On Grooved and Striated Rocks in the Middle Region of Scotland. By CHARLES MACLAREN, Esq., F.R.S.E., &c. (With a Map.) Communicated by the Author.*

Sir James Hall first called attention to the polished and striated rocks in the valley of the Forth, in a remarkable paper, read before this Society in 1812, and printed in the seventh volume of our Transactions. He specifies four localities where he observed them: At Torwood, about 4 miles north-west from Falkirk; at Corstorphine Hill; at Fenton Tower, in East Lothian; and at Fass Castle, in Berwickshire. With the striated rocks at these places he associated a peculiarity of form, which is conspicuous in nearly all the low hills of the same district, namely, that they present crags of bare rock on their west, and deposits of soil on their east sides. To this peculiarity he gave the descriptive name of "Crag-and-Tail." The direction of the striæ was nearly east and west at Corstorphine Hill, WNW. and ESE. at Torwood, Fenton Tower, and Fass Castle. He found examples of crag-and-tail also in the west and south of Scotland, but with different bearings. In the former, the crag faced the east; in the latter, it faced the north. After careful consideration of the facts, aided by collateral lights derived from other natural phenomena, he concluded that the striæ and grooves, and the smoothing of the surface, to which he gave the name of *dressing*, must have been produced by fragments of rock, gravel, and sand, driven over the land by a great wave, or succession of waves, rushing from the Atlantic in an east or south-east direction; that one part of the wave passed right across Scotland, grooving the rocks in its course, laying bare the western fronts of the hills over which it swept, and depositing tails of soil in the sheltered spaces behind them; that another portion of the wave was arrested by the high mountains, and turned back, flowing off to the

* Read before the Royal Society of Edinburgh on 2d April 1849.

sea, westward or southward, producing groovings on the rocks, and the phenomena of crag-and-tail, in directions corresponding to the course of the return waves.

This theory bears the stamp of the acute and original mind of its author, and it offered perhaps the best explanation of the phenomena, which the range of geological information at that time could supply. In the same year we find specimens of striated rocks and crag-and-tail noticed by Colonel Imrie, in his paper on the Campsie Hills, in the second volume of the Wernerian Society's Transactions, and an idea somewhat similar as to their origin thrown out. Sir James Hall's explanation of the phenomena was pretty generally accepted by geologists in this country; and it is still, I believe, adopted, though perhaps in a modified form, by some able men. I shall notice very briefly a few of the leading objections to it.

1*st*, Striæ must have been produced by a sliding motion, like that of a plane or graving tool, while stones propelled over a firm surface, by a current of water, would have a rolling motion, which might polish the rocks, but could not cut groves in them. 2*d*, Supposing stones impelled by water to cut grooves, these grooves would not occupy such positions as we find them in, on sloping surfaces like the steep sides of valleys; the force of gravity would render them more or less inclined, while, in such situations, we find them horizontal. 3*d*, The groovings so cut would be deflected to the right or left, by slight inequalities of surface, and would not possess that wonderful straightness and parallelism which they generally exhibit, and which Mr Lyell has seen extending over a length of 100 yards in the United States. 4*th*, *A* great wave or debacle of the magnitude assumed, coming from the west or north-west, would have filled up deep valleys transverse to its course, like that called the Great Glen. Now, that glen, so far from being filled up, has a depth of 770 feet in Loch Ness, measured from the surface of the water,—a depth exceeding that of the German Ocean. The fact, that this deep fissure has not been filled up, is presumptive evidence, that no such wave has ever passed over the

island. *5th*, The cause assigned does not explain how boulders weighing many tons were carried from the Grampians across the central valley of Scotland, the bottom of which is only 200 feet above the sea, and deposited on the Pentlands, at spots 800 feet higher. A current of water, however powerful, would have dropt them in the low country. *6th*, The debacle does not explain other distinct traces of the action of water upon our hills. Mr Chambers, in his recent work, has shewn that satisfactory evidence exists of the presence of the ocean in its proper form of a horizontal sheet of water, up to 1500 feet above its present level. Had this fact been known, and carefully studied, Sir James Hall would have been spared the necessity of resorting to a great hypothetical Atlantic wave.

No agent yet known but ice, or ice conjunctly with water, seems capable of explaining the phenomena for which Sir James Hall called in the aid of a *debacle*. Those who have read the excellent works of Professor Forbes and Professor Agassiz, are aware that a glacier, during its slow progressive motion, transports vast masses of rock over a distance of many miles; secondly, that it grooves and polishes the bottom and sides of the valley containing it, by means of the stones and gravel which it brings down; and, thirdly, that many of these stones are themselves grooved by the attrition they have undergone in sliding over the fixed rocks. We know also, that as floating ice lifts large stones from the bottom and sides of rivers, or the shores of the sea, and carries them away, it may leave striæ on rocks over which it passes. Mr Lyell found well-marked striæ cut on a rock in the Bay of Fundy, which he attributed, on good grounds, to the packed ice of the preceding season, or of a period very little farther back. The pack ice accumulates there to the depth of fifteen feet.* If this was effected on the shore by so small a mass, it is easy to conceive that our plains might be grooved and abraded by icebergs, armed at bottom with stones or gravel, and floating in a sea 500 or 1000 feet deep. These

