

between the southern margin of the glacier and the moraine which marks the maximum recent extent of the ice (c. A.D. 1750). Movement between one summer and another is typical.

The stone shown in Figure 1 measured about 20 cm.  $\times$  6 cm.  $\times$  4 cm., and the fresh, white abrasion marks up-slope of it were about 25 cm. long on 2 August 1964. The stone had moved approximately down the line of greatest slope (about 24 degrees), oblique to the direction of old striations on the garnet mica schist bedrock. In 1963–64 the maximum snow depth in the area was about 170 cm., which is of the same order as the mean of recent years.



Fig. 1. Down-slope movement of stone. Old striations (top) run slightly across the slope; fresh abrasion marks behind the stone run down the line of greatest slope. Photograph taken 2 August 1964

During the winters, many stones are moved over the bare rock surface bordering Østerdalsisen, though few of them show any definite orientation relative to the slope. There seems no doubt that slow downhill creep of snow may result in abrasion of the underlying rock by loose stones at the bottom of the snow cover.

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SIR, *Comments on Paterson's paper "Variations in velocity of Athabasca Glacier with time"*

The coupling of a glacier to its bed is a most important current problem in glacier-flow studies. Paterson's (1964) paper presents data which contribute to an understanding of this. The magnitudes of velocity fluctuations for periods of a week to a year on Athabasca Glacier are consistent with the velocity-dispersion spectrum obtained from measurements made in 1952–54 on the neighboring Saskatchewan

Glacier (Meier, 1960, fig. 16). Short-interval accelerations in the velocity of Saskatchewan Glacier occurred at times of heavy precipitation (Meier, 1960, p. 17-18). Thus I suggested, as does Paterson, that changes in water lubrication at the ice-bedrock interface or along shear surfaces within the ice might cause short-interval velocity fluctuations.

Perhaps the most interesting result in this article concerns the travel time of subglacial run-off. Paterson compares stream-flow variations with velocity variations and finds a pattern which would be expected if melt-water fluctuations did cause velocity fluctuations and if it took 3 to 4 days for the melt-water perturbation to travel from under a stake pattern 2.6 km. above the glacier terminus to the stream-flow measuring station 500 m. below the terminus. Paterson points out that this result might have application to Weertman's theory of kinematic waves in a water layer beneath a glacier. However, several other observations must be noted:

- a. Mathews (1964[a]) performed a statistical analysis relating the Athabasca Glacier stream flow to air temperatures measured at Jasper. He found it possible to relate the daily stream flow to temperatures measured for the current day and several previous days. However, in all cases the influence of the previous day's temperature was less than the influence of the current day. Although air temperature at Jasper is a very crude and imperfect measure of the energy supply to cause melt on Athabasca Glacier, it appears from Mathews's results that the stream flow from a given melt event diminishes markedly after the first day.
- b. A pronounced diurnal fluctuation in stream flow at Athabasca Glacier (Collier, 1958, p. 353; Mathews, 1964[b], p. 159) seems to indicate that a major part of the run-off escapes from the glacier in less than a day. According to Mathews (1964[a], p. 294), "During summer months the discharge can fall by more than 50 per cent from 7:00 P.M. to 7:00 A.M. the following day".
- c. South Cascade Glacier, Washington, is a small temperate valley glacier; I know of no reason to believe that its melt-water transmission characteristics are different in principle from those of Athabasca Glacier. Detailed measurements of diurnal fluctuations of melt and stream flow on this glacier indicate that the peak in run-off occurs only 4 hr. after a peak in the rate of ice melt (Meier and Tangborn, 1961, p. 15-16). These diurnal melt-water curves are similar in shape to those of Athabasca Glacier.
- d. On South Cascade Glacier direct measurements of water travel times were made by means of dye experiments. These indicate that melt water flows through and under the tongue of this glacier at an average rate of about 1.0 km./hr.

These other results suggest that a major part of the melt water flows through or under the tongue at a rate which is perhaps an order of magnitude faster than Weertman's hypothesized thin film. Such a film may exist but the amount of water it carries cannot be more than a small fraction of the total subglacial run-off. Thus it would appear that a direct verification of the existence of a slow-moving film or its effect on glacial slip will require a difficult and sophisticated experiment. This is obviously a task of high scientific priority.

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