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THE GLACIAL PALAGONITE-FORMATION OF ICELAND.

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I. INTRODUCTION.

IN this paper some account is given of certain recent observations on the Tuff and Breccia or so-called Palagonite-formation of Iceland. By geologists generally this formation is believed to be of volcanic origin—to consist, in short, of fragmental ejecta principally. Interstratified with the breccia, however, there occur now and again beds of conglomerate, which are supposed to be old river-gravels. My observations lead me to very different conclusions. The breccias, in my opinion, are to some extent of glacial origin—many of them, in short, are indurated ground-moraines or "boulder-clays." Further, I believe that these "palagonite moraines" (as they may be provisionally termed) are the products of several successive glaciations, all of which preceded that final glaciation of the island which is the only one hitherto recognised by geologists.

The term "palagonite-breccia" has been so long current that it would perhaps be inconvenient to drop it, and I have therefore continued to employ it. I am well aware that Dr. Penck has shown that palagonite [1] is not a mineral, and it is further true that the "palagonite-moraines" are, strictly speaking, not breccias. I continue to use these terms, however, partly to emphasise the fact that the rocks in question have not now been observed for the first time, and partly to avoid confusion, as conglomerates made up of well-rounded stones are found to be interbedded with the morainic rocks.

The observations in question were made chiefly on mountains or

[1] A. Penck, "Ueber Palagonit- und Basalt-tuffe."—*Zeitschr. d. deutsch. Geol. Ges.*, 1879, p. 568.

hills rising out of or bordering the southern lowlands of Iceland. But before proceeding to describe them I may make some brief remarks on the geography and geology of the island, and more especially of the district I have just referred to.

We have at present a fairly good general knowledge of the physical features of Iceland, which is due largely to the untiring energy of the well-known Icelandic geographer and geologist, Dr. Th. Thoroddsen, to whose works I shall have frequent occasion to refer.

"Iceland, which has an area of 40,450 square miles, may be broadly described as a plateau land, built up of volcanic rocks of both older and newer formation"; the lowlands "embrace only about one-fourteenth of the entire area."[1] The largest of these lowlands lies in the south of Iceland "between the peninsula of Reykjanes and Eyjafjallajökull," and comprises "a tract some 1550 square miles in extent."[2] Of the rivers flowing across the southern lowland I may mention Hvítá and Thjórsá; the latter, 125 miles in length, is the longest river in the island.[3] The tributaries of the Hvítá are Tungufljót (on the right) and Stóra Laxá (on the left); Minni Laxá is tributary to the latter. The Thjórsá receives several tributaries, but I need mention only the Sandá and the Fossá, which skirt the west and the east sides respectively of the district named Thjórsárdalur. The region extending between the middle reaches of the Hvítá and the Thjórsá comprises the three districts known respectively as Hreppar, Ytrihreppur, to the west of Stóra Laxá, and Eystrihreppur to the east of it.

A few words now as to the geological constitution of Iceland. According to Dr. Thoroddsen the island is built up principally of basalts and palagonitic breccias, the former representing ancient lava-flows, while the latter are believed to be the consolidated fragmental materials of volcanic eruptions. These breccias, "which are of younger formation than the basalt, stretch in an irregular belt diagonally across the island."[4]

The lowland now occupies the south-western end of this very irregular belt, and is an "area of subsidence bounded by faults reaching down to the foundations of the mountains."[5]

The leading structural lines of the region, as exhibited by the trend of mountain-ridges, by chains of volcanic cones, by hot springs, and sometimes also by the river courses, have a SW. to NE. direction. The SW. to NE. faults or dislocations are crossed by transverse faults, and it is along these lines that portions of the breccia-plateau have subsided to form the lowland.

Looking west from the mountain-wall that towers above Stóra Laxá this structural feature is very apparent. The eye wanders over the broad county of Ytrihreppur, which is traversed from south-west to north-east by a series of brown escarpments of breccia-rock that alternate with green strips of marshy land. It looks as if some giant plough, moving in that direction, had broken up the rocky crust. But

[1] Thoroddsen, 'Explorations in Iceland during the years 1881-98."—*Geographical Journal* for March and May 1899.

[2] Thoroddsen *loc cit.*, p. 25.

[3] Thoroddsen, *loc. cit.*, p. 30.

[4] Thoroddsen, *loc. cit.*, p. 31.

[5] Thoroddsen, *loc. cit.*, p. 25.

the plough ridges are much interrupted, the larger portion of the shattered crust having subsided to form the low-lying marsh-lands. But the tilted position assumed by those portions of the ridges which still project, clearly indicates how great has been the havoc wrought upon the plateau, of which they are merely fragments.

Dr. Thoroddsen is of opinion that the southern lowland probably came into existence in late Tertiary times. After its formation it was overflowed here and there by doleritic lavas, which were grooved and polished by the glaciers of the subsequent ice age.[1] Dr. Thoroddsen remarks that he has nowhere found morainic débris or glacial striations underneath those glaciated streams of lava,[2] from which he concludes "that the lava was in all probability ejected anterior to the glacial epoch."[2] Again he states that, "At the time these pre-glacial lava-beds were laid down, the country had pretty much the same essential contours that it has at present."[3]

Now it is quite certain that these so-called "pre-glacial lavas" have been erupted anterior to a glacial epoch. As I shall presently show, however, the lavas in question are not really pre-glacial, but were actually preceded by earlier phases of glaciation. This is proved by the fact that mountains which overlook the lowland and others which rise like islands in its midst are partly built up of indurated bottom-moraines. The rocks of the mountains in question are clearly older than the lowland, and the lowland was certainly in existence before the so-called "pre-glacial lavas" were erupted. There can be no doubt, therefore, that the latter are younger than the glacial breccias which enter into the formation of the relict mountains referred to. This is an obvious conclusion, and its truth is confirmed as we shall see by the evidence of direct superposition.

I would here gratefully acknowledge my indebtedness to the Danish Government and the University of Copenhagen, whose liberality enabled me to make the excursions, the general results of which are here recorded. When I started on my journey I had no intention of making any special examination of the "palagonite-formation." The object I had chiefly in view was the investigation of the "post-glacial marine deposits" and raised beaches of the southern lowland, and my observations on these I hope to publish ere long. But when in Ytrihreppur I chanced to be struck with the resemblance which a breccia-rock, though tilted, presented to a very stony boulder-clay, and on closer examination I found that the breccia contained some stones that were apparently ice-scratched.

