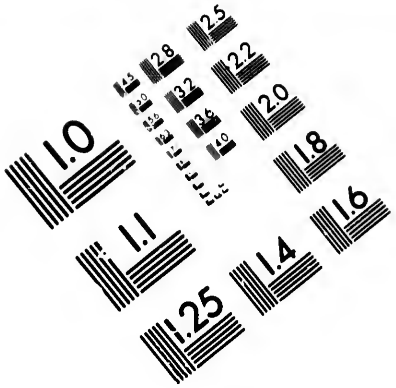

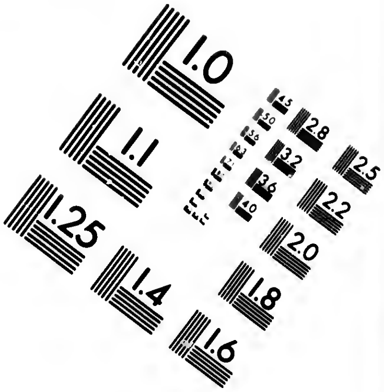

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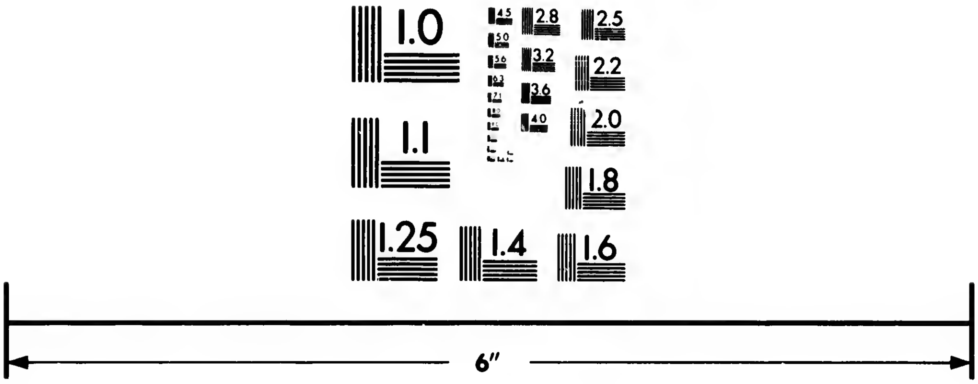

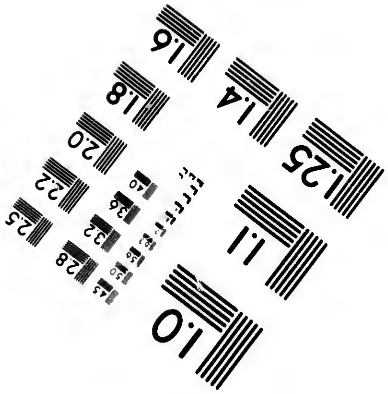

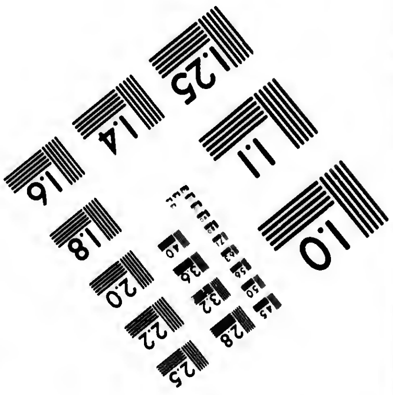

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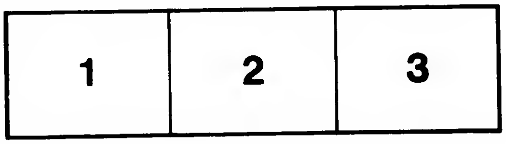

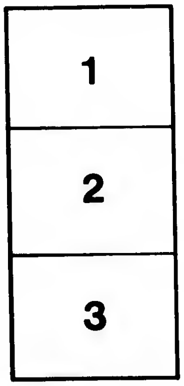

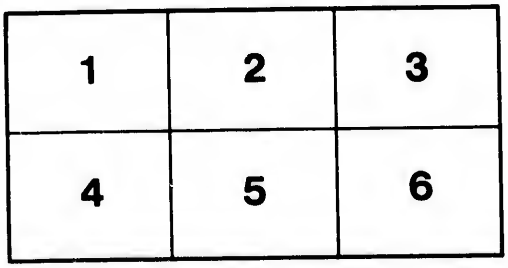

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GLACIAL-EROSION IN NORWAY AND IN HIGH LATITUDES.

ON THE THEORY OF GLACIAL MOTION.

By Prof. J. W. Spencer, M.A., Ph.D., F.G.S.

