XIV. *On the Physical Phenomena of Glaciers.*—Part I. *Observations on the Mer de Glace.*

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§ 1.

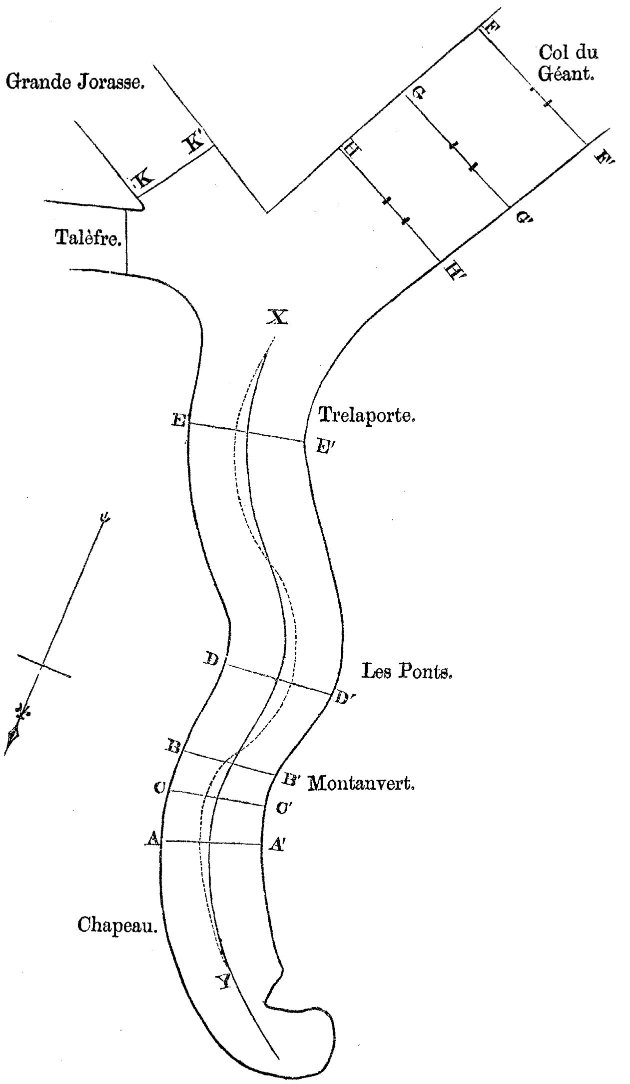
The Philosophical Transactions for 1857 contain a paper by Mr. Huxley and myself upon the Structure and Motion of Glaciers. The observations on which that paper was founded extended over a very brief period, and hence arose the desire, on my part, to make a second expedition to the Alps, in which I regret to say my friend was unable fully to join. The phenomena of the Mer de Glace being those on which the most important theoretic views of the constitution and motion of glaciers are based, I wished especially to make myself acquainted by personal observation with these phenomena. Six weeks of the summer of 1857 were accordingly devoted to the examination of this glacier. For the purpose of observing its motion, bearings and inclinations, and also of determining its width at various points, I took with me an excellent 5-inch theodolite, and a surveyor's chain; for both of which I am indebted to the kindness of the Director-General of the Geological Survey, and to Professor Ramsay. I propose to divide the investigation into two parts, the first of which forms the subject of the following paper, while the second will be the subject of a future communication. It gives me great pleasure here to record my grateful sense of the able and unremitting assistance rendered me throughout the entire period of the observations, by my friend Mr. T. A. Hirst, whose name indeed, had he permitted it, I should gladly have seen associated with my own at the head of this paper.

§ 2. *On the Motion of the Mer de Glace.*

Our first observation of the motion of the Mer de Glace was made on the 14th of July. On the steep terminal incline of the Glacier de Bois we singled out a tall pinnacle of ice, the front edge of which was perfectly vertical. In coincidence with this edge I fixed the vertical wire of our theodolite, and after three hours found that the ice cliff had moved downwards, the cross hairs being now projected against the face of the cliff several inches above its edge.

Our first line across the glacier was set out upon the 17th of July. The mode of proceeding in all such cases was this:—the theodolite was placed beside the glacier, quite clear of the ice, and usually at a sufficient height above it to command an uninterrupted view across the glacier. The plummet of the instrument being suspended, a stake was driven into the ground, or a fixed stone was carefully marked exactly under the point of the plummet. The direction of a line perpendicular to the axis of the glacier from this point being ascertained, a well-defined object was sought in the production of this line, at the opposite side of the valley—the sharp edge of a cliff, a projecting corner of rock, or a well-defined mark on the surface of the rock. This mark, and the objects surrounding it, were carefully sketched, so that in coming subsequently to the place the line was immediately recognized. The cross hairs being fixed upon the mark, the object-end of the telescope was lowered until the cross hairs cut the point at which a stake was to be placed. The positions of the stakes were found by means of an ordinary traveller's *baton*, which was set erect upon the ice and moved up or down in accordance with the signals from the observer at the theodolite, till the exact point was hit upon. Here the ice was pierced to the depth of about 18 inches, and a wooden stake was firmly driven into it. The position of each individual stake was secured by taking the angle of depression down to it, a precaution which was found very useful when subsequent reference to any particular stake was necessary. The exact time at which each stake was driven in was noted; and the time at which the displacements were measured being also observed, the motion was afterwards reduced, by calculation, to its diurnal rate.

Fig. 1.



The station from which our first line started was at some distance below the Montanvert Hotel, and about eighteen yards, in an ascending direction, from the station marked D on the Map of Professor FORBES*. The line is that marked AA′ on the sketch-map, fig. 1†.

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* We found this station marked by a chisel on a block of granite, and painted red.

† The side of the glacier opposite to the Montanvert is much crevassed, and while fixing a stake upon one

On the 18th of July we set out a second line above the Montanvert Hotel, and we afterwards measured the displacements of the stakes along the line AA′. The result led to the establishment of a hitherto unobserved law of glacier motion, which the discussion of the observations will gradually render manifest. Reduced to twenty-four hours, the motion of the stakes along our first line was as follows:—

First Line (AA′).—Mean Daily Motion.

No. of stake.	Motion in inches.	No. of stake.	Motion in inches.
West 1	12¼	6	
2	16¾	7	26¼
3	22½	8	
4	25½	9	28¾
5	24½	East 10	35½

Stake No. 7 of this series was about midway between the bounding sides of the Mer de Glace; No. 1 was near the lateral moraine at the Montanvert side, and the retarding influence of this side is very manifest. With slight breaches of regularity, the rate of motion increases gradually from the first stake towards the centre of the glacier.

But it will be observed that stake No. 7 by no means moves the fastest. Stake No. 10 stood far beyond the centre, and upon the portion of the glacier derived from the Léchaud and Talèfre. This portion is distinguishable at a glance by the quantity of dirt upon its surface, the portion derived from the Glacier du Géant remaining comparatively clean throughout the entire length of the Mer de Glace. Professor FORBES accounts for the excessive crevassing of the eastern side of the glacier by assuming that the Glacier du Géant, having by far the greater mass, moves most swiftly, drags its more sluggish companions after it, and thus tears them asunder. The foregoing observations show that this assumption is untenable. The difference here observed cannot be referred to the slip to which reference has already been made in the note at the foot of this page, for the slip did not amount to more than 4 inches at the utmost. Further, the displacements were measured a second time on the following day, when the maximum movement of the Glacier du Géant portion was found to be 27½ inches, and that of the Léchaud and Telèfre side 32½.

