6. *On the* Mechanics *of* Glaciers, *with especial Reference to their supposed* Power *of* Excavation. By Rev. A. Irving, B.A., B.Sc., F.G.S. (Read December 6, 1882.)

Opinions as to the kind and extent of work done by glaciers upon the rocks over which they move seem still to be very divided in the geological world. On the one hand it is still maintained that these agents are capable of excavating basin-like hollows, such as those which are now (or have been) filled with lakes; on the other hand we find such high authorities as Profs. Bonney * and Credner † rejecting the hypothesis of *excavation*, while they fully recognize (as every Alpine observer must do) the scouring, grooving, striating and polishing work done by glaciers upon the floors and sides of valleys previously formed by ordinary valley-erosion, as well as their indirect action in contributing to the formation of lakes by the dams which their moraines form (*e. g.* at the southern end of Lake Garda) in some cases across valleys. Amid this diversity of opinion I may be pardoned for attempting to add something to the discussion of this interesting subject.

The whole discussion would seem to narrow itself, theoretically, to the answer to be given to the question, *Can a glacier dig or excavate basin-like hollows?*

Those who answer in the affirmative seem in their arguments to assume that the ice of the glacier moves as a *rigid mass*. If it did so, its scooping-out power would be enormous; but that it does not has been shown by Prof. Tyndall, in his little work 'Forms of Water' and elsewhere, and demonstrated experimentally by himself and Prof. Helmholtz ‡ of Berlin. The writings also of Forbes and others on this subject are no doubt familiar to geologists.

The snow of the upper *névé* becomes gradually transformed into the solid ice of the glacier in two ways:—(1) By pressure from above the crystalline particles are partly melted, the liquefied portions finding their way between those which still remain solid; (2) the heat of the sun melts the surface-particles, the water at 0° C. thus formed trickling into the snow. In both cases the water is again transformed into ice, its latent heat being taken up by the snow, which at these high altitudes is at temperatures below 0° C. *Regelation* occurs, as it does behind the shearing-wire in a well-known experiment. Liquefaction by *pressure* of portions of the ice-mass, and regelation at points where the pressure is relieved, are not confined to the *névé*; it goes on continuously throughout the mass of the glacier, though more in some parts than in others, and goes a long way to account for the "plasticity" of the ice-mass—its power, that is to say, of adapting itself to the form of the trough or hollow in which it lies.

* See Quart. Journ. Geol. Soc. vol. xxx. p. 479.
† 'Elemente der Geologie,' p. 245. ‡ *Vide* Lecture, 'Eis und Gletscher.'

Prof. J. Thomson has deduced from the mechanical theory of heat, and Sir W. Thomson has verified by experiment, the law that *the freezing-point of water is lowered by pressure*; and Helmholtz * has shown how it follows, as a corollary to this important law, that the temperature of ice is lowered when it is subjected to pressure within a confined space, the ratio of the liquid water to ice being at the same time increased. The thermal energy which is generated by pressure becomes latent in the newly liquefied ice, and so is not available to affect the temperature of the mass. This liquefaction must take place most in the lower layers of the glacier; and owing to the great latent heat of water (=nearly 80 thermal units at a pressure of one atmosphere) the pressure, though great, melts only a small proportion of the ice-mass, which is very large. Helmholtz † has pointed out the bearing of this principle upon glacier-work. The ice being pressed, and a small portion of it melted, the water is free to escape. The temperature of the pressed ice is lowered, but not that of the water, which, being free to escape, does not suffer any lowering of temperature. "So we have, under these circumstances, ice colder than 0°C. in contact with water at 0°C. The consequence of this will be, that water is continually frozen around the pressed ice and forms new ice, while a portion of the pressed ice is melted." Owing partly to imperfect homogeneity of the ice of a glacier, partly to the inequalities of its bed, pressure acts more upon some points and in some directions than in others. Several results may follow. (1) If the pressure is applied continuously and rapidly enough, and the temperature of the ice is below that required for liquefaction under the given pressure, the ice cracks; work is done in overcoming cohesion. (2) Some ice is melted, mechanical force is transformed into heat, which becomes latent in the melted ice, the water is squeezed out and regelates in contact with the colder ice, its latent heat being given up to the colder ice in contact with it, raising the temperature of this ice, until it and the regelated film have acquired again a uniform temperature. (3) *Friction* follows, if, as in the glacier, the force continues to be applied, by the faces of the cracks sliding over one another. Heat is generated; portions of the ice surfaces are liquefied, the water trickling out as before and becoming regelated in contact with colder ice, the thermal energy given up by it in the act of regelation being diffused by slow conduction, as before. (4) As the heat given up by the water in the act of regelation to the contiguous ice is transmitted by slow conduction through the neighbouring ice, it causes expansion, or a tendency to expand, which can only be prevented by increase of resistance. (5) If expansion occurs, as in (4), or water trickles out, as in (2) and (3), its tendency will be, under the influence of gravitation, rather downwards than in any other direction; and so the centre of gravity of the whole mass is lowered, though the mass may not be moving as a rigid body. This I conceive to be the outline of the history of the expenditure of that portion of the potential energy of the weight of

