Journal of Glaciology, Vol. 18, No. 80, 1977

ARTIFICIALLY INDUCED THERMOKARST IN ACTIVE GLACIER ICE: AN EXAMPLE FROM NORTH-WEST BRITISH COLUMBIA, CANADA

By N. Eyles* *and* R. J. Rogerson
(Memorial University of Newfoundland, St John's, Newfoundland, Canada)

Abstract. Warm waste water, at 30°C, has been discharged from a copper concentrater on to the active terminal ice of Berendon Glacier, British Columbia, since 1970. As a result, rapid basal ice melt causes the formation of caverns and subsequent collapse features referred to as glacier thermokarst. A review of the literature reveals that such features have been described elsewhere from active ice, and the usual conditions assumed for the development of glacier thermokarst (stagnant, heavily debris-covered ice) should be redefined to include these examples.

Résumé. *Thermo-karst provoqué artificiellement dans la glace de glacier actif: un exemple dans le Nord-Ouest de la Colombie Britannique, Canada.* De l'eau chaude résiduelle à 30°C a été déversée à partir d'un concentrate de cuivre dans la langue terminale active du Berendon Glacier, B.C., depuis 1970. Il en est résulté une fusion rapide de la glace basale qui a provoqué la formation de cavernes et des manifestations d'effondrement constituant un thermokarst glaciaire. Une revue de la littérature révèle que de tels comportements ont été décrits ailleurs de la part de glaces actives et que les conditions habituellement jugées favorables au développement de thermokarst glaciaire (glace stagnante, lourdement chargée de moraine) devraient être révisées afin d'inclure ces exemples.

Zusammenfassung. *Künstlich erzeugter Thermokarst in aktivem Gletschereis: ein Beispiel aus Nordwest-British-Columbia, Kanada.* 30°C warmes Abwasser wurde seit 1970 aus einer Kupfer-Aufbereitungsanlage auf das aktive Zungeneis des Berendon Glacier, British Columbia, abgeleitet. Die dadurch hervorgerufene rasche Abschmelzung von Untergrundeis führt zur Bildung von Hohlräumen und mit deren Einbruch zu Erscheinungen, die als glazialer Thermokarst bezeichnet werden. Die Durchsicht der Literatur lässt erkennen, dass solche Erscheinungen in aktivem Eis schon anderweitig beschrieben wurden. Die Bedingungen, die gewöhnlich für die Entwicklung von glazialem Thermokarst angenommen werden (stagnierendes, stark mit Schutt bedecktes Eis) sollten so erweitert werden, dass auch das genannte Beispiel erfasst ist.

Introduction

Within a few hundred metres of the terminus of Berendon Glacier, British Columbia, a copper processing plant has operated for 5 years (1970–75). Warm waste water, at 30°C, is discharged directly on to the glacier margin. Collapsed caverns, ice-walled canyons, natural bridges and caves have developed in an assemblage of forms normally described as glacier thermokarst (French, 1976). This paper reviews the conditions associated with glacier thermokarst, examines the evolution of Berendon Glacier thermokarst over 5 years and summarizes the effects of pumping warm water on to an active glacier terminus.

Glacier thermokarst

Sub-surface thermal erosion by melt water of caverns and a variety of subsequent collapse features in glacier ice are now often expressed as analogous to those developed in limestone terrane (Embleton and King, 1968) and the term "thermokarst" has been used to describe the karst process in glacier or ground ice (Sweeting, 1972; Healy, 1975; French, 1976). Clayton (1964) was the first to consider the topography of stagnant glaciers in terms of a karst cycle. "Ice-sinks" formed by roof collapse of subglacial caverns, natural bridges and blind valleys were described on stagnant ice of Malaspina and Martin River Glaciers, Alaska. It is held generally that, for glacier thermokarst to develop, glacier ice must be stagnant and heavily mantled with supraglacial debris (Clayton, 1964; Embleton and King, 1968; Jennings, 1971; Sweeting, 1972); the absence of glacier movement and a thick protective debris layer allows englacial and basal melt to predominate over surface melt rates. The