Our second line, marked BB′ upon the sketch-map, had its terminal station on the ancient moraine a little higher up the glacier than the Montanvert Hotel. Along this line thirty-one stakes were driven on the 18th of July, and their displacements measured the day following. The results reduced to twenty-four hours are as follows:—

of the ice ridges here, the whole mass slid suddenly some inches forward. Were special attention directed to the crevassed portions of a glacier, the same phenomenon might, I doubt not, be frequently observed.

Second Line (BB′).—Mean Daily Motion.

No. of stake.	Motion in inches.
West 1	7½
2	10¾
3	12¼
4	14½
5	14½
6	16
7	16¾
8	17½
9	19
10	19½
11	19½
12	21
13	21
14	21
15	22½
16	22½
17	22½
18	21
19	22½
20	20½
21	×
22	×
23	24½
24	×
25	21¾
26	×
27	×
28	22¼
29	22¾
30	25¼
East 31	25¾

The stakes marked thus × were fixed by the eye, their positions being such that they could not be seen by the theodolite. Some of them were placed in deep glacial hollows, where, without an instrument, it was difficult to keep them in the same vertical plane. The slight uncertainty thus arising induced me finally to reject them. The gradual augmentation of velocity from the side towards the centre is very manifest; but it will be observed that stake 31, which stood upon the Talèfre side of the glacier, moved quickest of all. The difference in favour of the latter side is, however, much less than it was lower down.

The reason why in the two cases just considered the terminal stake towards the eastern side of the glacier shows no retardation, is, that the state of the ice, and the position of the theodolite, were not such as to enable us to continue the line of stakes completely across the glacier to the eastern side, and hence the observations could not show the retarding influence of that side. In setting out the third line CC′, therefore, Mr. Hirst took up a position on the Chapeau side of the valley, from which the vision across the glacier was quite uninterrupted by ridges or other obstacles, while the crevasses were not impracticable. One of the fixed termini of this line was the corner of a window of the Montanvert Hotel. There were twelve stakes planted along the line, and the motion of these during twenty-four hours, from the 20th to the 21st of July, was as follows:—

Third Line (CC′).—Mean Daily Motion.

	East.											West.
No. of stakes.	1	2	3	4	5	6	7	8	9	10	11	12
Motion....	19½	22¾	28¾	30¼	33¾	28¼	24½	25	25	18	×	8½

Stake No. 1 was fixed in the ice, close to the eastern side of the glacier, and the retarding influence of this side is quite manifest from the measurements. A glance, however, reveals a fact confirmative of the former measurements; the daily motion of the extreme eastern stake is 14½ inches behind the maximum, while the motion of the extreme western stake is 25½ inches behind it. The stake No. 5, which moved at the maximum rate, was also much nearer to the eastern than to the western side of the ice-stream; the observation therefore corroborates those already made as regards the position of the point of maximum motion.

How then is the fact to be accounted for, that the point of maximum motion of the Mer de Glace is thus thrown towards its eastern boundary? Reflection suggested to me that the effect might be due to the curvature of the valley through which the Mer de Glace moves. At the place where the foregoing observations were made the glacier bends, turning its concave side to the Montanvert, and its convexity towards the Chapeau. M. Rendu insists on the complete analogy of the phenomena of a river and those of a glacier; and the idea has been to a great extent corroborated by the measurements of Professor Forbes and M. Agassiz; but let us make a bolder application of the analogy than any of them contemplated, confining our view to the influence of curvature merely. The point of maximum motion of a river moving through a channel similar to that occupied by the Mer de Glace, would lie on that side of the centre of the channel towards which the river turns its convex curvature. Can this be the case with the ice? If so, the place of maximum motion ought to be different where the glacier bends in the opposite direction. Fortunately the Mer de Glace itself enables us to bring this idea to a test.

Higher up the valley, and opposite to the passages called "Les Ponts," such a band occurs. Here the convexity is turned towards the Montanvert or western side of the valley. A line was set out across this portion of the glacier on the 25th of July, and its measurement upon the 26th gave the following results:—

Fourth Line (DD′).—Mean Daily Motion.

	East.													West.	
No. of Stakes.	1	2	3	4	5	6	9	10	11	12	13	14	15	16	17
Motion..	6½	8	12½	15¼	15½	18¾	19½	21	20½	23¼	23¼	21	22¼	17¼	15

After the setting out of this line, its length was measured by Mr. Hirst; and found to be 39 chains 25 links, which, as each chain is equal to 22 yards, gives 863 yards as the width of the Mer de Glace opposite the first "*Pont.*" A mark on the rock crossed by this *pont* constituted indeed one of the fixed termini of the line.

For the sake of stricter discussion, a copy of the notes of this measurement faces the next page.

The stakes along the line are marked thus, ⊙. The fixing of them commenced at the Echellets or eastern side of the valley, and they were numbered *from* this side: the measurement, on the contrary, commenced at the "Pont." Hence it is that the 17th stake was the first encountered in the measurement. This stake stood at a distance of 326 links, or nearly 72 yards from the edge of the glacier. Stake No. 1 at the other end of the line stood close beside the lateral moraine at the eastern side of the glacier.

