DIRECT OBSERVATION OF THE MECHANISM OF GLACIER SLIDING OVER BEDROCK*

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ABSTRACT. At the head of a tunnel driven to bedrock in Blue Glacier, Washington, the mechanism of sliding of the glacier over bedrock has been investigated. This mechanism involves (1) regelation-slip, which operates through the combined action of heat transport and mass transport (liquid and solid) in the immediate neighborhood of the glacier sole; (2) plastic flow, promoted by stress concentrations in the basal ice. We have observed and/or measured the following features of the basal slip process: 1. Slip rate in relation to internal deformation of the ice; 2. Time-variations of the slip rate; 3. Freezing of basal ice to bedrock upon release of overburden pressure; 4. Formation of a *regelation layer* in the basal ice, and detailed behavior of this layer in relation to bedrock obstacles and to incorporated debris particles; 5. Local separation of ice from bedrock and continuous formation of *regelation spicules* in the open cavities thus created; 6. Plastic deformation of basal ice as recorded in the warping of foliation planes and of the regelation layer. Simple experiments to test our interpretation of the regelation layer have been carried out, in which regelation flow of solid cubes of different materials frozen into blocks of ice was produced. The field measurements and laboratory results are used to test the theory by Weertman (1957, 1962) of the basal slip mechanism. It is found that the theoretical "controlling obstacle size" and "controlling obstacle spacing" that should correspond to our observations are about an order of magnitude too small. This quantitative failure represents an overemphasis in the theory on the importance of plastic flow as compared to regelation. A new theory has been constructed which gives results in better agreement with observation.

RÉSUMÉ. On a étudié au front d'un tunnel creusé jusqu'au lit rocheux du Blue Glacier (état de Washington) le mécanisme du glissement au fond du glacier sur le lit rocheux. Ce mécanisme comporte : (1) un glissement de "regélation", qui s'effectue sous l'action combinée d'un transport de chaleur et de matière (liquide et solide) au voisinage immédiat du fond du glacier; (2) un écoulement plastique, dû aux concentrations des tensions dans la glace de fond. Nous avons observé et/ou mesuré les aspects suivants du processus de glissement de la glace sur le lit. (1) La vitesse de glissement en relation avec la déformation interne de la glace. (2) Des variations dans le temps de la vitesse de glissement. (3) Une congélation de la glace de fond jusqu'au bed-rock suivant le relâchement de la pression superposée. (4) La formation d'une *couche de regélation* dans la glace de fond; le comportement intime de cette couche vis-à-vis des obstacles du lit et vis-à-vis des particules de débris incorporées à la glace. (5) Localement, une séparation de la glace et du lit; la formation continue de *spicules de regel* dans les cavités ainsi formées. (6) Une déformation plastique de la glace de fond, comme celle qui est enregistrée dans le gauchissement des plans de foliation et de la couche de regélation. Des expériences simples ont été réalisées pour éprouver la valeur de notre interprétation de la couche de regélation. Dans celles-ci, on a produit l'écoulement de regélation de cubes solides de divers matériaux congelés et assimilés à des blocs de glace. Les mesures sur le terrain et au laboratoire sont utilisées pour éprouver la théorie de Weertman (1957, 1962) sur le mécanisme du glissement sur le fond. On trouve que la "grandeur des obstacles qui réglent l'écoulement" et que "l'espacement de ces obstacles", théoriques, qui devraient correspondre à nos observations, sont d'un ordre de grandeur trop petit. Cette insuffisance quantitative montre qu'on accorde trop d'importance à la théorie de l'écoulement plastique par rapport au phénomène de regélation. Une nouvelle théorie a été bâtie: elle donne des résultats plus en accord avec les observations.

ZUSAMMENFASSUNG. Am Ende eines in den Blue Glacier (Washington) gebohrten Tunnels wurde der Mechanismus des Gleitens auf der Felssohle untersucht. Das Gleiten vollzieht sich auf zwei Arten: (1) durch Regelation, d.h. Massen- und Wärmetransport in der flüssigen und festen Phase in unmittelbarer Nachbarschaft der Gletschersohle und (2) durch plastische Deformation als Folge der Spannungskonzentration in der untersten Eisschicht. Folgende Einzelheiten des Gleitprozesses wurden gemessen bzw. beobachtet: 1. Gleitgeschwindigkeit und ihr Zusammenhang mit der internen Eisdeformation. 2. Zeitliche Änderungen der Gleitgeschwindigkeit. 3. Anfrieren des Eises am Felsuntergrund nach Druckentlastung. 4. Bildung einer *Regelationsschicht* im aufliegenden Eis und ihr Verhalten im Hinblick auf Unebenheiten der Unterlage und eingeschlossenes Moränenmaterial. 5. Stellenweise Ablösung des Eises vom Felsgrund und kontinuierliche Bildung von Regelations-Eisnadeln in den entstandenen Hohlräumen. 6. Plastische Deformation des aufliegenden Eises, ablesbar aus der Verbiegung der Foliations-Flächen und der Regelationsschicht. Zur Prüfung der Richtigkeit unserer Interpretation der Regelationsschicht wurden starre Würfel aus verschiedenem Material in Eisblöcke eingefroren und ihre Bewegung unter dem Einfluss einer angelegten Spannung beobachtet. Diese Bewegung erfolgt durch Regelationsfliessen im Eis. An Hand der Ergebnisse der Feldbeobachtungen und Laborversuche wird die Weertman'sche Theorie des Gleitmechanismus (1957, 1962) an

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der Gletschersohle diskutiert. Die von der Theorie geforderten "wirksamen Hindernisgrössen" und "wirksamen Hindernisabstände" werden von der Beobachtung nicht bestätigt und sind in Wirklichkeit etwa eine Zehnerpotenz grösser. Diese quantitative Diskrepanz bedeutet, dass Weertman's Theorie dem plastischen Fliessen eine im Vergleich zum Regelationsfliessen zu grosse Bedeutung beimisst. Eine neue, den Beobachtungen besser Rechnung tragende Theorie wird gegeben.

