XV. *On the Structure and Motion of Glaciers.*

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§ 1.

IN a lecture given at the Royal Institution on the 6th of June, by Mr. TYNDALL, 1856, certain views regarding the origin of slaty cleavage were brought forward, and afterwards reported in the 'Proceedings' of the Institution. A short time subsequently, the attention of the lecturer was drawn by Mr. HUXLEY to the observations of Professor J. D. FORBES on the veined or laminar structure of glacier ice, and the surmise was expressed, that the same explanation might apply to it as to slaty cleavage. On consulting the observations referred to, the probability of the surmise seemed apparent, and the result was a mutual arrangement to visit some of the Swiss glaciers, for the purpose of observing the structure of the ice. This arrangement was carried out, the field of observation comprising the glaciers of Grindelwald, the Aar, and the Rhone. After returning to England, the one in whose department it more immediately lay, followed up the inquiry, which gradually expanded, until at length it touched the main divisions of the problem of glacier structure and motion. An account of the experiments and observations, and our joint reflections on them, are embodied in the memoir now submitted to the Royal Society.

§ 2. *On the Viscous Theory of Glaciers.*

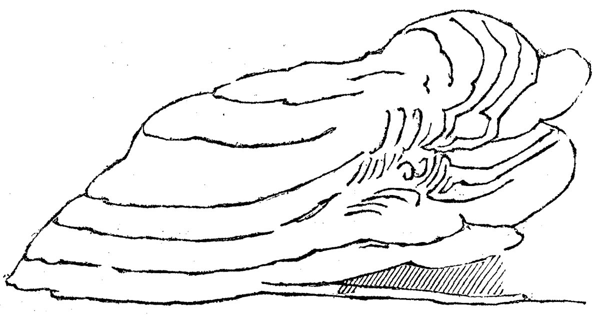
A glacier is a mass of ice which, connected at its upper extremity with the snow which fills vast mountain basins, thrusts its lower extremity into the warm air which lies below the snow-line. The glacier moves. It yields in conformity with the sinuosities of its walls, and otherwise accommodates itself to the inequalities of the valley which it fills. It is not therefore surprising that the glacier should have been regarded as an ice-river by those who dwelt in its vicinity, or that this notion should have found a place in the speculations of writers upon the subject. The statements of M. RENDU in connexion with this point are particularly distinct:—"There are," he writes, "a multitude of facts which seem to necessitate the belief that the substance of glaciers enjoys a kind of ductility which permits it to model itself on the locality which it occupies, to become thin and narrow, and to elongate itself like a soft paste*." But this observer put forward his speculations with great caution, and often in the form of questions which he confessed his inability to answer. "M. RENDU," says Pro-

* Théorie des Glaciers de la Savoie, p. 84.

fessor FORBES, "has the candour not to treat his ingenious speculations as leading to any certain result, not being founded on experiments worthy of confidence...... My theory of glacial motion, then, is this:—A GLACIER IS AN IMPERFECT FLUID OR VISCOUS BODY, WHICH IS URGED DOWN SLOPES OF A CERTAIN INCLINATION BY THE MUTUAL PRESSURE OF ITS PARTS."

"The sort of consistency to which we refer," proceeds Professor FORBES, "may be illustrated by that of moderately thick mortar, or the contents of a tar-barrel poured into a sloping channel." Treacle and honey are also referred to as illustrative of the consistency of a glacier. The author of the theory endeavours, with much ability, to show that the notion of semifluidity, as applied to ice, is not an absurdity, but on the contrary, that the motion of a glacier exactly resembles that of a viscous body. Like the latter, he urges, it accommodates itself to the twistings of valleys, and moves through narrow gorges. Like a viscous mass, it moves quickest at its centre, the body there being most free from the retarding influence of the lateral walls. He refers to the "Dirt-Bands" upon the surface of the glacier, and shows that they resemble what would be formed on the surface of a sluggish river. In short, the analogies are put forth so clearly, so ably, and so persistently, that it is not surprising that this theory stands at present without a competitor. The phenomena, indeed, are really such as to render it difficult to abstain from forming some such opinion as to their cause. The resemblance of many glaciers to "a pail of thickish mortar poured out;" the gradual changing of a straight line transverse to the glacier into a curve, in consequence of the swifter motion of the centre; the bent grooves upon the surface; the disposition of the dirt; the contortions of the ice, a specimen of which, as sketched near the Heisseplatte upon the Lower Grindelwald glacier, is given in fig. 1, and of which other striking examples have been adduced by M. ESCHER, in proof of the plasticity of the substance,—are all calculated to establish the conviction, that the mass must be either viscous, *or endowed with some other property mechanically equivalent to viscosity*. The question then occurs, is the viscosity real or apparent? Does any property equivalent to viscosity exist, in virtue of which ice can move and mould itself in the manner indicated, and which is still in harmony with our experience of the non-viscous character of the substance? If such a property can be shown to exist, the choice will rest between a quality which ice is *proved* to possess, and one which, in opposition to general experience, it is assumed to possess, in accounting for a series of phenomena which either the real or the hypothetical property might be sufficient to produce. In the next section, the existence of a true cause will be pointed out, which reconciles the properties of ice, exhibited even by hand specimens, with the apparent evidences

Fig. 1.



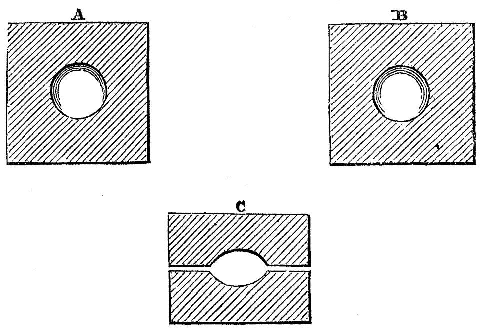
of viscosity already referred to, and which, though it has been overlooked hitherto, must play a part of the highest importance in the phenomena of the glacier world.

§ 3. *On the Regelation of Ice, and its application to Glacial Phenomena.*

In a lecture given by Mr. FARADAY at the Royal Institution on the 7th of June, 1850, and briefly reported in the 'Athenæum' and 'Literary Gazette' for the same month, it was shown that when two pieces of ice, at 32° FAHR., with moistened surfaces, were placed in contact, they became cemented together by the freezing of the film of water between them. When the ice was below 32°, and therefore dry, no adhesion took place between the pieces. Mr. FARADAY referred, in illustration of this point, to the well-known experiment of making a snowball. In frosty weather the dry particles of ice will scarcely cohere, but when the snow is in a thawing condition, it may be squeezed into a hard compact mass. On one of the warmest days of last July, when the thermometer stood at upwards of 80° FAHR. in the shade and above 100° in the sun, a pile of ice-blocks was observed by one of us in a shop window, and he thought it interesting to examine whether the pieces were united at their places of contact. Laying hold of the topmost block, the whole heap, consisting of several large lumps, was lifted bodily out of its vessel. Even at this high temperature the pieces were frozen together at the places of contact, though the ice all round these places had been melted away, leaving the lumps in some cases united by slender cylinders of the substance. A similar experiment may be made in water as hot as the hands can bear; two pieces of ice will freeze together, and sometimes continue so frozen in the hot water, until, as in the case above mentioned, the melting of the ice around the points of contact leaves the pieces united by slender columns of the substance.