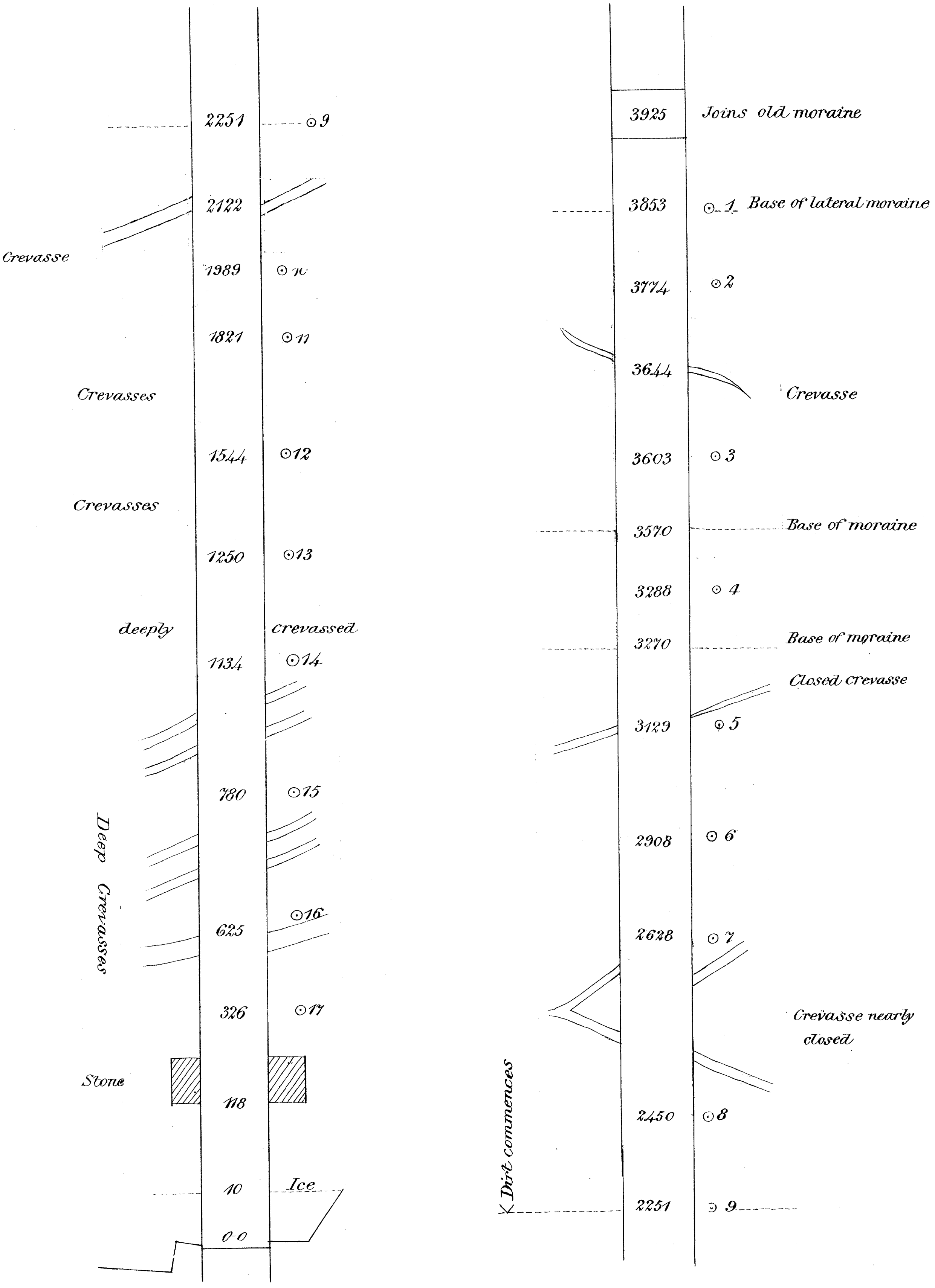
Referring to the notes, it will be seen that the place of maximum movement occurs between the stakes 12 and 13, the former at a distance of 1544 links, and the latter at a distance of 1250 links from the western side of the glacier. The mean of these is 1397 links; consequently, as the entire width is 3925 links, the point of maximum motion is here 1131 links nearer to the western than to the eastern side of the Mer de Glace. The dirt also which marks the junction of the portion of the ice derived from the Col du Géant, with that derived from the other tributaries, is crossed at the distance 2251; hence the place of maximum motion occurs at a point 854 links *west of the dirt*, while on the lines set out lower down the point of maximum motion was far in upon the dirt, eastward from the junction. The position of the point of maximum motion changes, therefore, in exact accordance with the explanation given above.

But the question is capable of still closer examination. The notes enable us to compare a number of points at the eastern side of the glacier with others, situated at the same respective distances from the western side. Let us call every pair of points, one of which is situated as far from the eastern boundary as the other is from the western, *corresponding points*. The corresponding points along our fourth line may then be ranged as follows:—

	S.	V.	S.	V.	S.	V.	S.	V.	S.	V.	
West....	17	15	16	$17\frac{1}{4}$	15	$22\frac{1}{4}$	13	$23\frac{3}{4}$	12	$23\frac{1}{4}$	... (A)
East	3	$12\frac{1}{2}$	4	$15\frac{1}{4}$	5	$15\frac{1}{2}$	7	$18\frac{1}{4}$	9	$19\frac{1}{2}$	

The numbers under the letter S are those of the stakes, those under V are the corresponding velocities. It will be seen that in each case the point on the western portion of the glacier moves quicker than the corresponding point on the eastern side. As a whole, therefore, the western side moves more speedily than the eastern, which is the reverse of what was observed lower down, but quite demonstrative of the explanation which refers the effect to the curvature of the valley.

An inspection of the notes also shows, that at the place where the fourth line crossed the glacier, the crevasses are found chiefly upon the portion derived from the Glacier du Géant. The dirt which announces the position of the other tributaries of the Mer de Glace is crossed at the distance 2251; and after this distance we find the remark "crevasse nearly closed," "closed crevasse;" so that not only is the eastern side of the glacier here less crevassed than the western, but crevasses previously formed are partially, or wholly closed up. The shifting of the place of strain consequent on the change of curvature, carried naturally along with it the shifting of the crevasses. It may be inferred from the notes that the measurement of such a line is not without its difficulties.



Lateral Moraine.

J. Basire, lith.

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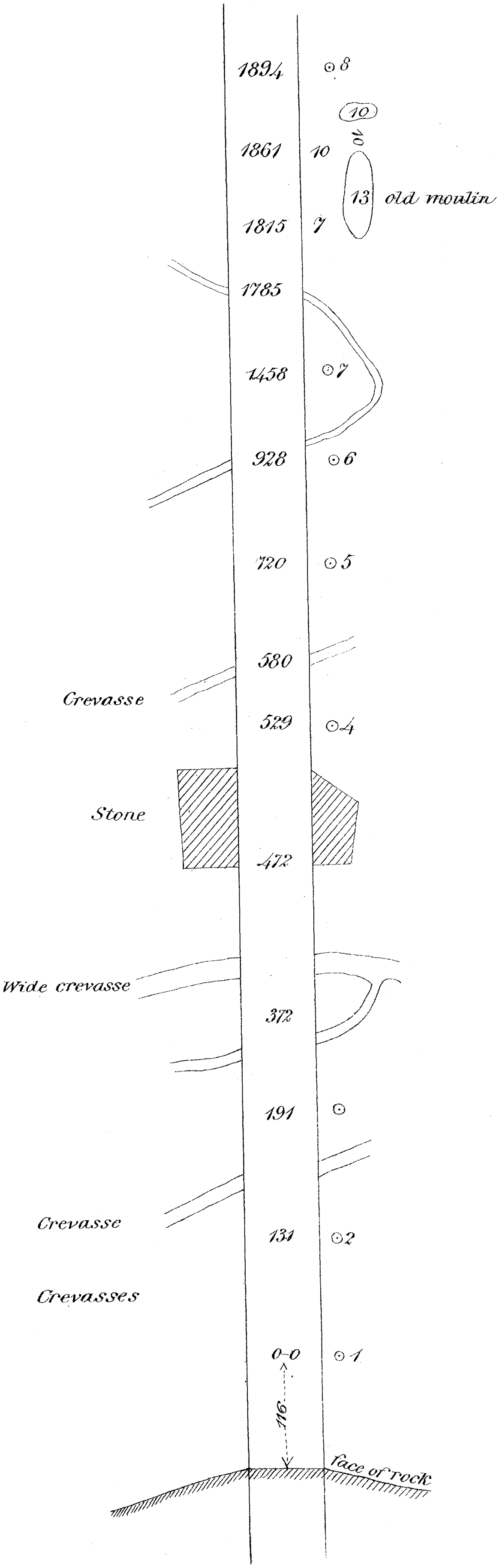
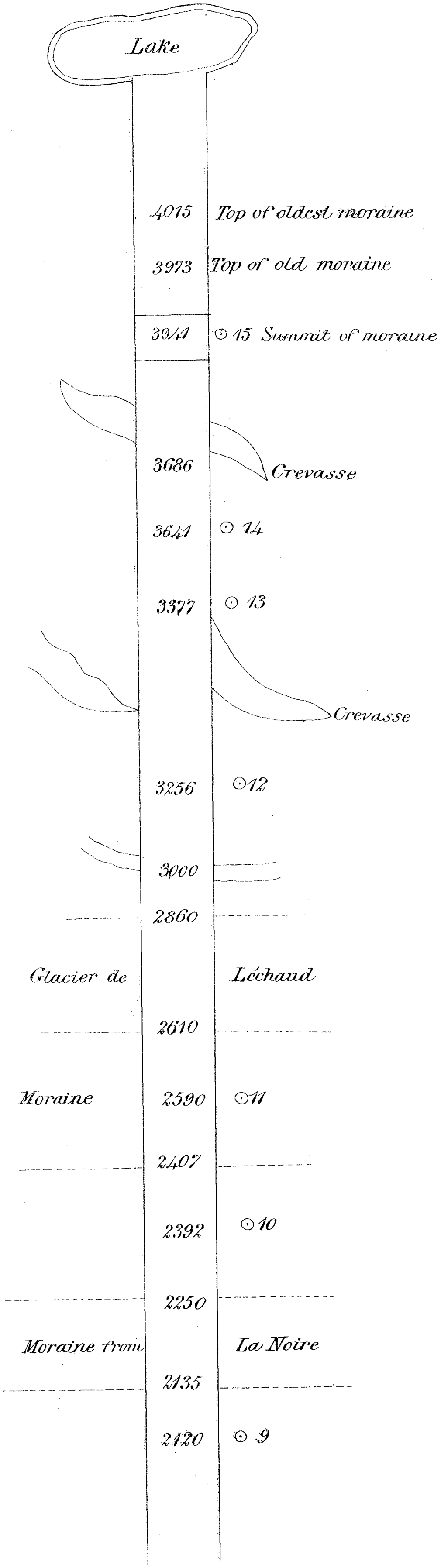