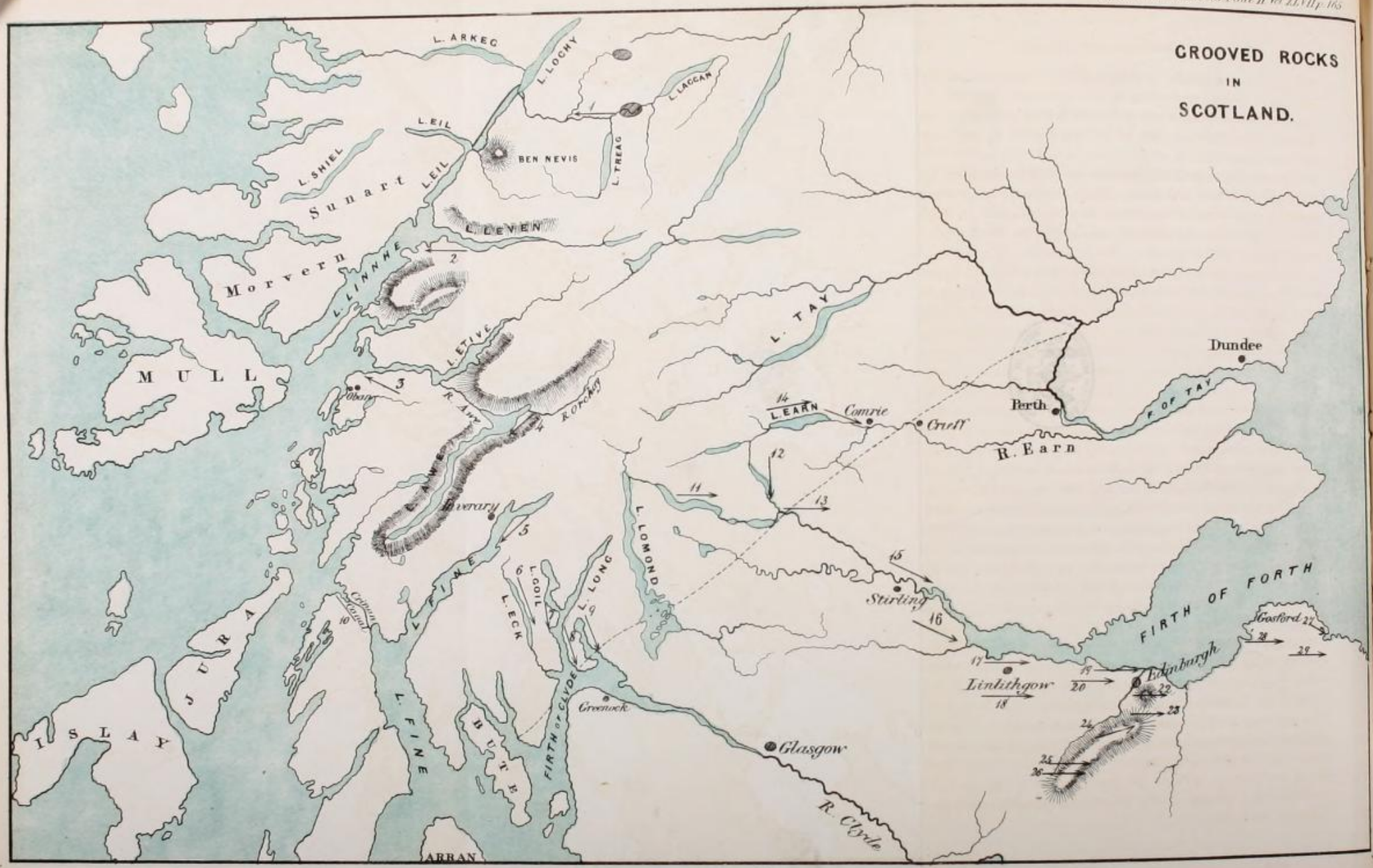
* Travels in North America, 1845, vol. ii., p. 173.

moving mountains of ice are known to have reached to a greater depth than this.

If the grooves, scratches, and polishing, seen on our rocks, were produced by ice, those in the deep valleys must be due to the action of glaciers, which are found in the Alps to glide downward at the rate of one or two feet per day, with gravel, stones, and sand adhering to their bottom. In this case the largest grooves should be on that side of prominent rocks which is toward the head of the valley, and this, it will be seen, holds true in Scotland. On the other hand, if the scratches, grooves, and polishing, were caused by an irruption of the ocean from the west, it is evident that the direct wave setting eastward would be vastly more powerful than the indirect or return wave, produced by the supposed recoil of the water from the hills, and setting westward. It follows, that in the west of Scotland, where the effect of both waves must be best seen, the grooving and abrasion should be greatest on the west side, and least on the east side, of exposed rocks. It will be found that the case is just the reverse.

Glaciers are rivers of ice, which have their source at a higher level in the mountains, in what the Swiss call *Mers de Glace*, or "Seas of Ice." To account for glaciers in the valleys shortly to be noticed, we must suppose that Scotland, at some former period, had a climate as cold as Labrador or Greenland, and that a permanent envelope of ice and snow covered all the higher region of the Grampians. There is nothing extravagant in the magnitude assigned to this envelope, for Agassiz informs us, that among the numerous mers de glace in the Alps, there are some 20 or 30 leagues* (50 or 75 miles) square. Glaciers or efflux streams of ice from this central mass would glide slowly downward through the openings at the outskirts of the mountains, such as the valleys of Loch Fine, Loch Long, Loch Etive, Loch Earn, and others; and if the hypothesis be correct, the sides and

* Agassiz *Etudes Sur les Glaciers*, p. 22.


