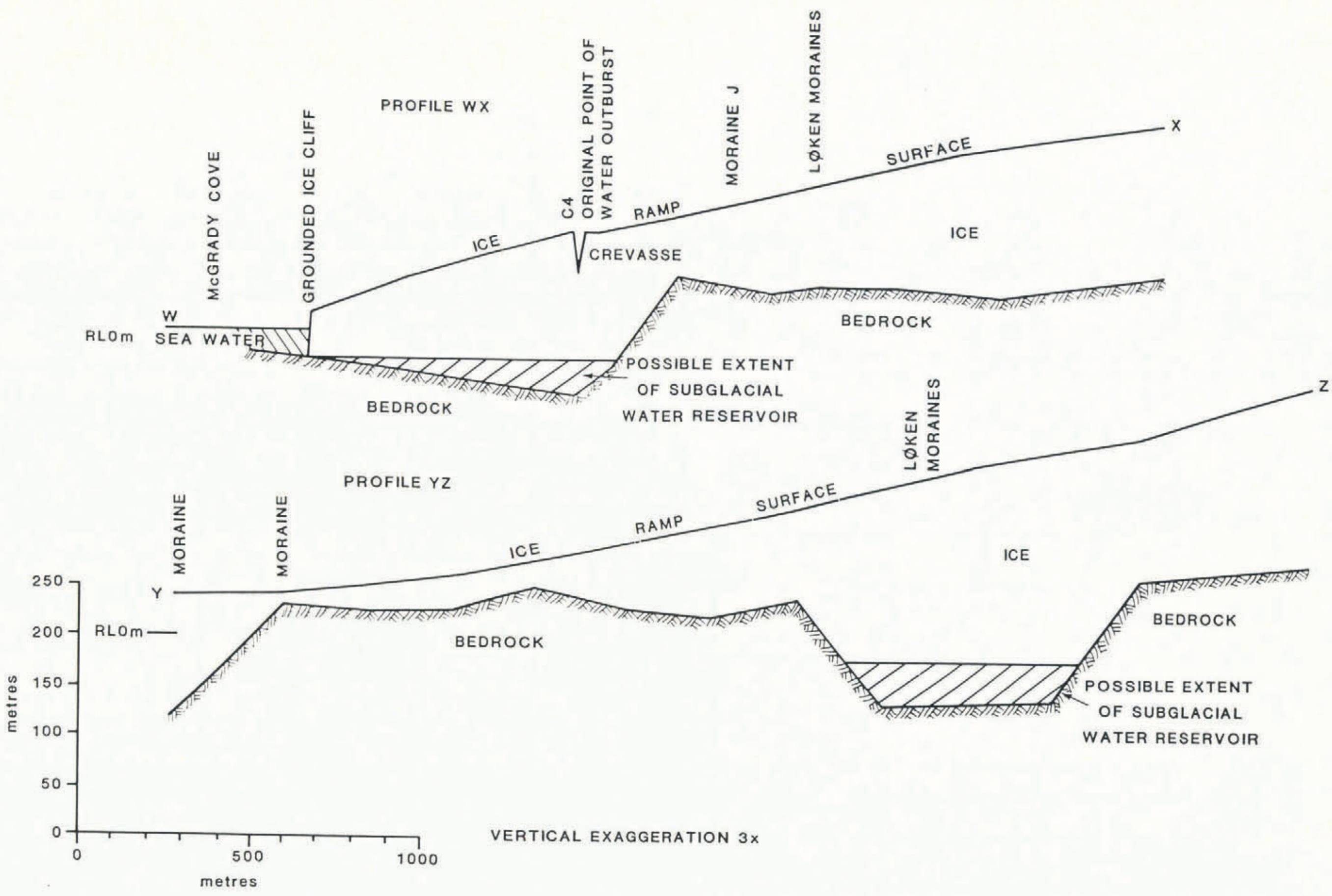

Fig. 8. Ice-ramp surface and subglcial bedrock profiles WX *and* YZ, *showing the possible extent of the subglacial water reservoir.*