J. Basire, lith.

Our next line (EE′) stretched across the glacier from the promontory of Trelaporte to the base of the Aiguille du Moine. The instrument being placed upon a grassy slope above the promontory, the line was set out on the 28th of July. The Trelaporte end of this line was immediately under the station marked G* on the Map of Professor Forbes; the displacements of the stakes were measured on the 31st of July, and were found to be as follows:—

Fifth Line (EE′).—Mean Daily Motion.

	West.														East.
No. of Stakes.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Motion......	$11\frac{1}{4}$	$13\frac{1}{2}$	$12\frac{3}{4}$	15	$15\frac{1}{4}$	16	$17\frac{1}{4}$	$19\frac{1}{4}$	$19\frac{3}{4}$	19	$19\frac{1}{2}$	$17\frac{1}{2}$	16	$14\frac{3}{4}$	10

The first of these stakes was about 80 feet distant from the face of the rock at Trelaporte; the 15th was on the lateral moraine, which moved along with the ice at the opposite side of the valley. The retarding influence of both sides is very clearly shown, the motion of the central stakes being nearly twice that of the extreme ones. As a whole, the rate of motion is slower here than at the "Ponts" or at the Montanvert.

This line was also chained by Mr. Hirst; a copy of his notes, showing the distances along the line at which the stakes were set, faces this page.

The chaining commenced at a point 116 links distant from the face of the rock at Trelaporte. Adding these 116 to the distance 3941, we have 4057 links, or 893 yards for the width of this portion of the Mer de Glace. The point of maximum motion occurs at stake No. 9, which is 2236 links distant from the rock at Trelaporte, or more than one-half the distance across; that is to say, the point of maximum motion is here nearer to the Talèfre side than to the Géant side of the glacier. Here, again, we have a result different from that obtained with our fourth line; and if we look to the sketch-map we shall see the reason. Between the fourth and fifth lines the Mer de Glace has passed a point of contrary flexure; and here at Trelaporte the convex side of the glacier is turned towards the base of the Aiguille du Moine.

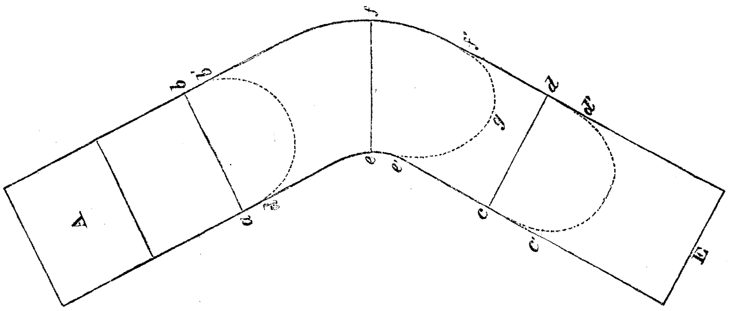
Taking the 116 links at the commencement into account, the following pairs of stakes may be regarded as corresponding points:—3 and 14; 4 and 12; 7 and 10; the small numbers referring to stakes at the western, and the large numbers to stakes at the eastern side of the glacier. The relative motions of these points are as follows:—

West...... 3—$12\frac{3}{4}$; 4—15; 7—$17\frac{1}{4}$.
East ...... 14—$14\frac{3}{4}$; 12—$17\frac{1}{2}$; 10—19.

Comparing this Table with Table A, we observe a reverse result; in the latter case the western stakes moved most swiftly; here the eastern ones do so; the deportment of the ice is the same as at the places intersected by our three first lines, and the curvature of the valley is also similar.

From the foregoing observations the following law of glacier motion is derived:—*When a glacier moves through a sinuous valley, the locus of the point of maximum motion does not coincide with a line drawn along the centre of the glacier, but always lies on the* *convex side of the central line. It is therefore a curve more deeply sinuous than the valley itself, and crosses the axis of the glacier at each point of contrary flexure**.

Fig. 2.



The law may be illustrated by the following experiment:—A, fig. 2, is a box filled with fine mud, which by raising a sluice in front flowed into the curved trough AE. A line *ab* was drawn upon the mud above the bend, a second line, *cd*, below the bend, and a third, *ef*, at the bend. The distortions of these three lines by the motion of the mud downward will reveal the position of the point of maximum motion at the particular places where they are drawn. The line *ab* was distorted to *a'b'*, the summit of the curve being exactly in the centre of the trough, thus proving that the centre was the place of maximum motion. The same was true of the line *cd*, which was distorted to *c'd'*. The line *ef* was distorted to *e'f'*, the summit *g* of the curve being nearer to the side *bfd* of the trough, this proving the point of maximum motion to lie towards that side.

I scarcely know a case more calculated to impress the mind both with the yielding power of ice to pressure, and the magnitude of the forces brought into play in the motion of glaciers, than the crushing of the three tributaries of the Mer de Glace through the throat of the valley between Trelaporte and the base of the Aiguille du Moine. Not wishing to trust the eyes in the estimation of distances here, each of the three confluent branches was measured. The width of the Glacier du Géant, a short distance above the Tacul, was found to be 5155 links, or 1134 yards. The width of the Glacier de Léchaud, just before its junction with the Talèfre, was found to be 3725 links, or 825 yards. That of the Talèfre, before it is influenced by the pressure of the Léchaud, that is, across the ice-cascade, was found, approximately, to be 2900 links, or 638 yards. Adding all together, we find the sum of the widths of the three branch glaciers to be 2597 yards. At Trelaporte these three branches *are forced through a gorge* 893 *yards wide*; and our measurements show that it passes through with a velocity of nearly 20 inches a day!