* 'Eis und Gletscher.' † *Loc. cit.*

a glacier-mass which is used up *within* the glacier. Now for the bearing of this upon the question of excavation.

Exactly so far as the glacier-mass possesses this yielding property due to the transformation within it of the mechanical energy due to its weight, *is its digging- or excavating-power diminished.* Further, whatever theory we adopt to account for the yielding property of ice (its "plasticity" or "Nachgiebigkeit"), it is plain that the forward and downward thrust is not wholly expended in propelling the glacier mass as a rigid whole; hence the absence of any traces of excavating-action where glaciers have receded in recent years. As it is, the forward thrust is to a very large extent resolved into an indefinite number of smaller forces, which are expended, either directly or indirectly (if first transformed into thermal energy), in overcoming cohesion. It follows at once from this, as a simple deduction from the law of the conservation of energy, *that the residuum of energy available for any supposed excavating action of a glacier is comparatively small.* And this deduction would seem equally sound whether (following Tyndall and Helmholtz, as I have done above) we adopt the *regelation-theory*, or the "viscous theory" which was propounded by Forbes, to explain the "flow" of the glacier. The essential point is, that the greater part of the forward thrust of the glacier mass is expended in overcoming cohesion and in causing movements among the parts of a glacier relatively to one another. Such relative movements of the parts of a glacier are, since the numerous observations of Tyndall and his fellow glacialists, too well known to need further description here; the relative rates (1) of the middle and the sides, (2) of the top and bottom, having been made matters of exact measurement *. Tyndall and Helmholtz have both also given experimental demonstrations of them.

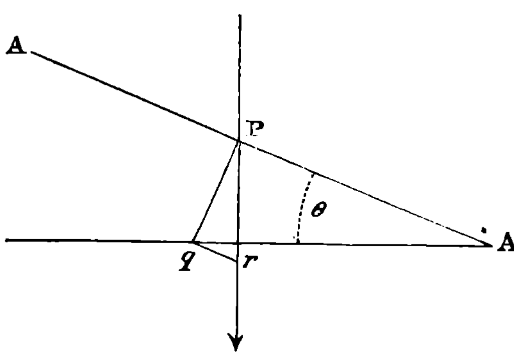
The above reasoning applies of course to such portions of the glacier as form a continuous whole. There is yet another way in which some part of the potential energy due to weight is expended; that is, in *the formation of crevasses.* Ice is not viscous, and therefore does not preserve its continuity under the influence of *tensile strain.* So small is its power to resist tensile force, that the slight bending of its mass which is caused (according to Helmholtz) by an increase of gradient in its bed of from 2° to 4° is enough to form *transverse crevasses* in its upper surface. Such crevasses penetrate further into the ice in proportion as the increase of gradient is greater. Here then is an expenditure of a portion of the weight of the ice-mass immediately below each crevasse, which is quite unavailable for purposes of erosion. Again, in the formation of the well-known *Bergschrund*, the ice below it having torn itself away from the *névé* above it, the weight of the latter is no longer capable of cooperating with the weight of the ice below it. *Marginal crevasses* result also from the same absence of ductility in ice. The movement forwards and downwards of the central parts of a glacier being greater than that of the lateral parts, which are retarded by friction against the sides of the valley, a strain and tear result;