Acquainted with these facts, the thought arose of examining how far, in virtue of the property referred to, the *form* of ice could be changed without final prejudice to its continuity. It was supposed that though crushed by great pressure, new attachments would be formed by the cementing, through regelation, of the severed surfaces; and that a resemblance to an effect due to viscosity might be produced. To test this conjecture the following experiments were made:—Two pieces of seasoned boxwood, A and B, fig. 2, 4 inches square and 2 deep, had two cavities hollowed out, so that when one was placed upon the other, a lenticular space, shown in section at C, was enclosed between them. A *sphere* of compact, transparent ice, of a volume rather more than sufficient to fill the cavity, was placed between the pieces of wood, and subjected to the pressure of a small hydraulic press. The ice broke, as was expected, but it soon re-attached itself; the pressure was continued, and in a few seconds *the sphere was*

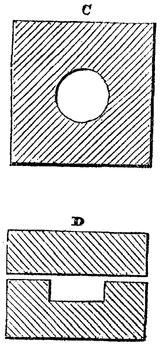
Fig. 2.



reduced to a transparent lens of the shape and size of the mould in which it had been formed.

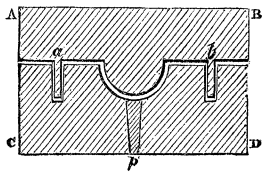
This lens was placed in a cylindrical cavity, two inches wide and half an inch deep, hollowed out in a piece of boxwood, C, fig. 3, as before; a *flat* plate, D, of the wood being placed over the lens, it was submitted to pressure. The lens broke as the sphere did, but the fragments attached themselves in accordance with their new conditions, *and in less than half a minute the mass was taken from the mould a transparent cake of ice.*

Fig. 3.



The substance was subjected to a still severer test. A hemispherical cavity was hollowed out in a block of boxwood, and a protuberant hemisphere was turned upon a second slab of the wood, so that, when the protuberance and the cavity were concentric, a distance of a quarter of an inch separated the convex surface of the former from the concave surface of the latter. Fig. 4 shows the arrangement in section. The pins of brass, *ab*, fixed in the slab AB, and entering suitable apertures in the mould CD, served to keep the two surfaces concentric. A lump of clear ice was placed in the cavity, the protuberance was brought down upon it, and the mould submitted to hydraulic pressure. After a short interval, it was taken from the press, and when the upper slab was removed, a smooth concave surface of ice was exposed. By tapping the conical plug *p*, this ice was lifted from the cavity, *the lump having been converted by pressure into a hard transparent cup of ice.*

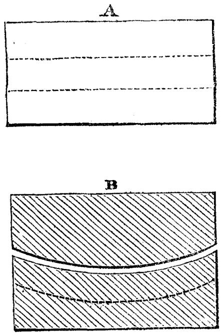
Fig. 4.



The application of the results here obtained to the "viscous flow" of glaciers, will perhaps be facilitated by the following additional experiments.

A block of boxwood (A, fig. 5), 4 inches long, 3 wide and 3 deep, had its upper surface slightly curved, and a longitudinal groove (shown in dots in the figure), an inch wide and an inch deep, worked into it. A slab of the wood was prepared, the under surface of which was that of a convex cylinder, curved to the same degree as the concave surface of the former piece. The arrangement is shown in section at B. A straight prism of clear ice, 4 inches in length, an inch wide, and a little more than an inch in depth, was placed in the groove, and the upper slab of boxwood was placed upon it. The mould was submitted to hydraulic pressure, as in the former cases; the prism broke as a matter of course, but the quantity of ice being rather more than sufficient to fill the groove, and hence projecting above its edge, the pressure brought the fragments together and re-established the continuity of the ice. After a few seconds it was taken from the mould, bent as if it had been a plastic mass. Three other moulds similar to the last, but of augmenting curvature, were afterwards made use of, the same prism being passed through all of them in succession. *At the*

Fig. 5.



conclusion of the experiments the prism came out, bent to a transparent semi-ring of solid ice.

In this way, by the proper application of force, all the bendings and contortions observed in glacier ice, and adduced in proof of its viscosity, can be accurately imitated. Any observer, seeing a straight bar of ice converted into a continuous semi-ring without being aware of the quality referred to, and having his attention fixed on the changes of external form alone, would be naturally led to the conclusion that the substance is viscous. But it is plainly not viscosity, properly so called, which enables it to change its shape in this way, but a property which has hitherto been entirely overlooked by writers upon glaciers.

It has been established by observation, that a vertical layer of ice originally plane, and perpendicular to the axis of a glacier, becomes bent, because the motion of its ends is retarded in comparison with that of its centre. This is the fact upon which the viscous theory principally rests.

