XXVI. *On the Physical Cause of the Motion of Glaciers.*

By JAMES CROLL, *of the Geological Survey of Scotland*[*].

I HAVE just seen an abstract of a most interesting paper by the Reverend Canon Moseley "On the Mechanical Possibility of the Descent of Glaciers by their weight only," which was read before the Royal Society on the 7th of January last[†]. In that memoir he arrives at the conclusion that, owing to the great resistance offered by the solid ice to *shearing*, it is impossible that glaciers can descend by their weight alone.

"All the parts," he remarks, "of a glacier do not descend with a common motion; it moves faster at its surface than deeper down, and at the centre of its surface than at its edges. It does not only come down bodily, but with different motions of its different parts; so that if a transverse section were made through it, the ice would be found to be moving differently at every point of that section. . . . . . There is a constant displacement of the particles of the ice over one another and alongside one another, to which is opposed that force of resistance which is known in mechanics as *shearing-force*."

He determines by calculation the amount of shearing-force which must not be exceeded if the displacement of the particles is to be effected by the weight of the ice alone. In the case of the Mer de Glace at the Tacul, the shearing-force of the ice must not exceed 1·3193 lb. per unit surface of one square inch, if that glacier descends merely by its weight, at the rate observed by Professor Tyndall. From experiments which he has made, he finds that the actual shearing-force of ice per unit surface is about 75 lbs. Consequently he concludes it is impossible that the motion of the glacier can be due to its weight alone; there must be some other force in addition to the weight impelling the ice forward. And he calculates that the amount of work performed by this unknown force is thirty-four times the amount performed by the weight of the glacier.

This is a most important conclusion. It is quite decisive against the generally received opinions regarding the descent of glaciers by their own weight.

But although it is thus demonstrated that glaciers cannot descend by means of their weight alone in the manner generally supposed, still, I venture to think that, notwithstanding the demonstration, gravitation after all may be the only force moving the ice.

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[*] Communicated by the Author.

[†] Proceedings of the Royal Society, vol. xvii. p. 202. [See p. 229 of our present Number, ED. *Phil. Mag.*]

The correctness of the above conclusion, that the weight of the ice is not a sufficient cause, depends upon the truth of a certain element taken for granted in the reasoning, viz. that the *shearing-force* of the molecules of the ice remains *constant.* If this force remains constant, then Canon Moseley's conclusion is undoubtedly correct, but not otherwise; for if a molecule should lose its shearing-force, though it were but for a moment, if no obstacle stood in front of the molecule, it would descend in virtue of its weight.

The fact that the shearing-force of a mass of ice is found to be constant does not prove that the same is the case in regard to the individual molecules. If we take a mass of molecules in the aggregate, the shearing-force of the mass taken thus collectively may remain absolutely constant, while at the same time each individual molecule may be suffering repeated momentary losses of shearing-force. This is so obvious as to require no further elucidation. The whole matter, therefore, resolves itself into this one question, as to whether or not the shearing-force of a crystalline molecule of ice remains constant. In the case of ordinary solid bodies we have no reason to conclude that the shearing-force of the molecules ever disappears, but in regard to ice it is very different.

If we analyze the process by which heat is conducted through ice, we shall find that we have reason to believe *that while a molecule of ice is in the act of transmitting the energy received* (*say from a fire*), *it loses for the moment its shearing-force if the temperature of the ice be not under* 32° F. If we apply heat to the end of a bar of iron, the molecules at the surface of the end have their temperatures raised. Molecule A at the surface, whose temperature has been raised, instantly commences to transfer to B a portion of the energy received. The tendency of this process is to lower the temperature of A and raise the temperature of B. B then, with its temperature raised, begins to transfer the energy to C. The result here is the same; B tends to fall in temperature, and C to rise. This process goes on from molecule to molecule until the opposite end of the bar is reached. Here in this case the energy or heat applied to the end of the bar is transmitted from molecule to molecule under the form of *heat or temperature.* The energy applied to the bar does *not change its character; it passes right along from molecule to molecule under the form of heat or temperature.* But the nature of the process must be wholly different if the transference takes place through a bar of ice at the temperature of 32°. Suppose we apply the heat of the fire to the end of the bar of ice at 32°, the molecules of the ice cannot possibly have their temperatures raised in the least degree. How, then, can molecule A take on, *under the form* *of heat,* the energy received from the fire without being heated or having its *temperature* raised? The thing is impossible. The energy of the fire must appear in A under a different form from that of heat. The same process of reasoning is equally applicable to B. The molecule B cannot accept of the energy from A under the form of heat; it must receive it under some other form. The same must hold equally true of all the other molecules till we reach the opposite end of the bar of ice. And yet, strange to say, the last molecule transmits in the form of heat its energy to the objects beyond; for we find that the heat applied to one side of a piece of ice will affect the thermal pile on the opposite side.