---

* Present address: School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, England.

surface morphology is controlled subsequently, from below, by the sub-surface pattern of ice wastage. Basal melt rates in temperate valley glaciers are normally low (Paterson, 1969) and a thick debris cover is a necessary factor in retarding surface-ice ablation. Thick debris covers are usually associated with inactive ice of terminal areas possessing low surface gradients and where ice-cored moraines may be a feature of the ice margin. In such conditions, thermokarst may be a natural mechanism for de-icing ice-cored moraines (Healy, 1975).

Where ice is active and relatively debris-free, enhanced basal and englacial melt rates may occur as a result of the release of ice-dammed water (Mougin, 1934; De Boer, 1949), volcanism (Thorarinsson, 1953) or concentrated channel flow by melt waters on ice margins or termini where ice is thin and where enhanced basal melt is more likely to be expressed at the surface (Haefeli, 1951; Paige, 1956; Loewe, 1957; Lliboutry, 1964–65). These have not normally been considered criteria for the development of glacier thermokarst, yet a review of the literature reveals many further examples. For example, Mougin (1934) reported glacier-surface depressions associated with the 1892 Glacier de Tête Rousse outburst near Mount Blanc. De Boer (1949) described surface depressions and associated concentric crevasse patterns from Leirbreen, Norway, where water from ice-marginal lakes had drained through subglacial tunnels which later collapsed. Thorarinsson (1953) attributed the 40 km² Grímsvötn depression in Vatnajökull, Iceland, to volcanically induced, accelerated basal melt.

Stokes (1958) described channel formation by the collapse of ice roofs at Flatisen, Norway, and a similar process may have been responsible for the large (1.5 km long) ice-walled canyon observed by Russell (1893) near an easterly margin of Malaspina Glacier. Ice-cavern collapse and ice-wall exfoliation was termed "subglacial stoping" or "block caving" by McCall (*in* Paige, 1956). Paige described stoping phenomena from the active ice of the terminal zone of Black Rapids Glacier, Alaska. There, ice canyons, with 23–30 m side walls, marked the exit of a large meandering subglacial stream revealed through cavern-roof collapse. Enhanced and strongly localized basal melt rates were expressed up-glacier in concentric crescentic crevasse patterns along the meandering course of the subglacial stream. Lliboutry (1964–65) described circular concentric crevasses from Glaciar Juncal Sud, generated at the margins of subglacial caverns. Hashimoto and others (1966) described a similar crevasse pattern from the active ice of Antler Glacier, Alaska; a type of crevassing known in the Icelandic literature as "undirvarp" (Ahlmann, 1938; personal communication from K. Thome). Halliday and Anderson (1970) reported exploration of the Paradise ice caves within Paradise Glacier, Mt Rainier National Park, Washington; collapse sinks connecting subglacial caves with the glacier surface have been described and distinguished from moulins.

Berendon Glacier: the physical setting

Berendon Glacier (lat. 56° 15′ N., long. 130° 05′ W.) occupies an eastward-facing 53 km² drainage basin in the Boundary Ranges of the northern Coast Mountains of British Columbia, one of the major metal-mining areas of western Canada. The glacier consists of North and South Arms which coalesce 2.2 km above the terminus and subsequently flow eastward into the Bowser River valley. In the terminal area, South Arm ice approaches a prominent granodiorite barrier between Summit Lake and the Salmon Glacier drainage system to the south, and Tide Lake Flats and the Bowser River drainage system to the north (Fig. 1). Summit Lake is impounded by Salmon Glacier to the south; up to the mid-1960's lake-overspill water flowed north across the divide into the Berendon Glacier basin and subsequently into Bowser River. The catastrophic drainage or "jökulhlaup" of Summit Lake to the south under Salmon Glacier has been described by Gilbert (1972, unpublished) and Mathews (1965, 1973). Annual lake levels since 1971 have not attained those reached earlier and lake-overspill waters no longer escape to the north. With further thinning and recession of Salmon Glacier, complete drainage of Summit Lake can be expected. A similar history has