Reprinted from Proceedings Royal Society, Canada, 1887; and *Geological Magazine* (London), 1887-8; *Extracted from* American Naturalist, Vol. XXII., 1888.

GLACIAL EROSION IN NORWAY AND IN HIGH LATITUDES.[1]

BY PROFESSOR J. W. SPENCER, M.A., PH.D., F.G.S.

Reprinted from Proceedings Royal Society, Canada, 1887; and "Geological Magazine" (London), 1887-8; extracted from "American Naturalist," Vol. XXII., 1888.

I.

DURING the summer of 1886, it was my good fortune to visit the three largest snowfields in Norway, namely, the Folgefond, at the head of Hardangerfjord in southern Norway, whose area is 108 square miles; the Jostedalsfond, two degrees to the north, beyond Sognefjord, whose area is 580 square miles, and the largest snowfield in Europe; and the Svartisen, extending from just inside the arctic circle for forty-four miles northward. All of these snowfields send down glaciers to within from 50 to 1,200 feet of the sea. These snowfields are not basins like those in the Alps, but are mantles covering the tops of plateaus from 3,000 to 5,000 feet or more above the tide, from which great cañons suddenly descend to the sea, and extend themselves as fjords, from 1,000 to 4,000 feet in depth.

Many of the Norwegian glaciers are rapidly advancing. In their progress they do not conform to the surfaces over which they pass, but are apt to arch over from rock to rock and point to point, especially as they are descending the ice-falls. Thus are produced great caverns into which the explorer can often wind his way for long distances.

Beneath the glaciers of Fondal, Tunsbergdal, and Buardal, in the northern, north-central, and south-central snowfields of Norway, as well as under other glaciers, I observed many stones enclosed in ice, resting upon the rocks, to whose surfaces—sometimes

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[1] **Read before the Royal Society of Canada, May 25, 1887, and the American Association for the Advancement of Science, New York, Aug. 1887. Printed from advanced sheets of the Proc. Roy. Soc. of Canada. See also "The Erosive Power of Glaciers as seen in Norway," Geol. Mag., London, Dec., iii., vol. iv., 1887, and "Ice Action in High Latitudes," ibid., vol. v., 1888, by Prof. J. W. Spencer, M.A., Ph.D., F.G.S.**

flat, sometimes sloping steeply—they adhered by friction, and by the pressure of the superincumbent weight. Although held in the ice on four sides, with a force pushing downward, the viscosity of the ice, or the resistance of its molecules in disengaging themselves from each other in order to flow, was less than that of the friction between the loose stones and the rock; consequently the ice flowed around and over the stones, leaving long grooves upon the under-surfaces of the glacier. The first observation made was at Fondalsbræen (Fig. 1), where an angular stone (Fig. 1 *d*) whose section was ten by eighteen inches, rested upon the sloping face of smooth rock (*a*). For twenty feet below the stone, the under-surface of the glacier was grooved (*f*) by the moulding of the ice about the obstacle. This distance showed the advance of the glacier after the stone had come in contact with the rock, for it had evidently been completely buried at the lower end of the groove, before the ice had begun to flow about it. As the ice between the stone and the rock gradually disappears, the embedded stone does not suddenly cease to move, but drags, until enough of the surface rests upon the rock to allow of friction between the two granitoid surfaces to overcome the viscosity of the ice, when the latter flows around the obstacle. Elsewhere, an example was seen of this action. The knife edge of a wedge-shaped piece of gneiss was protruding beneath the ice and resting upon the rock. The front end of this stone had moved beyond the subjacent surface, while the posterior

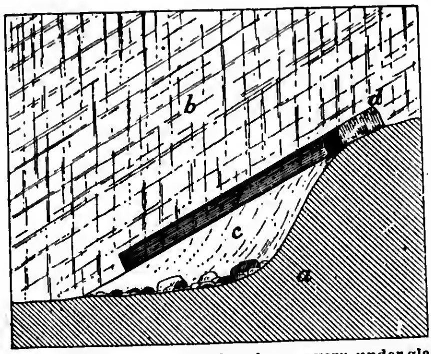

FIG. 1.—Section of Fondalsbræen, *a*, bed rock; *c*, cavern under glacier *b*; *d*, loose stone; *f*, groove under the ice.

end was still upon it. Yet the sharpness of the edge had scarcely been blunted.

Abundant examples were found to show that the flowing of the ice about loose obstacles was quite the rule. Both large and small (even an inch in length), angular and rounded masses, lying either upon the rock, or upon morainic matter, were sufficient to channel the bottom of an advancing glacier. No blocks of rock were seen in the act of being torn loose from the floor or sides of the valley, and certainly there were no loose or solid masses being picked up by the advancing glacier.