* *Vide* 'Forms of Water,' by Prof. J. Tyndall.

the ice parts asunder in a number of planes, forming an equal number of crevasses, which proceed with gradually diminishing width from the extreme lateral limits of the glacier towards the centre—not, however, in a strictly transverse direction, but in that of the tangent to the direction of the strain, tending upwards therefore towards the source of the glacier. Finally *longitudinal crevasses* are formed when a glacier has to force itself through a narrow gorge. As it emerges from the gorge, the central portions move on faster than the lateral portions, which are retarded by the sides; and that portion of energy (even here where the action against the rocky sides is at a maximum) which is expended in parting the middle portions from, and producing friction of them within the gorge against, the lateral portions, cannot be expended at the same time upon the work of erosion. Generally, we may say that the origin of all these varieties of crevasse is the same property of glacier-ice which makes it unable to yield to tensile force; and the consequence is, in each case, a breaking-up, more or less, of the glacier-mass, and the consequent distribution of its force as a moving body.

The whole weight of any given mass of the glacier may be resolved into two forces, the one acting parallel, the other at right angles, to the inclined plane on which the glacier lies*. The former, which will vary with the sine of the angle of inclination, and will therefore be *nil* when the glacier rests on a horizontal bed, is, as has been shown, partly used up within the glacier; and the portion thus used up, whatever it may be, is not exerted against the rocky floor, and therefore *can do no work in the way of erosion.* The ice moves on this floor, if it be inclined at a sufficient angle; but it moves with less velocity at its bottom than the centre of gravity moves.

* The relation which subsists between the angle of inclination of the slope on which a given mass of a glacier lies, and the pressure and shoving force due to the weight of the given mass, will be made clearer by the following simple mathematical reasoning. Suppose a given glacial mass to lie on a slope, represented in the accompanying diagram by a line AA′, which makes an angle θ with the horizontal; and let us suppose the whole weight of the given mass to be represented by one resultant force W, acting vertically through its centre of gravity, upon the point P, as indicated by the arrow. By a simple "triangle of forces" it is easy to see what parts of the weight W are represented by the forces acting (1) as pressure in the direction of the normal Pq upon the surface AA′ at P, (2) as a shoving force parallel to AA′. For the first we have



$$W \times \frac{Pq}{Pr} = W \times \cos\theta;$$

for the second,

$$W \times \frac{qr}{Pr} = W \times \sin\theta.$$

So far as we have now proceeded in the argument, this difference of velocities would appear to represent the work done within the glacier; and we might reason in a similar way as to the difference of velocities of the median and marginal portions.

In the above reasoning I have assumed only the action of a part of the shoving force due to gravity in making the glacier slide upon its bed. As a matter of fact, other causes may promote sliding by diminishing friction, such as (1) the non-contact of the ice with the rocks in places where the glacier streams are flowing, (2) the thermal effect of the heat flowing from the earth's crust by conduction from below, (3) comparatively warm water rising in places from deep-seated springs, (4) the partial liquefaction of the ice by pressure against the rocks. All these, by diminishing friction, dispense with some portion of the shoving force due to gravity; so that the proportion of that force used up within the mass of the glacier is even much greater than the estimate from the difference of velocities alone would give.