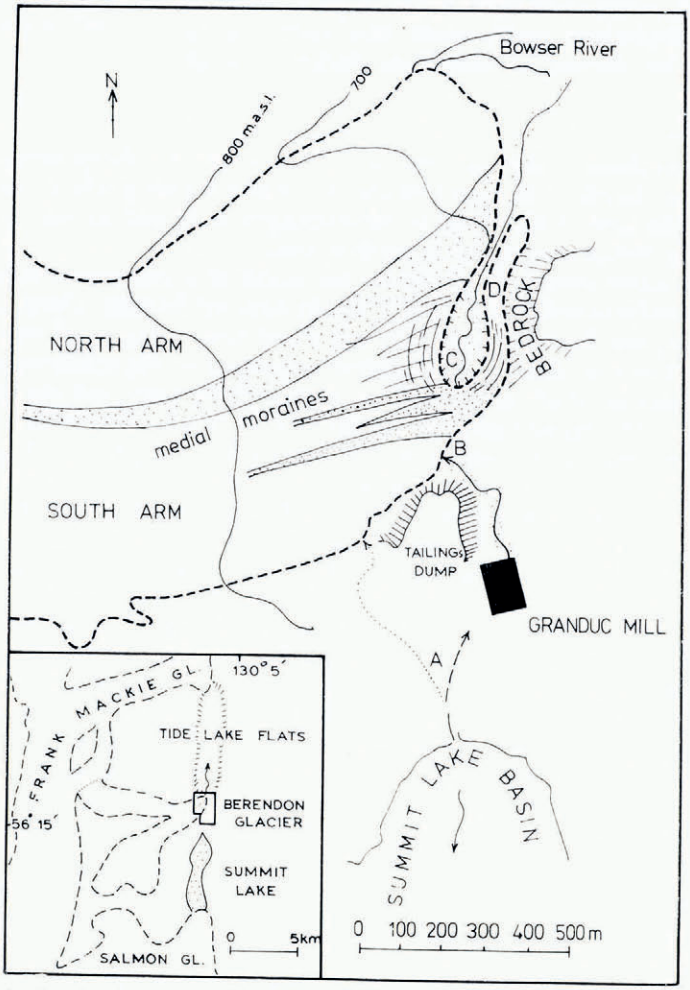


Fig. 1. Berendon Glacier, location (inset) and terminal zone. The old Summit Lake overflow stream is shown at A (dashed line), the diverted stream following Granduc construction by a dotted line. Warm mill effluent enters the ice front (at B), flows subglacially and emerges (at C) in an ice-walled channel (Fig. 2), leaving a berm of ice (D) on the lower slopes of a granodiorite outcrop whose surface dips steeply up-glacier (Fig. 3).

been attributed to Tide Lake Flats 5 km to the north, where varved lake clays and subaerially eroded deltas and the historical record provide evidence of prior glacial-lake ponding (Hanson, 1932; Haumann, 1960).

Berendon Glacier has attracted much interest recently by its proximity to copper-concentrating facilities and a mine access tunnel portal controlled by the Granduc Operating Company of Vancouver. The glacier terminus lies within 20 m of the plant which commenced full-scale production in 1970. Berendon Glacier is presently experiencing recession. The location of the mill has raised concern over the future activity of Berendon Glacier (Untersteiner and Nye, 1968; Fisher and Jones, 1971). McMechan (unpublished) has calculated the net specific balance of Berendon Glacier for the years 1968–72 and recorded more positive balances. Thus the possibility of terminal re-advance must be seriously entertained. The position of the terminus along its eastern and southern margins is controlled, unintentionally, by the release of warm waste mill water at 30°C from the copper-concentrating process. Waste water is discharged continuously year round at the rate of 13 500 l/min and has effected considerable thermal erosion of the glacier terminus.