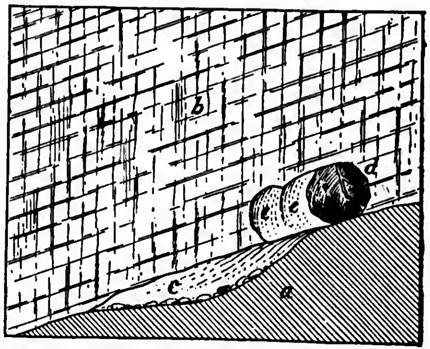

FIG. 2.—Section of Tunsbergdalsbræen, *a*, bed rock; *c*, cavern under ice *b*; *d*, boulder; *ee*, moulding in ice of the form of *d*.

At Tunsbergdalsbræen (Fig. 2), whose lower end is 1,600 feet above the sea, a modification of the above described phenomena was seen. A roughly rounded boulder (Fig. 2 *d*) of thirty inches diameter was enclosed in the convex side of the glacier, which rose above it from thirty to forty feet in height. It was resting upon a surface, sloping at a high angle, and was held in place by the ice itself. As the surface of the stone, bearing upon the rock, was small compared with that held in the ice, it should have been dragged along. But it was being rolled, as shown by the moulding (*e e*) of its form in the glacier which was advancing faster than the stone was rolling down the steep slope. The pressure upon this stone could not have been merely that of the superincumbent ice, a few feet thick, but also that of a powerful component of the weight of a glacier from 1,500 to 2,000 feet high descending more or less like a fluid. The energy upon the boulder was sufficient to crush it into one large and two smaller masses, together with stone dust. When seen, the three fragments had hardly begun to part company.

The abrasion of the solid rock by the fall of stones, and detached masses of ice and stones, was illustrated at the locality just named. The two guides and myself succeeded in detaching a large boulder of about five tons weight, adjacent to the edge of the glacier. It went rolling and sliding down a hundred feet or more, tearing away great blocks of ice which held a considerable amount of debris, and in its wake, the rock was more or less crushed or scratched.

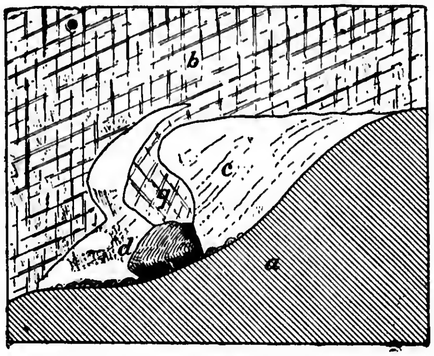

FIG. 3.—At Tunsbergdalsbræen. *d*, a loose boulder, resting on rock *a*, in cavern c, against which a tongue *q*, of the moving glacies *b*, impiges and is bent backward.

A further example of the ability of the ice to flow like a plastic body was shown in a cavern (Fig. 3 c) 400 feet higher than the end of the glacier, where the temperature was 4°C., while that outside was 13°C. Upon the debris of the floor rested a rounded boulder (*d*) whose longer diameter measured thirty inches. A tongue of ice (*q*), in size more than a cubic yard, was hanging from the roof, and pressing against the stone. In place of pushing the stone along or flowing around it, the lower layer of ice above the tongue had yielded, and was bent backward as easily and gracefully as if it had been a thin sheet of lead, instead of one of ice a foot thick.

According to the experiments of Herr Pfaff,[1] the temperature of

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[1] Nature, Aug. 19, 1875.

ice has a great deal to do with its flow about obstacles. Below freezing-point, the movement is scarcely more than appreciable, while above that point, but not below, it may reach twenty-eight inches a day, or more. The conditions arising from the temperature beneath the glaciers are more or less favorable for the movement of the ice, as the lower surfaces are never entirely below freezing-point, even in winter. Professor S. A. Sexe[1] found that the water flowing from a Folgefond glacier, in February, 1861, had a temperature of 1°R., whilst that of the air was 7°R. below freezing-point.