So far as any supposed excavating action is concerned which could form rock-basins, the *differential* movement of the upper portion of the glacier, as compared with its base, is the most important point. Measurements taken by Prof. Tyndall in the case of the Glacier du Géant, at the foot of the Tacul, showed a movement of the portions near the surface more than double that of the base. *A fortiori*, this differential movement must be greater, owing to the greater retardation of the base of the glacier, when on a horizontal bed—so much so, that the greater pressure acting at right angles to that bed (which varies *cœteris paribus* with the cosine of the angle of inclination of the bed) would seem to avail nothing, since the movement of the base of a glacier lying upon a horizontal bed would be *nil*. The only propelling force to which it could be subjected would be the shoving force acting against it from the weight of the glacier lying upon an inclined slope immediately above. Prof. Tyndall * has shown us how this would act. When the glacier passes from a steeper to a less steep gradient, the crevasses close up, the yielding-property of the ice comes into play, the ice at the surface is thrown into a series of transverse terraces or huge wrinkles, the differential motion is increased so much that stones of the medial moraine, which have fallen into the crevasses, are brought again to the surface. From all which it would appear that the movement of the *base* of the glacier upon a horizontal bed is *nil*; and therefore here, where a theory of excavation most requires it, its erosive action is almost *nil*. This reasoning seems further confirmed by observations made on the Morteratsch †. Some distance up the glacier the movement, at its maximum, was found to be 14 inches *per diem*; yet at the snout, which lies on a nearly horizontal bed, even without any ice in front to offer any resistance to its motion, the movement forward was only 2 inches in a day. It is no reply to this argument to say that, higher up, the erosive power must be greater. The ordinary law of valley-contour,

* Forms of Water, p. 180. † *Ibid.* pp. 96, 97.

the steepness of the valley as a rule increasing as we approach its head, is well known; and it follows from this that the biting-power of the glacier upon the rocks (which diminishes with the steepness in proportion to the cosine of the angle of inclination) is less as we ascend into the steeper slopes of the glacier-region. Moreover it is self-evident that it is not on such steeper parts of the valley that the advocates of the excavation-theory would call its action into requisition.

In the work of erosion, such as is imputed to glaciers, it is of course well known that the work is mainly done by the stones and sand which have found their way, either through crevasses or between the glacier and the rocky sides of its channel, to the base. These form the teeth of the file. We must recollect however (1) that these and the rocks upon which they act are of about equal hardness; only at most, therefore, one half of the finer detritus which comes away in the glacier-stream is produced by the grinding away by these stones of the rocks themselves, the wearing of the stones furnishing an equal amount of it; (2) that the stones held in the ice are only passive instruments, and can only do work upon the rocks when they move—that is, when the resistance to their motion against the rock is less than the yielding-power of the ice which holds them. Moreover, much of the detritus which comes away in the glacier-stream may well be derived directly from the finer portions of the moraines which have fallen to the bed of the glacier.

It has been suggested that the freezing of water within the crevices and pores of the rocky bed of the glacier must by its expansion break up the rock-surface, and thus furnish detritus for the glacier to carry away, as the loosened materials are caught up by the ice. This *primâ facie* seems a sound argument in favour of excavation; we must therefore examine it. We must recollect (1) that the water contained in this way within the rock is exposed to subterranean heat passing up by conduction from below, and that, if this is slow, owing to the low conductivity of the rock-materials, the cooling effect of the ice of the glacier is, *à fortiori*, equally slow. (2) The actual surface of the rock at any given point is in contact with either (*a*) the water of the glacier-stream, which is not below 0° C., and therefore cannot freeze the water within the rock, or (*b*) in contact with the ice (or a stone stuck in the ice and at the same temperature as the ice), in which case the ice may be either at or below 0° C., according to the pressure at the point of contact, as Helmholtz's reasoning shows. Ice at 0° C. has no power to freeze water at 0° C., since with equality of temperature there can be no exchange of heat between the bodies; and if the ice be below 0° C., it can only be so at a pressure proportionately greater. This very pressure must be exerted upon the rock, and so counteract the expansive force of the water within the rock. The hypothesis is thus shown to be wholly inadmissible. Further, the actual appearance of glaciated rocks shows that they have not been thus broken up by freezing water while the glacier covered them.