The glacier terminus

More than two-thirds of the terminal margin butts on to a sharp break of slope, where granodiorite of the Summit Lake stock disappears beneath a deep silt-covered glacier bed.

Ice depth in the area of discussion is approximately 30 m and ice flow, which is strongly compressive in the terminal area, averages 28 m year^{-1}.

Warm waste water enters the glacier to the north of a prominent mine-tailings dump (Fig. 1). It penetrates directly to the bed of South Arm ice through a large ice cave, the side walls of which are actively exfoliating. The mill water flows to the north in a large subglacial tunnel (Fig. 2) before emerging in an ice-walled amphitheatre, the southern termination of an open ice-walled canyon which empties to the north. When inspected toward the end of the melt season (1975), the channel was undisturbed except for a roof or bridge of debris-covered ice adjacent to the terminal outcrop of a large medial moraine present along the centre line of the glacier. The mill stream occupies the canyon floor and the northward course of the mill stream is determined by the sharp break in slope between the granodiorite barrier and the glacier bed; the stream is orientated along and against the "toe" of the granodiorite. The lower bedrock slope is marked by a fringing ice berm 15 m wide and of similar depth (Fig. 3) forming the eastern containing ice wall of the canyon. Ablating, partly debris-filled moulin shafts can be distinguished in the canyon walls. The fringing ice berm is connected with active glacier ice only in the south where it adjoins terminal ice of South Arm on which prominent medial moraines crop out (Figs 1 and 3). Measurements in a subglacial tunnel under the ice berm indicate that the ice berm is sliding down the bedrock slope, i.e. exhibits up-glacier movement. Ice falls from the walls of the ice-walled canyon and the large amphitheatre are common. On the surface ice around the latter, a concentric crescentic crevasse pattern (Paige, 1956) has developed, transected by a splaying crevasse system; failure of rectangular ice blocks results and the inner margins of the canyon are marked by a chaos of fallen ice.

The development of glacier karst

Analysis of air photographs (1961–74) and field observations during 1975 permit interpretation of features found in the terminal area of Berendon Glacier.

1961 air photography (Fig. 4a) depicts a lobate ice front during the height of the melt season. Summit Lake overflow water in its passage northward into the Bowser River drainage system maintains an ice-marginal course, resulting in local trimming and steepening of the ice front. Subglacial penetration only occurred near the large central medial moraine.