The movement or flow of the ice about detached stones, resting upon rocks, has been observed by Professor Sexe beneath the Buarbræ, and by Professor J. W. Niles beneath the Aletsch glacier.[2] Professor Sexe illustrates the moulding of the ice about a loose stone, which was held beneath the glacier by a projection of the rock. My observations were upon stones, not held up by rocky projections, but upon surfaces often sloping downward. Although Professor Niles did not record observations showing that there was definite movement of the stone, yet he concluded that there was a differential movement of the ice and the block. Whatever differential movement there is, it must be very inconsiderable, not only upon horizontal plains, but upon inclined surfaces. In the former case the movement of the ice is reduced almost to zero, as shown by the measurements of Professor Tyndall upon the Morteracht, where the velocity of the surface, some distance from its end, was fourteen inches, whilst that of the tongue of the glacier, as it reached the plain, was only two inches a day.[3]

The most important condition favorable for holding stones in ice as graving tools is low temperature, which impedes its progress; but this condition beneath glaciers does not generally exist. At higher temperatures, the velocity of the glacier is not great enough to overcome its plastic movement and to drag along detached blocks. However, when the whole mass of ice is charged with sand and stones, there is no doubt that polishing and scratching are effected; but when there are only occasional fragments in the bottom of the ice, as is commonly the case, the erosion from the sliding ceases as

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[1] Om Sneebræen Folgefon, af S. A. Sexe.

[2] American Journal of Science, Nov., 1878.

[3] Tyndall's Forms of Water.

soon as the resistance due to friction between the stones and the rock equals that due to viscosity, which, as observations show, is soon reached. Consequently, we should not expect to find great troughs or grooves scooped out of solid rock by the actual glacier. These I have not seen about the existing glaciers of Norway, which are not dependent upon atmospheric and aqueous erosion and the texture of the rock, although their surfaces may have been subsequently polished. Generally speaking—as seen in the valley behind Fondalen Gaard, where the glacier is nearly free from sand, and contains comparatively few stones, as well as at many other places—the surfaces of the subjacent crystalline rocks, although of the form of *roches moutonnées*, with angles mostly removed, are not smooth, but are as rough and as much weather-worn as similar rocks in warmer countries where no glaciers have been. Upon these surfaces, it is often difficult to discover scratches—even when present—for they are often so faint as to be only rendered apparent by moistening the rock. Even the face of the hummocks are commonly imperfectly polished. In other places, particularly at Tunsbergdalbræen which contains much sand along the margin, the rocks are highly polished, and but little scratched. One is everywhere surprised to find beneath the glaciers the great paucity of glaciated stones, and in many terminal moraines they are scarcely, if at all, to be found.

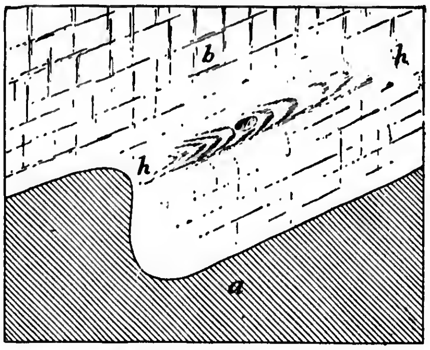

FIG. 4.—Section at Fondalsbræen, *hh*, zone along which ice (*b*) is flowing upon its lower layers.

The insufficiency of glaciers to act as great erosive agents is farther shown at Fondalen (Fig. 4), where a mass of ice thirty or forty feet thick abuts against a somewhat steep ridge of a rock, ten feet or less in height. In place of a stone-shod glacier sliding up and over the barrier, the lower part of the ice appears stationary, or else is moving around the barrier, while the upper strata bends and flows over the lower layers of ice (along the line *hh*, Fig. 4).

When the barrier to the advance of a glacier is met with, whether composed of hard rock, or of morainic matter, the ice, provided it be sufficiently high, flows over upon itself, yet when the sheet is no higher than the barrier, the lateral thrust may push it up somewhat. The best example of the consequences of such a condition is to be seen at Svartisen glacier (Fig. 5), at the head of Holandsfjord, which descends to within sixty feet of the sea, where it ends in a morainic lake of considerable size, the northern side of which is filled with the glacier. The water of the lake rises, in part, to the level of the ice, or over it, where the waves of the lake are depositing sand upon its surface. Part of the ice is not less than twenty-five feet thick, and most of it is probably double that thickness. Some of the strata of ice are pushed up and rest at 5° from the horizontal. But the interesting points are at the end of the glacier, where it impinges against the morainic barrier. Being unable to advance, the lateral pressure has forced up an anticlinal ridge or rather dome in the ice, to a height of fifteen feet, along whose axis there has been a fracture and fault. Upon this uplifted dome rests the undisturbed sand stratified in perfect conformity to the surface, which was formerly just below the level of the lake. As the ice about the line of fracture melts, the sand falls over and leaves a sand cone, of which there were examples—one at the end of the lake, and two in the centre—but the nuclei of the mounds were of

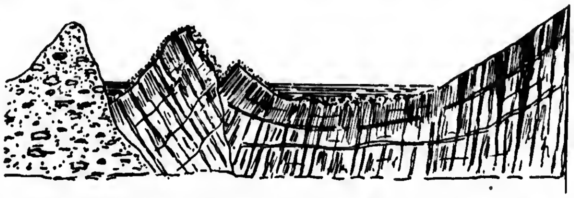

FIG. 5.—End of Svartisen glacier at head of Holandsfjord, moving through a lake against morainic barrier.

solid ice. By this lifting process, pockets of loose clayey sand were thrown on top of the morainic matter, producing thus the appearance of having been ploughed up by the glacier to even several yards beyond its termination, which has not been the case.