The passages I have cited from recent writings by the first authority on Icelandic geology will show that I could not have anticipated finding traces of glacial action on a lower geological horizon than the so-called "pre-glacial lavas." Indeed, I could hardly at first believe the evidence of my own eyes. It was difficult to realise that hard, tilted rocks, traversed by dykes of basalt, could be true bottom-moraines. But on following up my first observation I found it was impossible to escape the

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[1] Thoroddsen, *Jardskjálftar á Sudurlandi.* Edited by the Icelandic Literary Society. Kmh., 1899. P. 21.

[2] *Geographical Journal*, 1899, p. 23. [3] *Loc. cit.* p. 35.

conclusion, that a very considerable portion of the "palagonite-breccias" of the district was in reality of glacial origin.

The summer of 1899 was phenomenally rainy in the south of Iceland, whereby I was seriously hindered in my work in more than one respect.

II. Description of Localities.

It will be seen by reference to a map of Iceland, that a broad tongue of the high plateau stretches south-westward into the lowland, between the rivers Hvítá and Thjórsá. The south-western border of this mountainous region is rather broken up and irregular. In the south-east, Búrfell rises with steep acclivities to a height of 1450 Danish feet above the adjoining low grounds, while Berghylsfjall on the north-western corner has probably a similar height. A smaller portion of the plateau extends farther towards south-west than the mountains just referred to, and faces with steep walls the dislocated and depressed regions towards the east and west. These steep mountain-sides belong to Hlídarfjall, towards the west, on Stóra Laxá, and to Hagafjall rising over the Thjórsá towards the east.

My first observations on the indurated moraines or morainic breccias were made in the county of Ytrihreppur, to the south-west and south of Berghylsfjall, where the hills, or broken fragments of the breccia-plateau rise out of the marshy flats in such a manner as sometimes to remind one of tilted icebergs in a smooth sea.

One of these hills is Hellisholtsás, a short distance to the north of Midfellsfjall. This eminence presents a bold escarpment towards the east and a more gently inclined slope towards the west. The upper portion of the hill is composed of breccia, consisting of a grey, hard, sandy matrix crowded with a great number of mostly subangular blocks of basalt measuring up to 3 to 4 feet across. Many of the stones are distinctly striated and cannot in that respect be distinguished from striated stones in loose glacial accumulations, such as those which are seen on Midfellsfjall. The matrix is very hard and well jointed, the steep escarpment being determined by the jointing. When viewed from a distance the breccia seems in places to be made up of curved layers dipping steeply towards the south. Thin lenticular layers of fine-grained, distinctly stratified material are intercalated in the breccia, more particularly in its lower portions. I noted one sandy layer having a thickness of 4 to 5 inches and a length of nearly 2 feet. The matrix also seemed to be finer grained around some of the enclosed blocks. The breccia reaches a thickness of about 30 feet. It rests on basalt and is cut by a basaltic dyke about 3 feet thick. The underlying basalt seemed not to be intrusive here, and in a lower ridge to the west of Hellisholtsás, where the same sort of breccia rests on basalt, the latter had been broken up and blocks of it were enclosed in the breccia. The surface of the breccia itself appears to be moutonnée, but no striæ were observed.

This breccia I take to be a true ground-moraine—the product of an ice-sheet older than that which covered the country when the latter "had pretty much the same essential contours that it has at present."

My description of the grey breccia of Hellisholtsás applies to nearly all the grey breccias to be mentioned presently, their essential characteristics being: (1) the commingling of material of every size of grain, from fine clay up to big-sized blocks. The blocks are partly angular and partly blunted, the latter generally being most numerous, and some are striated. Sometimes, as in the breccia of Hellisholtsás, a rude bedding can be observed, when the section is viewed from a distance, but, as Professor Geikie remarks of certain Scottish boulder-clays, "on a nearer approach this appearance of stratification often vanishes—we cannot see the structure for the stones";[1] (2) the intercalation in the breccias of minor quantities of stratified, fine-grained material, the bedding often being diagonal. Further, as will be mentioned later on, some of the breccias were observed to rest upon a distinctly striated and grooved rock surface. This fact, taken in connection with the morainic character of the breccias themselves, seems to me to demonstrate the glacial origin of those breccias.

Nearly every hill I examined in Ytrihreppur was to a less or greater extent built up of these morainic breccias; but it would extend this paper to undue limits were I to record more than a few of my observations. My purpose at present is simply to call attention to the existence of these interesting glacial deposits rather than to give detailed descriptions. I will therefore make reference to only a few localities in Ytrihreppur in addition to that already described.

Midfellsfjall rises to a height of probably 1000 feet or thereabout above the surrounding marshes. It is an insulated and tilted fragment of the old breccia-plateau, the layers dipping north-westward. On the top of the mountain there is a lake extending from south-west to north-east.

In a ridge on the west side of the mountain, not far from the top, the following succession of rocks was observed:—

5. Loose glacial accumulations
4. Brown breccia (palagonitic) } about 40 ft.
3. Slaggy basalt
2. Grey breccia (indurated ground-moraine), 50 ft.
1. Basalt.

The basalt (1) underlying the breccia (2) was in one place seen to be distinctly striated in a direction about N. to S. The portion of the basalt on which these ice-markings occur seemed to be separated by rents from the main mass of the rock, but has remained in place, or very nearly so.

The grey breccia (2) closely resembles the breccia of Hellisholtsás already referred to, and contains a great number of distinctly striated stones, which hardly ever exceed a man's head in size. Towards the base of the accumulation occur in some places many angular blocks of basalt derived from the broken-up surface of the underlying rock. Near the line of contact of the breccia with the overlying slaggy basalt (3) blunted stones can be observed in a brownish-yellow matrix.

The breccia (4) contains slightly subangular stones in a brownish-yellow matrix, with many fragments of a basaltic glass, which also coats

[1] J. Geikie, *The Great Ice Age*, 3rd edition, p. 13.

some of the enclosed stones. It is in character very different from the grey breccia (2) and appears to be of volcanic origin.