It is conceivable that some of the surface-portions of the glacier which are melted by the sun's heat or by a warm current of air may, in penetrating the glacier, come into contact with ice which is locally colder than 0° C., and in this way undergo refrigeration. If this took place anywhere around a surface of contact of the ice and the rocky bed, the surface of contact being increased (as Helmholtz has shown in the valuable notes which he has appended to his lecture, 'Eis und Gletscher'), the pressure on the previous plane or point of contact would be distributed over a larger space, with the thermal effect which can easily be deduced from the foregoing principles. In this way as the glacier-mass is diminished at the surface, a partially compensating formation of ice may go on at the base. So far as it acted, there would be a transfer of materials to some extent away from the bed. A little further reflection will show us, however, that this could only happen where the water was unconfined, and consequently only where the glacier was moving down a slope. In such a case the result would seem to be rather adverse to erosion. When however the glacier lies on a level or hollow surface, such a process must soon bring itself to an end; for, the glacier being motionless at the base, all spaces would soon be filled with ice and cold water kept there by gravitation, and the whole pressure would bear directly upon the rock, tending, not to break it up, but to compress it.

A word or two is needed on the influence of *terrestrial heat.* The facts connected with the flow of heat by slow conduction from the interior to the exterior of the earth's mass can be learnt from any good text-book of physics. The point with which we are here concerned is this:—Since the rock in contact with the ice remains at the same temperature as the ice, it can only do so by parting with its heat to the glacier as it receives it from below. This heat must do work. What is that work? Clearly the heat must be expended in overcoming the cohesion of ice-particles in contact with the rock. And this it would do whether the ice were at or below 0° C., since in the latter case the heat received from the crust of the earth cooperates with the pressure which is the necessary condition of a temperature below 0° C. The bearing of this fact as tending to diminish friction, and therefore erosion, has been pointed out above*.

In connexion with glaciers there is, in addition to the polishing, striating, and grooving work, observable everywhere on glaciated rocks, a still more extensive work of erosion going on, by the action of the *glacier-streams* which flow beneath them. Such streams, while they intervene in places between the ice-mass and the trough in which the glacier moves, are capable of doing much more work than the ice itself, by virtue of the greater velocity with which they carry stones and sand along. Since, however, this action depends entirely upon the movement of the water, it is clear that a descent is necessary for this movement; and as water does not flow up-hill,

* The conduction downwards of absorbed solar heat from the sides of the valley to below the surface of the glacier produces in the summer a want of contact, for some feet down, between the ice and rock—a fact familiar to every observer of glaciers.

each glacier-stream must maintain an open channel for itself; for this reason the same objection applies to it as to a river flowing in an open valley, as an agent of excavation of basin-like hollows. Here and there, where we see the convergent surface-streams of the glacier rushing down the shaft of a *moulin*, and carrying from time to time earth and stones from the surface-moraines, a certain slight work of excavation is no doubt accomplished, such as we see now exposed to the light of day in the well-known "glacier-garden" at Lucerne; but this would hardly meet the requirements needed for the excavation of lake-basins. The main glacier-stream, just like any other stream, acts of course as an erosive agent and deepens the trough in which the glacier moves, an excellent example of which I observed only last summer at the end of the Hochjoch Glacier, at the head of the Rofen Thal, where the ice forms an arch resting upon the sides of the gorge as its buttresses.

Again it is undeniable that an advancing glacier may do a certain amount of "ploughing" work, such as Prof. Tyndall has described in connexion with the Görner Glacier *. This, however, is only evidence of the inability of the glacier-ice to move over the superficial obstacles which it encounters in its path; it would seem to tell rather against the notion of the ice being driven up-hill out of a basin, as is assumed by some writers; and it would be interesting to inquire whether such phenomena have ever been observed where a glacier was not descending a slope. All that has been put forward with reference to the distribution of the potential energy due to gravitation in the procession of the glacier down a valley must tell equally against the propulsion of it up-hill.