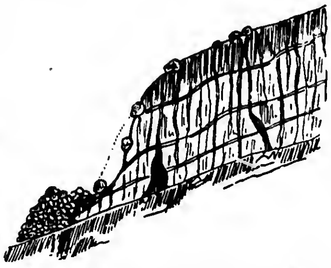

Fig. 6.—Buarbræen depositing morainic material upon a tongue of its ice, giving the false appearance of a glacial plough.

Nowhere is there apparently more ploughing action, and yet little or none to be seen, than at Buarbræ, which is advancing rapidly against a high lateral moraine. There is a large ridge (Fig. 6) of stone upon a thin snout of the glacier, just as if the ice were pushing under the boulders of earth. The glacier has a steep convex margin, from twenty to forty feet high, with many blocks and boulders upon it. These become detached, and, rolling down upon the lower tongues of ice, build up a ridge and leave a deep trough between it and the side of the glacier, and delay the melting of the layer of ice beneath, which is too thin to do any ploughing up of the moraine.

Fig. 7.—End of Suphellebræen advancing over a moraine.

An excellent illustration of a glacier advancing, without any ploughing action, over a moraine, and at the same time levelling it into a sort of ground moraine, was seen at Suphellebræen (Fig. 7). Here the glacier was moving up the slight elevation of a moraine produced by the early summer retreat of the glacier, although again advancing in July. The lower surfaces of the ice-tongue were furrowed by the loose stones of the soft incoherent water-soaked moraine, into which one's foot would sink when stepping upon it. The moraine was being levelled by the constant dripping of the water from the whole under-surface of the advancing glacier.

The glacier of Suphelle is the most remarkable of its kind, being a gigantic *glacier rémanié*. From the Jostedalsfond, which, near the head of the valley of Fjærland fjord, is 3,000 to 4,000 feet high, the clear, bluish ice falls over a precipice of dark rocks for about 1,000 feet, and at about 1,500 or 2,000 feet above the sea begins to re-form into a glacier extending down into and nearly across the valley of Fjærland for a distance of somewhat less than a mile, to a level of only 175 feet above the sea. The glacier is much crevassed, and covered and filled with debris. In fact, it was the most dirt-laden glacier seen—not excepting the Aar glacier in the Alps. This material is wholly derived from the side of the mountain, and is brought down by frosts, and more largely by the fall of ice as it dashes from one frost-cracked rock to another. One of these great ice-avalanches I witnessed from the other side of the valley, fully a mile distant. Thousands of tons must have fallen at this time, but as the ice fell from rock to rock, it was converted into what, seen at the distance, appeared to be white dust. There are no considerable streams from the upper glacier, but from the rapidly melting glacier below the fall the volume of water laden with mud is large. As this glacier is not ploughing up, but levelling down the inequalities of its bed of loose material, we cannot suppose that the mud comes from any other than the dirt upon and within the ice, and that obtained by the dripping water as it levels the terminal moraine. This is only one of the examples everywhere to be seen showing the erroneous estimate of glacier-erosion, when based upon the amount of mud carried down by the streams flowing from the glaciers; for the debris is brought upon their surfaces by other than grinding action, and, as far as observation goes, it is not derived from beneath them, at least, to any great extent.

Although I have seen some of the sharp angles of the rocks at 2,000 feet above the fjords along the sides of the valleys, somewhat rounded and scratched, yet the inequalities of the faces have not been removed by erosion of any kind. At numerous places in Norway, as well as in other countries, hummocks of rock rise above or out of the glaciers, as the ice flows around them at lower levels, these channels having been deepened, not by glaciers, but by subglacial streams.

Nowhere are the *roches moutonnées* so abundant as on the coast of Norway. In their more perfect form, they are not extensively developed along the coast at more than 250 feet above the sea. A higher altitudes they are best seen about glacier-falls, farther up the valleys. But during the Pleistocene days, the coast has been raised several hundred feet, at least. The form of the hummocks is precisely like what may be seen in southeastern Missouri and other States south of the line of northern drift, or are described as occurring in Ceylon, Brazil and other tropical countries, to which only are added the scratches. The forms of these hummocks must be principally attributed to the atmospheric erosion of the crystalline rocks where the debris has been swept away by currents or by ice. We see them more frequently swept clean upon the coasts of either cold or warm countries than in the interior, where the currents are only those from rain or local glaciers, for even the sweeping beneath the glaciers is principally effected by dripping waters or streams. Professor Kjerulf, of the University of Christiania, than whom there is no better authority, regards the production of hummocks and their glaciation up to a height of 600 feet upon the coast of Norway, as the result of floating ice.[1]

The absence of transported boulders and striations upon the surface of many parts of the high plateaus of Norway is doubtless, in part, attributable to the ability of ice to flow around loose obstacles, and the frequent want of higher ridges to furnish material by their debris falling upon the ice to work through the mass afterwards.