In the experiments with the straight prism of ice, four successive moulds, gradually augmenting in curvature, were made use of. In passing suddenly from the shape of one to that of the other, the ice was fractured, but the pressure brought the separated surfaces again into contact and caused them to freeze together, thus restoring the continuity of the mass. The fracture was in every case both audible and tangible; it could be heard and it could be felt. A series of cracks occurred in succession as the different parts of the ice-prism gave way, and towards the conclusion of the experiment, the crackling in some instances melted into an almost musical tone. But if instead of causing the change to take place by such wide steps as those indicated; if instead of four moulds, forty, or four hundred were made use of; or better still, suppose a single mould to have the power of gradually changing its curvature from a straight line to a semicircle under the hydraulic press; the change in the curvature of the ice would closely approximate to that of a truly plastic or viscous body. This represents the state of things in a glacier. A transverse plate of ice, situated between the mass in front of it and the mass behind, is virtually squeezed in a press of the description which has been just imagined. The curvature of the ice-mould *does* change in the manner indicated, and so slowly, that the bending closely resembles what would take place if the substance were viscous. The gradual nature of the change of curvature may be inferred from an experiment made by Professor FORBES on an apparently compact portion of the Mer de Glace. He divided a distance of 90 feet transverse to the axis of the glacier into spaces of two feet each, and observed with a theodolite the gradual passage of this straight line into a bent one. The row of pins bent gradually so as to form a curve convex towards the lower extremity of the glacier; their deviations from a perfect curve were slight and irregular, nor was any great dislocation to be observed throughout their whole extent. After six days the summit of the curve formed by the forty-five pins was one inch in advance of the straight chord which united its two ends. It is not surprising if, with this extremely gradual change, the motion should have appeared to be the result of viscosity. It may, however, be remarked, that the slight and irregular variations to which Professor FORBES alludes, and which are such as would occur if the motion were such as we suppose it to be, are likely to throw much light upon the problem. It is also extremely probable that the motion, if effected in the manner referred to, will be sometimes accompanied by an audible crackling of the mass. To this we paid but little attention when on the ground; for the significance of this as well as of many other points was first suggested by the experiments made after our return. It is, however, we believe, a phenomenon of common occurrence. Professor FORBES calls the glacier a "crackling mass;" he speaks of the ice "cracking and straining forwards;" and in that concluding passage of his 'Travels' which has excited such general admiration, he says of the glacier, "it yields groaning to its fate." Other observers make use of similar expressions. M. DESOR also speaks of the sudden change of the colour of the blue veins of the ice where a portion of the central moraine near the Abschwung is cleared away; the observation is very remarkable. "Au moment," says M. DESOR, "où on la met à découvert, la glace des bandes bleues est parfaitement transparente, l'œil y plonge jusqu'à une profondeur de plusieurs pieds, mais cette pureté ne dure qu'un instant, et l'on voit bientôt se former des petites fêlures d'abord superficielles, qui se combinent en réseau de manière à enlever peu à peu à la glace bleue toute sa transparence. Ces fêlures propagent également dans les bandes blanches, et lorsqu'on approche l'oreille de la surface de la glace, en entend distinctement un *leger bruit de crépitation* qui les accompagnent au moment de leur formation." These facts appear to be totally at variance with the idea of viscosity.

In a chapter on the "Appearance of the larger Glaciers," in an interesting little work by M. MOUSSON of Zürich, for which one of us has to thank the kindness of Professor CLAUSIUS, the phenomena which they exhibit are thus described*:—"The appearance of a large glacier of the first order has been compared, not without reason, with that of a high swelled, and suddenly solidified stream. It winds itself in a similar manner through the curving of the valley, is deflected by obstacles, contracts its width, or spreads itself out...... In short, the form is modified in the most complete manner to suit the character and irregularities of its bed. To this capacity to change its form, the ice of glaciers unites another property, which reminds us of the fluid condition; namely, the capability of joining and blending with other ice. Thus we see separate glacier branches perfectly uniting themselves to a single trunk; regenerated glaciers formed from crushed fragments; fissures and chasms closed up, and other similar appearances. These phenomena evidently point to a slow movement of the particles of which the glacier consists; strange as the application of such an idea to a solid brittle mass such as glacier ice may appear to be. The solution of this enigma constitutes one of the most difficult points in the explanation of glaciers."

When the appearances here enumerated are considered with reference to the experiments on the regelation of ice above described, the enigma referred to by the writer appears to have received a satisfactory solution. The glacial valley is a mould through

* Die Gletscher des Jetztzeit, by ALBERT MOUSSON. Zürich, 1854.

which the ice is pressed by its own gravity, and to which it will accommodate itself, while preserving its general continuity, as the hand specimens do to the moulds made use of in the experiments. Two glacial branches unite to form a single trunk, by the regelation of their pressed surfaces of junction. Crevasses are cemented for the same reason; and the broken ice of a cascade is reconstituted, as a heap of fragments under pressure become consolidated to a single mass. To those who occupy themselves with the external conditions merely of a glacier, it may appear of little consequence whether the flexures exhibited by the ice be the result of viscosity or of the principle demonstrated by the experiments above described. But the natural philosopher, whose vocation it is to inquire into the inner mechanism concerned in the production of the phenomena, will discern in the yielding of a glacier a case of simulated fluidity hitherto unexplained, and perhaps without a parallel in nature.

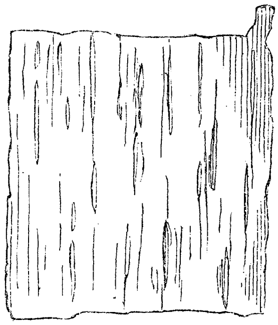
§ 4. *On the Veined Structure of Glacier Ice.*

This structure has been indifferently called the "veined structure," the "banded structure," the "ribboned structure," and the "laminar structure" of glacier ice. In a communication to the Geological Society of France assembled at Porrentruy in September 1838, M. Guyot gave the following interesting description of the phenomenon:—"Since the word layer has escaped me, I cannot help recording as a subject of investigation for future observers a fact, regarding which I dare not hazard an explanation; especially as I have not encountered it more than once. It was at the summit of the Gries, at a height of about 7500 feet, a little below the line of the first or high nevé, where the ice passes into a state of granular snow..... In ascending to the origin of this latter (the glacier of Bettelmatten), for the purpose of examining the formation and direction of the great transverse fissures, I saw under my feet the surface of the glacier entirely covered with regular furrows, from 1 to 2 inches in width, hollowed in a half snowy mass, and separated by protruding plates of an ice more hard and transparent. It was evident that the mass of the glacier was here composed of two sorts of ice, one that of the furrows, still snowy and more easily melted, the other that of the plates, more perfect, crystalline, glassy and resistent; and that it was to the unequal resistance which they presented to the action of the atmosphere that was due the hollowing of the furrows and the protrusion of the harder plates. After having followed them for several hundred yards, I reached the edge of a great fissure, 20 or 30 feet wide; which cutting the plates and furrows perpendicularly to their direction, and exposing the interior of the glacier to a depth of 30 or 40 feet, permitted the structure to be observed on a beautiful transverse section. As far down as my vision could reach I saw the mass of the glacier composed of a multitude of layers of snowy ice, each two separated by one of the plates of ice of which I have spoken, and forming a whole regularly laminated in the manner of certain calcareous slates."

A description of this structure, as observed upon the glacier of the Aar, was communicated by Professor Forbes to the Royal Society of Edinburgh on the 6th of December 1841, and published in the Edinburgh New Philosophical Journal for 1842*. He was undoubtedly the first to give the phenomenon a theoretic significance.

While engaged in the Lower Grindelwald glacier, we separated plates of ice perpendicular to the lamination of the glacier. The appearance presented on looking through them, was that sketched in fig. 6. The layers of transparent ice seemed imbedded in a general milky mass; through the former the light reached the eyes, while it was intercepted by the latter. Some of the transparent portions were sharply defined, and exhibited elongated oval sections, resembling that of a double convex lens, and we therefore called this disposition of the veins "*the lenticular structure.*" In other cases, however, the sharpness of outline did not exist, but still the tendency to the lenticular form could be discerned, the veins in some cases terminating in washy streaks of blue. This structure is probably the same as that observed by Professor FORBES on the Glacier des Bossons, and described in the following words:—"The veins and bands .... are not formed in this glacier by a simple alternation of parallel layers, but the icy bands have all the appearance of posterior infiltration, occasioned by fissures, *thinning off both ways*†."