Introduction

It has been demonstrated by direct observation in tunnels and by measurements of ice deformation in boreholes that an important mechanism in the flow of temperate glaciers is sliding of the ice over the bedrock at its base. Basal sliding or slip (Sharp, 1954, p. 826) normally accounts for the order of 50 per cent of the total surface velocity of typical valley glaciers in their thicker parts, the remainder being due to internal deformation within the ice (Gerrard, Perutz, and Roch, 1952; McCall, 1952; Mathews, 1959; Shreve, 1961; Savage and Paterson, 1963).

Observations of internal deformation are by now relatively numerous, and their broad features can be rather well accounted for quantitatively or semi-quantitatively, in terms of experimentally or theoretically derived concepts. Up to now, however, few direct observations of the basal-slip process in operation have been reported. Marginal slip has been measured on several glaciers (Sharp, 1954, p. 826; Glen, 1961; and a paper at present in preparation by M. F. Meier, C. R. Allen, W. B. Kamb, and R. P. Sharp on surface-velocity and surface-strain data from lower Blue Glacier, Washington), but the conditions of surface observation are such that it is difficult to draw conclusions as to the mechanism appropriate to basal slip at depth. Observations of basal slip at depths of 20 to 50 m. in ice tunnels and in deep marginal crevasses have been reported by Carol (1947), Haefeli (1951), and McCall (1952); in none of these cases, however, was the lowermost ice investigated closely enough to elucidate the process and rate-controlling mechanism of basal slip, attention being instead focused on other questions, such as erosion of the bed.

In a theoretical treatment of the basal-slip mechanism, given by Weertman (1957; 1962), the phenomenon is attributed very plausibly to the combined operation of two processes: (1) regelation-slip,* involving melting of the basal ice at points of increased pressure and refreezing at points of decreased pressure; (2) plastic flow, involving deformation of the ice due to stress concentrations. The regelation-slip process provides the necessary physical decoupling of the ice from its bed; the associated plastic flow is in a sense secondary, in that it simply allows the slipping ice mass to accommodate more readily to the larger obstacles in its path. It is known from tunnel observations in Greenland (personal communication from H. Bader) that there is no basal slip when the temperature at the bed is below freezing, so that regelation-slip cannot occur.

Regelation-slip is a process which intimately combines mass transport and heat transport at the glacier sole. It involves: (1) heat transport from points of local freezing to points of local melting; (2) mass transport of liquid water, in a thin basal layer, from points of melting to points of refreezing; (3) bulk transport of the main ice mass above, resulting from the operation of (1) and (2).

Since the quantitative treatment of glacier mass transport, budget, and response to climatic change (Nye, 1960, 1963) is based on the relation between flow rate and stress, and since basal slip contributes a significant to predominant (near the snout) fraction of the total flow, it is important that theoretical conceptions of the basal slip process be tested by critical observations and measurements of the actual process in operation. The need for an improved understanding of the phenomenon has been pointed up recently by the observation of large

* We propose to use the term *regelation* with the restrictive meaning (refreezing after pressure-melting of ice) that has become accepted ("Webster", 1934, p. 2096). As so defined, regelation is one aspect of a complex and imperfectly understood ice-cohesion phenomenon discovered by Faraday (1860), to which the same designation was originally applied, and it is the only aspect consistent with the etymology of the word, as pointed out by Thompson (1860, p. 154). Other aspects should best be designated by the appropriate modern technical terms *cohesion*, *sintering*, *cold welding*, etc., as done by Kingery (1960), who has made a valuable study of the nature of Faraday's phenomenon.

anomalous changes in the relative contributions of internal deformation and basal slip over short longitudinal distances in temperate glaciers (Kamb and Shreve, 1963; Savage and Paterson, 1963).

In the study reported below, we have observed directly the basal-slip process in operation, by means of a tunnel driven to the base of Blue Glacier, Mount Olympus, Washington. We have also carried out some simple experiments to provide a comparison with the field observations and with theoretical predictions.

One of the authors (Kamb) has made a detailed theoretical study of the basal-slip process. This study will be reported elsewhere, but it can be used to interpret some of our observations here.

Field Observations

Part of the 1962 program of ice-flow investigation of Blue Glacier, Washington, involved excavation of an ice tunnel, which entered the glacier near the top of and along the (true) left margin of the ice fall that separates the lower valley-glacier tongue from the accumulation basins above. For a general description of the glacier see LaChapelle (1959) and Allen and others (1960). The tunnel, whose plan and profile are shown in Figures 1 and 2, reached bedrock 50 m. in from the surface and at a vertical depth of 26 m. beneath the surface. Numerous observations of ice deformation and flow were made in the tunnel over a period of nearly seven weeks during July and August 1962. A general account of the results is being prepared for publication separately. In the following sections we summarize our observations and measurements bearing on the basal-slip mechanism and on the behavior of ice in the lowermost part of the glacier.

Measurement of flow and deformation rates

1. Precision dial micrometers were used to observe the motion of ice with respect to bedrock immediately below. A stake anchored in the ice a distance 10 cm. above bedrock