The faith in glaciers, as great erosive agents, has been so severely shaken that few geologists, who personally study those still existing, now attribute to them greater power than that of removing soft materials, and of this power many others are sceptical, *e.g.*, Professor Penck,[2] of the University of Vienna, who has been misquoted as having proved their great efficiency in eroding basins in hard rocks. To this scepticism, it seems to me that these notes must contribute; especially when glacial erosion is applied to the hypothetical excavation or modification of great lake-basins, and the transportation of the northern materials in the boulder clay ove the broad plains of America, as there were no mountains of adequate height with peaks, or *séracs*, to supply the detritus sufficient to furnish the tops of the glaciers with all the boreal material of the drift, which "covers half a continent."

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[1] Discourse before Meeting of Scandinavian Naturalists, Copenhagen, 1873.

[2] Geological Magazine, April, 1883.

In connection with this paper, the observations of Herr Payer and other arctic explorers are important. The snow-line of Franz Joseph Land descends to within a thousand feet of the sea, and the numerous glaciers discharge great quantities of icebergs as they move down into the ocean. Payer says: "However diligently I look for them, I never saw unmistakable traces of grinding and polishing of rocks by glacier-action."[1]

Lieutenant Lockwood[2] found in central Grinnell Land a thick ice-cap, extending for a distance of from seventy to ninety miles, faced by an ice-wall of from 125 to 200 feet high, irrespective of topographical inequalities. It was free from rock debris, except in a valley confined by mountain-walls thousands of feet high. Along its foot there was almost an absence of morainic deposits, and even where present these were unimportant ridges. The general absence of rock and dirt in the arctic glaciers is a common subject of remark. The snow line in the high latitude of central Grinnell Land is 3,800 feet above the sea, and the glaciation of the rock about the adjacent Lake Hazen (500 feet above tide) is not recent.

In Spitzbergen, where the snow-line is much higher, striated rocks, according to Nordenksjold, occur only below 1,000 feet.[3] The same holds true for Labrador, where the scratches are confined to the lower thousand feet, although the mountains rise to 6,000 (Bell).[4]

In the Antarctic regions, the officers of the "Challenger" remarked the absence of detritus in the icebergs and southern ice, although Wilkes and Ross saw rocks upon a few bergs. These last are supposed to have come from valleys in the volcanic mountains.

Indeed, outside of valleys, explorers in high latitudes have not found, in the margins of such ice-caps visited, the tools capable of great erosion. The continental area of North America presents very much lower and less abrupt prominences than the reliefs of Greenland, Grinnell Land, Spitzbergen or Franz Joseph Land. Overhanging mountains seem to be necessary to supply glaciers with tools by which alone any abrasions can be accomplished, and

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[1] New Lands within the Arctic Circle, 1872–74.

[2] Three Years of Arctic Service, 1881–4, Greely.

[3] See Geological Magazine, 1876.

[4] Dr. Robert Bell, in Hudson's Bay Expedition of 1884.

these conditions belong only to valleys of great mountain ranges. However, there is one condition under which glaciers, when shod with graving tools, ought to be great eroders, viz., when their motion is much more rapid than the flow of land ice,—which si almost invariably less than three feet a day, under which condition, included stones commonly adhere by friction to the subjacent rocks, and cause the lower surfaces of the ice to be grooved. This condition of extraordinarily rapid movement has been seen at Jacobshavn glacier in Greenland, where Professor Helland[1] found a velocity of from forty to sixty feet a day. In Alaska, Lieutenant Schwatka[2] and Professor G. F. Wright[3] observed glacier movements of from forty to seventy feet a day. In these cases the glaciers are moving into the sea, and the new element of partial flotation or sliding, which does not belong to land glaciers, is here introduced. The great velocity of these glaciers is far beyond any observed ability of ice to flow as plastic bodies; consequently, one is led to conclude that, under partial flotation, stones may be held firmly as graving tools by glaciers.

Hereby we are able to explain the occurrence, in many Alpine valleys, of a greater glaciation than we see in progress to-day, as being due to glaciers rapidly advancing into fjords, during a period of partial submergence.