major trough-shaped depressions, two of which are subglacial extensions of embayments in Newcomb Bay. The depth of these troughs is between 60 and 80 m below sea-level, and their orientation is parallel to the ice-movement direction at the last glacial maximum (Cameron and others, 1959). Figure 8 shows two ice-surface and subglacial bedrock profiles WX and YZ which transect the trough extension of McGrady Cove. Profile WX shows that the jökulhlaup site C4 is located vertically above the trough whose depth is 63 m below sea-level. Down-stream from this point the bedrock delineates a reverse gradient to the ice margin where the 15 m high ice cliffs are grounded at a depth between 25 and 30 m below sea-level. Profile YZ shows the up-stream extension of the trough at a depth of 68 m below sea-level. It is probable that the reverse bedrock gradient combined with the grounded ice cliffs form a potential barrier to the subglacial melt-water flow. This would result in the development of a subglacial water reservoir up to 35 m deep, similar to the type discussed by Björnsson (1975).

However, since there is no direct evidence for the existence of a subglacial water reservoir, further investigations were made of the basal ice and supraglacial moraines up-stream of the jökulhlaup site for supporting evidence on subglacial water drainage. These investigations revealed that moraines J and H located 400 m apart on a clear, vertically dipping ice foliation, 500 m up-stream of the jökulhlaup site C4, exhibited sedimentological characteristics unique to the remainder of the Løken Moraines and are indicative of the hydraulic action of subglacial water, as discussed below.

Moraines J and H are composed entirely of unweathered, fractured homogeneous granitic rock similar to the lithologies exposed at the base of the ice ramp. This strongly suggests that these moraines were derived from a local source. Vertically dipping, boulder-sized blocks comprise the majority of moraine J and are up to 1.5 m in diameter. They have extremely angular corners, showing little or no wear from transport or contact with the zone of traction over the bed (Fig. 9). In addition, Figure 10 shows the extremely angular sediment-shape distribution of moraine J based on the roundness measurement of 100 pebbles using the index of Cailleux and Tricart (1963). Three smaller moraines consisting of the same angular, homogeneous material also crop out along the 400 m exposure between moraines J and H. In 1958, Hollin and others (1961) observed boulders melting out of the ice ramp forming moraine J. They noted that clay was still compacted to the unoxidized boulders, and that some were so precariously poised that their exposure had been extremely recent. The net accumulation of winter snows around moraine J in the intervening years between 1958 and 1985 have protected the material from significant frost-shattering. Boulton (1978) stated that a very angular composition which is similar to moraine J is indicative of supraglacially derived debris clasts which have been transported englacially. Since there are no nunataks on Law Dome and the angularity of the material is not derived from surface frost-shattering, it is probable that the material in moraine J originated from subglacial bedrock plucking. Subsequent englacial transport by the upward shear of the inland ice would explain the lack of wear on the boulders. The close proximity of boulders partially melted out in moraine J together with a dolerite band in each of the boulders, allows the boulders to be visually pieced together to form one 50 m long slab of rock. It is the strength of this evidence that suggests the material in moraine J originated from the plucking of a single sub-glacial bedrock slab, near the ice margin.

Röthlisberger and Iken (1981) found that similar large slabs of rock could be plucked from the bedrock as a result of rapid basal water-pressure variations, induced when melting or lake drainage surmounts the capacity of the subglacial drainage system. They suggested that high water pressure in lee bedrock cavities results in rapid glacier displacement capable of plucking large slabs of rock into the cavity. These are subsequently incorporated on to the glacier sole as a result of a heat-pump effect (Robin, 1976)

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Fig. 9. Supraglacial moraine J *in profile showing the angularity of the dolerite and granite boulders, together with the possible matching of adjacent boulders. Each division on the markers is 10 cm long.*

