Conclusions

The method described, of using gravity values to determine the thickness of a glacier, has been shown to give reasonable results, with little expenditure of time in the field. Obviously, a direct measurement of the ice thickness is preferable, but that method is slower and more costly, so that when the seismic programme is undertaken, it is suggested that the gravity survey be continued. If the magnitude of the variation of the terrain effect across the valley can be accurately determined by finding the thickness by seismic methods at one point near the centre of each traverse, the accuracy of the estimates of the glacier thickness at other points along the traverse should be almost as high as that of the seismic measurements.

Acknowledgements

We are very grateful to Professor J. M. Bruckshaw of Imperial College, London, for the loan of the Worden Gravity Meter which was used in this survey. It is a pleasure to thank the other people who have been so helpful in the work. Miss A. Lathbury and Miss J. Hogbin, of the Department of Geography, Cambridge University, greatly assisted us during the field work and without their willingness to wade streams and jump crevasses the survey would not have been completed. During the working up of the results and their presentation, the interest and advice of Mr. J. E. Jackson and Mr. W. V. Lewis have been invaluable. To the Royal Society, the Royal Geographical Society, the Everest Foundation, Cambridge University and to others, the Expedition is grateful for financial assistance.

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TEMPERATURE MEASUREMENTS AT A CIRQUE BERGSCHRUND IN BAFFIN ISLAND: SOME RESULTS OF W. R. B. BATTLE'S WORK IN 1953

By H. R. Thompson *and* B. H. Bonnlander

(Arctic Institute of North America)

Abstract. Thermograph, thermistor, and thermometer readings at a 30 m. deep bergschrund from June 6 to July 22, 1953, showed that there was little direct relationship between air temperatures outside and at the bottom of the schrund. The air temperature inside ranged from −3·7° C. (25·3° F.) to +0·5° C. (32·9° F.), but from July 2 onwards it oscillated between −0·5° C. and +0·5° C., with a 3–4 day periodicity. The ice temperature at the bottom of the schrund behaved similarly, though it was about 0·5° C. colder. The oscillations may have been caused by the interplay of flowing melt water (source of heat) and air drainage in quiet weather (source of cold). The granite-gneiss headwall, where not sheathed by refrozen melt water, appeared to be chemically and mechanically unweathered, which supported the conclusions of Battle's earlier tests in deep bergschrunds and in the laboratory.

Zusammenfassung. Thermograph-, Thermistor-, und Thermometerablesungen an einem 30 m tiefen Bergschrund vom 6. Juni bis zum 22. Juli 1953 zeigten, dass zwischen der Lufttemperatur ausserhalb des Schrundes und der auf seinem Grund wenig Beziehungen bestanden. Die Lufttemperatur im Innern bewegte sich zwischen −3,7° C und +0,5° C; beginnend mit dem 2. Juli schwankte sie jedoch bei einer 3- bis 4-tägigen Periodizität zwischen −0,5° C und +0,5° C Obgleich ungefähr 0,5° C kälter, verhielt sich die Eistemperatur am Grund des Schrundes ähnlich. Die Schwankungen haben wohl in der Wechselwirkung von fliessendem Schmelzwasser (Wärmequelle) und abfliessender Luft bei ruhigem Wetter (Kältequelle) ihre Ursache. Die aus Granitgneiss bestehende Kopfwand war, wo sie nicht durch gefrorenes Schmelzwasser bedeckt war, chemisch und mechanisch unverwittert, welche Tatsache die Ergebnisse Battles früherer Untersuchungen in tiefen Bergschründen und im Laboratorium unterstützte.

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Fig. 6. Air photograph of Austerdalsbreen, showing the form of the valley, and the approximate positions of profiles D, E, F and G

Photograph by Widerøe's Flyveselskap og Polarfly A/S, Oslo

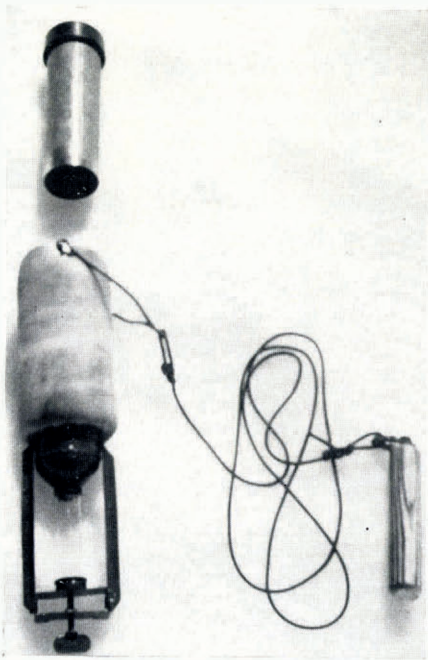

Fig. 1. Centrifuge for separating water from melting snow (see E. R. LaChapelle, p. 769)