The loose glacial accumulations (5), with blunted and indistinctly striated stones, occur in small quantities in hollows of the ridge. The ridge next to the east of this forms the highest part of the mountain, and overlooks the lake. Here the same section of rocks could be observed as above, with exception of the basalt (1). The grey breccia (2) was better jointed here than in the western ridge, and the enclosed stones were cut by the joints. A basalt dyke cutting the breccia seemed to have about the same direction as the lake (NW. to SE.)

Farther north in the same ridge a grey breccia, probably the continuation of that just mentioned, was observed resting on and succeeded by basalt. Every stone I cut out of it showed distinct glacial striæ. It has the usual grey tint, but towards its line of contact with the upper basalt it becomes reddish in places. The breccia is of very variable thickness, dwindling in one place to some 5 or 6 feet.

The mountain descends to the marshes on the east with a steep declivity, broken by irregular steps towards the base. A brown morainic-looking breccia with blunted stones—none of which, so far as I saw, showed striæ—was observed at a height of about 60 feet above the marshes. Higher up there is a partly grey and partly brown breccia, in which I found one boulder showing very clearly marked glacial striation. The thickness of this sheet is about 20 feet. Farther north one step-like bench in the mountain-slope consists of hard, grey breccia with many striated stones; it rests on basalt, and its greatest thickness is 80 to 90 feet. Whether this layer is a continuation of the 20 feet sheet I cannot say; it presents a very great likeness to the 100 feet layer in Búrfell to be mentioned later on.

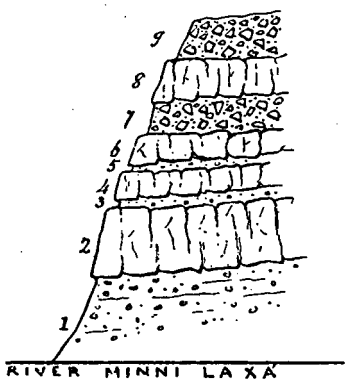

FIG. 1.

1. Conglomerate, 40 to 50 ft. visible: 2. Basalt (thick): 3. Volcanic Breccia: 4. Basalt (thick): 5. Volcanic Breccia: 6. Basalt: 7. Morainic Breccia: 8. Basalt, 80 ft.: 9. Morainic Breccia, about 70 ft.

It would thus seem that there are several separate and distinct sheets of indurated ground moraine entering into the composition of this mountain. It is possible, nevertheless, that there may be but one—the same sheet having perhaps been brought down to different levels by faults. Unfortunately bad weather prevented me spending as much time upon this somewhat difficult investigation as I should have liked.

My next excursion was to Berghyls-fjall, 4 to 5 miles to the north-east of Midfellsfjall. I ascended the mountain from the east. Here, in a steep cliff, the base of which is washed by the river Minni Laxá, the following section is exposed (Fig. 1):—

The bottom of the conglomerate (1) was not seen, but its surface rises towards the north until the bed reaches a visible thickness

of 40 to 50 feet. The constituent stones are well rounded and of a rather equal and moderate size, none being observed to reach that of a man's head, and the aspect of the rock is very different from that of the morainic breccias. The conglomerate graduates downwards into what would be more properly called a sandstone; it has a greenish hue and contains many boulders of a soft greyish-green rock, probably a very decayed basalt. The colour of the conglomerate is changed to reddish-grey down to a depth of about 4 feet beneath the overlying basalt (2). The breccia (3) is composed of red scoriæ or cinders in a red matrix. The basalt (4) overlying it is very like the basalt (2). [It may be that the breccia (5), which is very similar to (3), does not rest directly upon the basalt (4), and that some rock intervenes between the two, for I have only noted that (5) is on a higher level than (7).]

The breccia (7) is of a brown or greyish-brown colour, and contains big subangular stones and a greater number of smaller boulders, which, although for the most part scattered irregularly through the whole mass, yet sometimes show a linear arrangement, indicating a kind of bedding. Some of the stones were striated, and I suppose it is safe to conclude that the whole deposit is an indurated ground-moraine.

The breccia (9) overlying the thickest sheet of basalt (8) is in its lower portions greyish and charged with blunted stones, while here and there appear lenticular layers of stratified fine-grained materials. Passing upwards, the matrix becomes greyish-yellow, and contains slaggy fragments of basalt—the whole resembling very much a volcanic breccia, throughout which, however, some blunted stones are scattered. This yellow breccia graduates in a horizontal direction into a grey rock of the usual morainic character. In this I found one boulder showing glacial striæ. On the west side of a hollow of erosion the continuation of this grey morainic rock is exposed in a section showing a thickness of about 60 feet. Striated stones were rare.

To the west of this ridge is a deeper hollow, on the other side of which the chief bulk of the mountain lies. Glancing up the mountain slope, it appears to be built up of basalt to a greater extent than of breccia. A bed of the latter rock, which from a distance seemed to have a morainic aspect, was thought likely to be the continuation of the 60 to 70 feet breccias described above. At a considerably greater height I observed a breccia, with blunted stones, resting on basalt. The rock was 20 feet thick, and had a morainic appearance, but striated stones were not detected. This breccia is apparently represented a little higher up and farther north by a similar rock which has a thickness of 40 feet. It is traversed from north to south by a dyke of basalt 2 feet thick. The breccia is reddened for a distance of 6 to 8 inches from the walls of the dyke. A little distance farther north and higher up I observed a considerable mass of breccia having essentially the same structure and appearance as that just referred to, but its constituent boulders were not so big, and a few of them showed glacial striæ. Here, also, a basalt dyke (8 feet or so thick) cuts the rock from north to south, and reddens the breccia for a distance of 2 feet on either side.

Here the breccia was overlaid by a sheet of polished and striated

basalt. The direction of the striæ on the surface of the basalt was NE. to SW., but on a corner of rock the direction was observed to be about E. to W. I was not able to make out with certainty whether this special case is one of intersecting striæ of different age, or whether the divergence was simply due to deflection. But at several other places, to be subsequently referred to, I observed intersecting striæ having the same directions, and the E. to W. system could be clearly shown to be the younger.