GROOVED ROCKS
IN
SCOTLAND.
L. ARKEG
L. LOCHY
L. LAGGAN
L. EIL
L. SHIEL
BEN NEVIS
L. TREAG
Suart Leil
L. LEVEN
Morvern
L. LINNHE
L. ETIVE
MULL
Oban
R. AWE
ROPACH
L. AWE
Inverary
L. TAY
Dundee
Perth
FIRTH OF TAY
L. EARN
Comrie
Crieff
R. Earn
L. LOMOND
Stirling
FIRTH OF FORTH
Gosford
Edinburgh
Linlithgow
L. FINE
L. GOIL
L. ECH
L. LONG
Crinan Canal
Greenock
Glasgow
FIRTH of CLYDE
R. Clyde
BUTE
ARRAN
JURA
ISLAY
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bottom of these valleys should be grooved and abraded, and the marks of abrasion and grooving should be most conspicuous on that side of prominent rocks facing the head of the valley. We shall see how far this conclusion is confirmed by facts.

I begin with Gareloch, because the markings there are peculiarly distinct; and I was able to examine them more carefully than those of any other locality. It will be sufficient here to give a condensed outline of the two papers I published in 1845.

Gareloch.—The arrows 8 and 9, in the map (Plate II.), indicate the direction of the striæ and groovings here. They all point SSE., corresponding very correctly with the axis of the loch. They are very numerous, and while some of them are fine scratches only visible when the surface is wetted, others are grooves several inches, or even feet, in breadth. There is one face of rock 8 feet high and 2 feet broad, in a position not far from vertical, which is entirely covered with groovings, generally about an inch broad, and nearly horizontal. The markings are found several feet *under the high-water line*, and, though most abundant in low positions, some may be traced at a height of 300 feet above the sea, and three grooves were seen at an elevation of 600 feet, on the top of the ridge which divides Gareloch from Loch Long, and quite conformable in their bearing with those below. The grooves are cut on the edges of the laminæ of the mica-slate; and all those portions of the surface which are not striated are smoothed as if by abrasion. There are many dome-shaped prominent rocks; and the sides of these which face the head of the valley, are more abraded than those which look in the opposite direction, shewing that the abrading and grooving agent (*agent sulcateur* of the French geologists) moved from the NNW. to the SSE. Masses of rocks weighing many tons have also been moved in this direction. Stones with striated surfaces are found on the beach; and on the east side of the valley, at a height of 500 feet, fragments of what seems to be a lateral moraine are visible. In short, marks of the ancient existence of a glacier in the valley are numerous and remarkably complete.

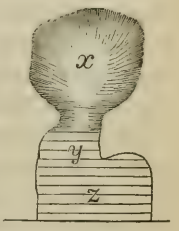
Loch Long—Arrows 7 and 8.—I found grooves on the beach, on the east side, at a hamlet called Letter, though the coarse texture of the slate here is ill fitted to retain them. They run parallel to the line of the loch. A friend of mine saw others on the west side, a mile or two north of Holy Loch. But the most conspicuous and characteristic are on a vertical surface of rock on the west side, immediately below the junction of Loch Goil with Loch Long They are horizontal, from one to two inches broad, and cover some square yards. When the rock is wet they are seen from the deck of the Loch Goil steamer at the distance of 50 feet. Large grooves of this kind, on a vertical surface (and the examples are not rare), as they could only be produced by an immense *lateral* pressure, acting at right angles to the force of gravity, seem to me of themselves conclusive against the hypothesis which ascribes their production to currents of water charged with stones and gravel.

The local position of these well-marked grooves seems to illustrate an opinion lately put forth by Agassiz, Desor, and Charles Martins. They say it is necessary to the formation of a glacier that a cavity (*cirque*, *amphitheatre*) much wider than itself should exist above it on the mountain, to serve as a reservoir for the collection of the ice and snow which feed it.* Now, Loch Goil meets Loch Long at an angle of about 40°, forming with it a figure resembling the letter Y. When ice and snow filled both valleys to the depth of 1200 feet, the comparatively low hill in the bifurcation, called Argyle's Bowling-Green, would be nearly covered, and the upper portion of the valley would form a reservoir or mer de glace six or seven miles wide, such as Agassiz describes. But taking them in their present state, each of the lochs, before they join, is as broad as the united loch after the junction; and if they were filled with ice moving slowly southwards, that ice would be powerfully compressed when the united mass was forced into a channel only half as broad as the two channels

* Paper by Charles Martins, Edinburgh New Philosophical Journal, No. lxxxv., p. 54.

it had previously occupied, and would exert an immense lateral pressure on the walls of the valley confining it. Hence it is in situations like this that deep groovings, and especially on vertical surfaces, should be looked for.

Something of the same kind is seen at Gareloch, which has a form resembling the figure annexed. Striæ and grooves abound in the circular valley *x*, where the ice must have collected; those in the bottom are few and large; those on the sides numerous, but generally small. At *y*, where the valley is contracted to a gorge half a mile in breadth, the bottom, being covered with salt water, can no longer be seen; but great numbers of striæ are found on the sides, and of various sizes, up to 6 or 8 inches in breadth. At *z*, where the loch widens out to a mile in breadth, and where the lateral pressure would, of course, be greatly relaxed, the striæ disappear, and are no more seen till we come to Row, five miles southward, where the breadth of the loch is again contracted by the point of land at Roseneath. At this place a few are visible (one 16 inches broad) scooped out across the laminæ of the clay-slate, which here succeeds to the mica and chlorite slate.