Fig. 6.



In 1842 Professor FORBES undertook the survey and examination of the Mer de Glace, and finally arrived at a theory of glacier lamination, which both in his 'Travels' and in a series of letters, extending over a period of several years, he has expounded and illustrated with great skill. The theory is summed up in the following words:—"The whole phenomena in the case of any of the semifluids I have mentioned (treacle, tar, &c.), are such as, combined with the evidence which I have given, that the motion of a glacier is actually such as I have described that of a viscid fluid to be, can leave, I think, no reasonable doubt, *that the crevices formed by the forced separation of a half rigid mass, whose parts are compelled to move with different velocities, becoming infiltrated with water, and frozen during winter, produce the bands which we have described* ‡."

This theory has been opposed by Mr. HOPKINS, whose excellent papers, published in the 26th volume of the Philosophical Magazine, are replete with instruction as to the mechanical conditions of glaciers. On the other hand, the theory of Professor FORBES is defended in the same journal by Dr. WHEWELL §. We will leave the points discussed

* This communication gave rise to a discussion as to priority between Professor FORBES and M. AGASSIZ, for the details of which we must refer to the original papers on the subject.

† Travels, p. 181.

‡ Ibid. p. 377. M. AGASSIZ also seems disposed to regard the blue bands as the result of the freezing up of fissures, which, however, are supposed to be formed in a manner different from that assumed by Professor FORBES. But M. AGASSIZ calls the attention of future observers to some of the related phenomena; and gives it as his opinion, "qu'il n'est aucune phénomène dont l'explication offre plus des difficultés." See his important work, 'Système Glacière,' which, until quite recently, we had not the opportunity of examining.

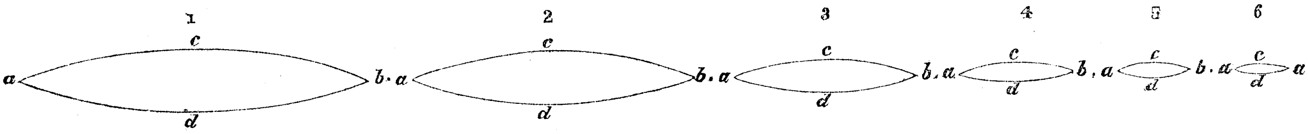
§ Philosophical Magazine, S. 3. vol. xxvi. pp. 171, 217.

in their communications for the present untouched, and confine ourselves to stating a few of the circumstances which appear to us to render the theory doubtful.

1. It is not certain that the colds of winter penetrate to depths sufficient to produce the blue veins, which, it is affirmed, are "an integral part of the inmost structure" of the ice. SAUSSURE was of opinion that the frosts of winter did not penetrate to a greater depth than 10 feet, even at the summit of Mont Blanc, and Professor FORBES considers this opinion to be a just one. But if so, there would be some difficulty in referring to the frosts of winter the blue veins which M. AGASSIZ observed at a depth of 120 feet below the surface of the glacier of the Aar.

2. It will be remembered that M. GUYOT'S statement regarding the blue veins is, that he saw the mass of the glacier composed of a multitude of layers of white ice, separated, each from the other, by a plate of transparent ice. The description of Professor FORBES is briefly this:—"Laminæ or thin plates of transparent blue ice, alternate in most parts of every glacier with laminæ of ice, not less hard and perfect, but filled with countless air-bubbles which give it a frothy semitransparent look." But there is another form of the blue veins, already referred to, which consists in transparent lenticular masses imbedded in the general substance of the white ice. Horizontal sections of these transparent lenses were exposed upon the surface of the Grindelwald glacier, and vertical sections of them upon the perpendicular sides of the water-courses, and upon the walls of the crevasses. The following measurements, taken on the spot, will give an idea of their varying dimensions:—

Fig. 7.



Dimensions.

	in.	in.		in.	in.
No. 1.	*ab* 24	*cd* 2	No. 4.	*ab* $3\frac{1}{2}$	*cd* $\frac{1}{2}$
2.	*ab* 10	*cd* 1	5.	*ab* $1\frac{3}{4}$	*cd* $\frac{1}{4}$
3.	*ab* 6	*cd* 1	6.	*ab* 1	*cd* $\frac{1}{12}$

Such masses as these here figured were distributed in considerable numbers through the glacier; they had all the appearance of flattened cakes, and the smaller ones resembled the elongated green spots exhibited by sections of ordinary roofing-slate cut perpendicular to the planes of cleavage. Now it appears mechanically impossible that a solution of continuity, such as that supposed, could take the form of the detached lenticular spaces above figured.

3. The fissures to which the blue veins owe their existence are stated to be due to the motion of the glacier; and as this motion takes place both in summer and winter, it is to be inferred that the fissures are produced at both seasons of the year. Now as the fissures formed in winter cannot be filled with ice during that season for want of *water*, and as those formed in the ensuing summer cannot, while summer continues, be

frozen for want of *cold*, we ought at the end of each summer to have *a whole year's fissures* in the ice. These fissures, which the ensuing winter is, according to the theory, to fill with blue ice, must, in summer, be filled with *blue water*. *Why then are they not seen in summer?* The fissures are such as can produce plates of ice varying "from a small fraction of an inch to several inches in thickness," which, according to our own observations, produce lenticular masses of ice 2 feet long and 2 inches thick, or even (for we have seen pieces of this description) 10 feet long and 10 inches thick; and M. DESOR informs us in the memoir from which we have already quoted, that under the medial moraine of the Aar glacier, there are bands 10 inches and even a foot in thickness. Such fissures could not escape observation if they existed, but they never have been observed, and hence the theory which makes their pre-existence necessary to the production of the blue veins appears to us improbable.

§ 5. *On the Relation of Slaty Cleavage to the Veined Structure.*

Within the last few years a mechanical theory of the cleavage of slate rocks has been gradually gaining ground among those who have reflected upon the subject. The observations of the late DANIEL SHARPE appear to have originated this theory. He found that fossils contained in slate rocks were distorted in a manner which proved that they had suffered compression in a direction at right angles to the planes of cleavage. His specimens of shells, which are preserved in the Museum of Practical Geology, and other compressed fossils in the same collection, illustrate in a remarkable manner his important observations. The subsequent microscopic observations of Mr. SORBY, carried out with so much skill and patience, show convincingly that the effects of compression may be traced to the minutest constituents of the rocks in which cleavage is developed. More recently, Professor HAUGHTON has endeavoured to give numerical accuracy to this theory, by computing, from the amount of the distortion of fossils, the magnitude of the change which cleaved rocks have undergone. By the united testimony of these and other observers, whose researches have been carried out in different places, the association of cleavage and compression has been established in the most unequivocal manner; and hence the question naturally arises, "Is the pressure sufficient to produce the cleavage?" SHARPE appears to have despaired of an experimental answer to this question. "If," says he, "to this conclusion it should be objected, that no similar results can be produced by experiment, I reply, that we have never tried the experiment with a power at all to be compared with that employed; and that this may be one of the many cases where our attempts to imitate the operations of nature fail, owing to the feebleness of our means, and the shortness of the period during which we can employ them." The same opinion appears to have been entertained by Professor FORBES:—"The experiment," he says, "is one which the boldest philosopher would be puzzled to repeat in his laboratory; it probably requires acres for its scope, and years for its accomplishment."