Arrived at the highest ridge, which is sprinkled with erratics and perched blocks of basalt, I observed a very peculiar-looking greyish breccia. It had a kind of slaty structure, as it were, and could be more or less readily split up. The rock is decidedly morainic, containing as it does a number of polished and striated boulders. It rests on basalt, many angular fragments of which, reaching the size of a man's head, are included in the lowest portions of the breccia. Higher up the stones are subangular, and curved layers of sand appear.

Farther east, on the same ridge, the breccia reaches a thickness of 20 feet or more. The "slatiness" is here not so well marked, or is even absent altogether. The underlying basalt at this place has the same shattered and broken appearance; but at one spot where it projects about a foot beyond the outcrop of the overlying breccia it shows a fine surface of glacial polish and striation. I satisfied myself that there could be no mistake as to the relative position of this glaciated rock-surface—it clearly passes in below the breccia. Moreover, its situation is such as to preclude the possibility of its having been produced during the latest glaciation of the district. The rock-surface in question shows two sets of striæ which could hardly have been engraved at one and the same time. It is not, in my opinion, a case of deflection. One set trends from north to south, or a few degrees east of south, while the direction of the other is from N. 35° W. to S. 35° E. The inequalities of the surface exposed are slight, but the N. to S. striæ appear on what are lee-sides with regard to the south-east movement, from which I infer that the N. to S. set is the older of the two.

The breccia is traversed from north to south by two parallel basalt-dykes, which have a thickness of about 2 and 8 feet respectively—the distance between them being 60 to 70 feet. It may be noted that these dykes correspond in thickness and direction to the two which were observed at a lower level on the same mountain-slope.

The presence of those dykes, and of others which I saw but have not specially referred to, shows how greatly the configuration of the region has changed since the latest of the indurated ground-moraines was accumulated. For it is obvious that the mountain-ridges I have been describing could not have existed as such when the liquid igneous material was injected into the fissures, where it cooled and solidified. This of itself is sufficient to prove that the morainic breccias are older than the so-called "pre-glacial dolerites" which occupy the low grounds. The former were in existence before the old plateau became shattered and dislocated; the latter were not erupted until after this process had been completed.

In trying to ascertain how many separate beds of morainic breccia occur in the locality at present under review, we meet with the same difficulty as was experienced in Midfellsfjall. We cannot be quite sure that the breccias which crop out at different heights occur on just so many different geological horizons. It may be that the same bed is sometimes repeated by faulting. In the present case, however, this source of error is excluded for two of our breccias—namely, for the beds (7) and (9) in the section on Minni Laxá. To the west of a considerable hollow another section showed a breccia which I took to be the continuation of the layer (9). The bed numbered (7), however, did not appear; it had probably dipped out of sight, the inclination of the strata being westerly. Higher up than (9) two apparently separate and distinct sheets of moraine crop out, but I could not be quite certain that these were not outcrops of one and the same breccia repeated by faulting. It seemed to me, however, extremely improbable that bed (9) and the uppermost moraine (which rests on a striated surface of basalt) could be outcrops of one and the same sheet. I therefore incline strongly to the view that in this mountainous fragment of the old plateau there are at least three separate and distinct sheets of morainic breccia. And there may well be more, for I did not examine Berghylsfjall so carefully and minutely as I could have desired. To go over the mountain in such a way as to exhaust the evidence would probably take as many days as I spent hours in my examination; and a similar remark, unfortunately, would hold true for nearly all the localities I visited.

Hlídarfjall rises steeply to the east of Stóra Laxá, and from its summit one looks over an extensive, nearly flat surface, which has its continuation in that of Galtafellsfjall, the precipitous slopes of which front Laxá on the west. When the flat summits of these mountains are seen from the top of Midfellsfjall, they seem to form a nearly continuous plain, which presents a very marked contrast to the broken, hilly surface of Ytrihreppur. The summit of Hlídarfjall is composed of basalt, which shows a highly glaciated surface. Close to the edge of the bounding precipice of the mountain, the smoothed basalt shows in one place two sets of grooves and striæ very distinctly. The older set (consisting of grooves) trends SSW., while the younger set (consisting of striæ) trends a few degrees N. of W.

Under the basalt comes grey, morainic breccia, with blunted stones of different sizes, the biggest measuring nearly 2 feet across. Striated stones were rare. Abutting against the south side of a very stony portion of the breccia, a layer of stratified sandstone was observed. In another place a kind of rude curved arrangement appeared, while little lenticular layers of fine-grained material were quite common. These layers seemed to accommodate themselves to the bigger blocks.

The basalt, forming the topmost layer of Galtafellsfjall, was observed in one place overlying a grey rock, which on examination proved to be a conglomerate of well-rounded stones. This bed has a visible thickness of 30 to 40 feet, and is coarsest towards the top. For these details I am indebted to my friend Mr. Páll Lýdsson (of Hlíd, Eystrihreppur), who visited the locality at my request. Bad weather had, unfortunately, pre-

vented me going to the place. During a part of my journey I was accompanied by my friend, who is an excellent observer, and keenly interested in geology. I shall have occasion in the sequel to mention some observations he made when in late autumn he was travelling over the uninhabited regions to the north of these districts, on the look-out for stray sheep.

The base of the conglomerate referred to is not seen, but it probably rests on ground-moraine, like that observed underlying the basalt of Hlídarfjall.

For one who, like myself, had set out on his investigations in the belief that "the general structure and contour-lines of Iceland were in all respects essentially the same before the glacial epoch that they are to-day," it was certainly strange to realise that the mountains of which our morainic breccias constitute a part, are merely the relics or fragments of an old land-surface which in the districts I have been describing has now largely disappeared. Strange indeed was it to reflect that the existing configuration of the land is of more recent origin than glacial accumulations which are themselves probably not the oldest of their kind in Iceland.

We now proceed eastward to the hills of Stórinúpur, near Thjórsá. These hills rise to a height of probably 400 or 500 feet above the river, and on the south side of it they are continued by Skardsfjall which, according to Dr. Thoroddsen, has a height of 724 feet above the surrounding plain. So far as I was able to make out, the breccia of the hills of Stórinúpur is entirely of glacial origin. The stones of this breccia are mostly blunted; only few, however, appear to be distinctly striated. But one of the finest examples of glaciated stone I ever saw was detected in the freshly fractured face of a huge block of brown breccia which had been rent from the rocky wall above, during the tremendous earthquakes in 1896.