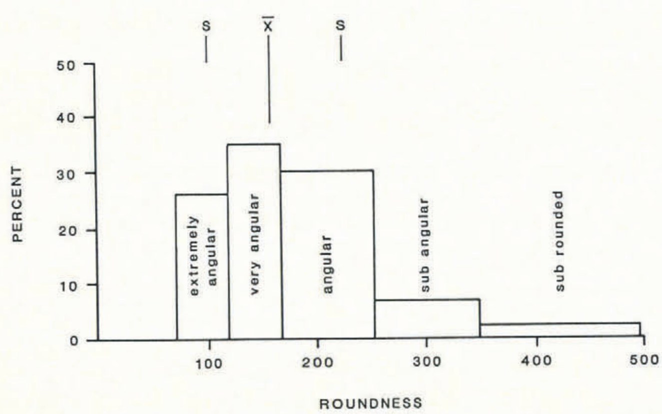

Fig. 10. Sediment-shape distribution for moraine J *based on the roundness index of Cailleux and Tricart (1963) for 100 pebbles.*

where regelation occurs due to a decrease in water pressure.

The above evidence indicates that the subglacial environment up-stream of the jökulhlaup site has been subject to strong water-pressure variations. Analysis of both the horizontal ice-movement direction from the accurate shape of the foliations and moraines, together with the vertical dip of the foliations, suggests that this subglacial area is within the major trough up-stream of profile YZ. Furthermore, this supports the suggestion of a dynamic subglacial drainage system as the source of the jökulhlaup water. However, the triggering mechanism of the jökulhlaup remains uncertain due to insufficient data on the subglacial morphology and extent of the reservoir. One possible mechanism for the outburst is the development of a migrating freeze front following the progressive surface down-wasting and thinning of the present ice margin. It is probable that melt-water overflow from the subglacial reservoir was previously discharged into the sea through conduits at the ice/bedrock interface beneath the McGrady Cove ice cliffs. With the development and migration inland of a freeze front, these conduits may have closed, forcing the reservoir level to rise which decreased the potential barrier. Consequently, a combination of decreasing water-storage volume and continuing melt-water flow into the reservoir would create high hydrostatic water pressures capable of discharging water through structural weaknesses in the ramp.

CONCLUSIONS

Previous reports of water discharging from beneath cold glacier termini have been confined to observations of up-welling turbid water, presumably of subglacial origin, in front of tide-water glaciers (Paterson, 1986). This unique observation of an Antarctic jökulhlaup event provides previously unreported evidence for the discharge of water from beneath a cold ice-cap terminus on land. Surface investigations of the ramp ice and the ice cliffs abutting McGrady Cove revealed no evidence for a previous event and hence no pattern of cyclic discharge, which is often associated with jökulhlaup reports worldwide. This lack of evidence for periodicity of discharge events prior to the 1985 and 1986 cycle suggests that the Casey Station jökulhlaup was initiated by recent changes to the physical nature of the ice margin, the subglacial drainage system or an increase in subglacial melting rates. Since the surface morphology indicates a progressive thinning of the ice margin, a plausible mechanism for the jökulhlaup events is water expulsion resulting from the development of an inland-migrating freeze front. However, until further field work has been completed, the triggering mechanism of the jökulhlaup remains uncertain.

Chemical and isotopic analysis of the jökulhlaup water determined its origin as basal melt water which had been derived from the melting of ice from before the last glacial maximum. The solute analysis revealed a large solute enrichment dominated by the alkali ions Na^+ and K^+. This alkali dominance indicated that the water had been squeezed through fine-grained subglacial sediments with a significant clay-sized fraction. The combination of a large total solute load and alkali dominance of the solutes probably results from a long residence time in the subglacial drainage system and extensive contact with clay-sized sediment layers. This implies that a saturated sediment layer may exist over a large area beneath Law Dome.

An ice-marginal subglacial reservoir is suggested as the storage source of the jökulhlaup water from investigations of the subglacial topography, basal ice exposures, and sedimentological characteristics of adjacent supraglacial moraines. The extent and depth of the reservoir are relatively unknown. Further field work is proposed to define the morphology of this subglacial reservoir and to determine the subglacial hydrological regime beneath the Law Dome ice cap.

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