The cavity *x* would serve as a reservoir for the ice, or *mer de glace*, when the glacier occupying the valley was small; but the grooves found on the top of the ridge dividing Gareloch from Loch Long (on a surface wonderfully smoothed and levelled) point to glacial phenomena on a grander scale. They can only be accounted for, in my opinion, by assuming that one vast mass of ice filled Gareloch and Loch Long, covering the ridge which divides them, and that the whole moved simultaneously in a SSE. direction, constituting a glacier four miles broad, and probably 1000 feet in depth.*

The smooth sides, and even or gently-undulating outlines of the hills between Gareloch and Loch Lomond, which contrast so remarkably with the rough surface and serrated

* See my paper in Edinburgh New Philosophical Journal, No. lxxxiii., p. 35.

ridges of the mountains northward, led me, at first, to think that the protuberances and salient points of the former had been ground off by icebergs. I had then no data in my possession, authorising me to conclude that glaciers ever attained the depth of 2400 feet, necessary to cover the ridge on the west side of Loch Lomond; but the objection on this ground is now removed. The able French geologist named (M. Martins), has found traces of an ancient glacier on the Alps, 758 metres (2468 English feet) above the bottom of the valley which contained it. There is no difficulty now, therefore, in admitting, that a glacier might abrade the surfaces of the highest of these ridges.

Loch Eck—Arrow 6.—The rocks on the two sides of this loch are smoothed and rounded off in a manner so conspicuous, that it cannot fail to strike the most careless observer. In a hasty journey through it, I saw no striæ; but the coarse surface of the slate is ill fitted to shew them. Dome-shaped rocks, however, with one side rough, clearly shew that the abrading agent moved in the same direction as at Gareloch,—namely, SSE.

Loch Fine—Arrow 5.—I found some distinct groovings on the beach at St Catherines, opposite Inverary. Their bearing was conformable to that of the loch, or about SSW. It is worth remarking that there is a bifurcation here, caused by the meeting of two valleys, in the form of Y, like that which occurs at the junction of Loch Long and Loch Goil.

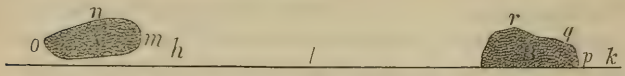
Loch Awe—Arrow 4.—Smoothed rocks of gneiss are numerous at the foot of the hill of Stobacherachrun, on the north side of the loch, and many of the islets in it seem to be low, abraded domes. On the south side of the loch, about a mile west from Dalmally Inn, there are two little hills on the right and left sides of the road, which exhibit the crag-and-tail form, on a small scale, in a position the reverse of that we are accustomed to. The east side of each is laid bare and smoothed, while a mass of stones and soil covers the west side. On the face of the hill lying on the left or south side of the road, I found a few grooves, which pointed ENE. and WSW. Taken in connection with the crag-and-tail, they indicate that the abrasion and grooving were

produced by agents coming from WSW., where the deep glen, the Orchay, is situate, which may once have been the seat of a glacier. I found traces of broad grooves also on two small hills which rise abruptly from the valley, about a mile south from the inn.

Loch Etive—Arrow 3.—I examined only a small portion of the southern shore of this loch, extending about a mile and a half westward from Connel Ferry. The coast here is formed of basaltic clinkstone, which pushes out a series of salient points, sloping gently to the sea, and each resembling a segment of a *discus*. They are finely rounded and polished, though the rock is divided into thousands of polygons a few inches broad, by fissures, in which fuci have their roots. I found striæ on several of these points, in the space between high and low water, where the smaller fuci grow. They were narrow, about the breadth of straws, but were rendered quite distinct by washing the surface. They were all on that face of each *discus* which sloped eastward or south-eastward, and which was generally more abraded than the face which sloped north-westward. Their bearing surprised me. It was not conformable to the line of the shore—that is, east and west, but ESE. and WNW., as if produced by agents coming from Loch Awe, which is ten miles distant, and divided from Loch Etive here by hills from 300 to 500 feet high. Professor Forbes has shewn, that glacier-ice has a considerable degree of plasticity; and Agassiz infers, from the occasionally-oblique position of the striæ, that it mounts over obstructing masses of rock. Shall we, then, assume, that the basin of Loch Awe was filled with it to the height of 1000 feet, and that a portion of it might find its way over the broad hilly barrier in this direction? The facts yet observed are inadequate to support such a conclusion; but I give them as they presented themselves.

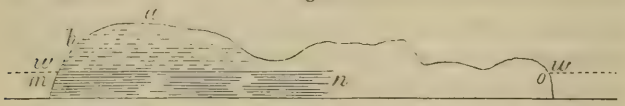
Loch Leven—Arrow 2.—About a mile westward of Balahulish Ferry are two small outliers of the granite mountain, which skirts the shore there. They are about 80 feet long, and rise about 6 feet above the high water level. The eastern has the sea on three sides, the western is an island at high water.

Fig. 1.



h l k is the line of the shore, which runs east and west; A the western rock, B the eastern. A portion of the surface of both rocks is grooved, and the position of the grooved surfaces is highly instructive. The north-eastern face of B, from *q* to *r*, which is nearly vertical in its lower part, and rounded off above, is almost entirely covered with grooves, which are horizontal, straight, and parallel, generally about one inch broad, and so uniform and close together, as to remind one of the flutings of a Doric column. They cease at *r*, precisely at the point where the rock begins to face the north-west; and the north-west, as well as the west face, is entirely ungrooved, but considerably abraded. The east face *p* is partially grooved. The islet A presents appearances precisely similar. The north face, and a portion of the east end,—that is, from *m* to *n*,—are beautifully marked with horizontal grooves, which entirely disappear on the part from *n* to *o*. The grooving agent, then, had power to cut furrows in rocks facing the ENE. and N., but no power to furrow rocks facing the WNW., or even NNW.,—so rigid and steady was its westerly motion. Could water act in this way? All the ungrooved sides of the rock are, less or more, smoothed, and the roughest part is the west end *o*. There is one distinct groove on the top of the islet 3 or 4 feet long, and $1\frac{1}{2}$ inch broad, pointing exactly east and west.

Fig. 2.