While one of us was engaged in 1855 in examining the influence of pressure upon magnetism, he was fortunate enough to discover that in white wax, and other bodies, a cleavage of surpassing fineness may be developed by pressure, and he afterwards endeavoured, in a short paper*, to show the application of this result, both to slaty cleavage and to a number of other apparently unrelated phenomena. The theory propounded in this paper may be thus briefly stated. If a piece of clay, wax, marble or iron be broken, the surface of fracture will not be a plane surface, nor will it be a surface dependent only on the form of the body and the strain to which it has been subjected; the fracture will be composed of innumerable indentations, or small facets, each of which marks a surface of weak cohesion. The body has yielded, where it could yield, most easily, and in exposing these facets, in some cases crystalline, in others purely mechanical, wherever the mass is broken, it is shown to be composed of an aggregate of irregularly-shaped parts, which are separated from each other by surfaces of weak cohesion. Such a quality must, in an eminent degree, have been possessed by the mud of which slate-rocks are composed, after the water with which the mud had at first been saturated had drained away; and the result of the application of pressure to such a mass would be, to develope in it a lamination similar to that so perfectly produced on a small scale in white wax. Thus one cause of cleavage may be stated, in general terms, to be the conversion by pressure of irregularly-formed surfaces of weak cohesion into parallel planes. To produce lamination in a compact body such as wax, it is manifest that while it yields to the compression in one direction, it must have an opportunity of expanding in a direction at right angles to that in which the pressure is exerted; a second cause is the lateral sliding of the particles which thus takes place, and which may be very influential in producing the cleavage†.

Before attempting to show the connexion between this theory and the case at present under consideration, a mode of experiment may be described which was found to assist in forming a conception of the mechanical conditions of a glacier, and which has already been resorted to by Professor FORBES in demonstration of the viscous theory. Owing to

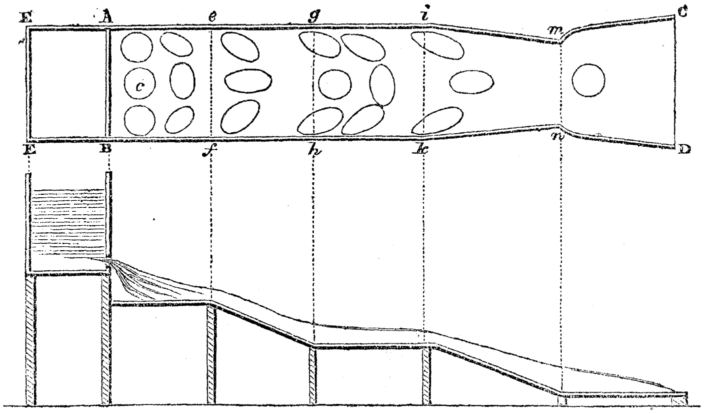
* Proceedings of the Royal Institution, June 1856; Philosophical Magazine for July 1856.

† Three principal causes may operate in producing cleavage:—1st, the reducing of surfaces of weak cohesion to parallel planes; 2nd, the flattening of minute cavities; and 3rd, the weakening of cohesion by tangential action. The third action is exemplified by the state of the rails near a station where the break is applied. In this case, while the weight of the train presses vertically, its motion tends to cause longitudinal sliding of the particles of the rail. Tangential action does not however necessarily imply a force of the latter kind. When a solid cylinder, an inch in height, is squeezed by vertical pressure to a cake a quarter of an inch in height, it is impossible, physically speaking, that the particles situated in the same vertical line shall move laterally with the same velocity; but if they do not, the cohesion between them will be weakened or ruptured. The pressure will produce new contact, and if the new contact have a cohesive value equal to that of the old, no cleavage from this cause can arise. The relative capacities of different substances for cleavage, appears to depend in a great measure upon their different properties in this respect. In butter, for example, the new attachments are equal, or nearly so, to the old, and the cleavage is consequently indistinct; in wax this does not appear to be the case, and hence may arise in a great degree the perfection of its cleavage. The further examination of this subject promises interesting results.

the property of ice described in § 3, the resemblance between the motion of a substance like mud and that of a glacier is so great, that considerable insight regarding the deportment of the latter may be derived from a study of the former. From the manner in which mud yields when subjected to mechanical strain, we may infer the manner in which ice would be *solicited to yield* under the same circumstances.

To represent then the principal accidents of a glacial valley, a wooden trough, ABCD, fig. 8, of varying width and inclination, was made use of. From A to C the

Fig. 8.



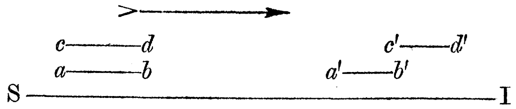
trough measures 6 feet, and from A to B, 15 inches. It is divided into five segments; that between AB and *ef* is level, or nearly so, that between *ef* and *gh* is inclined; from *gh* to *ik* is again nearly level; from *ik* to *mn* inclined, while from *mn* to CD the inclination is less than between *ik* and *mn*. The section of the bottom of the trough is figured underneath the plan. ABEF is a box supported at the end of the trough, and filled with a mixture of water and fine pipe-clay. The front, AB, can be raised, like a sluice, and the mud permitted to flow regularly into the trough. While the mud is in slow motion, a coloured circle, *c*, is stamped upon the white clay between AB and *ef*; the changes of shape which this circle undergoes in its passage downwards will indicate the forces acting upon it. The circle first moves on, being rather compressed, in the direction of the length of the trough until it reaches *ef*, on crossing which, and passing down the subsequent slope, it elongates as in the figure. Between *gh* and *ik* the figure passes through the circular form, and assumes that of an ellipse, whose shorter axis is parallel to the length of the trough. It is manifest from this that the mud between *ef* and *gh* is in a state of longitudinal tension, while between *gh* and *ik* its state is that of longitudinal compression. On crossing *ik* and descending the second incline, the figure is again drawn out longitudinally, while between *mn* and CD the ellipse widens on account of the permission given to lateral expansion by the augmented width of the trough.