The question is susceptible of a clear and definite answer. When heat is applied to a molecule of ice at 32°, the heat applied does not raise the temperature of the molecule, it is consumed in work against the cohesive forces binding the atoms or particles together into the crystalline form. The energy then must exist in the dissolved crystalline molecule, under the statical form of an affinity—crystalline affinity, or whatever else we may call it. That is to say, the energy then exists in the particles as a power or tendency to rush together again into the crystalline form, and the moment they are allowed to do so they give out the energy that was expended upon them in their separation. This energy, when it is thus given out again, assumes the dynamical form of heat; in other words, the molecule gives out *heat* in the act of freezing. The heat thus given out may be employed to melt the next adjoining molecule. The ice-molecules take on energy from a heated body by melting. That peculiar form of motion or energy called heat disappears in forcing the particles of the crystalline molecule separate, and for the time being exists in the form of a tendency in the separated particles to come together again into the crystalline form.

But it must be observed that although the crystalline molecule, when it is acting as a conductor, takes on energy under this form from the heated body, it only exists in the molecule under such a form during the moment of transmission; that is to say, the molecule is melted, but only for the moment. When B accepts of the energy from A, the molecule A instantly assumes the crystalline form. B is now melted; and when C accepts of the energy from B, then B also in turn assumes the solid state. This process goes on from molecule to molecule till the energy is transmitted through to the opposite side and the ice is left in its original solid state. This is the *rationale* of Faraday's property of regelation.

This is no mere theory or hypothesis; it is a necessary consequence from known facts. We know that ice at 32° cannot take on energy from a heated body without melting; and we know also equally well that a slab of ice at 32°, notwithstanding this, still, as a mass, retains its solid state while the heat is being transmitted through it. This proves that every molecule resumes its crystalline form the moment after the energy is transferred over to the adjoining molecule.

This point being established, every difficulty regarding the descent of the glacier entirely disappears; for a molecule the moment that it assumes the fluid state is completely freed from shearing-force, and can descend by virtue of its own weight without any impediment. All that the molecule requires is simply room or space to advance in. If the molecule were in absolute contact with the adjoining molecule below, it would not descend unless it could push that molecule before it, which it probably would not be able to do. But the molecule actually has room in which to advance; for in passing from the solid to the liquid state its volume is diminished by about $\frac{1}{10}$, and it consequently can descend. True, when it again assumes the solid form it will regain its former volume; but the question is, will it go back to its old position? If we examine the matter thoroughly we shall find that it cannot. If there were only this one molecule affected by the heat, this molecule would certainly not descend; but all the molecules are similarly affected, although not all at the same moment of time.

Let us observe what takes place, say at the lower end of the glacier. The molecule A at the lower end, say, of the surface, receives heat from the sun's rays; it melts, and in melting not only loses its shearing-force and descends by its own weight, but it contracts also. B immediately above it is now, so far as A is concerned, at liberty to descend, and will do so the moment that it assumes the liquid state. A by this time has become solid and again fixed by shearing-force; but it is not fixed in its old position, but a little below where it was before. If B has not already passed into the fluid state in consequence of heat derived from the sun, the additional supply which it will receive from the solidifying of A will melt it. The moment that B becomes fluid it will descend till it reaches A. B then is solidified a little below its former position. The same process of reasoning is in a similar manner applicable to every molecule of the glacier. Each molecule of the glacier consequently descends step by step as it melts and solidifies, and hence the glacier, considered as a mass, is in a state of constant motion downwards. The fact observed by Professor Tyndall that there are certain planes in the ice along which melting takes place more readily than others will perhaps favour the descent of the glacier.