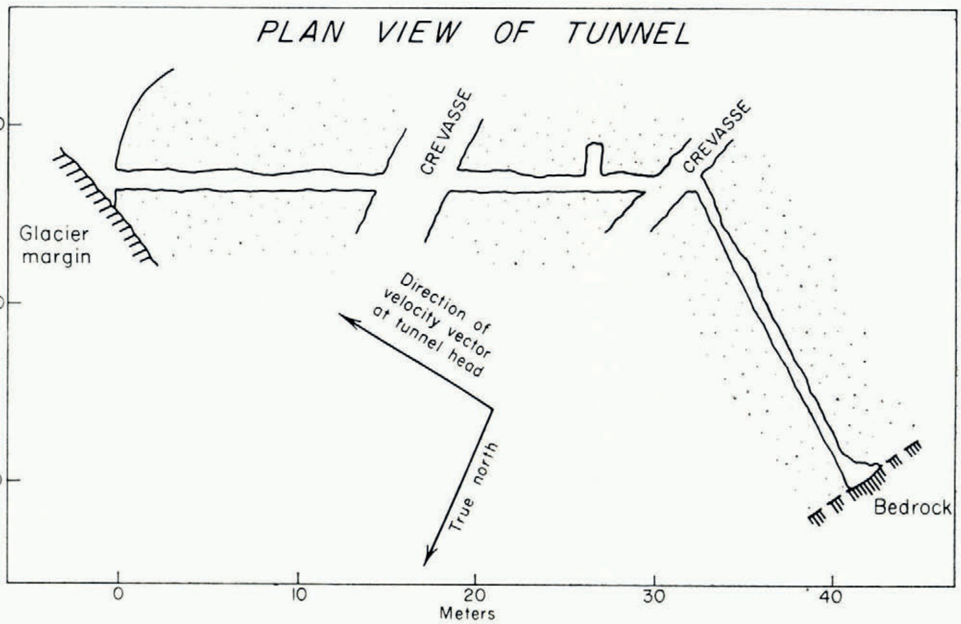

Fig. 1. Plan view of tunnel in Blue Glacier, excavated June–July 1962. Observations reported were made in chamber at head of tunnel, adjacent to bedrock

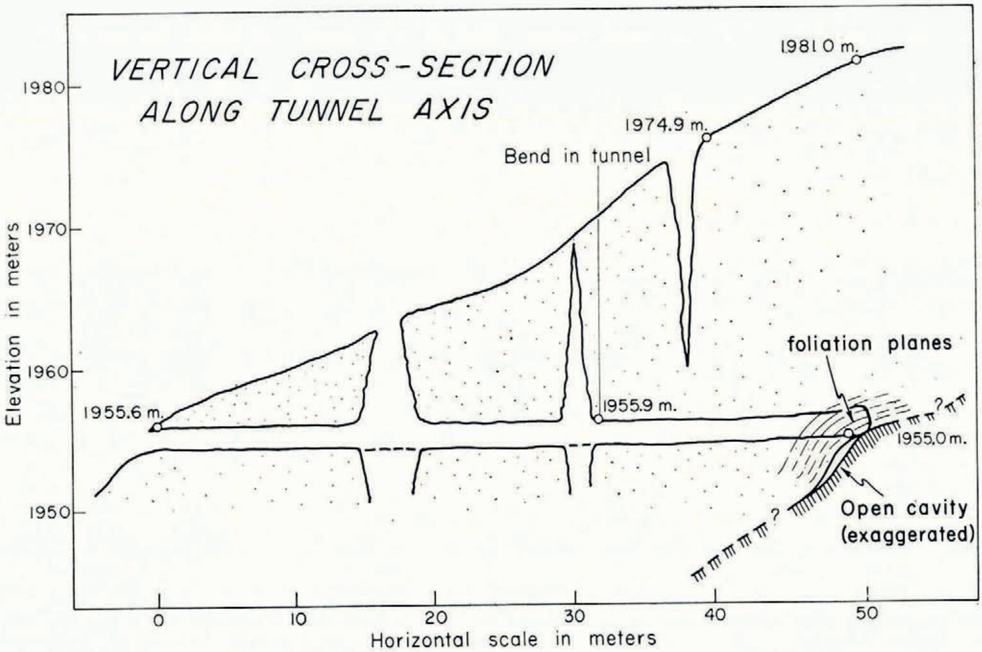

Fig. 2. Vertical cross-section along axis of tunnel. Configuration of ice foliation near the tunnel head is indicated, and ice separation from bedrock is shown schematically. Crevasses shown approximately only

showed an average motion of 1·6 cm. day^{-1} parallel to the bed. A stake 150 cm. above bedrock moved 12 per cent faster. By means of a vertical profile of marker pegs spaced 10 cm. apart, it was found that most of this 12 per cent differential motion occurred within the lowermost 50 cm. of ice, as shear uniformly distributed except for two irregularities suggestive of "shear zones", which, however, had only intermittent activity. In any case essentially all of the motion of 1·6 cm. day^{-1} took place as slip at the bedrock–ice interface.

2. Surface flow-velocity measured at a point approximately above the tunnel head was essentially identical in magnitude and direction to that observed at height 150 cm. above bedrock in the tunnel (1·8 cm. day^{-1}). Thus about 90 per cent of the total glacier motion at the observation site took place by basal sliding and only about 10 per cent by internal deformation. At the tunnel site, located near the glacier margin, the flow velocity was, of course, much less than that in the center of the ice stream some 200 m. distant, measured at over 1 m. day^{-1}.

3. The observed slope of the bedrock at the tunnel head was 22 degrees, but immediately down-glacier the bedrock dropped off steeply at an angle of about 55 degrees. The average local shear stress on the bed estimated from the slope of the glacier surface (28 degrees) and the presumed density profile of ice and firn is 0·7 bar; the estimated normal stress or overburden pressure is 1·6 bar. Because the observation site is in the marginal shear zone of the glacier, the shear stress is probably larger than that estimated from the local overburden alone. The hydraulic radius of the channel, which is known reasonably well from thermal borings, sets an upper limit of 2·1 bar to the shear stress at the observation site.

4. The measured basal slip velocity was not steady with time but showed marked irregularities over time intervals of the order of seconds. The mean flow rate varied up to 10 per cent from day to day. These phenomena will be reported in detail in a separate paper.

Structural and textural observations

1. When overburden pressure is removed from ice in contact with bedrock, by excavating

away the ice above and around it, the basal ice freezes fast to the rock. When the basal ice is cut away quickly from the tunnel wall, without initial excavation and release of overburden pressure, it comes free from the sole and is not frozen to it. This observation demonstrates the presence of a thin layer of liquid water, at the pressure melting point, along the ice–bedrock interface.

2. Excavated blocks of basal ice were freed from the sole by irradiating momentarily with a photoflood lamp. The blocks were faced down and polished on the top and sides, to reveal internal structures. After examination in bulk, thin sections cut parallel and perpendicular to the basal slip direction in planes perpendicular to the sole were prepared to reveal the structure and texture of the lowermost 1 m. of ice. Seventeen thin sections, made from nine blocks of basal ice, were examined.