The above is a view of the north face of the islet, drawn shortly after the visit, from memory, and not pretending to literal accuracy; *m n* the grooved part, *n o* the ungrooved part. It is a curious fact, that *the most distinct grooves are in the space between high and low water*. Above the high water line *w w* they become fainter and fainter, till they disappear. This

holds true of both A and B. It seems strange that the action of the tide, which might be expected to obliterate the grooves, should be the means of preserving them. Such, however, is the fact; and perhaps it admits of explanation. The agent chiefly concerned in wasting the surface of the granite above the water, appears to be a sort of grey fog (a cryptogram, I suppose), everywhere visible, which takes root upon it, and, falling off, and being renewed periodically, carries minute grains of the rock with it, and thus gradually wears down the surface, and obliterates all fine markings upon it. The part beneath the high water line is protected from this vegetation by the tide, and still more, by a sort of black pigment which the sea deposits upon the rock. To the eye, it has exactly the aspect of a coat of paint, and is probably about the 100th part of an inch thick. When examined with a lens, it is seen to be divided by innumerable cracks into polygonal facets, from a 40th to a 200th part of an inch in breadth. This coating is probably permanent, or at least very durable; and it covers most of the large groovings which are under the high water level, apparently without rendering them less conspicuous. I found it also on the basaltic clinkstone at Loch Etive (arrow 3); but there it seemed to be confined to the parts of the rock near the high water line, and probably to those daily wetted by the spray. It was thick enough to conceal the fine striæ, which were visible at a greater depth.

These two granitic masses seem to me to present a crucial test for Sir James Hall's theory, and entirely to disprove his fundamental proposition. From the facts detailed, two conclusions inevitably result: First, that the agent which produced the grooves moved from east to west; secondly, that no agent capable of producing groovings, and acting contemporaneously, moved in the opposite direction, or from west to east. We have here the advantage so seldom obtainable, of proving a negative. Sir James Hall, according to his theory, would have said that the grooves on the east ends of A and B were produced by the recoil wave, thrown back by the mountains; but if the recoil or secondary wave, forming but a fraction of the great *debacle*, had sufficient power to do this, the direct and primary wave which immediately preceded it,

consisting of the whole mass of water, and moving here freely over an open bay 5 miles wide, would have had much more. The west ends of A and B, then, should have been much more deeply grooved than the east; while, in point of fact, the former are not grooved at all. It is plain, therefore, that the hypothetical wave had no existence.

On a flat surface of the rock, at *l* in front of the granite quarry, striæ and grooves running E. and W., and beautifully distinct, cover several square yards. The north front of the granite hill presents abundant marks of abrasion, but I saw no grooves, though, doubtless, they once existed there.

On the edges of the clay-slate, which is quarried for roofing, 2 miles east of the ferry, there are large conspicuous grooves running horizontally at an elevation of probably 40 feet above the sea. Some of them seemed to be 5 or 6 inches broad.

Glen Spean—Arrow 1.—From the Catholic chapel, a short distance eastward of Glen Roy, to the granite hill towards Loch Laggan (represented by an oval, shaded space, on the map) a line of 4 miles, abraded rocks are very numerous: striæ were not common, but they were found at four or five places. They were horizontal, and on vertical or inclined surfaces. That the motion of the body which produced them was from east to west, might be inferred from the abrasion being greatest on the eastern sides of the rocks; but a more direct proof was afforded by the distribution of the granite boulders. These are scattered in thousands over the surface of the mica-slate for a mile westward of the granite hill, and of all sizes, up to blocks weighing ten tons. Smaller masses are found as far west as the bridge of Roy, and beyond it. Granite blocks are also met with on the terraces of the parallel roads. I counted twelve on two miles of the lower and second terraces, varying in bulk from half a cubic yard to two cubic yards. As they had lost their angles by weathering, specimens were not easily procured, but I was able to satisfy myself that some of them were identical with the rock eastward, alluded to. Others may belong to the granite mass seven miles northward, at the head of the River Roy. Mr Darwin found granite blocks on the hills between

Glen Roy and Loch Lochy, at the height of 2200 feet above the sea.

Loch Earn—Two arrows 14.—At the west end of the village of Comrie there is a broad platform or shelf of clay-slate, projecting ten yards from the hill above, and of which Fig. 3

Fig. 3.

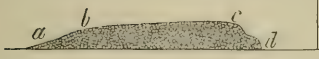


Fig. 4.

is a section lengthways. It rises 25 feet above the road, is about 200 feet long from *a* to *d*, flat on the top *b c*, truncated at the east end, *c d*, but terminating in a beautifully rounded and smoothed declivity *a b*, at the west end. This form is shewn in the section, and prevails among the adjacent rocks. The platform, *b c*, exhibits a fine specimen of grooving. The whole area is smoothed, and the grooves appear at intervals over all the flat part of it, of which they cover a considerable proportion. They are from ¼ inch to a full inch in breadth, straight as mathematical lines, and everywhere rigorously parallel. Their bearing is WNW. and ESE., or more correctly N. 60 W., and S. 60 E., and they cross the planes of the slate at an angle of 25° or 30°. One space, 10 feet by 3, is entirely grooved.

In the picturesque and beautiful district from Comrie to St Fillans, at the east end of Loch Earn, a succession of rocks occur on both sides of the road, which present smoothed and abraded faces, *e f* (Fig. 4), to the west, while the eastern side, *f g*, is rugged or uneven.

At the east end of the loch, on the south side, there is a section of the rock exposed, close to the cart-road. It is 10 feet long and 6 feet high, and is entirely covered with grooves from ¼ to 1½ inch in breadth, and nearly horizontal. The grooved area faces the NNW., crossing the axis of the loch at 15° or 20°, and is inclined to the horizon at 35°. It is about 5 or 6 yards above the level of the water. I found striæ also on the north side of the loch at two places, running

east and west. The surface was wet with rain ; in a dry day they would have escaped observation.