Fig. 4. Summit of morainic arc of Litle Jiek'kevarribreen (see R. W. Galloway, p. 730)

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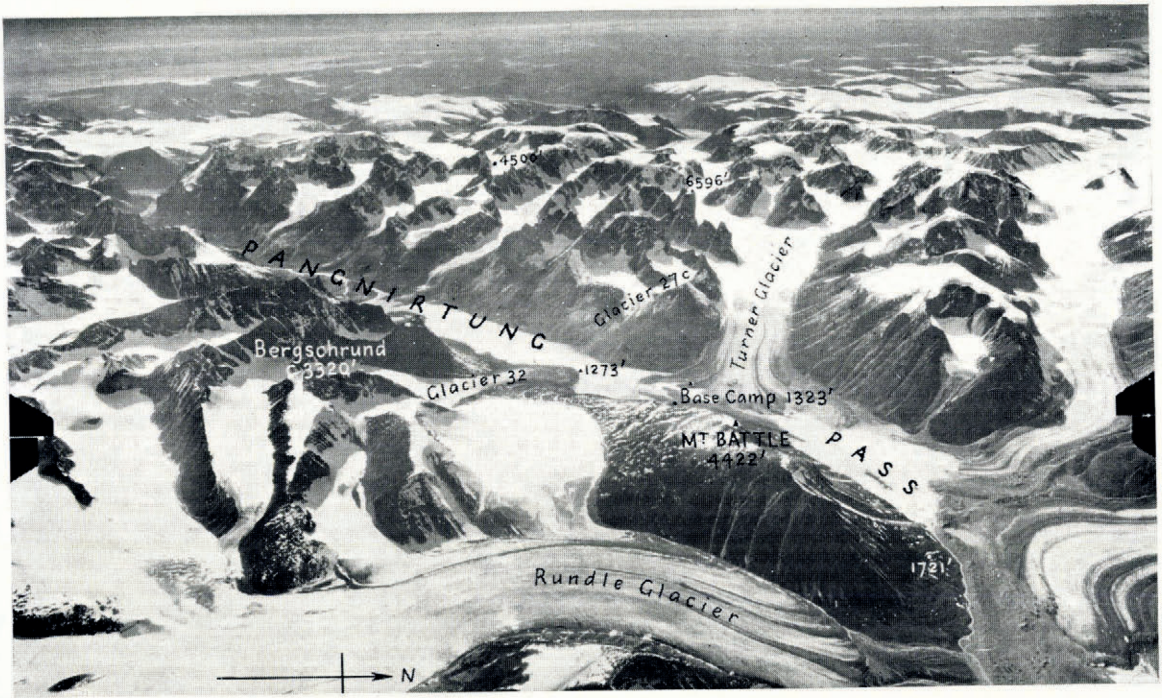

Fig. 1. The general setting of Glacier 32 and Battle's bergschrund. The latter lies 5·3 km. south of and 610 m. above the expedition's Base Camp, which itself lies at the divide of Pangnirtung Pass. Heights in feet
R.C.A.F. Crown Copyright photo.

Introduction

The accidental death of Ben Battle during the Baffin Island Expedition of 1953 ended a series of fundamental observations concerning the formation of cirques[8]. In the laboratory he had tested the reactions of different rocks to varying freeze-thaw conditions, finding that rapid, large, and frequent temperature changes were almost essential to induce shattering[4]. In East Greenland[2, 3], Norway[5, 6] and Switzerland[9] he had measured the fluctuations of air temperature actually occurring in cirque bergschrunds, where, under the Johnson hypothesis, shattering should be intense[7]. But in fact the fluctuations observed were always small and temperatures seldom rose above the freezing point. In view of these inconsistencies, Battle and Lewis[6] have stressed the importance of latitude, altitude, depth and openness of the bergschrund, and past changes of climate. Other key factors include the orientation of the cirque and the detailed petrology and structural relations of the bed rock[4, 5, 7]. Because Battle's measurements have shown that frost-shattering of unweakened rock was unlikely to occur in deep bergschrunds under present conditions, Lewis has recently turned to pressure release as a mechanism for effecting such weakening beneath thick glaciers[9].