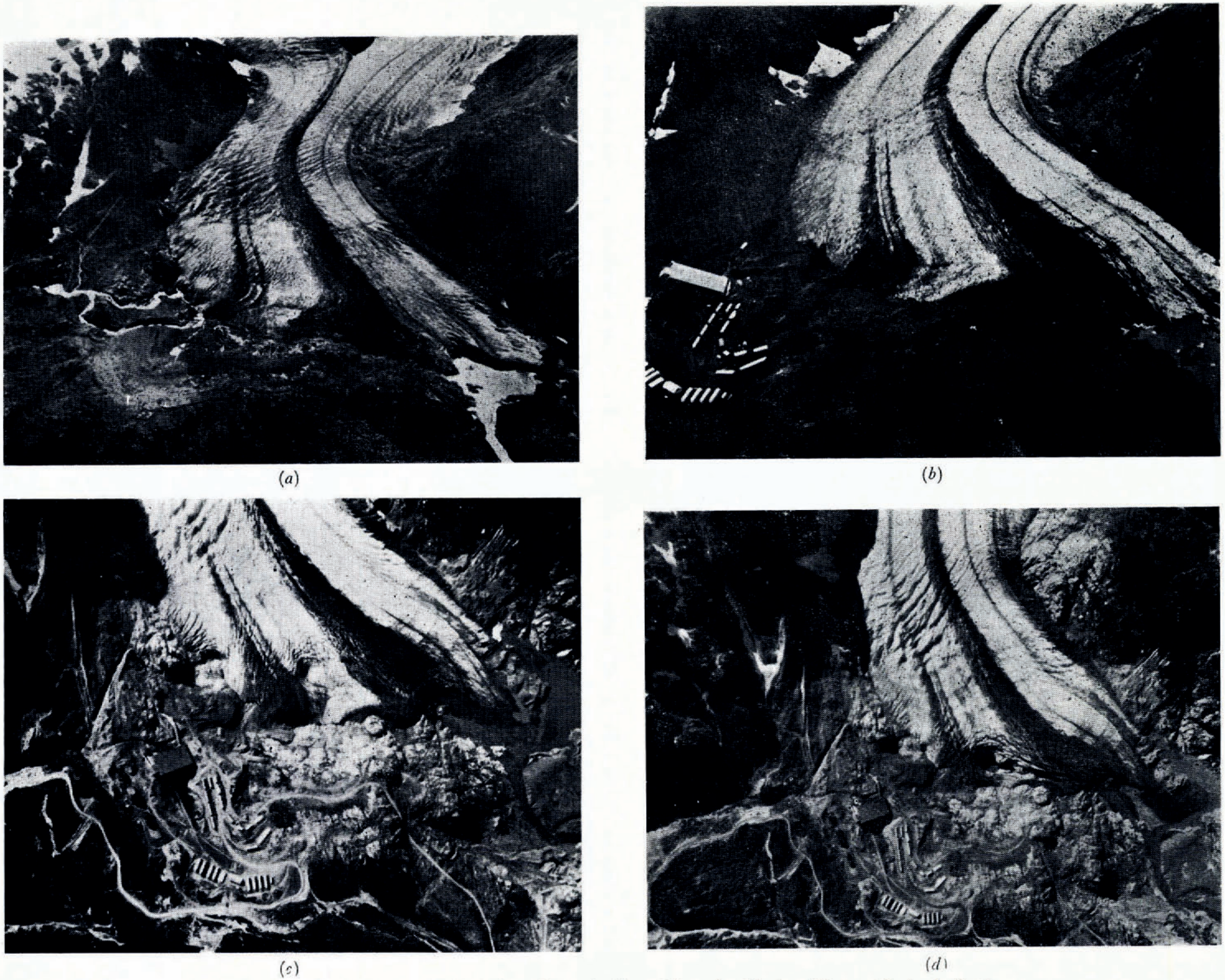
1964 and 1965 air photographs (not shown) and 1969 (Fig. 4b) depict ice thinning and terminal recession away from the granodiorite divide area. Subglacial penetration of Summit Lake water at the time of the 1964 air photography is suggested by the absence of thermal erosion of the ice front by marginal melt streams. By 1968, Summit Lake water had been diverted by Granduc Operating Company construction of the mill site; full-scale mill production and release of waste mill water commenced in the fall of 1970.

By 1972 (Fig. 4c), marked ice-surface depressions 75 m in diameter and attendant concentric crescentic crevassing were present. A linear depression 50 m wide terminates in an oval-shaped, intensely crevassed depression close to the central medial moraine and is marked by local enhanced recession and cave formation.

By 1974 (Fig. 4d), the central circular depression had moved over 100 m down-glacier and collapse and enlargement had occurred in analogous fashion to the formation of dolines in

Fig. 2. Subglacial exit of the mill stream in a large ice-walled channel; note actively exfoliating ice walls.

Fig. 3. Granduc mill stream flowing in the ice-walled channel formed by roof collapse over a subglacial tunnel; an ice berm resting on the lower bedrock slopes forms one wall of the channel. At bottom left centre a debris-rich shear plane formed by over-riding of ice lodged against bedrock; direction of ice flow from right to left. Granduc mill in background.