The walls of a ravine in the neighbourhood of the parsonage of Stórinúpur are beautifully grooved and striated. Here the stones of the breccia had undergone a renewal of their glacial experiences, and appeared on the polished rock-wall as patches of a colour different from that of the brown matrix in which they are set. At the bottom of this same ravine occurs a patch of recent ground-moraine of a grey and brownish-grey colour. The stones of this boulder-clay could easily be dug out with a spade, and neither in form nor in the character of their striation could they be distinguished from the glaciated stones of the "palagonite-moraines," which could only be extracted from their matrix by means of hammer and chisel. It is worthy of note that the quantity of the unconsolidated moraine or boulder-clay is quite trifling in comparison to the enormous masses of the "palagonite-moraines."

The most interesting district I visited in the course of my investigations was the mountain-slope to the west of Thjórsá (Hagafjall) and Thjórsárdalur. I was accompanied on the occasion of my visit by Mr. P. Lýdsson, and for a few days we were favoured with good weather. I could examine only a comparatively small portion of this district, and that not in so detailed a manner as I wished, but the deluge of rain that

succeeded our short interval of fair weather rendered further investigation impossible.

As before indicated, Hagafjall on the Thjórsá represents the eastern border of a comparatively continuous stretch of plateau, as Hlídarfjall represents its western border. Separated from Hagafjall by a hollow are two smaller promontories, rising with precipitous walls from the Thjórsá. These are named Bringa and Gaukshöfdi, the first mentioned being farthest north. Just here we obtain as good evidence as one could desire to show that the "palagonite-moraines" are not the products of one single glaciation.

Thus in Bringa (see fig. 2) the following succession of beds is clearly exposed:—

The breccia (1) is of a decided morainic character. It contains striated stones of moderate size, rarely exceeding that of a man's head, set in a light grey, fine-grained matrix, and rests on a striated surface of basalt. The striation is not very distinct, but seems to have a N. to S. direction. The rocks below this point (which was at a considerable height above the river) were inaccessible.

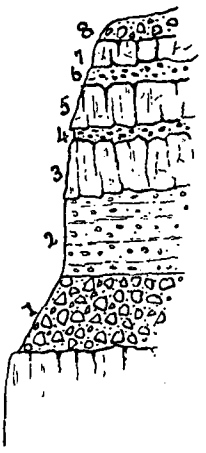

FIG. 2.—SKETCH—SECTION OF BRINGA.

1. Morainic Breccia, 20 ft.: 2. Conglomerate, 30 ft.: 3. Basalt: 4. Volcanic Breccia, 6 ft.: 5. Basalt: 6. Volcanic Breccia, 12 ft.: 7. Basalt: 8. Morainic Breccia, 14 to 16 ft. The beds dip north.

The conglomerate (2) appears to be made up chiefly of well-rounded stones, the grey matrix, which enters so largely into the composition of the underlying bed (1), being nearly absent here. The conglomerate is arranged in layers that dip at a considerable angle towards south.

Above the superjacent columnar basalt (3) comes a true volcanic breccia (4). It is composed entirely of scoriæ or cinders, imbedded in a greyish-yellow matrix, which probably represents volcanic ash or dust.

The basalt (5) is of inconsiderable thickness, and is notably slaggy in its lower portion.

This basalt is succeeded above by another volcanic breccia (6), in the upper part of which occurs a bed of laminated volcanic sand about 1 foot in thickness. Although obviously forming a portion of the breccia, into which it graduates above and below, the sand apparently points to deposition in or arrangement by water.

The highest bed is a breccia (8) which differs somewhat from the breccia (1). Its matrix is in places of a brownish colour and not so fine-grained as that of (1). The enclosed blocks vary much in size, some of them measuring 7 to 9 feet across, and many are very well striated. Lenticular sandy layers, showing diagonal bedding, and reaching occasionally 3 feet in thickness, are intercalated in the breccia, more particularly towards its base. Occasionally a layer could be seen abutting directly against one of the biggest blocks—some of which showed distinct glacial grooving.

This morainic breccia is quite indurated and forms the top of the hill. It has been itself glaciated, and shows a moutonnée surface.

The whole series of beds now described dips towards the north, so that as we go in that direction the beds gradually descend, until the conglomerate (2) appears at the level of the river. From a point near the hill-top the two morainic breccias (1 and 8) with the intervening beds are very clearly seen, being so well exposed that no doubt as to the succession is possible.

A similar succession of beds is met with at about the same height in Hagafjall, on the west side of the hollow which separates Bringa from that mountain. It is as follows:—

	Feet.
7. Basalt	
6. Breccia (morainic?)	
5. Basalt	
4. Breccia (volcanic)	6
3. Basalt (columnar)	
2. Conglomerate	40 to 50
1. Breccia (morainic), bottom not seen	

It will be seen that from (1) to (5) this section exactly corresponds to that of Bringa already described. But the uppermost volcanic breccia of Bringa seems to be absent here. The mountain-wall, however, was inaccessible above the basalt (3), and I may easily have been mistaken as to the true character of the layer numbered (6). Should it be really a moraine, the discrepancy between the two sections might be accounted for by unequal glacial erosion. We might infer that the ice-sheet underneath which bed (6) accumulated had elsewhere (as in the Bringa section) removed pre-existing layers of rock. But should the bed in question (6) prove to be a volcanic breccia, the difference between the sections at Bringa and Hagafjall is quite inconsiderable—it is only that the upper moraine of the former does not appear in the latter.

It will further be observed that the conglomerate of the Hagafjall section is considerably thicker than the corresponding bed in Bringa. Owing to its greater accessibility it could be more readily examined (see fig. 3). It may be described as a coarse conglomerate, somewhat indistinctly bedded. It is readily distinguished from the underlying moraine, its matrix being meagre in amount, while the constituent stones are much more rounded and worn than those of the moraine, and show no striation. The greater portion of the bed consists of this coarse material. Immediately above the latter comes an inconsiderable thickness of yellowish sandstone, containing only a few pebbles, and this is followed in succession by a greater thickness of alternating layers of sandstone and gravelly conglomerate, dipping south, as in Bringa. The uppermost part of the conglomeratic bed consists of a series of pebbly

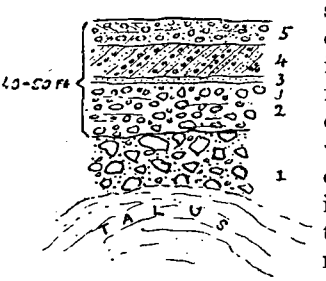

FIG. 3.—SECTION OF HAGAFJALL CONGLOMERATE.