Limiting our view to one of the glaciers thus compressed, the facts appear still more astonishing. Previous to its junction with the Talèfre, the Glacier de Léchaud has a width of thirty-seven chains and a half. In passing through the jaws of the granite vice at Trelaporte, this broad ice river is squeezed to a driblet *less than four chains in width*! This fact illustrates the relation of the size and power of a glacier to the quan-

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* If the defined line between X and Y on the sketch map represents a line drawn along the centre of the glacier, the dotted line will represent the locus of the point of maximum motion.

tity of snow drainage which supplies it. The Talèfre has its basin, and the Géant has its vast plateau, from which the respective glaciers derive nutrition; but the Léchaud is fed by two or three couloirs merely, which descend principally from the Mont Mallet and Les Jorasses. The Géant, in the struggle for place at Trelaporte, takes up more than half the valley, and the others come in the order of the drainage which supplies them.

The velocity of the Mer de Glace at Trelaporte being about 20 inches, it seemed probable that the velocity of the Glacier du Géant above the Tacul, and also of the Léchaud above its junction with the Talèfre, would be considerably less, in consequence of the greater width at these places. This proved to be the case. On the 29th of July a line was set out across the Glacier du Géant, a little above the Tacul. There were ten stakes in this line, and their motions reduced to twenty-four hours were as follows:—

Sixth Line (HH′).—Mean Daily Motion.

No. of Stakes.	1	2	3	4	5	6	7	8	9	10
Motion......	11	10	12	13	12	$12\frac{3}{4}$	$10\frac{1}{2}$	10	9	5

The velocity here is considerably under that of the Mer de Glace at Trelaporte.

On the 1st of August we set out a line across the Glacier de Léchaud immediately above where it is joined by the Talèfre. The line commenced at the side of the glacier beneath the block of stone called the Pierre de Béranger, and ran perpendicular to the axis of the glacier to the other side. The displacements were measured on the 3rd of August: reduced to twenty-four hours, they are as follows:—

Seventh Line (KK′).—Mean Daily Motion.

No. of Stakes.	1	2	3	4	5	6	7	8	9	10
Motion......	$4\frac{1}{2}$	$8\frac{1}{4}$	$9\frac{1}{2}$	9	$8\frac{1}{2}$	$7\frac{1}{2}$	$6\frac{1}{4}$	$8\frac{1}{2}$	7	$5\frac{1}{2}$

The stakes 8 and 9 were at opposite sides of a "moulin," which was found to share the general motion of the glacier. A new crevasse crossed our line above 8 and below 9, and the greater advance of stake No. 8 was probably owing to the yielding which this crevasse permitted. The rates of motion, it will be observed, are still less than those upon the Glacier du Géant.

Were the Glacier de Léchaud subjected to no waste during its descent, and did no accumulation take place at any point, equal quantities of ice would pass through all its cross sections in the same time. The compression which takes place at Trelaporte is not a change of *volume* but of *form*. The mass is squeezed laterally, and no doubt expands vertically. Comparing the velocities and widths at Trelaporte and opposite the Pierre de Béranger, we should be led to the result that the depth of the Glacier de Léchaud at the former place would, if no waste had taken place, be at least four and a half times its depth at the latter. The loss of ice by superficial and subglacial melting must materially modify this result; but some interesting observations might be made in connexion with the point, and I think one result of such observations would be the establishment of the comparative shallowness of the Glacier de Léchaud.

There is another characteristic of glacier motion which was predicted by Professor Forbes, before any observations had been made upon the point, and afterwards confirmed both by his own measurements and those of M. Martins,—I allude to the fact that the glacier is not only retarded by its sides, but by its bottom, the superficial ice thus moving more quickly than that in contact with the bed of the glacier.

Objections have been made to both the measurements alluded to, and I was therefore desirous to submit the question to a new test. The experiments which I have to record were made upon the face of an ice precipice, which offered a rare opportunity for an observation of the kind. The face formed the eastern boundary of the Glacier du Géant near the Tacul, was about 140 feet in height, and nearly vertical. I requested Mr. Hirst to place two stakes, one at the top and the other at the bottom of this precipice. This was done on the 3rd of August; and on the 5th it was found that the stake at the top had moved through 12½ inches, while that at the bottom showed an advance of 6 inches only. There was some uncertainty regarding this latter result, on account of the danger incurred by the assistant, from the stones which fell incessantly from the top of the precipice, and which compelled him to retreat several times before the measurement could be effected.

I was reluctant, however, to leave an observation of the kind with a shade of uncertainty attached to it. On the 11th of August, therefore, I fixed myself two stakes, one at the top and the other at the bottom of the precipice, and feeling strongly impressed with the importance of ascertaining the motion of a point midway between top and bottom, I cut steps in the ice, climbed the face of the precipice, pierced the ice with an auger, and drove a stake firmly into it. Until Monday the 17th of August I was unable to reach the place again. On this day I penetrated through dense fog and snow to the Tacul, and found the highest of the three stakes standing, but the two lower ones were buried in a heap of snow which lay at the base of the precipice. On the following day the perilous process above described had to be repeated; and on Tuesday the 20th of August the displacements were measured. Reduced to twenty-four hours, the motion of the three stakes was found to be as follows:—

	inches.
Top stake	6·00
Middle stake	4·59
Bottom stake	2·56

The distance from the top of the ice-wall to its base was found, by measurement with a rope, to be 140·58 feet, but it was not quite perpendicular at its upper portion; the height of the middle stake from the ground was 35 feet, and of the bottom one 4 feet. It is therefore proved by these measurements that the bottom of the ice-wall at the Tacul moves with less than half the velocity of the summit; while the deportment of the intermediate stake shows how the velocity increases from the bottom upwards.

§ 3. *On the Cause of Glacier Motion.*

The various theories which have been advanced to account for the progression of glaciers are too well known to need detailed discussion here. SAUSSURE, and some before him, thought that the glacier slid along its bed*. CHARPENTIER thought that the motion was due to the freezing of water in capillary fissures, and the consequent swelling of the contents of these fissures. Other hypotheses have been advanced without producing any deep impression. It has been objected to SAUSSURE's theory, that were it true, glaciers must slide down with an accelerated motion; but reflection alone would deprive this objection of weight, and an experiment of Mr. HOPKINS completely refutes it†. When incessantly checked by the surface over which they slide, even avalanches may, and do, sometimes descend with a uniform motion. The motion of a man in walking down stairs is on the whole uniform, but it is actually made up of an aggregate of small motions, each of which is accelerated. It is easy to conceive that ice moving over an uneven bed, will, when it is released from one opposing obstacle, be checked by another, and its motion thus be rendered sensibly uniform. So many obstacles exist along the bed of a glacier, that sudden slipping forwards of the mass through any considerable distance is not to be expected. But the real weak point of SAUSSURE's theory, though partly true, is its inability to account for many facts observed since his time. The theory of CHARPENTIER, though not always fairly represented, has been shown to be untenable.