The appeal to the greater magnitude of the glaciers, as producing effects not now seen as the result of those of the present day, seems to be begging the question, for the action of thicker glaciers differs from that of thinner in amount rather than in kind; for increased pressure, raising the temperature, increases the plasticity of the ice, as it is seldom if ever lower than freezing point. Consequently it seems improbable that stones should be held more firmly in glaciers of thousands of feet in thickness than in those of hundreds of feet. In addition, the friction between the stones held in the ice, and the surface of the subjacent rock, is proportionally increased by the greater weight of the glacier.

Over the vast area of action, the work of floating or sea-ice, in some forms, is enormous. On the northern side of Hudson Strait

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[1] Ice-fjords of North Greenland, Quart. Jour. Geo. Soc., 1877, A. Helland.

[2] "Times" Alaska Expedition, New York, 1886, Schwatka.

[3] The Muir Glacier, Am. Jour. of Sci., 1887.

Dr. John Rae,[1] who had very extensive arctic experiences, found that snow drifting over precipices into the sea resulted in the formation of bergs, sometimes a hundred feet thick, filled with the loose rock debris of the coast, and having the form of the shore where formed. Most of them break loose and drift away to melt or become stranded elsewhere.

Greely describes the great momentum with which the floe-bergs come together. By their meeting the ice is crushed, and raised up into ridges fifty or sixty feet high.

One cannot read carefully the results of the British Arctic Expedition of 1875–6 without being impressed with the erosive power of drifting ice, moving with a velocity never acquired by glaciers. Floe-bergs are pushed upon a shelving sea-bottom, until the ice has risen from twenty to sixty feet, after their first stranding in perhaps only from eight to twelve fathoms of water, although weighing tens of thousands of tons.[2]

As the grounded floe-bergs are forced up the shelving sea-bottoms, ridges of earth and stones are pushed up in front of them. Floe-bergs which have been toppled over, thus showing their original bottoms, and also masses of pushed-up coast ice are found to be grooved and to contain angular stones with their exposed surfaces scratched and polished. As the movement is greater than the velocity of glaciers flowing about obstacles, it is only natural to expect that the enclosed stones should be held firmly as graving tools, or be wrenched out owing to the brittleness of the ice under such great stress.

In describing the ice action on the coast of Labrador, Professor H. Y. Hind says the "pan-ice" (from five to twelve feet thick) is polishing the surfaces and sides of the rocky coast, and producing boulder clay. He says: "When the pans are pressed on the coast by winds, they accommodate themselves to all the sinuosities of the shore line, and being pushed by the unfailing arctic current, which brings down a constant supply of floe ice, the pans rise over all the low lying parts of the Islands, grinding and polishing exposed shores, and rasping those that are steep-to. The pans are shoved over the flat surfaces of the Islands, and remove with irresistible force every obstacle which opposes their thrust, for the

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[1] In Canadian Journal, Toronto, 1859.

[2] British Arctic Expedition of 1875–76, Sir George Nares.

attacks are constantly renewed by the ceaseless ice stream from the northwest, and this goes on uninterruptedly for a month or more."[1] Similar results elsewhere have been frequently recorded, as those of Professor Milne in Newfoundland.[2]

While the power of glaciers, under favorable conditions, to abrade and scratch rock surfaces, as "sand-paper" scratches "a cabinet," is not questioned; yet these observations, in Norway and elsewhere in high latitudes, all confirm the correctness of the verdict given by many geologists—especially in Europe—who have had the opportunity of personally studying living glaciers, that the potency of land-glaciers to act as great eroding agents, capable of "planing down half a continent," or ploughing out great valleys, or lake-basins, or even of greatly modifying them, is not only not proved, but most strongly negatived. Even the power of glaciers to abrade is reduced in many cases almost to zero.

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[1] Notes on Some Geological Features of the Northeastern Coast of Labrador, Can. Nat. 1878.

[2] Ice and Ice Action, Newfoundland, Geol. Mag., 1876.

ON THE THEORY OF GLACIAL MOTION.

As the foregoing paper contains some observations bearing upon the character of glacial motion, the correlation of these observations and a short consideration of the latter subject forms an appropriate supplement to it.

As glaciers disport themselves like rivers, in that they are constantly flowing, with greater velocity at their centre than their margins, above than below; as they form pools and rapids, and conform themselves to channels, Prof. Forbes was led to propose the theory that: "A glacier is an imperfect fluid or viscous body which is urged down slopes of a certain inclination by mutual pressure of its parts."[1] He explained the veined structure of glaciers as being due to the differential movement of its parts.