1. Morainic Breccia: 2. Coarse, indistinctly bedded Conglomerate: 3. Thin yellowish Sandstone, with few pebbles: 4. Alternating layers of Conglomerate and Sandstone: 5. Horizontally bedded gravelly layers, showing here and there diagonal bedding.

layers, showing here and there diagonal bedding. A thin sheet of intrusive basalt traverses the conglomerate, dwindling in thickness towards the north.

We next proceed to Gaukshöfdi, which, as already mentioned, is situated farther south than Bringa, and rises with a steep, and in part almost vertical, wall to a height of probably 300 feet above the river. The lower portion of the hill consists of a grey morainic breccia charged with blunted and striated stones. At the top of this breccia is seen a very hard, bluish-black, fine-grained rock; in this bluish-black matrix occur a few stones, some of which are well striated. This rock passes upwards into "palagonite" of a fine brown colour, the change being so gradual that it was hard to tell where the one kind of rock ended and the other began; a boulder enclosed in the "palagonite" appeared to be striated. The uppermost part of the brown breccia forming the top of the hill contains a great number of slightly subangular stones in a brown matrix. I could not satisfy myself as to the precise nature and origin of this breccia; it did not present any great resemblance to the volcanic breccias of Bringa, while it differed decidedly from the underlying grey breccia.

The surface of the breccia in question is grooved and fluted to an extent I have not seen elsewhere in Iceland, and a big erratic is perched on the slanting, northerly shoulder of the hill. On the southern slope (the lee side) of the hill there is an accumulation of unconsolidated morainic material—a bluish-grey argillaceous mass containing striated stones. Were this boulder-clay indurated, it would strongly resemble the lower moraine of Bringa. Here, as at Stórinúpur, one is struck by the insignificant amount of this moraine—a product of the last ice-sheet—when contrasted with the much more extensive accumulations of the older glaciations.

As will be seen, the two hills described, although they have much the same configuration, are yet built up in a very different way, and since the dip of the rocks is towards the north, the moraine of Gaukshöfdi probably occupies a lower horizon than those of Bringa.

Somewhat farther south we ascended the side of Hagafjall, which probably rises about 1400 feet above the river. At an inconsiderable height we saw a breccia which seemed to be morainic; it was overlaid by a sheet of basalt showing the two sets of striæ already mentioned. Farther up the mountain-slope a step or terrace is formed by the outcrop of a brown "palagonitic breccia," in which striated stones are very numerous; this breccia is exposed for a thickness of 30 to 40 feet, and is succeeded by basalt. Possibly these breccias are really portions of a single bed which has been faulted. It was evident, at all events, that portions of the mountain had subsided along lines of fracture.

A third breccia of morainic aspect was observed. Higher still appeared a "palagonite-breccia," which is probably of volcanic origin. The enclosed lumps and blocks of basalt are highly vesicular, and often so decayed that they were easily cut into with a knife. This rock was traversed in one place by a branching sheet of basalt.

The highest ridge of the mountain is moutonnée, and presents a

great resemblance to the corresponding part of Berghylsfjall. This ridge is partly composed of grey breccia, which yielded striated stones, every stone I cut out of it being distinctly glaciated. At other parts of the ridge the rock was quite different—being brownish in colour, and containing both angular and subangular stones. Glaciated stones, however, were rare, and those observed were not very distinctly striated.

A little farther south, on the Thjórsá, one encounters low-lying masses of a fine, brown "palagonite." This rock contains, here and there, a few subangular blocks of basalt, while in some places it showed conglomerate 3 to 4 feet in thickness. I detected in the "palagonite" only one stone which seemed to have been glaciated. Two veins of basalt (2 to 3 inches and 2 feet in thickness respectively) were observed cutting the palagonite.

Making every allowance for the repetition of outcrops by faulting, it seems hardly possible that the several glaciations recorded by the indurated ground-moraines, which have now been described or referred to, can be fewer than three, and they may be four in number.

Returning now towards the north I shall record some observations made in the Thjórsárdalur (valley of the Thjórsá), which is somewhat of a misnomer. This tract lies north of the Thjórsá, west of Búrfell, and is drained, as already mentioned, by Sandá in the west and by Fossá in the east. My observations relate, of course, to the mountain-slopes that flank the valley.

In the steep side of Skridufellsfjall on the Sandá two separate layers of morainic breccia were observed—the upper one occurring at 600 or 700 feet above the river. The height of the lower moraine I have omitted to note; it consists of two layers—the lower dark grey and the upper yellowish-grey. Striated stones were readily detected; had it been otherwise, they would hardly have been found at all, for I had no time for a prolonged search. The upper moraine has a thickness of probably over 100 feet. In this rock grey portions, charged with numerous blocks, rarely exceeding 2 feet in diameter, are seen alternating with others of a more yellowish colour and containing fewer stones.

About a quarter of an hour's ride to the north-east, the Sandá is overlooked by a rocky wall, probably not much exceeding 100 feet in height. I shall not attempt to describe the truly astonishing aspect of this cliff, but will confine attention to points of special geological interest (see fig. 4). Beginning at the north end, the rock is seen to consist of a coarse breccia, the enclosed blocks frequently measuring 3 to 4 feet across. Towards the top of the cliff is a sheet of intrusive columnar basalt 4 to 5 feet in thickness (fig. 4, *a*). Where accessible this rock showed a thin tachylytic and scoriaceous crust above and below. Going southwards one comes to a mass of basalt reaching from top to bottom of the cliff (fig. 4, *b*). At its northern end, however, it is covered by the breccia; its base is not seen. This black basalt rock is not one homogeneous mass, but consists of a series of beds—vesicular and compact, and sometimes almost sandy-looking layers alternating. The beds are very nearly on end, their dip being 80° towards the east, and they strike obliquely to the direction of the cliff for a distance of about 300

feet. The approximately horizontal layer of intrusive columnar basalt, already referred to as occurring near the top of the cliff, traverses the rock-wall from one end to the other—passing through the breccia and continuing its gently undulating course across the nearly vertical basalt beds. It is clearly an intrusive sheet, and some boulders of the breccia have been caught up in it. At the top of the cliff the dark basalt rocks, where they are not too decayed, show the two sets of striæ already mentioned as occurring at several other localities.