The facts submitted to our consideration are briefly as follows:—We see the glacier winding through a valley, squeezing itself through a gorge, and widening where it has room. We see that the centre moves more quickly than the sides, and the top more quickly than the bottom; and the next demand of the mind is for a general principle which shall unite these facts, and from which they shall follow as physical corollaries. Professor FORBES seeks this principle in the *viscosity* of the ice. Ice, according to him, is a substance resembling treacle, honey, or tar, and the observed phenomena are a consequence of this property. In this assumption consists what is called the *viscous theory*‡.

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* I hardly think, however, that SAUSSURE would have subscribed to some of the interpretations of his theory now extant.

† See HOPKINS in Philosophical Magazine, vol. xxvi. p. 4. Were it not that this objection is thoughtlessly repeated in every work upon glaciers, I would not dwell upon it here. The objection drawn from the deportment of secondary glaciers lying on steep slopes is also very commonly dwelt upon, but it is equally without weight; and applies with at least as much force to the viscous theory as to the theory of SAUSSURE.

‡ The name of M. RENDU will always be honourably associated with the theory of glacier motion. He first drew attention to the power of the glacier to move through a sinuous valley, to narrow and widen and behave like lava or like "a soft paste." He conjectured also that the centre would move more quickly than the sides. In fact he appears to have had a correct conception of almost all that the subsequent observations of Professor FORBES established. I regret to say that I have not been able to obtain M. RENDU's original memoir.

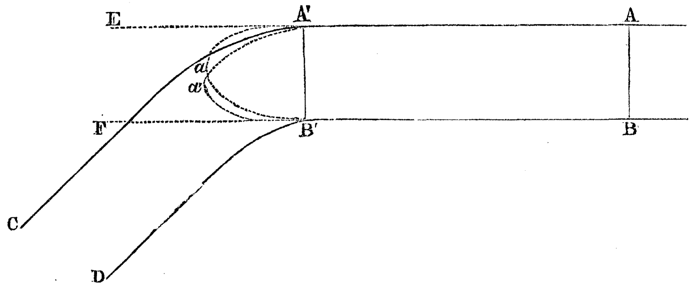
August 1859.—Thanks to my Zürich friends, I have recently had the pleasure of reading M. RENDU's paper, the perusal of which has confirmed my estimate of his sagacity. Had this gentleman been a philosopher instead of an ecclesiastic, we should doubtless have heard more about his claims than we have hitherto done.

Before entering upon the examination of this theory, I would ask permission to make the following remarks:—I am aware that the paper published by Mr. HUXLEY and myself has produced considerable diversity of opinion among scientific men. Some, whose opinions are entitled to every respect, regard the views there advocated, and the experiments there described, as consistent with and explanatory of the viscous theory; while others, of equal eminence, believe that if the views referred to be sound, the viscous theory can no longer be maintained. Under these circumstances it behoves me to state distinctly the point of view from which I intend to examine the theory, submitting myself completely to the public sense as to whether this point of view be the correct one or not. Both the terms and the illustrations made use of by Professor FORBES have diffused ideas regarding the physical qualities of ice which render a strict examination of the subject essential. Let me here briefly state what I understand by viscosity, and what I, and other more competent persons, at one time believed to be a demonstrated property of ice*.

By viscosity, I understand that property of a semifluid body which permits of its being drawn out when subjected to a force of *tension*, the particles of the substance taking up new positions of equilibrium, so that when relieved from the strain the substance has no distortion to recover from. A capacity to change the form under crushing *pressure* is not, I think, a test of viscosity; for this power is possessed by substances, to which we should never think of applying the term viscous.

In examining whether glaciers possess the power of yielding to tension like viscous bodies, I would refer:—1. To the shifting of the place of strain by the curvature of the valley, to which I have already referred. Let ABCD, fig. 3, embrace a curved portion of a glacial valley, and let AB be a linear element of the glacier transverse to its axis.

Fig. 3.



As the ice descends AB becomes curved in consequence of the quicker movement of its centre. Did the valley continue straight in the direction of E and F, the point of maximum velocity would, after a certain time, be found at *a*, midway between the lines AE, BF; but the curving of the valley throws the point *a* to *a'*, and thus increases the strain upon the branch *a'*A' of the curve, while it diminishes the strain upon *a'*B'. The conse-

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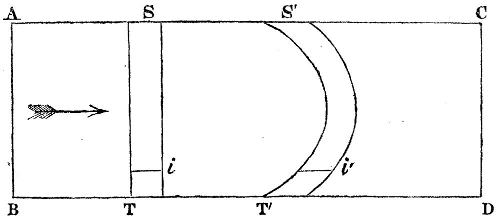
* "*Gluey tenacity*" is the quality which I have heard ascribed to ice by intelligent and cultivated persons.

quence of this difference of action upon the two branches, is that the side of the glacier which is subjected to the augmented tension does not yield to the strain as a viscous body would do, but *breaks*. In the words of Professor Forbes, the glacier at this place becomes "*excessively crevassed*." This fact, therefore, as far as it goes, is opposed to the idea of viscosity as above defined.

2. The fact that the centre of a glacier moves more quickly than the sides, is that on which the viscous theory is chiefly based: let us examine the circumstances connected with this motion, availing ourselves while doing so both of the figure and the reasoning of Mr. Hopkins. Let ABCD, fig. 4, be a sloping canal, into which is poured a quantity of treacle, honey, tar, or melted caoutchouc, all of which have been referred to as illustrative of the character of ice; and let the mass move down the slope in the direction of the arrow. Let ST be a narrow segment of the viscous substance; this segment, as it moves downwards, will take the form S′T′. Supposing T*i* to be a square element of the mass, it will be distorted lower down into the lozenge T′*i*′, and the line T*i* will become T′*i*′. Now the analogy between such a substance and ice fails in this respect; in the viscous mass the short diagonal of the square *stretches* to the long one of the lozenge, but, in the glacier, the ice breaks at right angles to the tension, and *marginal crevasses* are formed. It was by means of the simple diagram here sketched that Mr. Hopkins showed why the marginal crevasses of a glacier are inclined towards its source[*]. This fact, therefore, so far as it goes, is also opposed to the idea of viscosity.

Fig. 4.



But it is known that in the case of a substance confessedly viscous, a sudden shock or strain may produce fracture. Professor Forbes justly urges, "that sealing wax at moderate atmospheric temperatures, will mould itself (with time) to the most delicate inequalities of the surface on which it rests . . . . . but may, at the same time, be shivered to atoms by a blow with a hammer[†]." Hence, in order to estimate the weight of the objection, that the glacier breaks when subjected to strain, we must know the conditions under which the force is applied.

The fifteenth station on the line (EE′) at Trelaporte stands on the lateral moraine of the glacier; between it and the fourteenth, a distance of 300 links, or 190 feet, intervenes, and within this distance the glacier suffers its maximum strain. Let AB (fig. 5) be the

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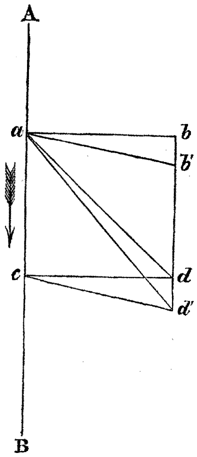
[*] Philosophical Magazine, vol. xxvi. page 160.