We have in this theory a satisfactory explanation of the origin of "crevasses" in glaciers. Take, for example, the transverse crevasses formed at the point where an increase in the inclination of the glacier takes place. Suppose a change of inclination from, say, 4° to 8° in the bed of the glacier. The molecules on the slope of 8° will descend more rapidly than those above on the slope of 4°. A state of tension will therefore be induced at the point where the change of inclination occurs. The ice on the slope of 8° will tend to pull after it the mass of the glacier moving more slowly on the slope above. The pull being continued, the glacier will snap asunder the moment that the cohesion of the ice is overcome. The greater the change of inclination is, the more readily will the rupture of the ice take place. Every species of crevasse can be explained upon the same principle.

This theory explains also why a glacier moves at a greater rate during summer than during winter; for as the supply of heat to the glacier is greater during the former season than during the latter, the molecules will pass oftener into the liquid state.

As regards the denuding power of glaciers, I may observe that, though a glacier descends molecule by molecule, it will grind the rocky bed over which it moves as effectually as it would do did it slide down in a rigid mass in the way generally supposed; for the grinding-effect is produced not by the ice of the glacier, but by the stones, sand, and other materials forced along under it. But if all the resistances opposing the descent of a glacier, internal and external, are overcome by the mere weight of the ice alone, it can be proved that in the case of one descending with a given velocity the amount of work performed in forcing the grinding materials lying under the ice forward must be as great, supposing the motion of the ice to be molecular, in the way I have explained, as it would be supposing the ice descended in the manner generally supposed.

Of course, a glacier could not descend by means of its weight as rapidly in the latter case as in the former; for in fact, as Canon Moseley has shown, it would not in the latter case descend at all; but assuming for the sake of argument the rate of descent in both cases to be the same, the conclusion I have stated would follow. Consequently whatever denuding effects may have been attributed to the glacier, according to the ordinary theory, must be equally attributable to it according to the present theory.

This theory, however, explains, what has always hitherto excited astonishment, viz. why a glacier can descend a slope almost horizontal, or why the ice can move off the face of a continent perfectly level.

Canon Moseley suggests that heat passing into the ice might by its mechanical energy, together with the weight of the glacier, be sufficient to account for the motion. But the mechanical energy of heat is not required to push the glacier forward; gravitation alone, as we have just seen, will suffice. Besides, heat entering ice could not produce a mechanical pressure that would move the glacier; for heat produces contraction of volume, not expansion. True, heat no doubt destroys the crystalline structure of the ice-molecule by tearing the constituent particles separate; but nevertheless the volume of the mass is diminished by this process, for ice in losing its crystalline structure, or, in other words, in passing from ice to water, decreases in volume.

XXVII. *On* Mr. J. Croll's *paper "On Geological Time, and the probable Date of the Glacial and the Upper Miocene Period"*[*]. *By* R. A. Peacock, *C.E.*[†]

THE writer hereof believes that Mr. Croll's paper is of great value; and if a few remarks are ventured upon below on small points of detail, they no more detract from the general value of the paper than a few "striæ" or scratches would detract from the value of a good painting.

"The only evidence which we can now reasonably expect to find in the stratified rocks of the existence of land-ice of former epochs, is the presence of erratic blocks which may have been transported by icebergs and dropped into the sea. But unless the glaciers of that epoch reached the sea or the sea was frozen, we could not possibly have even this evidence. Traces in the stratified rocks of the effects of land-ice of former epochs must, from the very nature of things, be rare indeed" (p. 364).

On the contrary, might we not have striation on the stratified rocks pretty often in this way? When we remember the frequent oscillations of land by sinkings and risings in every part of the globe since the commencement of the glacial period (assuming that to have commenced 240,000 years ago and to have lasted 160,000 years), the following may *often* have happened. Suppose (as must have been the case) many glaciers to have been making each its way down its own valley in the usual manner, bearing its lines of moraines, as in Switzerland at present. The glaciers would then striate the stratified rocks of every valley. Such striations would continually go on increasing as long as the glaciers existed. And considering the vast tract of the earth which must have been thus operated on during 160,000

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[*] Philosophical Magazine, November 1868.

[†] Communicated by the Author.