The side circles in the same figure will enable us to study the influence of lateral friction upon the descending stream. These circles are distorted into ellipses, whose major axes are oblique to the direction of the trough's length. Above the line *ef* central fissures perpendicular to the axis of the trough cannot be formed; for here, instead of tending to open into fissures, the flattening of the central circle shows that the mud is longitudinally compressed. On the slope below *ef*, the distortion of the circles into ellipses is very pronounced; and as the longer axis of each ellipse marks the line of maximum tension, and as the tendency of the mass is to form a fissure at right angles to such a line, we should have here, if the substance were not so plastic as to prevent the formation of fissures, the state of things observed upon the corresponding portion of the glacier; namely, central fissures perpendicular to the longitudinal axis of the trough, and side fissures inclined to the same axis because pointing in the direction of the shorter axis of each ellipse. Between *gh* and *ik* the longitudinal tension is changed to compression; the central figure is flattened, while the side ones remain stretched. In the corresponding portion of the glacier we should expect the central fissures formed between *ef* and *gh* to be squeezed together and closed up, while the lateral ones would remain open. This is also the case*. Between *ik* and *mn* we have again longitudinal tension, and at the corresponding portions of the glacier the transverse central crevasses ought to reappear, which they actually do. Below the line corresponding to *mn*, the widening of the valley, in the case now in our recollection, causes the ridges produced at the previous slope to break across and form prismatic blocks; while lower down the valley these prisms are converted by the action of sun and rain into shining minarets of ice. These results appear to be in perfect accordance with those arrived at by Mr. Hopkins on strict mechanical reasoning†.

We will now seek to show the analogy of slaty cleavage to the laminar structure of glacier ice. Referring to fig. 8, it will be seen that in the distortion of the side circles one diameter is elongated to form the transverse axis of the ellipse, while another is compressed to form the conjugate axis. In a substance like mud, as the elongation of the major axis continues, its inclination to the axis of the glacier continually changes; but were the substance one of limited extensibility like ice, fissures would be formed when the tension had reached a sufficient amount, or in other words, when the major axis of the ellipse had assumed a definite inclination to the axis of the glacier.

Thus, in a glacier of the form represented by our trough, owing to the swifter motion

* The possibility of the coexistence of lateral crevasses and compression at the centre may, perhaps, be thus rendered manifest:—let *ab*, *cd* be two linear elements of a glacier, situated near its side S I.



Suppose, on passing downward, the line *ab* becomes shortened by longitudinal pressure to *a'b'*, and *cd* to *c'd'*, which latter has passed *a'b'* on account of its greater distance from the side of the glacier. Taking the figure to represent the true change both of dimension and position, it is plain, that though each element has been *compressed*, the differential motion has been such as to *distend* the line of particles joining *a* and *d*, in the ratio $\frac{ad}{a'd'}$. If this ratio be more than that which the extensibility of ice can permit of, a side fissure will be formed.

† Philosophical Magazine, 1845, vol. xxvi.

of the centre, we have a line of maximum pressure oblique to the wall of the glacier, and a line of maximum tension perpendicular to the former; crevasses are formed at right angles to the direction of tension, and *it is approximately at right angles to the direction of pressure, as in the case of slate rocks, that the lamination of glacier ice is developed.*

Under ordinary circumstances, therefore, the lamination near the sides of the glacier would, in accordance with the theory of compression, be oblique to the sides, which it actually is. It would be transverse to the crevasses wherever they occur, which it actually is. If the bed of a glacier at any place be so inclined as to cause its central portions to be longitudinally compressed, the lamination, if due to compression, ought to be carried across the glacier at such a place, being transverse to the axis of the glacier at its centre, which is actually the case. This relation of the planes of lamination to the direction of pressure is constant under a great variety of conditions. A local obstacle which produces a thrust and compression is also instrumental in developing the veined structure. In short, so far as our observations reach, wherever the necessary pressure comes into play, the veined structure is developed; being always approximately at right angles to the direction in which the pressure is exerted.

But we will not rely in the present instance upon our own observations alone. Before he formed any theory of the structure, and in his first letter upon the subject, Professor FORBES remarks, that "the whole phenomenon has a good deal the air of a structure induced *perpendicularly to the lines of greatest pressure.*" His later testimony is in substance the same. In his thirteenth letter, read before the Royal Society of Edinburgh on the 2nd of December, 1846, he says that the blue veins are formed *where the pressure is most intense.* In his reference to the development of the laminar structure on the glacier of the Brenva, the pressure is described as being "*violent*," the effect being such as to produce "*a true cleavage when the ice is broken with a hammer or cut with an axe.*" So also with regard to the glacier of Allalein *, he says "the veined structure is especially developed in front, *i. e.* against the opposing side of the valley, where the pressure is greater than laterally." In fact, the parallelism of the phenomenon to that of slaty cleavage struck Professor FORBES himself, as is evident from the use of the term "now" in the following passage:—"It will be understood that I do not *now* suppose that there is any parallelism between the phenomenon of rocky cleavage and the ribboned structure of the ice." This reads like the giving up of a previously held opinion; the term *now* being printed in italics by Professor FORBES himself. The adoption of the viscous theory appears to have carried the renunciation of this idea in its train.

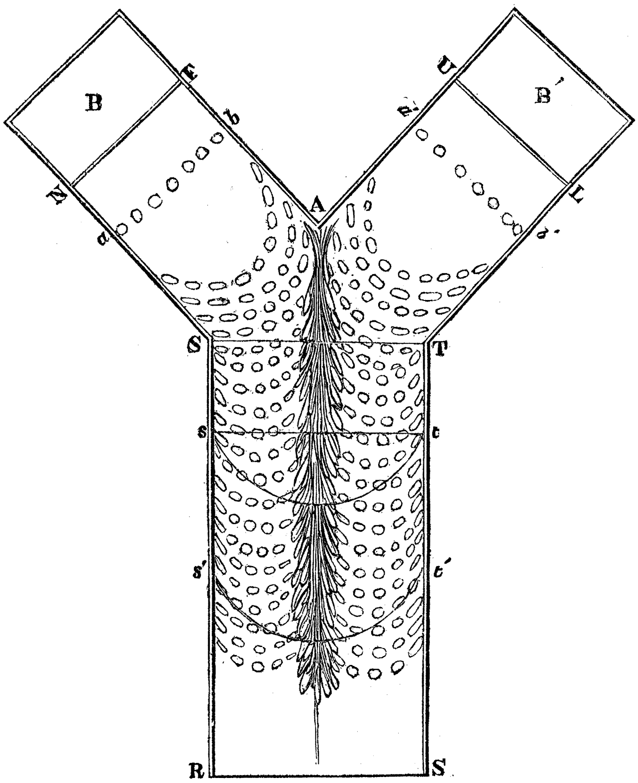
Later still, and from a source wholly independent of the former, we have received additional testimony on the point in question. The following quotation is from a letter, dated 16th November, 1856, received by one of us from Professor CLAUSIUS of Zurich, so well known in this country through his important memoirs on the Mechanical Theory of Heat:—"I must now," writes M. CLAUSIUS, "describe to you another singular coincidence. I had read your paper upon the cleavage of rocks........ and it occurred to