Since it was his own research that had modified current views on cirques and shattering[7], Battle regarded his season's work on Baffin Island in 1953 as a useful test of his own previous conclusions. Later he intended to investigate the effects of chemical weathering at low temperatures, as another line of attack on the cirque problem.

Location and Nature of the Bergschrund

The great through-valley of Pangnirtung Pass has been gouged into the uplifted erosion surface of Cumberland Peninsula in eastern Baffin Island[1]. On the flanks of the Pass are many hanging valleys, most of them containing glaciers, of which many head in cirques. It was in a cirque at the head of Glacier 32, near the expedition's Base Camp, that Battle carried out the work summarized

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below (Fig. 1, p. 764). Trending from south-south-east to north-north-west the glacier had a length of 3·6 km. The eastern of its two feeder-cirques was about one kilometre across and was overlooked by a headwall 600 m. high, cut in massive granite and granite-gneiss.

Although the bergschrund was later found to be extensive it was only with difficulty that Battle and Bonnlander forced an entrance to it on 30 May, near the base of a steep gully. The schrund was 30 m. deep, excluding an unknown thickness of ice debris. Its ice walls were extremely irregular in their smoothness and in their distance apart, while between them were crammed snow and ice ledges and fallen ice blocks of enormous size. The descent, made in torchlight by nylon ropes and rope ladders, therefore led alternately through narrow clefts and caverns up to 6 m. broad. The "floor" of the bergschrund was filled with treacherously loose (but fairly small) blocks of ice to an unknown depth; its width was about 7 m. Icicles were everywhere, festooning the wedged ice blocks and clinging to the ice walls. The tilting and inversion of many unbroken rows of icicles implied movement of the glacier itself since a previous melt season. Nor were icicles the only traces of melt water, for the walls of the schrund, particularly near the base, were coated (to a thickness of over 20 cm. in places) with transparent ice quite different from the glacier proper. This refrozen melt water occurred in irregular sheets and lobes, completely obscuring the headwall of the cirque, except at one point, where an unstriated, uncracked, unweathered knob of granite-gneiss was found. Even at the end of the ablation season no boulders or stones were seen in the bergschrund, nor was there a dirty "sole" between ice and headwall. This schrund was therefore almost identical to that of Grifgletscher (East Greenland) studied by Battle in 1948[3].

Although in May and early June, 1953, the bergschrund gave the impression of being an old and permanent feature, the large quantities of dripping and flowing melt water observed in July suggested that all the interior details of the schrund could be rapidly transformed. Battle made no note of melt water refreezing in the schrund; on the contrary, he stated on 11 July that the bottom was "flooded". When the thermograph was collected on 12 August, however, the bergschrund was quite dry.

Installation and Performance of Instruments

On 6 June Battle, Thompson, and Bonnlander placed a Taylor four-pen thermograph in a snow-cavern at the top of the bergschrund. The two short leads were used to measure the temperatures of the snow surface and of the open air 60 cm. above it. Two 27 m. leads were drawn to the bottom of the schrund and began recording air and ice temperatures there. Particular care was taken to embed the 5 cm. thermograph bulbs firmly in the snow and in the ice. The bulb measuring the air inside the schrund was allowed to dangle from an overhanging ice block. Unfortunately, in the absence of a screen, the bulb in the open air also had to dangle, which meant that it was exposed to direct and reflected solar radiation and was only useful as an indicator of the daily march of temperature. None of the leads was long enough to reach the rock outcrop at the base of the schrund.

Battle (twice accompanied by Bonnlander and once by J. R. Weber) revisited the bergschrund every few days, until his death on 13 July, to check the thermograph pens, to replace the charts, to obtain test readings with thermistors and alcohol thermometers, and further to explore the bergschrund. Pens, charts and the thermograph's clockwork motor all gave trouble, in addition to which the machine and the two outside leads were several times dislodged by avalanches. The last thermograph chart was installed on 11 July, the motor stopped on 22 July, and the instrument was finally removed from the cirque on 12 August. Even if Battle had lived, the bergschrund was becoming so dangerous by mid-July that further descents and spot checks might well have become impossible.