Both in block specimen (Fig. 3) and in thin section (Figs. 4 and 5), there is revealed a basal ice layer that is structurally and texturally distinct from the ice above. The thickness of this layer as seen in our specimens varies from a maximum of about 2·9 cm. to nearly zero where the layer pinches out against bedrock protuberances. On the down-stream side of such protuberances the layer reforms; this is shown in Figures 3 and 6. Where it thus reforms, the upper boundary of the newly formed ice layer is always nicely matched to the crest of the preceding obstacle (Fig. 6). These features, as well as others detailed below, indicate that the layer is formed by the regelation process. Hence we propose to call it the *regelation layer*.

3. The regelation layer contains regular trains of fine spherical bubbles or very elongate, tubular cavities aligned in the flow direction (Fig. 4). The bubble trains at different levels may mark the heights of different obstacles over which the basal ice has passed in its immediate pre-history.

4. The upper boundary of the regelation layer represents a sharp textural break, as seen under crossed polaroids (Fig. 5). The average grain size in the layer is distinctly smaller than in the ice above. Some grains in the regelation layer show crystallographic continuity with grains in the ice above, as would be expected from the point of view of growth nucleation. There is sometimes a suggestion of multiple textural breaks corresponding to the bubble trains at different levels.

5. The upper boundary of the regelation layer always appears perfectly planar as seen in sections cut parallel to the flow direction. In perpendicular sections, it shows some undulation suggestive of transverse topographic irregularities, so that in fact the boundary is a cylindrical surface.

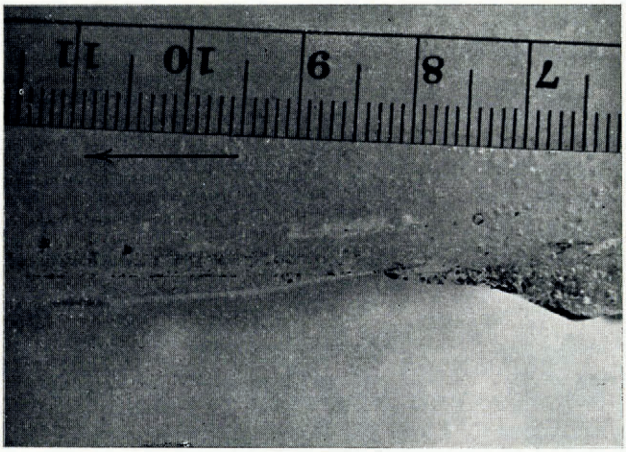

Fig. 3. Regelation layer in block of ice from base of glacier. The block of ice is shown upright; the bedrock sole conformed to the base of the block as seen. Saw-cut front face is vertical and parallel to direction of glacier motion, which is shown by arrow. Regelation layer is the apparently lighter zone at the base of the block, beneath the sharply defined, straight contact (× 0·6)

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6. The regelation layer is heavily loaded with debris in comparison with the ice above. The debris content varies markedly from place to place with the layer, but is nowhere greater than about 10 per cent by volume of the layer. The debris consists of fine mud and of rock fragments up to 1 or 2 mm. in size. A debris-laden basal layer, which may have been identical to the regelation layer as defined here, was reported by Haefeli (1951) and McCall (1952, p. 128).

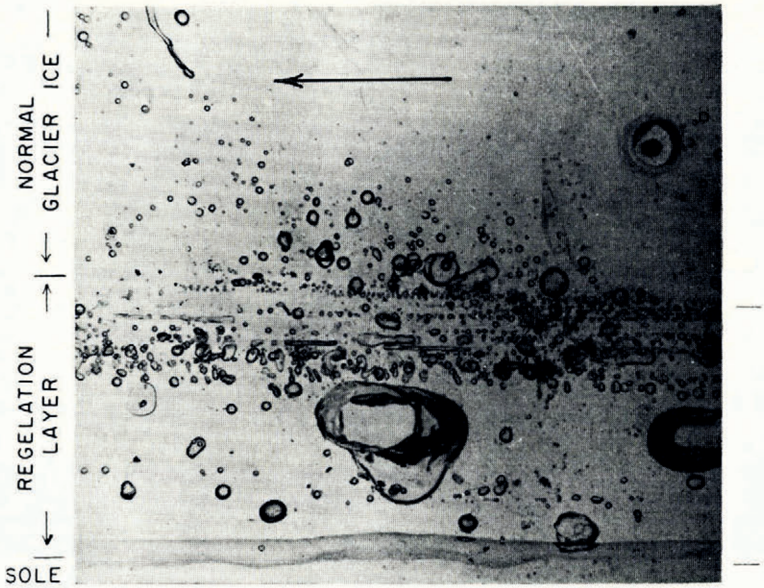

Fig. 4. Thin section of regelation layer in contact with the immediately superjacent glacier ice. Regelation layer contains included trains of fine bubbles and cylindrical cavities in its upper part. Largest cavity, in lower part of photograph, contained a rock fragment. Thin section is cut vertical and parallel to the velocity vector, shown by arrow (× 4)

7. Rock debris accumulates on the up-stream side of bedrock protuberances, as shown in Figure 6. From the crest of such protuberances there extends down-stream a train of debris particles evidently derived from the accumulation on the up-stream side.

8. Where there are depressions below the general local level of the sole, as contrasted with protuberances, the ice does not fill these in but instead bridges over them. This occurs for cavities ranging in width from 4 cm. to at least 10 m.; the corresponding separation of ice from bedrock ranges from about 1 cm. to 20 cm. An example of a bridged depression is shown in Figure 7. It is difficult from our observations to define precisely the circumstances under which a depression will or will not be filled by the regelation layer, but in general, if a depression is not preceded up-stream by a complementary protuberance, it will be bridged.