On the other hand, we may, I think, draw a distinction between the "ice plough" and what I may be allowed to call the "ice chisel." In cases where successive portions of a glacier descend a vertical, or nearly vertical, precipice, a different set of mechanical conditions is presented to us. Impact may in this case perhaps do the work of excavation to such an extent as is represented in the excavation of many small rock-basins, such as some of those which lie upon the Bernina Pass, or at the foot of the precipices of Snowdon. But when all this is admitted we have no right to reason from "the hundreds of tarns that are found in all glaciated mountain-countries" to the formation of lake-basins which form long depressions in narrow valleys. Many tarns, however, do not occupy rock-basins at all; some are formed by moraine-heaps left by the retreated glaciers, between which and the mountain-side they may be frequently observed to lie in the Alps; other tarns simply fill depressions formed by earth-movements on the mountain-slope, where the clayey materials produced by the disintegration of hornblendic, augitic, and felspathic *débris* get loosened by water and move unequally downwards, as clay often does on a smaller scale in a railway-cutting. Numerous instances of such could be pointed to in the Alps and in other mountain regions.

It is not without regret personally that I find myself driven to

* Forms of Water.

conclusions adverse to the theory of excavation which has been advocated for some twenty years by Sir A. Ramsay, to whose geological writings we are all so greatly indebted.

General Conclusions.

It will be seen from what has been advanced that I do not question the power of glaciers to do a good deal of surface-erosion in grinding, polishing, grooving, and striating the rocks; no one who has seen any thing of glaciers or of glaciation could do this for a moment. My contention, from the consideration of mechanical and physical principles, is that far too much work has been ascribed to them by some writers in the way of erosion, and that the notion of actual *excavation* of lake-basins is inadmissible, except under very special circumstances such as those under which some tarns may have been formed.

The causes of the differential movement of glaciers would appear to be three:—

(1) Cracking and partial melting in places under pressure and strain, followed by regelation, as propounded by Tyndall and accepted (after independent experimental investigation of the phenomena) by Helmholtz. This is probably the principal regular cause.

(2) Friction generating thermal energy, and so producing liquefaction, which is followed by regelation.

These two causes, it will be seen, are in constant operation, and *à fortiori* must have operated still more powerfully when the glaciers were of much greater dimensions.

(3) There remains to be accounted for a *secondary* differential motion, which has, it appears, not yet received a satisfactory explanation, though some recent writers have attempted it *: the movement is greater (*a*) by day than by night, (*b*) in summer than in winter. This was very nearly explained some years ago by Canon Moseley, when he maintained that somehow or other 'radiant heat' must enter the ice. Had he known those principles of physics which are illustrated by the action of Crookes's radiometer, there is little doubt that he would have seen his way to the right explanation. The theory which I venture here to advance is based upon a series of experiments with ice subjected to different sources of radiant energy, in which I have been engaged, an account of which I hope to publish elsewhere †. For the present purpose we must consider *heat* to mean energy capable of melting ice or tending to melt it. Whatever notion we may attach to the term "radiant heat," it is clear to me from my experiments that heat, *qua* heat, cannot enter the ice and be afterwards expended in the work of liquefaction—that is to say, in overcoming cohesion and so promoting differential movements of parts of the glacier. All such heat must become latent in the liquefaction of ice at the surface. It is in the *transformation of energy* that the clue is to be

* See Croll, 'Climate and Time,' chap. xxxi.

† See Nature, No. 693.

found. To say that ice is transparent is to say that *luminous radiant energy* can freely traverse it. It does not do so however equally at all times. Obviously, more luminous energy enters the glacier from the sun by day than by night—more during the more numerous hours of daylight, the higher ascension of the sun, and the greater freedom from the diffusive action of the snow at the surface in summer than in winter. A certain amount of the luminous portion of a beam of solar radiation is absorbed by even clean ice, more especially by granular ice, otherwise the beautiful silvery blue colour which is perceived in the ice overhead when one enters an ice-cavern would be wanting. But it is chiefly by opaque and semi-opaque bodies within the glacier (stones, earth, organic germs, &c.) that the luminous solar radiation which enters the ice is absorbed; and the radiation thus absorbed is, in accordance with the law of conservation of energy, converted into heat, just in the same way as it is in an ordinary greenhouse. Heat thus developed within the mass of the glacier, during the hours of daylight, and most so during the summer, must promote the differential movement of the glacier. Of course, if the glacier is clean enough and thin enough, some of the luminous energy may penetrate to the rocks beneath; but the transformation of energy would in that case be the same, the heat developed promoting the descent of the glacier as a whole, instead of its differential motion.