Though the base of this basalt-complex is not exposed, it seemed to me most probable that it is not *in situ*, but really a huge boulder. At the top of the cliff, on the south side of this supposed big erratic, the breccia shows a kind of rude bedding, which, viewed from a distance, has the appearance of a basin-shaped arrangement (fig. 4, *c*), in which the breccia is not so coarse as elsewhere. Some large blocks, however,

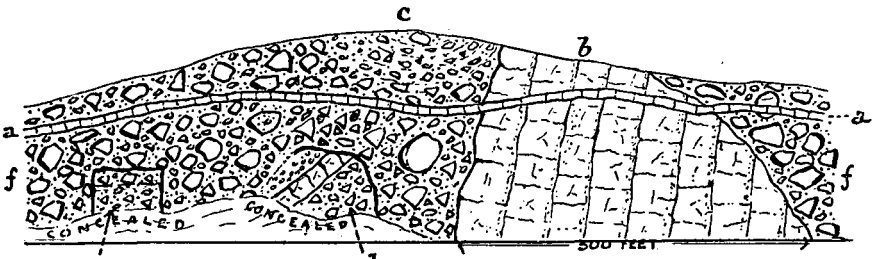

Fig. 4. Diagram of Cliff on Sandá

project from it at the moutonnée surface above, and have been thus grooved and striated by the last ice-sheet. The coarse breccia contains many blocks of a grey, indurated moraine (both of the bluish-grey and the yellowish-grey varieties to be described presently). It also includes blocks of lava that measure 12 to 14 feet in length, and having reddened, rounded stones caught up in their scoriaceous portions. These blocks are fragments of the basalt-lava which occurs in the remarkable rock mass which I now proceed to describe. A little way south from the rudely bedded breccia mentioned above we come upon a rock mass, projecting somewhat from the breccia in which it is included, and reaching a height of probably 40 to 50 feet above the river (fig. 4, *d*). Its base is not exposed. It is made up of the following layers, which are inclined at an angle of 40° to 45° towards north-east :—

	Feet.
5. Breccia, yellowish-grey 4. Breccia, dark grey 3. Breccia, bluish-grey	20 to 25
2. Basalt	20
1. Conglomerate	16 to 18 visible

The conglomerate (1) is composed of well-rounded stones of moderate size; here and there are bands of sandy clay which have been burnt to a red "brick," while the stones have been reddened to a distance of 6 to 8 feet from the overlying basalt. Quite close to the scoriaceous layer

of the basalt—into which many rounded stones have been kneaded—the scanty, fine-grained material of the conglomerate is of a greyish colour.

The surface of the basalt (2) exhibits very distinct glacial grooving and striation passing in under the bluish-grey breccia (3), which is of the usual morainic character and only a few feet in thickness. It is very hard, and its uppermost part is made up of a succession of corrugated layers. The next succeeding layer (4) is somewhat finer-grained and darker in colour. It is followed by the yellowish-grey breccia (5) which constitutes the greater part of the rock overlying the basalt (2). This layer (5) contains towards its base a number of blocks of the underlying dark grey breccia (4), measuring up to a foot across, but with these exceptions the enclosed stones are hardly ever larger than one's fist. The rock is clearly marked off from the surrounding coarse breccia of the cliff, which is of a similar colour.

Although the base of this complex boulder or erratic was not seen any more than was that of the great basalt mass already mentioned, I could have no doubt that it was simply a large complex block enclosed in the surrounding coarse-grained breccia.

Continuing our walk southwards along the base of the cliff for a few minutes we next come to another large boulder in the breccia. It extends up to a height of 30 to 40 feet above the river, the base being concealed under talus (fig. 4, *e*). The vertical sides of this rock seem to be grooved, and it is made up of bluish-grey and yellowish-grey breccia, but here the quantity of the former exceeds that of the latter.

This was the last and the smallest of the huge erratics met with, but south of this several blocks of basalt, measuring up to 12 to 14 feet across, were seen enclosed in the breccia, together with smaller blocks of the bluish-grey breccia. Here also the coarse breccia seemed to rest upon a striated surface of basalt, the direction of the striæ appearing to be NNW. to SSE.

The intrusive sill of basalt, which I have described as traversing the cliff from end to end and cutting across the largest of those boulders (the basalt-complex), does not intersect the two smaller erratics, which occur in the lower part of the cliff, and are therefore at a lower level than the sill.

The evidence furnished by this locality as to the glacial succession in Iceland, taken together with that derived from Hagafjall, Berghylsfjall, and elsewhere, leads to the conclusion that at least three separate sheets of indurated ground-moraine occur in the tuff- and breccia-formation.

The mountains on the east side of the Thjórsárdalur are Búrfell in the south, Stangarfjall in the north, and between them Skeljafell.

At the top of Stangarfjall, probably 800 feet above the valley bottom, a bed of columnar basalt occurs, the columns having a length of 20 to 30 feet (fig 5, *a*). At the southern extremity of the mountain this basalt caps a ridge which declines rapidly to the valley in the west, and to the high-grounds in the east, above which it does not rise more than 100 feet. On the west side the basalt is seen resting on conglomerate (fig. 5, *b*). This conglomerate has previously been

examined by Dr. Thoroddsen,[1] but probably I did not visit the precise spot described by him. The included stones are small as a rule—only few being seen which equalled one's fist in size. The conglomerate passes downwards into sandstone and a more argillaceous rock containing a few small pebbles. Some of the stones, as Dr. Thoroddsen remarks, seem to be derived from the underlying breccia. On the south-east side of the ridge I found the conglomerate underlaid by a grey morainic breccia (fig. 5, *c*), in which distinctly striated stones were observed at a depth of 60 to 70 feet below the overlying basalt bed. Farther west on the ridge appeared a very different rock. It consisted of angular and subangular blocks of vesicular basalt set in a light-coloured matrix, scattered through which were small fragments of tachylyte or volcanic glass. The whole presented some resemblance to the similar rock seen in the section on Minni Laxá (Berghylsfjall), and there could be no doubt that the conglomerate was succeeded downwards by morainic breccia.