9. Where a depression is bridged, there is found forming in the open cavity, just down-stream from the point of separation of ice from bedrock, a mass of coarse, needle-like ice particles (length *c.* 5 cm.) that we propose to call *regelation spicules*. These spicules are formed in loose aggregates aligned in the direction of ice flow (Fig. 7). They are only weakly attached to the ice undersurface, or actually sag or drop away from it. The smaller spicules are single crystals. Although production of the spicules appears to be continuous, the larger open cavities beneath the ice undersurface do not become filled solidly with them, the spicular ice being carried along and presumably reincorporated into the regelation layer at the down-stream edge of the open cavities. Spicule ice probably evaporates also, in cases where the open

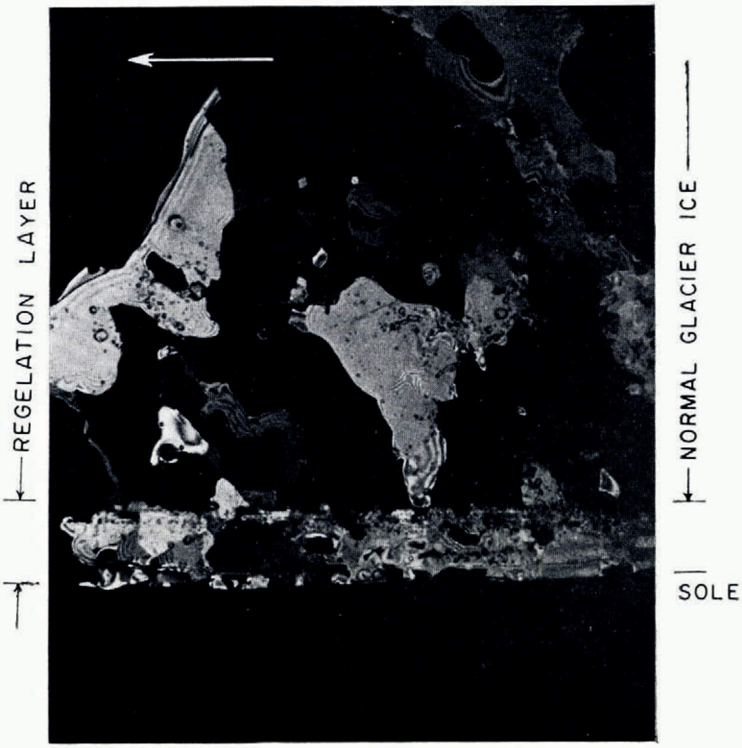

Fig. 5. The thin section of Figure 4 is seen here between crossed polaroids, and on a smaller scale (× *1·2*). *Regelation layer is at bottom, below sharp, straight textural break*

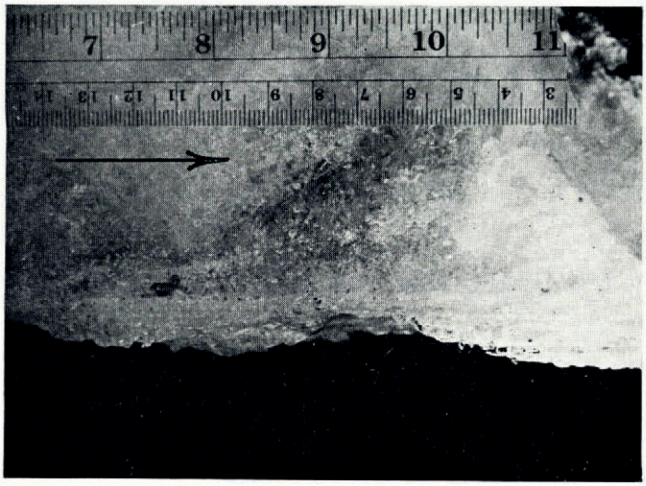

Fig. 6. Edge of an ice block from base of glacier, oriented as in Figures 4 and 5. Block conformed to bedrock at the bottom. Note accumulation of debris particles (*dark*) *on the up-stream* (*right*) *side of the bedrock protuberance in the center, and the entrainment of particles along a line down-stream from the crest of the protuberance. Another train of debris particles, inherited from further up-stream, can be seen 2 mm. above the one just mentioned. Top of the regelation layer is at the upper train of particles. Note "reworking" of some debris fragments to slightly higher levels in basal ice* (*this can be seen also in Figure 3*) (× *1·5*)

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cavities interconnect to the surface so that there can be air flow through them, as observed for larger cavities encountered in the tunnel. The spicule ice, when it is attached firmly enough to the base of the regelation layer that the two can be thin-sectioned together, shows a contrasting texture and in particular a lack of included air bubbles or bubble trains. Spicule formation is inhibited where the ice of the regelation layer is heavily debris-laden. This may be the reason that regelation spicules have not been reported by previous observers (Carol, 1947; Haefeli, 1951; McCall, 1952).

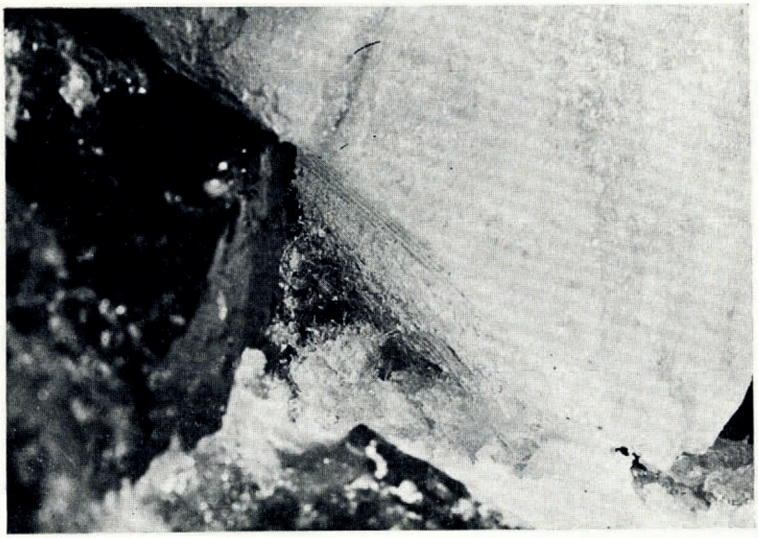

Fig. 7. Regelation spicules in cavity down-stream from bedrock step. Ice flow is from upper left to lower right. Spicules are visible attached to the undersurface of the moving ice and also detached, forming a jumbled mass in the cavity below. Height of step is about 15 cm. (× 0·2)