[†] Philosophical Magazine, Fourth Series, vol. x. p. 201. Proceedings of the Royal Society, June 14, 1855.

side of the glacier, and let the direction of motion be that indicated by the arrow. Let $abcd$ be a square element of the glacier with a side of 190 feet. The whole square moves downwards with the glacier, but the side bd moves quickest. The point a moves 10 inches, the point b, 14·75 inches in twenty-four hours, the differential motion thus amounting to an inch in five hours. Let $ab'cd'$ be the shape of the figure after five hours' motion, the distance $bb'=dd'$ being 1 inch; then the line ab would be extended to ab', and the line cd to cd'.

Fig. 5.



But the extension of *these* lines does not mark the *maximum strain* to which the ice is subjected. Mr. Hopkins has shown this strain to take place along the line ad, which encloses an angle of 45° with the side of the glacier. In five hours, then, this line, if capable of yielding, would be stretched to ad'.

In the right-angled triangle abd' we have $ab=2280$ inches, $bd'=2281$, and hence we find ad' to be 3225·1 inches; the diagonal ad is 3224·4 inches; and the amount of yielding required from the ice is that the latter line shall be extended by five hours' gradual strain to the length of the former.

This is the utmost demand made upon the presumed viscosity of the ice, but the substance is unable to respond to it: instead of stretching, it breaks, and copious fissures are the consequence. It must not be forgotten that the evidence here adduced merely proves what ice *cannot* do; what it *can* do in the way of viscous yielding we do not know. There is no experiment on record, with masses great or small, to show that the substance possesses, in any measurable degree, that power of being drawn out which is the very essence of viscosity.

Further, the case here referred to is not solitary, but typical. I dare say every single glacier of the first order would furnish proofs of the absence of viscosity equally cogent with that here brought forward. The marginal crevasses of glaciers usually result from an incapacity on the part of the ice to respond to a demand upon its viscosity, not greater than that just cited *.

When a person unaccustomed to glacier life observes, from a safe distance, the profound fissures by which the ice is intersected, the question sometimes arises, "what if one of these chasms should suddenly open beneath the traveller's feet?" There is, however, no fear of this. The crevasses, when first formed, are exceedingly narrow, and they

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* It may, however, be urged that I do not know how much the ice observed in the locality referred to had been stretched before it arrived there. Extend an elastic string to the point of breaking, and a small additional force would break it; but this latter small extension would be no measure of the extensibility of the string. To this I reply, that it is the very essence of a viscous mass to accommodate itself to the forces which act upon it, so that in each new position the texture of the substance shall be in a state of equilibrium. If such a mass be broken it will have no distortion to recover from. The idea that a glacier is typified by such a string as that referred to, has been expressly rejected by the ablest advocates of the viscous theory; in proof of which I would refer to the lucid note of Dr. Whewell, in the 26th volume of the Philosophical Magazine, page 172. Cases may occur where the lateral yielding produced by the *pressure* along bc, fig. 5, may satisfy the *strain* along ad; in such a case no marginal crevasses would be formed.

open with extreme slowness. While standing one evening, in company with Mr. Hirst, on the Glacier du Géant, both of us were startled by a sound like a heavy explosion in the body of the glacier, underneath the place where we stood. This was instantly followed by a succession of loud cracks, accompanied by a low singing noise. The ice continued cracking for an hour; but notwithstanding the manifest breaking of the glacier, which was to some extent awe-inspiring, we could not, for a long time, detect any trace of rupture. The escape of air-bubbles from the surface first informed us of the position and direction of the incipient crevasse, for such it was. It was so narrow that the thinnest blade of my penknife would not enter it.

On another occasion, our guide, while engaged in setting out one of our lines, observed the ice to break beneath his feet, and a rent to propagate itself suddenly, with loud cracking, to a distance of 50 or 60 yards across the glacier. These fissures are produced by tension, and the velocity with which they widen is a measure of the amount of relief demanded by the glacier. The crevasse last alluded to required several days to attain a width of 3 inches, and the opening of the one on the Glacier du Géant was far slower than this. This is their general character. They form *suddenly* and open *slowly*, and both facts are demonstrative of the non-viscosity of the ice. *For were the substance capable of stretching, even at the small rate at which they widen, there would be no necessity for their formation*[*].

There is another point of view from which the question of viscosity may be examined; but as the observations which bear upon it possess a general value, I will devote a special section to them; choosing afterwards those which more particularly apply to the case now under consideration.

§ 4. *On the Inclinations of the Mer de Glace.*

By calculation from heights and distances, Professor Forbes obtained approximately the inclinations of some portions of the Mer de Glace[†], but no direct observations on the subject have been hitherto made. On the 4th of August we transported our theodolite to the Jardin, for the purpose of ascertaining its inclination, and that of the Glacier du Talèfre. From the green space on which visitors to the place usually repose, the angle of elevation to the top of the Jardin is 24° 7′, and from the same place downwards to the bottom of the Jardin the inclination is 30°. From the bottom of the Jardin, for some distance along its medial moraine, the ice is nearly level, its inclination being only 21′. A succession of slopes then follows, enclosing with the horizon the following angles of depression:—3° 5′; 4° 25′; 6° 50′; 8° 5′ and 9° 40′, which last brings us to the brow of the ice cascade. The inclination of the fall is 25°,—producing a line drawn along the centre of the cascade until it cuts the moraine between the Talèfre and Léchaud: the inclination along this line, from the base of the cascade downwards, is 7° 30′.

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[*] For an interesting account of the formation of a number of new crevasses, see Agassiz, 'Système Glaciaire,' p. 310.

[†] Travels, p. 117.

The descent of the ice through this gorge from the basin of the Talèfre, is adduced by Professor FORBES as an illustration "which will appear to the impartial reader almost a demonstration" of the principle of viscosity. "The ice is compact," he urges, "and almost without fissures. . . . . The open crevasses which commence a little above AB are turned towards the basin*." The line AB here referred to is actually in the jaws of the gorge, and apparently at a considerable distance below where the ice enters it. The description certainly would not apply to the ice of the year 1857. Long before reaching the summit of the fall the most skilful iceman would find himself in difficulties. We proceeded as far as we dared amid the pits and chasms into which the glacier is torn, and which followed each other so speedily, that the ridges between the fissures were often reduced to mere plates and wedges, which were in many instances bent and broken by the lateral pressure. At some places vortical forces seemed to have acted upon the mass, and turned huge pyramids so far round as to place the structural veins at right angles to their normal position. Looking downwards towards the summit of the cascade, the ice was frightfully riven. The glacier descends the cascade itself in wedges, pyramids, and columns, which latter often fall with a sound like thunder, and crush to pieces the ice crags below them. After this description I do not think that the case is likely to be accepted as a demonstration of the viscosity of ice.