* Travels, p. 352.

me at the time that the blue veins of glaciers, which indeed I had not seen, but which had been the subject of repeated conversations between Professor STUDER of Berne, Professor ESCHER VON DER LINTH, and myself, might be explained in the same manner. When, therefore, I reached the Rhone glacier for the first time, I walked along it for a considerable extent, and directed my attention particularly to the structure. I repeated this on the other glaciers which I visited during my excursion. I did not indeed pursue the subject so far into detail as to be able in all cases to deduce the blue veins from the existing conditions of pressure, but the correctness of the general explanation impressed itself upon me more and more. This was particularly the case in the glacier of the Rhone, where I saw the blue bands most distinctly, and where also their position harmonized with the pressure endured by the glacier when it was forced to change the direction of its motion. You can therefore imagine how astonished I was to learn that at the same time, and on this very glacier among others, you had been making the same investigations." It ought also to be remarked, that a similar thought occurred to Mr. SORBY, from whom after his return from Switzerland one of us received a note, in which pressure was referred to as the possible cause of the veined structure of glacier ice.

A fine example of ice lamination is that produced by the mutual thrust of two confluent glaciers. The junction of the Lauter Aar and Finster Aar glaciers to form the glaciers of the Unter Aar is a case in point, and the results obtained with a model of this glacier were highly interesting. Fig. 9 is a sketch of the trough in which the experiments were made. The branch terminating at UL is meant to represent the Lauter Aar glacier; that ending at FN the Finster Aar branch. The point at A represents the "Abschwung," so often referred to in the works of M. AGASSIZ. B and B′ are two boxes with sluice fronts, from which the mud flows into the trough, The object was to observe the mechanical state of the mass along the line of junction of the two streams, and along their respective centres, and compare the result with the observations upon the glacier itself. The mud was first permitted to flow simultaneously from both

Fig. 9.



boxes, and after it had covered the bottom of the trough to some distance below the line ST, the end of a glass tube was dipped into a fine mixture of the red oxide of iron and water, and the two arms of the glacier were covered all over with small circles similar to those between the points *ab* and *a'b'*. The mud was then permitted to flow, and the mechanical strains exerted on it were inferred from the distortion of the small circles. The figure represents the result of the experiment. The straight rows of circles bent in the first place into curves; at the point A both streams met, and by their mutual push actually squeezed the circles into lines. Along this central portion in the glacier itself the great medial moraine stands, and under it and beside it, as already stated, the lamination is most strikingly developed; the blue veins being parallel to the axis of the glacier, or, in other words, coinciding with the direction of the central moraine. Midway between the moraine and the sides of the glacier the structure is very imperfectly developed, and the deportment of our model, which shows that the circles here scarcely change their form, tells us that this is the result which ought to be expected. It may be urged, that the structure is here developed, because of the sliding motion produced by the swifter flow of one of the glaciers; but some of the experiments with the model were so arranged, that both of the branch streams flowed with the same velocity; the distortions, however, were such as are shown in the figure. The case is precisely the same in nature. On reference to the map of M. AGASSIZ, we find a straight line set out across the Unter Aar glacier bent in three successive years into a curve; but on the central moraine, which marks the common limit of the constituent streams, we find no breach in the continuity of the curve, which must be the case if one glacier slid past the other.

§ 6. *On the "Dirt-Bands" of Glaciers.*

Wherever the veined structure of a glacier is highly developed, the surface of the ice, owing to the action of the weather, is grooved in accordance with the lamination underneath. These grooves are sometimes as fine as if drawn by a pencil, and bear in many instances a striking resemblance to those produced by the passage of a rake over a graveled surface. In the furrows of the ice the smaller particles of dirt principally rest, and the direction of the furrows, which always corresponds with that of the blue veins, is thus rendered so manifest, that a practised observer can at any moment pronounce upon the direction of the lamination from the mere inspection of the surface of a glacier. But besides these narrow grooves, larger patches of discoloration are sometimes observed, which take the form of curves sufficient in width to cover hundreds or thousands of the smaller ones. To an eye placed at a sufficient height above a glacier on which they exist, their general arrangement and direction are distinctly visible. To these Professor FORBES has given the name of "Dirt-Bands," and the discovery of them, leading as it did to his theories of glacial motion, and of the veined structure of glacial ice, is to be regarded as one of the most important of his observations.

On the evening of the 24th of July he walked up the hill of Charmoz to a height of about 1000 feet above the level of the glacier, and, favoured by the peculiar light of the hour, observed "a series of nearly hyperbolic brownish bands on the glacier, the curves pointing downwards and the two branches mingling indiscriminately with the moraines." The cause of these bands was the next point to be considered, and his examination of them satisfied him "that the particles of earth and sand and disintegrated rock, which the winds and avalanches and water-runs spread over the entire breadth of the ice, formed a *lodgement* in those portions of the glacier where the ice was most porous, and that, consequently, the 'dirt-bands' were merely *indices of a peculiarly porous veined structure traversing the mass of the glacier in these directions*."

Professor FORBES was afterwards led to regard these intervals as the marks of the annual growth of the glacier; he called the dirt-bands "annual rings*," and calculated, from their distance apart, the yearly rate of movement. In fine, the conclusion which he deduces from the dirt-bands is, that a glacier throughout its entire length is formed of alternate segments of porous and of hard ice. The dirt which falls upon the latter is washed away, as it has no hold upon the surface; that which falls upon the former remains, because the porous mass underneath gives it a lodgement. "The cause of the dazzling whiteness of the glacier des Bossons at Chamouni is the comparative absence of these layers of granular and compact ice: the whole is nearly of uniform consistence, the particles of rock scarcely find a lodgement, and the whole is washed clean by every shower†." "It must be owned, however," says Professor FORBES, "that there are several difficulties which require to be removed, as to the recurrence of these porous beds." In his fifteenth letter upon glaciers, and in reference to some interesting observations of Mr. MILWARD'S, he endeavoured to account for the difference of structure by referring it to an annual "gush" of the ice, which is produced by the difference of action in summer and winter. We are ignorant of the nature of the experiments on which this theory of the dirt-bands is founded, and would offer the following simple explanation of those which came under our own observation.