10. The lowermost 0·5 m. of ice above the regelation layer was relatively bubble-poor and appeared unfoliated. (A similar basal zone was found by McCall (1952, p. 128) at depth 50 m. in a cirque glacier.) Above this zone, typical bubble foliation was prominent. Its attitude was grossly conformable with the sole at the tunnel head, but there was a variation in attitude from one side of the tunnel to the other, outlining a broad anticlinal structure plunging in the direction of flow. It thus appears that the tunnel struck bedrock near the crest of a bedrock prominence. This is further indicated by the configuration of the bedrock observable down-stream, below the level of the tunnel floor (Fig. 2), where there was ice separation over a distance of about 10 m. The abrupt steepening of the bed is reflected in a bending downward of the ice foliation planes and the regelation layer, as traced down-glacier. This is indicated in Figure 2.

11. The "shear zones" suggested by the vertical velocity profile in the basal ice were not reflected in any textural or structural peculiarities in the ice itself, as seen in thin section.

Experiments

We have tested the concept of the *regelation layer*, introduced above, by producing a similar feature experimentally. This was done as follows. A 1-cm. cube of solid material, to which a constantan wire 0·812 mm. in diameter was attached, was frozen into a block of ice about 40 cm. in size. A load of 17·5 kg. was applied to the constantan wire from the outside, and the ice block allowed to warm gradually to the melting point. The motion of the cube under con-

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stant load was measured as a function of time by observing the displacement of the constantan wire against a reference scale anchored in the ice. The arrangement is shown in Figure 8.

The experiment was carried out for cubes of dunite (olivine rock), plexiglass (polymethyl-methacrylate), and aluminum. The observed time–displacement curves are shown in Figure 9. It is inferred that the large acceleration in the motion that took place about 15 hr. after the start of the experiments corresponds to the time during warm-up at which the pressure-melting point was reached at the loaded face of the cubes, and hence at which regelation-slip started.

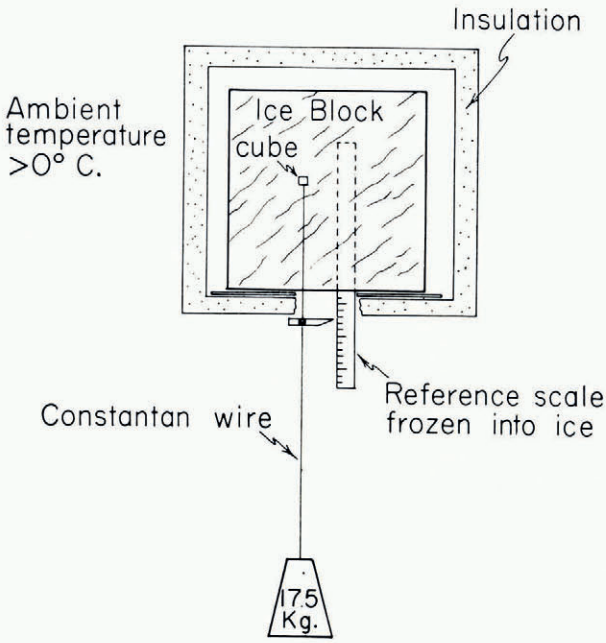

Fig. 8. Arrangement for experimental study of regelation flow

After termination of the experiments, the ice blocks were faced down to thick slabs, examined, and then thin-sectioned through the area of interest around the cubes. The following features were observed:

1. The ice behind the plexiglass cube (Fig. 10), in the volume swept out by its motion, were similar in texture and structure to ice in the regelation layer of the glacier: they have similar grain sizes, similar extent and sharpness of the textural break between regelation zone and adjacent ice, and similar presence of bubble trains parallel to the motion (compare Figs. 5 and 10). Refreezing within the regelation zone in this experiment was almost complete.

2. The volume swept out by the dunite cube was only partially refrozen, about half remaining as liquid water, containing a small bubble of air and/or water vapor. The walls of the liquid cavity, adjacent to the surrounding host ice, were lined with a regelation layer of ice similar to that in the previous experiment.

3. Refreezing behind the aluminum cube was also only about 50 per cent effective, but in this case the excess water drained away along the constantan wire, leaving a hollow space behind the cube. Surrounding this there was, again, a regelation layer adjacent to the host ice.

4. Texture and structure of the host ice around the paths followed by the cubes were not noticeably disturbed, as would have been required if a sizable fraction of the cube motion had been produced by plastic deformation of the ice.