Because of the troubles noted above and the inherent difficulty of writing up a colleague's work, the temperature records from 6 June to 22 July, 1953, are by no means complete or consistent. However Battle made enough spot checks to compute correction factors for the leads inside the bergschrund, so that traces (c) and (d) on Fig. 2 (p. 767) are thought to be quite accurate. Trace (b)

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has been corrected for altitude from the Base Camp records (using a normal lapse rate of 0·6° C. per 100 metres[10]) because of the incorrect exposure of its thermograph lead in the cirque, but the plotted times are still those of known maxima, minima, and spot checks at the bergschrund. The pen recording snow temperatures worked so badly that its trace has been omitted from Fig. 2.

During the summer Battle experimented with several instruments designed to count the number of times the bergschrund air temperature crossed the freezing point. No results were recorded, but this seems a most promising line of research. The counters are discussed in Reference 6.

Weather During the Measurements

Both Orvig[10], writing of the Penny Ice Cap, and Bonnlander[1], writing of the Base Camp, have concluded that the weather experienced by the 1953 expedition was close to normal, so far as could be judged from the short-term meteorological records at Padloping Island and Pangnirtung Post. Since the Base Camp lay only 5·3 km. north of, and 610 m. below, Battle's bergschrund, it is likely that the latter also had an "average" spring and summer. One could usually see that the weather was comparable with that at the Base.

The first three weeks of June were cold, moist, windy, and almost without sunshine, but the final week brought warm, sunny days and mild nights. The weather continued generally warm and settled until 19 July, though it was during this period that the first heavy rains fell. Cool, moist, and rainy weather persisted for the last ten days of July.

Air Temperature Outside the Bergschrund

Battle made 11 spot checks of the air temperature outside the bergschrund. The highest value reached was 11·9° C. (53·4° F.) on 15 July, and the lowest, −6·5° C. (20·7° F.) on the nights of 12–13 and 14–15 June. The abrupt rise of open air temperatures on 25 June shows clearly on Fig. 2. Diurnal ranges also increased at that time, and there were only 12 nights altogether on which the air temperature did not fall below 0° C. The freezing point was actually crossed on 35 occasions, though only 12 times did the fluctuation cross both +1° C. and −1° C. Even such fluctuations might be insufficient, judging by Battle's laboratory experiments[4], to cause shattering of the massive granite-gneiss headwall nearby.

The dominant rhythm of the open air temperature fluctuations was diurnal, due to the balanced interaction of incoming and outgoing radiation. The somewhat irregular fluctuations occurring during the entire period were largely due to the influence of passing pressure systems with their accompanying weather conditions.

Air Temperature Inside the Bergschrund

Battle made 10 spot checks of the air temperature inside the bergschrund. The highest value attained was +0·5° C. (32·9° F.) on 4 July, and the lowest, −3·7° C. (25·3° F.) on 7 June. There was a distinct rise of temperature on the night of 24–25 June and a still larger one on the evening of 2 July, both of which were probably connected with the opening of the bergschrund mouth by avalanches and melt water (Fig. 2). After 2 July the temperature oscillated about the freezing point until the end of the record. The freezing point was crossed on 10 occasions, but the amplitude of the fluctuation exceeded 1° C. only on the first crossing, when it was 1·8° C., spread over 58 hours. Although positive temperatures in deep bergschrunds were unusual in Battle's experience[8], there is no doubt that they occurred in Glacier 32. But the fluctuations were far from being the large, rapid, and frequent ones demanded by Battle's laboratory tests[4]. As in previous cases[3, 6], Battle thought it improbable that the exposure of granite-gneiss in the Baffin schrund could be shattered in average years of the present climate and with the glacier at its present thickness. Lewis points out, however, in a personal communication, that comparatively recent spalling may have laid bare the present fresh rock; but the fact remains that there was no rock debris and no "dirty" ice in the schrund in 1953.