Loch Lubnig—Arrow 12.—Striæ were seen on the east side of the loch, close to the road, one mile from the south end. They ran north and south, were on a surface highly inclined, and would not have been visible if the rock had not been wet.

Loch Katrine—Arrow 11.—At one spot on the north side, near the east end, striæ were seen, running nearly E. and W. on a horizontal surface.

Callender—Arrow 13.—On the top of the hill, which rises like a wall behind the village, I found grooves running nearly east and west. The hill consists of beds of coarse conglomerate, mixed with beds of red sandstone, all very highly inclined. The grooves were on a portion of the edges of the sandstone, which was nearly level.

I consider the proofs of an easterly motion in the grooving agent at Loch Earn and Comrie, to be quite conclusive, and on the strength of this evidence, have assumed that the motion was easterly also at Loch Katrine and Callender, and southward at Loch Lubnig, as the arrows 11, 12, 13, indicate.

The dotted line in the map, extending from Bute to Crieff, and onward to the River Tay, shews the junction of the old red sandstone and clay-slate, and marks the eastern boundary of the mountainous country.

Horizontal groovings are seen at the west end of the Crinan Canal, on a vertical surface (No. 10), a little above the level of the water; but there is nothing to indicate in what direction the object which caused them moved.

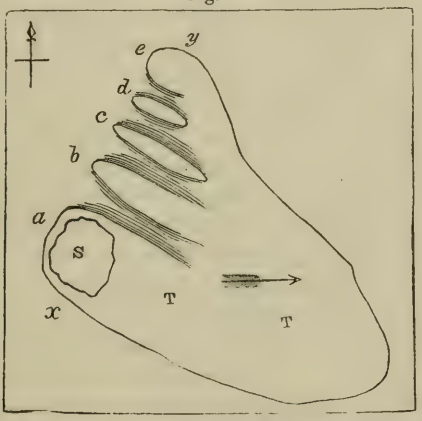
In the basin of the Forth the striæ run in lines approaching to east and west ; and the appearance of the hills, which present the phenomena of crag-and-tail, entitles us to conclude that the agents which produced the striæ moved from the west to the east. In the map an attempt has not been made, except in a few instances, to give the direction of the lines within less than one point of the exact bearing, many of the observations having been made some years ago, when a minute attention to this matter was not thought necessary. Some of them, too, are on vertical surfaces, and so placed as

to indicate that the grooving agent was deflected from its original course. In the district generally, the uniformity of direction being so great, a mere list of the localities is nearly all that is requisite.

Arrow No. 15. On the west shoulder of Demyat, three miles from Stirling, 500 feet above the sea, direction ESE.

16. At Torwood, four miles NW. from Falkirk, arrow 16, direction ESE., observed by Sir J. Hall. In this and the preceding, the bearing of the striæ corresponds with that of the upper part of the Frith of Forth, and with the remarkable furrows on the rock of Stirling Castle, of which the figure below is a rough sketch, borrowed from the "Sketch of the Geology of Fife and the Lothians."

Fig. 5.



This rock forms an isolated hill, rising 300 feet, at S, above the plain which surrounds it. The highest part is an escarpment of trap, *a*, *b*, *c*, *d*, *e*, fronting the north-west. The furrow, or rather ravine, dividing the ridge *a*, from the ridge *b*, is about 60 feet deep, and sharply cut. The others, between *b* and *c*, *c* and *d*, *d* and *e*, are from 15 to 40 feet, and they all point north-westward. The coincidence in bearing of these furrows with the striæ on Demyat, 3 miles northward, and with the others at Torwood (arrow 16) is interesting.

17. On trap, one mile south from Borrowstounness, about 150 or 200 feet above the sea.

18. On sandstone, at Hillhouse Quarry, one mile south from Linlithgow.

19. On the shore at Granton Pier, nearly one point north of east—(*Dr Fleming*).

20. On Corstorphine Hill, nearly one point north of east—(*Sir J. Hall*); also at Ravelston and Craigleith Quarry, seen by myself.

21. On the north limb of Arthur Seat, 500 feet above the sea—(*Dr Fleming*); and on the Queen's Drive, south side of the hill.

23. Westward of Craigmillar Castle, exposed in a quarry some years ago.

24, 25, 26. On Pentland Hills. Few groovings have been found on the Pentland Hills, but those known are interesting. I found well-marked striæ on the banks of Westwater (arrow 26), about a mile north from Dunsyre, at an elevation of 800 or 900 feet above the sea. The valley, which was not deep, runs south and north, and the striæ crossed it, running exactly east and west. The grooving agent, therefore, did not move downward from the summits of the Pentlands, but crossed one of their southern declivities at an angle of 45°, with the direction of the chain. That agent, therefore, could not be a glacier descending from the Pentlands. Arrow 25 marks the situation of striæ near a place called "Thomson's Wa's," and about 1400 feet above the sea. They were seen by Dr Fleming, who described them as running east and west. On a recent visit to the place, I could not discover a trace of them; owing, no doubt, to the blocks of sandstone on which they were, having been removed in quarrying. They were on or near the ridge which constitutes the watershed, and about half a mile east from East Cairn Hill, whose height is stated to be 1800 feet.