(a) (b) (c) (d)

Fig. 4. *The development of glacier karst in terminal ice of Berendon Glacier. (Photography by A. Post.)*

(*a*) 1961 (*F3-61 124 8-8-61*). (*b*) 1969 (*6941 8-2-69 16: 22*). (*c*) 1972 (*72V3—005 8 900*). (*d*) 1974 (*74 VI—124 10 000*).

limestone. Foundering of the ice roof had also occurred along the linear depression demarcating a subglacial tunnel; sections of the roof formed natural bridges in 1975. Enlargement of the ice cave at the inlet of mill waters and isolation of the fringing ice berm at the foot of the granodiorite rock barrier had also occurred.

Discussion

The development of the surface morphology on terminal ice has been determined by the pattern of subglacial erosion effected by mill water. The northward-trending linear surface trough apparent in the 1972 air photography demarcates the mill stream aligned along the foot of the granodiorite rock barrier: the circular surface depressions or "sinks" have developed where mill-stream flow is concentrated by projecting bedrock spurs resulting in ice-cavern formation. Subglacial ice caves have been generated from the progressive thermal erosion by mill water. In the summer of 1975 these were penetrated for some distance. The development of open ice-walled channels from the enlargement of subglacial channels followed by the collapse of the ice roof is analogous to gorge formation in limestone. Where sections of the roof remain, natural bridges are formed. Sections of the roof which survived into 1975 along the ice-walled canyon were debris-covered and may have survived longer as the result of such protecting debris.

The progressive foundering of the cavern roofs, resulting in an ice-walled amphitheatre has been accompanied by concentric crescentic crevassing, as described in the glacier-thermokarst literature. The down-glacier movement of the whole assemblage of thermokarst features implies a continuing control over subglacial water routes once the thermokarst tunnels have been initiated.

Terminal recession

Terminal recession of Berendon Glacier has accelerated since 1970 with the action of warm mill waters (Rogerson and Eyles, unpublished). Prior to 1970, recession was a seasonal phenomenon which alternated with winter freeze-up and still-stand. It is likely that this has been replaced by continuous recession due to the year-round outfall of waste mill-water. This may result in the rapid destruction of glacier thermokarst, as the ice front recedes up-slope from the point of warm-water discharge.

SUMMARY

Thermokarst in clean, active terminal ice of Berendon Glacier, British Columbia, has been generated by the release of warm (30°C) mill waters from a copper-concentrating plant, enhancing basal and englacial melt rates. These features include ice-walled canyons, natural bridges, unroofed caverns and "block-caving" or "subglacial stoping" activity and crescentic concentric crevasses, the result of locally enhanced basal melt controlling surface-ice morphology. A literature review indicates that features of a thermokarst origin have been observed elsewhere on active, generally debris-free glacier ice. Published models of thermokarst developed on glacier ice emphasize too greatly the prerequisite of stagnant, heavily debris-covered ice for the development of thermokarst. The sufficient factor in its development is the predominance of greatly enhanced basal and englacial ablation over rates of supraglacial melt.

ACKNOWLEDGEMENTS

The research embodied in this paper was part of a larger project financed by an Environment Canada, Water Research Incentives grant (5043-5-5-103 1975). Granduc Operating Company of Vancouver provided generous base-camp support.

MS. received 2 March 1977

REFERENCES

Ahlmann, H. W. 1938. *Land of ice and fire.* London, Kegan Paul, Trench, Trubner and Co. Ltd.

Clayton, L. 1964. Karst topography on stagnant glaciers. *Journal of Glaciology*, Vol. 5, No. 37, p. 107–12.

De Boer, G. 1949. Ice margin features, Leirbreen, Norway. *Journal of Glaciology*, Vol. 1, No. 6, p. 332–36.

Embleton, C., *and* King, C. A. M. 1968. *Glacial and periglacial geomorphology.* London, Edward Arnold.

Fisher, D. A., *and* Jones, S. J. 1971. The possible future behaviour of Berendon Glacier, Canada—a further study. *Journal of Glaciology*, Vol. 10, No. 58, p. 85–92.

French, H. M. 1976. *The periglacial environment.* London and New York, Longman.