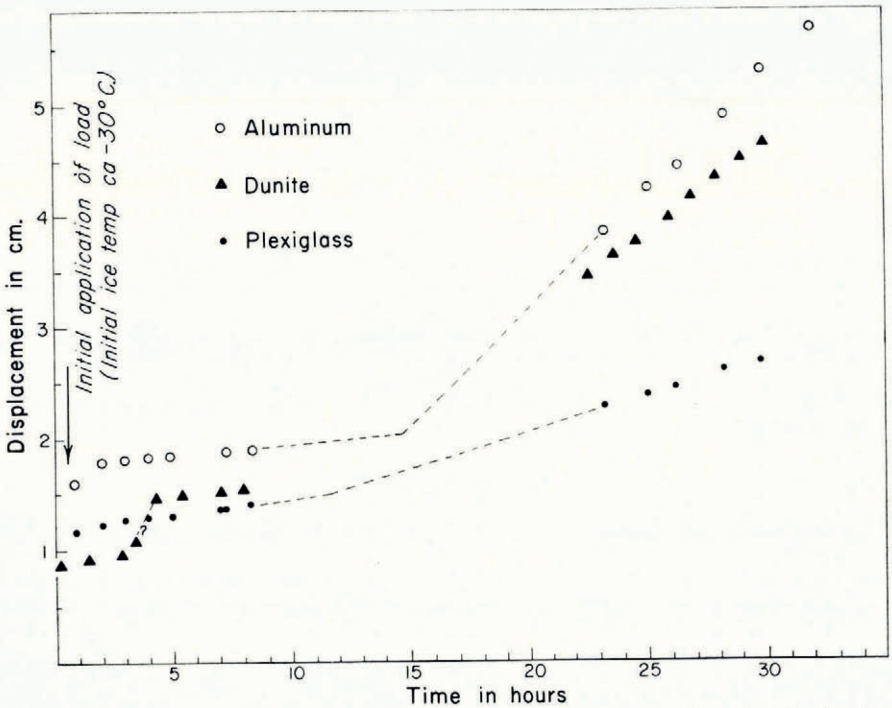

Fig. 9. Observed cube displacement as a function of time in the regelation-flow experiments. Observations for the cubes of different materials are indicated by separate symbols as shown. Motion intervening between observed points is indicated hypothetically by dashed lines

Interpretation of Results

The similarity between the experimentally produced regelation layers or zones and their natural counterparts, and the detailed structural features of the latter (particularly the behavior of entrained debris particles in the vicinity of bedrock protuberances, as described in paragraph 7 of the structural and textural observations reported above) leave little doubt that we are dealing here with the portion of the glacier that is directly involved in the regelation-slip process. Direct observation of the regelation layer enables us to apply some quantitative considerations to the basal-slip phenomenon.

Consider first the experiments. The motion before onset of regelation is doubtless due to plastic deformation of the ice around the cubes. The warm-up time to onset of regelation-flow corresponds reasonably to the calculated thermal relaxation time for the ice specimens used, about 10 hr. Part of the motion that occurred during this time interval must represent time-decreasing transient creep of the ice (Glen, 1955). The steady-state rate of cube motion due to plastic flow is therefore smaller than suggested by the initial parts of the displacement curves (Fig. 9). This accords with the fact that the total amount of plastic flow recorded in disturbance of texture and structure of the ice specimens is small compared to the amount of regelation flow.

The observed flow rate after onset of regelation may be readily compared with theoretical prediction in the case in which the thermal conductivity of the cube is large compared with that of ice, so that the heat flow is one-dimensional within the cube. In that case

$$v_R = \frac{kC\sigma}{H\rho L}$$

where k is the thermal conductivity of cube material, C the slope of the pressure–melting point curve (0·0074°C. bar^{-1}), $H\rho$ is the heat of ice fusion per unit volume, L the cube

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edge length, and σ the compressive stress on loaded face of the cube. The predicted and observed rates are shown in Table I.

TABLE I. PREDICTED AND OBSERVED RATES OF REGELATION FLOW

Material	k cal.cm.$^{-1}$ sec.$^{-1}$ °C.$^{-1}$	v_R (*calculated*) cm. day^{-1}	v (*observed*) cm. day^{-1}
Plexiglass	0·012	1·8	1·6
Dunite	0·012	1·8	3·4
Aluminum	0·49	74	5·4

Fig. 10. Experimentally produced regelation zone, seen in thin section between crossed polaroids (× 2). Space occupied by 1-cm. plexiglass cube at termination of the experiment is the roughly square, black area below center of picture. Total regelation displacement of cube was 13 mm., in the direction of the arrow

Although there is a qualitative parallelism between thermal conductivity and observed flow rate, the quantitative agreement between calculated and observed flow rates is not good. The disagreement can probably be accounted for as follows. The loss of melt water by leakage along the constantan wire, in the case of the aluminum cube, removed to the outside of the ice block part of the heat source needed for regelation flow, so that the flow rate was mainly limited by the conductivity of ice rather than of aluminum. In the case of the dunite cube there was also significant heat conduction from the surface of the ice block, because the refreezing was incomplete. (The work furnished by the applied load is negligible.) The flow rate must therefore have been limited by a higher "effective conductivity" than that of the dunite alone, otherwise refreezing behind the cube would have been complete. At first sight it seems paradoxical that heat can be conducted from the surface into the interior of an ostensibly

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isothermal block of ice at the melting point, but in fact the temperature at the stressed face of the cube is below 0° C. (actually about −0·1° C.) and temperature gradients therefore exist in the ice. It would be necessary to eliminate the effect of this by a different experimental arrangement in order to get quantitative agreement between predicted and observed regelation flow rates; it is significant that the best agreement is obtained in the case where refreezing was essentially complete.

The observations of cube motion are pertinent to the bedrock slip phenomenon in glaciers on account of the fact that Weertman (1957, 1962) based his theory of this phenomenon on the resistance to slip offered by obstacles of cubical shape. If we apply this theory (in its 1962 form) to our slip-rate measurements in Blue Glacier, it appears at first sight to give rather reasonable results. Taking the measured slip rate of about 600 cm. yr.$^{-1}$ and an estimated average shear stress of 0·7 bar at the bed, we compute from Weertman's equation (4) (1962, p. 32) a "controlling roughness ratio" $r_c = 9{\cdot}5$ (we used $n = 3{\cdot}2$), and then from equation (3) the "controlling obstacle size" $L_c = 0{\cdot}56$ cm. The corresponding "obstacle spacing" is $L_c' = 5{\cdot}3$ cm. Such obstacle sizes and spacings are indeed comparable to those that produce the regelation layer we observed. (For the limiting shear stress of 2·7 bar the theoretical quantities are $r_c = 5{\cdot}5$, $L_c = 0{\cdot}56$ cm., $L_c' = 3{\cdot}1$ cm.)

However, the controlling obstacle size is supposed in the theory to be that for which accommodation of the basal ice to bedrock obstacles is accomplished equally by regelation and by plastic flow, whereas in actual fact there is *no significant plastic deformation* occurring around obstacles of the size and spacing that produce the regelation layer. This is proved in repeated instances by close examination of the regelation layer, whose upper surface is perfectly planar (strictly, cylindrical) and shows no trace of warping even over the largest obstacles that generate the layer (see Figs. 3 and 6). Plastic deformation, indicated by bending of foliation planes and of the regelation layer as traced down-stream, becomes evident only over distances of about a meter, much larger than the calculated "controlling obstacle spacing" of 5·3 cm.