Arrow 26. Very distinct striæ have been recently exposed about half a mile west from Bonally, where a reservoir is now constructing. Mr Leslie, the engineer who planned the works, obligingly called my attention to them. They occur on the north face of Torduff Hill, about 30 or 35 feet above the bottom (the *real* bottom of rock) of the deep and narrow valley between that hill and Warklaw Hill. The face

of the rock (a felspathic claystone), dips at 40°; the striæ are horizontal, parallel, and quite straight, and extend over a surface from 1 to 3 feet in breadth (vertically), and about 25 feet in length. Their direction corresponds with that of the valley at the place, being precisely ENE. and WSW. The valley is about 300 feet in depth, and, including the upper portion, which curves round the west end of Torduff Hill, about three quarters of a mile in length. It is such a valley as might give birth to a glacier at a glacial epoch. On the top of the same hill, about 900 feet above the sea, striæ and grooves, in short lines, can be detected at intervals, pointing also very uniformly ENE. and WSW. A floating body, such as ice, coming hither from the west, would have a course perfectly unobstructed for 20 miles; for the high ground in a WSW. direction presents the aspect of a plain. Such a body, as it passed along, would graze the western front, the top, and the flanks of this hill; and accordingly we find that, like the hills in the low country, it has the crag-and-tail form, with the crag to the west. Both the head and foot of the hill exhibit proofs of abrasion and grooving, but whether by glacier ice, or floating ice, or both, is still a problem.

27. At Fenton Tower, direction ESE. and WSW., noticed by Sir James Hall.

28, 29. At Old Markle and Gosford Spittle, on the North British Railway, the groovings horizontal, and very distinct, but the surfaces are vertical, they seem to me to give no sure indication of the line of motion.

My principal object in this paper was to register the phenomena observed; and, in speaking of their probable causes, I shall endeavour to be brief.

The Grampian District.—We have seen that, on the east side of this district, at Loch Tay, the abrading and grooving agents moved eastward; that on the west side, at Glen Spean, Loch Leven, and Loch Etive, they moved westward; and that on the south side, at Loch Fine, Loch Eck, Loch Long, and Gareloch, they moved southward. It follows that the nucleus of this physical force, the common centre from which the agents moved, was in the group of mountains extending from Loch Goil northward to Loch Laggan, dividing the

springs of the Spean, the Leven, and the Orchay, from those of the Spey, the Tay, the Earn, and the Forth. And the force must have resided in some substance which admitted of accumulation to a vast extent, for the abrasion produced by it can be traced to the height of more than 2000 feet. Now water could not be so accumulated here *except in the form of snow and ice*, and even if it were so accumulated in the liquid state, it could not, as has been shewn, produce the effects fairly ascribable to it. These effects are such as cannot be ascribed to any agency known, except that of glaciers, aided perhaps, in some cases, by floating ice.

Professor Forbes, in his paper on the Cuchullin Hills in Skye (in No. 79 of this Journal), describes well-marked groovings on their sides, radiating from the hills in different directions, as from a common centre, so disposed, he observes, that they can be accounted for neither by mountain lakes nor great oceanic waves, nor by any great agent known but glaciers.

I have not yet examined the channels of the Spey, the Findhorn, or the Dee, but I have no doubt that groovings pointing northward and eastward, will be found in them. I infer that the mountainous country, west of the Great Glen, from Morvern northward to Sunderland, was another centre of glacial action ; and further, that the Great Glen itself was probably the seat of a glacier which found an exit by its north and south ends, and was fed by the smaller glaciers flowing into it from the east and west.

The striæ, groovings, and kindred phenomena, in the great central valley between the Frith of Forth and the Frith of Clyde, and on the hills contained in it, do not seem to admit of explanation on precisely the same principles. The striæ in this district have a direction always approximating to east and west, and there is good evidence to shew that the abrading agent moved eastward. No glacial markings have yet been discovered, so far as I know, running in lines at right angles to the sides of the Pentlands, such as glaciers in the transverse valleys would produce. On the other hand, the striæ found on their summits and flanks (arrows 24, 25, 26), either run along the chain, or hold their course independently of it.

Much remains yet to be done before adequate materials for a satisfactory theory are collected. In the mean time, a few conjectures may be indulged in provisionally.

The transportation of a block of mica slate, weighing 8 or 10 tons, from the Grampians, across the low land, to a point in the Pentlands 1000 feet above the sea, is scarcely susceptible of explanation, except by calling in the agency of ice floating on an ocean at a far higher level than the present. The existence of such an ocean, with masses of ice floating on it, whether in the shape of icebergs, field-ice, or coast-ice, being admitted, it seems a legitimate inference, that the ice, borne eastward by a current, and having probably stones and gravel adhering to it, or imbedded in it, might produce the striæ on the top of Torduff Hill, arrow 24, and those at the other high localities 25 and 26. Farther, as the ocean, in ascending to its higher position, or descending from it, must have assumed different levels in succession, the striæ on Arthur Seat, and Corstorphine and Ravelstone Hills, and at all the other localities, high and low, from Stirling to Gosford and Fenton Tower, might be the result of the same agency. This seems a more reasonable hypothesis than that which assumes, that a vast sheet of ice covered the country from the Grampians to the Lammermuirs (a breadth of 50 miles), and, in moving eastward, grooved both the high lands and the low. It seems to afford a better explanation of the phenomena.

The craig-and-tail form is so often accompanied with groovings, that it is due probably, in a greater degree, to floating masses of ice than to the current which bore them along.