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The most remarkable feature of trace (c), air temperature inside the bergschrund, is its regular fluctuations. Although these are most marked during the July ablation season, they also characterize the last 12 days of June, before which our records are poor. The periodicity is not quite as regular as that found in Norway[6], but the order of magnitude is again 3–4 days. Why such a rhythmic oscillation should occur is not known. Battle and Lewis[6] suggested that it represented the time taken for an indraught of cold air to be warmed up to ice temperature, which they assumed (without measurements) to be 0° C. in the ablation season. But since our trace (d), discussed below, fluctuates in sympathy with the air trace (c), the ice can scarcely be considered quite such a strong stabilizing force, though its lower temperature and dominating presence must exercise some control over the bergschrund air. From trace (a) on Fig. 2, it is clear that periods of low wind speed and katabatic drainage do not always precede falls in the bergschrund air temperature, though the correlation in July is sufficient to provoke thought.

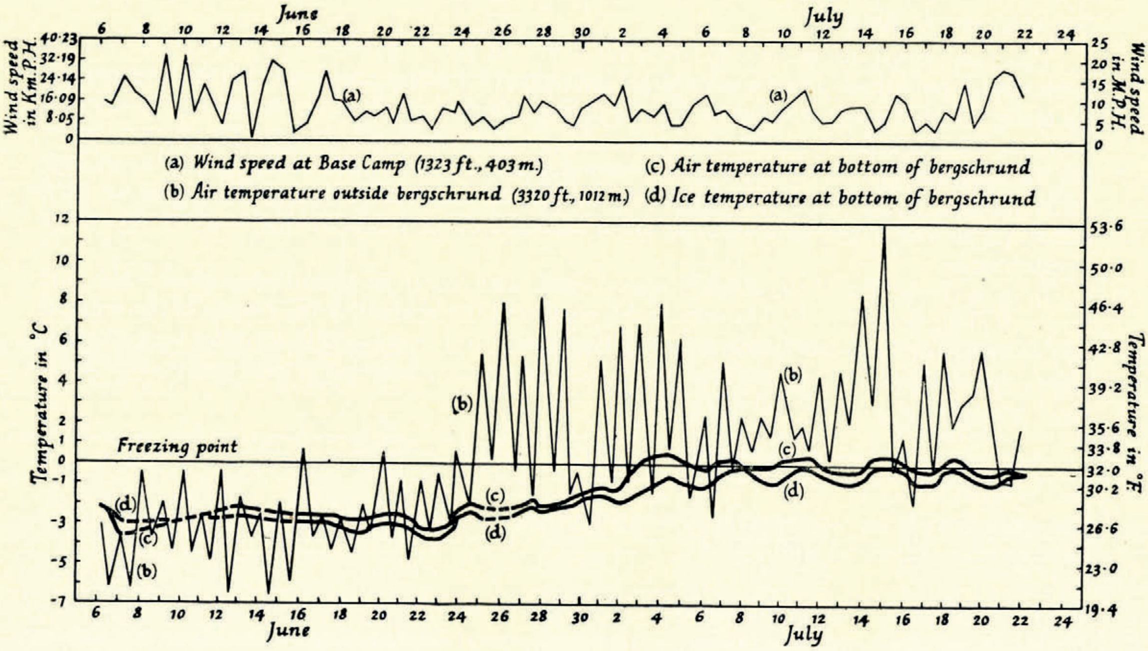

Fig. 2. Graph summarizing the results of W. R. B. Battle's work in the bergschrund of Glacier 32, Pangnirtung Pass

Perhaps we should think in terms of successive indraughts of cold air being warmed up not by the ice but by the melt water which began to trickle into the schrund towards the end of June and which had developed into streams by 4 July*. Battle has left no record of the water freezing in the schrund, and indeed Lewis[7] has shown that water may penetrate far below a bergschrund without freezing. Although they are not obviously related to outside diurnal maxima and minima, the temperature oscillations in the bergschrund do bear some resemblance to the march of *mean* daily temperatures, which certainly affect the supply of melt water. The time lag between the development of melting conditions on the glacier surface and the arrival of plentiful water at the base of the schrund may explain the lag of the bergschrund temperature fluctuations behind those of the open air. But even if melt water is the source of heat, and down-flowing air the source of cold, it is still not certain why their interplay should produce a rhythmic oscillation. The oscillations in fact provide an important problem for further research.

* Battle measured 42 cm. of ablation on the glacier surface between midnight on 26–27 June and 0400 hrs. on 11 July.