Hence the theoretical "controlling obstacle size" has no physical meaning in relation to our actual observations. The trouble lies in the predicted distance scales over which regelation or plastic flow should predominate. A similar difficulty with the theory is seen in relation to the cube experiments. If we use the nearly appropriate figure 2 of Weertman's 1957 paper, slightly modified to take into account a factor of 2 for the stress value pertinent to plastic deformation under the experimental conditions,* we find that the theory predicts a plastic slip rate that should exceed the regelation slip rate by about an order of magnitude whereas in actual fact the regelation rate is about an order of magnitude faster, and the amount of plastic deformation, which, if the theory were correct, would have been prominent in the internal structure of the specimens, is small.

Although Weertman's theory thus appears inapplicable quantitatively, we wish to emphasize that we think the general qualitative ideas on which it is based are correct.

It might be possible by adjusting arbitrarily the constants in Weertman's theory to improve its applicability to our observations, but this does not seem to us a very satisfying approach. Instead, we have developed a new analytical treatment of the basal slip mechanism, which among other things avoids the rather implausible model of cubical obstacles. In our theory, a natural length emerges which is associated primarily with the *spacing* of obstacles and only secondarily, if at all, with their *size*, in contrast to Weertman's approach. This natural length corresponds to the transition from regelation slip to plastic slip, and turns out to have a value of about 0·5 to 1 m. for situations of practical interest, corresponding rather well with our observations of the scale of plastic deformation in the tunnel.

* Weertman assumes that the resisting stress on the cube is equally divided between relative compression on the up-stream face and relative tension on the down-stream face. Since in our experiment there can be no actual tensile stress on the down-stream face, liquid water being present, the entire load stress must be borne by the up-stream face, and hence in this case a factor of ½ should not be applied to the stress to estimate the creep rate, as done by Weertman.

One element of the new theory can be checked directly against our observations of the regelation layer in process of formation. Since we know that the local resistance to basal slip provided by the obstacles that are observed to produce the regelation layer is due solely to the requirements of the regelation process, plastic flow not being involved, we can compute the local average shear stress at the bed from this process alone. We consider a bed roughness corresponding to the largest such obstacles indicated in Figures 4 and 7, having spacings (wavelength of irregularities) $\lambda \approx 4$ cm. and 9 cm. and sizes (crest to trough amplitudes) $2a \approx 0\cdot4$ cm. and $1\cdot0$ cm. respectively. From our theory we can then compute the shear stress τ at the bed from the regelation slip velocity v_R and the roughness wavelength λ and amplitude a as follows:

$$\tau = \frac{\pi}{2\sqrt{2}} \frac{H\rho a^2 v_R}{(k_1+k_2)C\lambda}$$

where k_1+k_2 is the sum of the thermal conductivities of bedrock and ice, taken to be $0\cdot01$ cal. cm.$^{-1}$ °C.$^{-1}$ sec.$^{-1}$. We obtain $0\cdot2$ bar and $0\cdot7$ bar respectively. These values are somewhat below the overall shear stress of about $1\cdot5$ bar (limiting range $0\cdot7$ to $2\cdot1$ bar) estimated mechanically, which is to be expected, since the largest contribution to the shear stress should come from bedrock irregularities on a scale of the natural length mentioned previously.

A complicating factor in the discussion of applicability of the Weertman theory is the relatively low value ($1\cdot6$ bar) of the normal stress or overburden pressure at the point of observation, which allows a significant amount of ice separation from bedrock. If the Weertman theory were applicable to our observations, so that $L_c = 0\cdot5$ cm. and $L_c' = 5$ cm. were physically meaningful lengths, then bedrock separation should be most prominent over distances of this order, since the "controlling obstacles" of the theory are those to which the basal ice has the greatest difficulty accommodating (so that the required basal stress concentrations are the largest). For obstacle spacings of the order of meters, much longer than L_c', plastic flow should allow ready accommodation of the ice to its bed. In actual fact, ice separation is prominent over distances of this order, much more so than over distances of order L_c'. Significant bedrock separations have been observed at overburden pressures up to about 5 bar in other glaciers (Carol, 1947; Haefeli, 1951; McCall, 1952, p. 127). These considerations, as well as our experimental results, all point to the same difficulty with the Weertman theory: that it overemphasizes the contribution to basal-slip of plastic flow as compared with regelation.

The maximum thickness of the regelation layer (1 to 3 cm. in our specimens) is only slightly larger than the crest-to-trough amplitudes of the bedrock irregularities of spacing 5 to 10 cm. that are observed to produce the layer, whereas, according to the interpretation presented here, a thickness of about half the amplitude of the irregularities on a spacing of the order of the natural length mentioned above could be expected to occur. For equal roughness ratios, the expected thicknesses might therefore be almost an order of magnitude larger than those observed. This difficulty has been noted by Glen (verbal communication). Several factors probably contribute to the effect: 1. The observation site is near the crest of a bedrock prominence, where the regelation layer corresponding to bedrock topography wavelengths of the order of a meter or longer would have minimum thickness; in conformity with this, the thickest part of the regelation layer (3 cm.) is found in the specimen of ice examined from farthest down-stream. 2. In the bedrock area actually observed, there seems by chance to be a scarcity of well-defined irregularities of wavelength near 50 cm. 3. The tendency for bedrock separation to occur prominently over distances of the order of 1 m. or more effectively reduces the amplitude of irregularities of these wavelengths. 4. It is possible that thicker regelation layers inherited from farther up-stream could have been obliterated by recrystallization, or by progressive melting without concomitant refreezing at the sole. The question of the "ultimate" thickness of the regelation layer can be discussed more thoroughly on a theoretical basis. In the present paper we wish to point out only that the natural distance scale for transition from regelation slip to plastic slip expresses itself basically in terms of the wavelength of the irregularities rather than in terms of their amplitude. The thickness of the regelation layer, which involves the effective bed roughness, is of less basic significance.

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