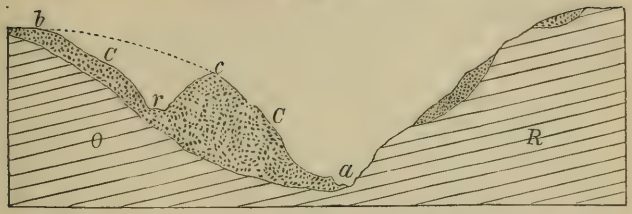
There is a class of phenomena best accounted for by the agency of coast-ice, which is well known to lift stones and gravel from the bottom and sides of rivers and bays, and transport them over moderate distances. Mr Lyell cites examples of blocks weighing 50 tons, being removed in this manner by the ice of the St Lawrence. In this way we may explain such facts as the following. 1. Thousands of granite blocks lifted from the hill in Glen Spean (arrow 1), near Loch Laggan, and carried westward; a vast number of them dropped within a furlong or half a mile of their original site, a smaller number conveyed a mile, and a few to much greater

distances; here, however, part of the effect may be due to glaciers. 2. Travelled masses of trap and other enduring rocks in the basin of the Forth, carried eastward from their parent rock in great numbers, and chiefly for short distances. 3. Numerous blocks of the greenstone of Salisbury Crag, torn from the top of the precipice, and carried eastward, most of them only for a space of one or two furlongs, but some transported across the ravine, and lodged on Arthur Seat. On the same principle, the removal of the multitude of angular blocks of porphyritic basalt, resting on the skirts of the south-east limb of Arthur Seat, and evidently torn from the upper part of that limb, may be accounted for.

Rarity of ancient moraines.—I looked in the grooved valleys of the Grampians for remnants of ancient lateral moraines, but saw nothing that could be considered as such, except in one instance at Gareloch. Perhaps their disappearance may be referred to certain geological changes, of which, in the opinion of Agassiz, and some American geologists, distinct traces exist. They think that at the close of the glacial epoch the sea rose and covered the mountains of the northern parts of Europe and America to a great height, and then again subsided and left the land dry as before, though not perhaps at the same level. During the rise and fall of the water, deposits of moveable matter, like these moraines, must have been very often remodelled or swept away. We have evidence in support of the alleged changes of relative level in the fact that striæ and grooving, certainly produced by glaciers on *terra firma*, are found covered by the old boulder clay, which has been deposited from water, and which ascends to the height of 800 feet at least above the present seas.

A similar inference may be drawn from facts which the beds of our rivers present, and which indicate three successive conditions. First, the bed was a channel cut on the dry land by the stream; next, the land was submerged, and the channel was filled up by the boulder clay; thirdly, the land rose again above the sea, when the river began to resume possession of its old channel, or in some instances, perhaps, formed a new one. I refer, as an example of these changes, to a section on the River Allan near Stirling.

Fig 5.



The rock O R consists of beds of conglomerate and sandstone dipping to the west at an angle of 5° or 10°. The ravine at the Bridge of Allan is from 150 to 200 feet deep. C C is a deposit of clay, of which the lower half has distinctly the character of the older diluvium, being very firm, and inclosing striated blocks of chlorite slate and other travelled stones. It descends to the water-course at *a*, and the deep cut *b r c* made on it for the railway, which occupies the hollow *r*, assures us that the clay is not a mere superficial covering which may have slid down from above and concealed the face of the rock, but the remnant of a deposit which once filled, or nearly filled, the ravine. The depth, in the direction *r c*, is, at least, 80 feet. The rock is not visible on this side, but it reappears in a quarry half a mile westward with the usual dip, at an elevation exceeding that of the point *c*, and is also seen on the left of the railway farther north. The legitimate conclusions deducible from the facts, I think, are these; that the ravine was excavated in the rock by a river, and nearly to its present depth; that the land then sunk under the sea, and remained there during the deposition of the older and newer boulder clay, which filled up the ravine wholly or partially; that after this the land rose again above the water, when the river sought out and re-opened its old channel.

Examples of similar phenomena are probably not rare. There is a mass of dark coloured clay, 40 feet in height, forming the south bank of the Water of Leith at Coltbridge, which seems to indicate that that portion of the bed of the stream was excavated before the diluvium was deposited. It is alluded to in Sir James Hall's paper. In the parish of Muiravonside, westward from Linlithgow, the River Avon flows between two precipices of the old boulder clay from 100 to 150 feet in height. For the space of a mile above Side-

trees, no rock is visible in the water-course, except a vein of trap at a mill; the distance from bank to bank varies from a furlong to a quarter of a mile, and the clay is so hard and tenacious that it rises at several points almost vertically, like a wall, from the water edge to the height of more than 100 feet. Where the clay was laid open by lateral rivulets, I found grooved stones embedded in it, some of them of chlorite slate. Farther south, sandstone is seen on both sides. The ravine seems, in short, to be an ancient water-course re-opened. The absence of visible rock on the west side, behind the clay, may, indeed, suggest the idea that there is nothing but clay in that direction; but the height and form of the land there, and other circumstances, satisfy me that this is not the case. Perhaps some of the ancient channels, when filled up with the boulder clay, were in the condition described by Playfair, namely, chains of lakes connected by streams whose channels abounded in cataracts. If the idea here thrown out be correct, that some of our rivers are now flowing in ancient channels reopened, it follows that the subsidence and re-elevation of the land through a space of more than 1000 feet, had done very little to disturb the levels. But the subject yet requires investigation.

On a Simple Form of Rain-Gauge. By the Rev. JOHN FLEMING, D.D., &c., Professor of Natural Science, New College, Edinburgh. Communicated by the Author.*

The defects with which rain-gauges may be charged, at present, seem referable to inattention to the influence of the wind on the falling *rain-drop*. If the drop was influenced only by gravity in its descent to the earth, the form and position of the rain-gauge would be comparatively of little importance. But in addition to its centripetal tendency, regulated in velocity by its size and the height of the fall, the rain-drop is frequently acted upon by the wind, and deflected more or less from its normal path, according to the velocity and direction of the current. While the wind thus influences

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* Read before the Royal Society of Edinburgh, 16th April 1849.