Discussion.

Mr. Callard stated that in 1878 he had had the opportunity of studying the base of the Rhone glacier, which glacier has been slowly receding for a length of time. Beneath the glacier, as seen in the terminal ice-cave, the ground was not ploughed but only somewhat smoothed.

Prof. Seeley pointed out that before we could accept the author's views it would be necessary for him to explain the origin of the quantity of detritus carried out from the end of the glacier and the smoothed surfaces on the bottom and sides of the glacier-bed. He thought that the effect of the continual melting and freezing of water at the bottom of the glacier on the rock masses below had been overlooked by the author, and that these effects must be very striking. The late Mr. Clifton Ward had shown that some lake-basins occur at the point where tributary glaciers join the principal ones.

Mr. Blanford referred to the *à priori* argument, based on the fact that rock-bound lake-basins abound in districts which have been glaciated, and are rare in other regions. He pointed out that the author seemed to have lost sight of the fact that the erosion was performed not by ice but by stones &c. held in the ice.

Lieut.-Col. H. H. Godwin-Austen said that the great glaciers of the Himalayas, which are so much larger than those of the Alps, are advancing, breaking away the ground along their sides, and pushing forward their older moraines. It must also be remembered that glaciers of the great thickness of the older glaciers in Switzerland must have produced very different effects on rocks of different degrees of hardness, and that thus rock-basins might have been produced.

Mr. Walter Browne agreed with previous speakers that the fact that the rivers flowing from the ends of glaciers contain so much mud is proof positive that they erode their beds. He had seen the Görner glacier pushing the turf of fields before it like a plough. He called attention to considerations laid before the Royal Society in his recent paper, especially that the Greenland glaciers move, in the depth of winter, at temperatures far below 0° C.; and he thought this fatal to the movement of glaciers being due to regelation. According to the author's theory, glaciers would cease to move when they reach a horizontal surface.

Dr. Hicks thought that the author had proved his case, which was, that ice, by itself, cannot erode rock-surfaces.

Dr. Woodward referred to the observations of Dr. Hector, in New Zealand, and said that no glaciers are absolutely clean, but all contain rock fragments, consequently all glaciers are capable of erosive action.

Mr. Bauerman objected to the author's comparison of ice and glass. Ice is perfectly crystalline, as shown when examined by polarized light, the principal axis of the crystals being perpendicular to the planes of cooling. Apart from this point, he was inclined to agree with the conclusions of the author. He did not think there were any experiments which could be quoted in support of the view that glaciers can erode rock-basins. He thought that what is usually called glacier-erosion would be found to be due to the erosion of water in confined channels beneath the glacier.

The Rev. E. Hill said that the argument that the thrust was mainly expended in overcoming cohesion rather told against the author's views than supported them, as the friction of the sides of the glacier is necessary to produce a resistance to the thrust.

The Rev. E. S. Dewick agreed with Mr. Bauerman's views on the subject.

The Author said that, in the remarks objected to by Mr. Hill, he had been merely arguing against the view that the glacier moves as a solid mass. He fully recognized the "filing" action of the stones held in the ice; but since these stones and the rocks they grind against are of *equal hardness*, only at most one half of the pulverized material brought away by the glacier-stream comes from the rocks over which the glacier moves. He agreed with Mr. Bauerman as to the work done by streams beneath the glacier, and had given an illustration of it in the paper. He argued, not against the erosive power of glaciers, but against their power of cutting rock-basins such as those occupied by lakes. He had already met many of the objections raised to his views in a paper to be read in a fortnight's time. He had pointed out one cause of the motion of glaciers which is quite independent of climatal conditions, namely the conduction of heat to the glacier from below. The surface-conditions in a region of *excessive radiation* like Siberia, which Mr. Browne had referred to, were not comparable with the conditions found beneath the glaciers in Greenland.