I now pass on to the inclinations of the Glacier du Géant. For some distance below the base of the so-called *Seracs* the irregularities of the glacier render an estimate of its general inclination somewhat difficult, but I should judge it to be about 13°. From the end of this steeper portion, two slopes, one of 4° 37′, and the other of 3°, bring us to the Tacul, and from this point to the bottom of the ice valley at Trelaporte we have the following series of inclinations:—2° 15′; 3° 15′; 5° and 9°; thence to the Grand Moulin the slope is 3° 30′, and afterwards, down the glacier to a point nearly opposite to the Grande Cheminée below l'Angle, the inclinations are 3° 10′; 5°; 6° 25′, and 4°. The glacier then descends a slope of 9°, and afterwards passes the Montanvert at an inclination of 4° 45′. Below the Montanvert it falls steeply for some distance, the inclination being 16°. Between the base of this slope and the brow which marks the termination of the Mer de Glace and the commencement of the Glacier des Bois, the slope is 5° 10′. The ice afterwards descends an incline of 22° 20′ in a state of great dislocation. From the base of this incline the general inclination of the lower portion of the glacier is 10°.

A brief reference to the Glacier de Léchaud will complete this portion of our subject. The upper portion of the glacier, to the base of the steep snow slopes which rear themselves against the Grande Jorasse, has an inclination of 4° 29′. Opposite to the icefall of the Talèfre, the inclination, for a short distance, is 3° 17′, and afterwards down to the Tacul, where the Léchaud and Géant join, the slope is 5° 22′.

I will now endeavour to show the theoretic significance of the observations above recorded, referring in the first place to the great terminal slope of the Glacier des Bois,

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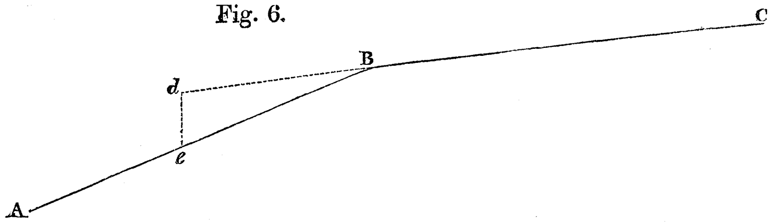
* "Reply to HOPKINS," Philosophical Magazine, 1845, vol. xxvi. p. 415.

down which the ice is shot in crags, pinnacles, wedges, and castellated masses, all tossed together in the utmost confusion. Regarding this portion of the glacier, Professor FORBES writes as follows:—"Escaping from the rocky defile between the promontory of the Montanvert and the base of the Aiguille de Dru, it pours in a cascade of icy fragments, assuming the most fantastic forms, into the valley beneath." Above the fall the ice is compact: Professor FORBES compares it to the dark unruffled swell of swift water rushing to precipitate itself in a mass of foam over a precipice.

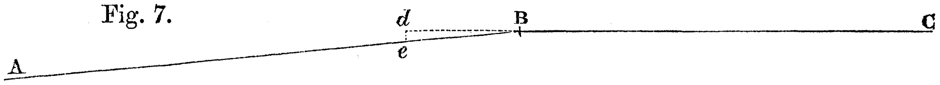
In fig. 6 I have protracted the inclination of the fall and of the glacier above it, one of them, BC, making an angle of 5° 10′, and the other, BA, an angle of 22° 20′ with the horizon. Supposing the ice to pursue the direction which it had previous to reaching the fall, it would, at the end of a certain time, reach the point *d* *; but the ice is not rigid enough to do this, and the mass descends to *e*. Now if it be the viscosity of the substance which has carried it in a certain time from B to *d*, that same property ought, one would think, to enable it to drop down the vertical *de* without breaking. But so far from its being able to do this, the glacier descends the slope BA as "a cascade of icy fragments." The fact, therefore, adds its evidence to that already adduced against the viscosity of the substance.

Fig. 6.



But the case will appear much stronger when we revert to other slopes upon the Mer de Glace. For example; the inclination of the glacier above l'Angle is 4°: it subsequently descends a slope of 9° 25′, and in doing so is so much fissured as to be absolutely impassable. The chasms cut the glacier from side to side, and present clear vertical faces of great depth†. Subtracting the smaller of the above angles from the larger, the difference, 5° 25′, gives the *change* of slope which produces the chasms. In fig. 7 the two adjacent slopes are protracted to a proper scale. Now the velocity of the glacier here, in the direction of its length, is to the vertical velocity with which it would have to sink to reach its bed, as B*d*: *de*, or as the cosine of 5° 25′ is to its sine, or as 996 : 94, or, in round numbers, as 10 : 1. Hence if it be viscosity which enables the mass to move from B to *d* in a certain time, the same property ought, one would think, to permit it to *sink* through the space *de*, which is only one-tenth of B*d*, in the same

Fig. 7.



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* I here assume that the general inclination of the surface of the glacier changes in accordance with that of its bed, which will hardly be questioned.

† I once found myself alone upon this portion of the glacier towards the close of a day's work, and experienced great difficulty in escaping from the entanglement of chasms in which I had involved myself.

time. But this is not the case. In accommodating itself to the change of inclination, the glacier breaks and is fissured in the manner described.

The change of inclination last mentioned, so far from marking the limit at which transverse crevasses begin to be formed, is sufficient to produce chasms of great magnitude, and in most inconvenient numbers. Higher up the glacier, transverse crevasses are produced by a change of inclination from 3° 10′ to 5°. If this change be accurately protracted, the mere inspection of it will illustrate more forcibly than words can do the absence of the power of viscous yielding on the part of the ice.

Looked at broadly, then, two classes of facts address themselves to the attention of the glacier investigator; one entirely in accordance with the idea of viscosity, and the other as entirely opposed to it. The affirmers and deniers of the viscous theory have perhaps been influenced too exclusively by one or the other of these classes of phenomena. The analysis of the facts gives the result, that where *pressure* comes into play we have the evidences of apparent viscosity*, but where *tension* is active we have evidences of an opposite kind. One of these classes of effects is as undeniable as the other, and hence the true theory of glaciers must render an account of both.

When the mountain snow is first moistened, it becomes more coarsely granular; these granules abut against each other, and hold air and water in their interstices. But as successive layers press upon the mass, the granules are squeezed more closely together; rupture and liquefaction, succeeded by regelation, take place at the points of abutment; water and air are expressed by the process, and the mass becomes more and more consolidated. But although powerfully squeezed, each portion of the deeper ice is surrounded on all sides by a resistent mass; it is thus compelled to yield very gradually to the pressure and moves slowly through into the valley of *écoulement*. As far as external appearances go, there is, of course, almost a perfect similarity between such an action and one due to viscosity.

But when a force of tension is applied, the case is wholly different. That intestine mobility which characterizes a truly viscous body, and enables one molecule to move round another while clinging to it, or one particle to advance while another slides in laterally to supply its place, being absent, the only way in which such a body can meet the requirements of a strain is by breaking, the fissures widening as the strain continues.

Thus, I think, we take account of all the facts adduced in proof of viscosity, and also furnish a satisfactory explanation of the other set of facts on which the opponents of the viscous theory have hitherto based their arguments.

Royal Institution, May 1858.

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* The ingenious experiment of Mr. CHRISTIE with a bomb-shell filled with water and submitted to a freezing temperature, belongs, of course, to this class of effects.