Gilbert, R. 1972. *Drainings of ice-dammed Summit Lake, British Columbia.* Ottawa, Environment Canada. Inland Waters Directorate. Water Resources Branch. (Scientific Series No. 20.)

Gilbert, R. Unpublished. Some aspects of the hydrology of ice-dammed lakes: observations on Summit Lake. [M.A. thesis, University of British Columbia, 1969.]

Haefeli, R. 1951. Some observations on glacier flow. *Journal of Glaciology*, Vol. 1, No. 9, p. 496–500.

Halliday, W. R., *and* Anderson, C. H., *jr.* 1970. Glacier caves. *Explorers Journal*, Vol. 48, No. 2, p. 131–35.

Hanson, G. 1932. Varved clays of Tide Lake, British Columbia. *Transactions of the Royal Society of Canada*, Ser. 3, Vol. 26, Sect. 4, p. 335–39.

Hashimoto, S., *and others.* 1966. Glaciological studies of the Antler Glacier, Alaska, by S. Hashimoto, H. Shimizu and K. Nakamura. *Journal of the Faculty of Science, Hokkaido University*, Ser. 4, Vol. 13, No. 3, p. 237–56.

Haumann, D. 1960. Photogrammetric and glaciological studies of Salmon Glacier. *Arctic*, Vol. 13, No. 2, p. 74–110.

Healy, T. R. 1975. Thermokarst—a mechanism of de-icing ice-cored moraines. *Boreas*, Vol. 4, No. 1, p. 19–24.

Jennings, J. N. 1971. *Karst.* Cambridge, Mass., M.I.T. Press. (An Introduction to Systematic Geomorphology, Vol. 7.)

Lliboutry, L. A. 1964–65. *Traité de glaciologie.* Paris, Masson et Cie. 2 vols.

Loewe, F. 1957. Subglacial stoping or block caving. *Journal of Glaciology*, Vol. 3, No. 22, p. 152. [Letter.]

McMechan, R. D. Unpublished. A study of Berendon Glacier, near Stewart, British Columbia: recent history, variations and flow rates. [B.Sc. thesis, University of British Columbia, 1975.]

Mathews, W. H. 1965. Two self-dumping ice-dammed lakes in British Columbia. *Geographical Review*, Vol. 55, No. 1, p. 46–52.

Mathews, W. H. 1973. Record of two jökulhlaups. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Commission de Neiges et Glaces. Symposium on the Hydrology of Glaciers, Cambridge, 7–13 September 1969*, p. 99–110. (Publication No. 95 de l'Association Internationale d'Hydrologie Scientifique.)

Mougin, P. 1934. Cinématique glaciaire. *Études Glaciologiques*, Nouvelle Sér., Tom. 1, p. 239–68.

Paige, R. A. 1956. Subglacial stoping or block caving: a type of glacier ablation. *Journal of Glaciology*, Vol. 2, No. 20, p. 727–29.

Paterson, W. S. B. 1969. *The physics of glaciers.* Oxford, etc., Pergamon Press. (The Commonwealth and International Library. Geophysics Division.)

Rogerson, R. J., *and* Eyles, N. Unpublished. The form of medial moraines, their sediments, and terminal ice melt studies, Berendon Glacier, B.C. [Report to Glaciology Division, Environment Canada, Ottawa, Canada. 1976.]

Russell, I. C. 1893. Malaspina Glacier. *Journal of Geology*, Vol. 1, p. 219–45.

Stokes, J. C. 1958. An esker-like ridge in process of formation, Flatisen, Norway. *Journal of Glaciology*, Vol. 3, No. 24, p. 286–89.

Sweeting, M. M. 1972. *Karst landforms.* London, Macmillan.

Thorarinsson, S. 1953. Some new aspects of the Grímsvötn problem. *Journal of Glaciology*, Vol. 2, No. 14, p. 267–75.

Untersteiner, N., *and* Nye, J. F. 1968. Computations of the possible future behaviour of Berendon Glacier, Canada. *Journal of Glaciology*, Vol. 7, No. 50, p. 205–13.