Standing at a point which commanded a view of the Rhone glacier, both above and below the cascade, we observed that the extensive ice-field above was discoloured by sand and débris, distributed without regularity. At the summit of the ice-fall the valley narrows to a gorge, and the slope downwards is for some distance precipitous. In descending, the ice is greatly shattered; in fact, the glacier is broken repeatedly at the summit of the declivity, transverse chasms being thus formed; and these, as the ice descends, are broken up into confused ridges and peaks, with intervening spaces, where the mass is ground to pieces. By this breaking up of the glacier the dirt upon its surface undergoes fresh distribution: instead of being spread uniformly over the slope, spaces are observed quite free from dirt, and other spaces covered with it, but there is no appearance of regularity in this distribution. At some places large

* "I cannot help thinking that they are the *true annual rings* of the glacier, which mark its age like those of a tree."—Appendix to Travels, p. 408.

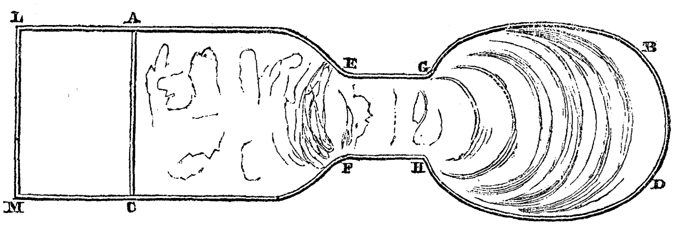
† Travels, p. 406.

irregular patches appear, and at others elongated spaces covered with dirt. Towards the bottom of the cascade the aspect changes; but still, were the eye not instructed by what it sees lower down, the change would have no significance. When the ice has fairly escaped from the gorge, and has liberty to expand laterally in the valley below, the patches of dirt are squeezed by the push behind them, and drawn laterally into narrow stripes, which run across the glacier; and as the central portion moves more quickly than the sides, these strips of discoloration form curves which turn their convexity downwards, constituting, we suppose, the "Dirt-Bands" of Professor FORBES. On the Grindelwald glacier, where one of us, in his examination of the bands, was accompanied by Dr. HOOKER, this change in the distribution of the dirt,—the squeezing, lateral drawing act, and bending of the dirt patches below the bottom of the ice-fall,—was especially striking.

Such then appears to be the explanation of the dirt-bands in the cases where we have had an opportunity of observing them. We have not seen those described by Professor FORBES, but the conditions under which he has observed them appear to be similar. An illustration of the explanation just given is furnished by the dirt-bands observed below the "cascade" of the Talèfre. The character of this ice-fall may be inferred from the following words of Professor FORBES, and from the map which accompanies his 'Travels.' "The structure," he says, "assumed by the ice of the Talèfre is extirpated wholly by its precipitous descent to the level of the Glacier de Léchand, where it reappears, or rather is reconstructed out of the broken fragments according to a wholly different scheme." One of the results of this "scheme" would, it is presumed, be a redistribution of the dirt, and the formation of bands in the manner described. Those who consult the map will, however, see dirt-bands marked on the Glacier du Géant also, while no cascade is sketched upon it; but at page 167 of the 'Travels,' Professor FORBES, in referring to this glacier, says, "I am not able to state the exact number of dirt-bands between *the foot of the ice cascade* opposite La Noire and the corner of Trelaporte." Here we are not only informed of the existence of a cascade, but are left to infer that the dirt-bands begin to form at its base, as in the Glacier du Géant, and in those which have come under our own observation. The clean Glacier des Bossons, also, which was referred to by Professor FORBES, in one of his earliest letters, as affording no lodgement to the dirt, possesses its cascade (page 181), and here also we find (page 182) "that the peculiar phenomena of '*dirt-bands*' on a great scale are not wanting, although from the dazzling whiteness of the ice they may be very easily overlooked." We make these remarks with due reserve, not having yet seen the glaciers referred to.

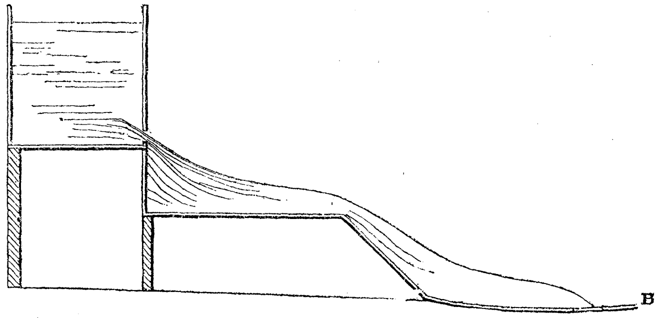
The explanation just given has been brought to the test of experiment. ABCD, fig. 10, is a wooden trough intended roughly to represent the glacier of the Rhone, the space ACEF being meant for the upper basin. Between EF and GH the trough narrows and represents the precipitous gorge down which the ice tumbles, while the wide space below represents the comparatively level valley below the fall, which is filled with the ice, and constitutes the portion of the glacier seen by travellers descending from the Grimsel or the Furka pass. ACLM is a box with a sluice front, which can be raised so that the fine mud within the box shall flow regularly into the trough, as in the

Fig. 10.



cases already described. The disposition of the trough will be manifest from the section, fig. 11. While the mud was in slow motion downwards, a quantity of dark-coloured

Fig. 11.



sand was sifted over the space ACEF, so as to represent the débris irregularly scattered over the corresponding surface of the glacier; during the passage of the mud over the brow at EF, and down the subsequent slope, it was hacked irregularly, so as to represent the dislocation of the ice in the glacier. Along the slope this hacking produced an irregular and confused distribution of the sand; but lower down, the patches of dirt and the clean spaces between them gradually assumed grace and symmetry; they were squeezed together longitudinally and drawn out laterally, bending with the convexity downwards in consequence of the speedier flow of the central portions, until finally a system of bands was established which appeared to be an exact miniature of those exhibited by the glacier. On fig. 10 is a sketch of the bands observed upon the surface of the mud, which however falls short of the beauty and symmetry of the original. These experiments have been varied in many ways, with the same general result.

In conclusion we would remark, that our joint observations upon the glaciers of Switzerland extended over a period of a few days only. Guided by the experience of our predecessors, much was seen even in this brief period; but many points of interest first suggested themselves during the subsequent experimental investigation. While, therefore, expressing our trust that the substance of the foregoing memoir will be found in accordance with future observation, we would also express our belief in the necessity of such observation. Indeed the very introduction of the principle of regelation, without which it may be doubted whether the existence of a glacier would be at all possible, opens, in itself, a new field of investigation. This and other questions, introduced in the foregoing pages, must however be discussed with strict reference to the phenomena as Nature presents them. Much might be said even now upon these subjects, but the known liability of the human mind to error when speculation is substituted for observation, renders it safer to wait for more exact knowledge, than to hazard opinions which an imperfect acquaintance with the facts must necessarily render to some extent uncertain.

Royal Institution,
January 1857.