Against this view, it was urged that ice is a brittle solid, which in the laboratory cannot be moulded as a semi-fluid, or even in nature, when in passing over a change of declivity of even 4½° it becomes ruptured. Consequently, Prof. Tyndall applied Faraday's "Law of Regelation,"[2] that ice when broken and moistened, reunited and could be moulded into any form by repeated crushing and pressure, and proposed the "Fracture and Regelation theory." He explained the veined structure of glaciers as being analogous to the slaty cleavage of certain rocks—the result of transverse pressure.

Canon Moseley[3] calculated that the resistance of ice to descent is thirty-four times gravitation, and, therefore, fracture and gravitation could not be maintained. He likened the motion to the creeping of a leaden roof, owing to the expansion and contraction from change of temperature, which expansion Dr. Croll[4] modified in assuming the transmission of heat from molecule to molecule with successive liquefaction and solidification of the glacial waters.

Malleability, plasticity and viscosity are different degrees of the same property. Prof. Heim[5] distinguishes between these last two semi-fluid forms. In plastic bodies, the internal cohesion is less than internal resistance, and, therefore, under pressure these will flow, but under tension they are not drawn out, but are brittle. In viscous bodies, the internal cohesion is greater than internal resistance, and, therefore, they will not only flow under pressure, but in tension they are drawn out before rupture. He concludes that glaciers are plastic bodies, and explains the veined structure as being due to partial liquefaction under compression in passing through narrow channels, as it had been discovered that ice can be melted by pressure (Thomson). He attributes the motion to plastic flow under gravity, rupture, partial regelation, and a sliding motion (which is slight).

From observations in the Alps, and especially in Norway, my conclusions are that the motion, in the main, is the result of gravity on a semi-fluid body, wherein there is viscosity as well as plasticity,

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[1] **Travels in the Alps, 1843.**

[2] **Forms of Water.**

[3] **Proc. Royal Society, 1869.**

[4] **Climate and Time.**

[5] **Handbuch der Gletscherkunde von Dr. Albert Heim, Stuttgart, 1885**

as defined by Prof. Heim; the motion, of course, being greatly modified by heat. My conclusions are based upon:—(1) The flow of the glacier, not merely in conformity to the channel, but about loose stones, which cause the lower surfaces of the glacier to be grooved (see fig. 1 of "Glacial Erosion, in Norway," etc.) without any lateral ridges being produced from the ice that filled what are now its channels, such being moulded into the mass (this is *plasticity*). (2) A tongue of ice (see fig. 3) pushing against a boulder, was bent back without rupture on either side of the hanging plate—the ice on one side being in tension and on the other in compression (here is *viscosity*). (3) A large rounded boulder (see fig. 2), held in the side of a moving glacier, where the rounded ice-wall rose about thirty feet above the stone, which was being rolled along as the ice moulded around it, had just been crushed. The glacier rose along its winding course to the snow fields, 1,500 to 2,000 feet above the stone. Consequently the crushing weight upon the granitoid boulder must have been derived from the vertical component of the momentum of descent of the whole mass, which could be transmitted thus only through a semi-fluid body. (4) The flow of the upper layers of ice over the lower was seen when the glacier was impeded by a barrier (see fig. 4).

The experiments of Herr Pfaff[1] prove that a solid body can be pressed into ice at a temperature about freezing point as rapidly as glaciers ordinarily move; while at a temperature a little above, the motion is greatly accelerated, but if below 0° C, the plasticity of the ice diminishes rapidly to almost zero. However, as shewn by the subglacial streams in winter, the temperature of the inferior surface of a glacier is not below freezing-point.

The effects of increased summer sunlight, as well as direct heat, as proved by the experiments of Rev. A. Irving,[2] in which he transmitted both sunlight and heat waves through ice, is to accelerate the movement as the former is converted into heat undulations, and radiated against the lower part of the glacier from the adjacent rocks, thus increasing the fluidity of the ice and flow of the glacier, owing to increase of temperature.

The temperature of the lower surface of the glacier is also increased by the radiation of the internal heat of the earth; yet this is slight, as the amount radiated per annum is only enough to melt a layer of ice, 6.5 millimetres in thickness.[3]

Although glaciers do not conform to all the inequalities of their beds, and at the ice-falls and elsewhere become fractured, and subsequently reunited, whether by heat regelation or plastic flow, the fluidity theory is the most acceptable explanation of the motion of glaciers, especially when the angle of descent is reduced almost to zero, and modern observations only supplement the good reasons upon which Prof. Forbes proposed his theory more than forty years ago.

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[1] Nature, Aug. 19th, 1875.

[2] Quart. Jour. Geo. Soc., Feb., 1883.

[3] Élie de Beaumont, Thomson, Woodward and others give the range as from five to eight millimetres.

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