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Ice Temperature Inside the Bergschrund

Battle made only 5 spot checks of the ice temperature inside the bergschrund, but the close parallelism of its trace with that of the air inside has enabled adequate corrections to be made. The highest temperature reached by the ice was 0° C. (32° F.) on 15 July, and the lowest was −3·8° C. (25·1° F.) on the night of 22–23 June. Trace (d) on Fig. 2 shows that the temperature of the thick sheets of frozen melt water veiling the headwall followed closely the variations of the adjacent air. The ice was generally 0·4° C. to 0·6° C. colder than the air, though the difference was irregular. In some of its rhythmic oscillations between 0° C. and −1° C. the ice lagged slightly behind the air, but again there was no consistency.

No temperature measurements were made on the down-glacier side of the bergschrund, where frozen melt water covered the glacial ice to a depth of 10–20 cm. or more.

Summary of the Results

The temperature measurements made by Battle on Baffin Island in 1953 generally confirm those already published. There is some slight indication that falls of temperature in the bergschrund generally followed periods of gentle winds, during which cold air drained downwards into the schrund. The warming up of the schrund air after "cold" spells may not have been controlled by the ice walls, for the temperatures of the latter fluctuated with the air, but by incursions of melt water from the glacier surface, controlled by the diurnal mean temperatures of the open air. It is almost certain that draughts of warm air could not reach the bottom of such a deep and obstructed bergschrund.

Even at the height of the ablation season much melt water ice remained to protect the rock headwall of the bergschrund. The only visible portion of the headwall at the bottom of the schrund was uncracked and chemically unweathered. Similar features were found in the other bergschrunds visited and in the ice fall cavern. Five isolated thermistor measurements of rock temperature in the main bergschrund gave the following results:

Date	*20 June*	*25 June*	*27 June*	*29 June*	*2 July*
° C.	−2·5	−3·0	−2·2	−2·6	−1·9

But since there is no way of cross-checking these figures they should be interpreted only qualitatively when compared with Fig. 2.

Battle's Views on Cirque Formation

Finally we should like to add some of the more general ideas on cirques that Battle was known to hold at the time of his death. The details are based on his publications and his Ph.D. thesis (all of which are listed in the References), on his own field notes and on notes made by Thompson during field work and conversations with Battle.

(1) The zone in which rock headwall, glacier surface, and freely circulating air meet may be the zone of maximum frost-shattering, though under suitable conditions shattering occurs lower down behind the glacier too. As the glacier has thickened and thinned the zone of greatest destruction may have migrated up and down the headwall. Probably the only time at which the entire headwall is exposed to shattering comes when the glacier is very thin. Conversely, shattering may be reduced (though glacial scour may be increased) when the ice is very thick.

(2) One factor contributing to the steepness of the exposed headwall at almost any stage of glacierization is the relatively rapid (compared with mass wastage) removal of loose debris that would otherwise pile up in protective screes.

(3) The problem of cirque formation must be studied against the background of "the dynamic Pleistocene". Even though frost-shattering does not now occur in a parti-

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cular bergschrund, it may do so in extreme summers, or it may have done so in the past, when the glacier was thinner, the bergschrund more open, and the climate different. Moreover, nivation must have alternated with glacial scour, fluvial erosion and mass wastage in most cirques.

(4) In keeping with a statistical approach to bergschrund temperatures, we must analyse the slopes of cirque headwalls and beds in a far more rigorous manner. The methods of Strahler[11] were prominent in Battle's notes and conversation in 1953.

(5) "Our ultimate object as geomorphologists must be to provide a process and chronology for the various stages of corrie [cirque] development."[3]

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THE CENTRIFUGAL SEPARATION OF FREE WATER FROM MELTING SNOW

By EDWARD R. LACHAPELLE

(United States Forest Service)

IN the course of recent investigations into the precise measurement of ice melt at an ablating snow surface, it was found that the amount of ice melted during a given period often failed to correspond with the ablation (surface wastage) for the same period. Obtaining a quantitative relationship between ice melt and surface wastage over short time intervals required a method for rapid measurement of free water content in the surface snow layers. Calorimetry was tried and found unsatisfactory by reason of its slowness and the requirement of precise thermometry difficult to meet in the field. A review of possible methods other than calorimetry lead to the conclusion

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