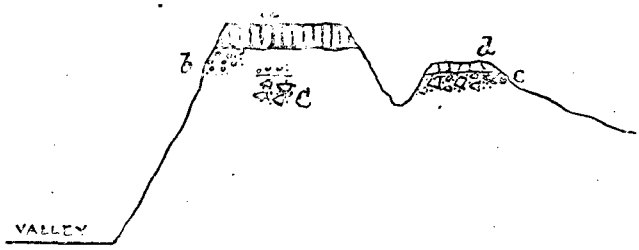

FIG. 5.—DIAGRAM SECTION OF STANGARFJALL.

To the east of the ridge referred to above, and separated from it by a gully occupied by a brook, a low rock of dolerite is seen resting on breccia (fig. 5, *d*). This dolerite in grain and colour closely resembles the so-called "pre-glacial" dolerite (that of Reykjavík, for example), and its surface exhibits clearly the two sets of ice-markings of which mention has already been made. One set consisted of broad grooves, reaching a depth of nearly 2 feet, and having a N. to S. direction. But no striæ having the same direction were observed. The grooves were crossed, however, at nearly right angles by striæ measuring $\frac{1}{2}$ to 2 inches in breadth. Here, as elsewhere, the markings left by the ice-sheet that moved southwards indicated more intense grinding than those engraved by the ice that flowed towards the west. As seen in section the dolerite reaches a thickness of 6 to 8 feet, but in places it has been ground away down to the basal vesicular-scoriaceous portion—a thickness of scarcely 2 feet being left, and no doubt a great part of the rock has wholly disappeared.

The underlying breccia is grey, presents the usual morainic aspect, and contains a great number of distinctly striated stones. It includes also numerous boulders of what seemed to be a still older moraine. The

[1] Dr. Thoroddsen, "En Rejse gjennem det indre Island i Sommeren, 1888."—*Dansk. Geograf. Tidskr.*, Bd. x. p. 15.

dolerite sends off a vesicular vein 4 feet long by 1 foot thick into the underlying breccia. (A similar vein, seen in the morainic breccia on the top of Hagafjall, perhaps indicates the former presence there of a sheet of basalt which has been entirely worn away.)

The story told by the evidence obtained in Stangarfjall may be summarised as follows:—The conglomerate underlying the columnar basalt represents an old river-channel excavated in ground-moraine before the broad valley to the west of Stangarfjall had come into existence. Perhaps the river, the work of which is here recorded, was contemporaneous with the watercourses represented by the conglomerates in Bringa-Hagafjall and Galtafellsfjall (Núpstúnsfjall). Eventually the old valley was invaded by a great lava-flow underneath which the river-gravels were entombed. Thus protected, the old river-bed has escaped denudation and now enters into the formation of a prominent ridge. It would appear, however, that the valley to the west of this ridge is in great measure due to subsidence rather than to erosion. But the hollow lying on the east side of the ridge is a hollow of erosion, and into it flowed a stream of doleritic lava. At a later period the whole country was overwhelmed by an ice-sheet—and this glacial invasion may have been repeated oftener than once.[1]

According to Dr. Thoroddsen the mountain-slope that overlooks the broad valley (Fossalda) on the west shows the same geological succession as Stangarfjall, consisting as it does of dolerite resting on "palagonite-breccia." This strengthens the conclusion that the subsidence to which the valley mainly owes its origin took place after the formation of the columnar dolerite. Possibly the subsidence may even be of later date than the effusion of the dolerite which I have described as lying to the east of the ridge. It would seem that the great plateau has experienced towards the north-east successive collapses of this kind. Close to the west of the place, where the Fossá in a magnificent fall plunges down from the plateau, the mountain-side appears to have subsided along a series of concentric and radial faults after the last ice-sheet had melted away from the district. The scene is one of an indescribable rugged grandeur. The presence of the gigantic blocks in the morainic breccia on the Sandá, as described above, becomes more intelligible and less surprising when we keep in view the probability that such shattered rock-masses or mountain-fragments may have lain in the path of the crushing and grinding glacier.

Unfortunately time did not allow me to visit this place—the so-called "Hrun"—last summer. I had seen it some years ago, but I was then unacquainted with glacial phenomena.

According to Dr. Thoroddsen, the columnar dolerite which is so well seen in Stangarfjall, can be observed also in the imposing cliff behind the fall of the Fossá, and Mr. P. Lýdsson informs me that the rock on which the dolerite rests is very similar to the morainic breccia in Stangarfjall.

[1] It is probable, as I shall try to show in the sequel, that the columnar basalt of the ridge had been subjected to glaciation before the eruption of the dolerite which occupies the hollow to the east of the ridge.

Leaving Stangarfjall and passing southwards along the east side of the valley, we come to Skeljafell, where the Fossá is nearest to it. The rock here is a brownish-yellow breccia, composed of blunted stones of variable size. It has quite a morainic appearance, but no striated stones were observed. It closely resembles the lowest rock of Búrfell, which I shall presently describe.

The mountain of that name rises with bare rocky steeps to a height of 1450 feet above the river. On the north side, however, it is not precipitous. I ascended it from the west, and at a height of about 400 feet above the Thjórsá, encountered an extremely hard, grey breccia, with blunted stones of varying size and aspect. Distinctly striated stones were detected, but they did not seem to be numerous. Higher up and farther south I noticed a brown breccia, apparently volcanic, which was overlaid by a bed of morainic breccia, the latter in its turn being covered by a brown-coloured rock. These rocks, however, were so difficult to get at that I could not examine them satisfactorily.

The breccias referred to are succeeded by basalt, probably 150 to 200 feet in thickness, and supporting a much jointed grey breccia some 100 feet or so in thickness. The joints cut through stones and matrix alike. When, after some ineffectual attempts, I at last got to the top of the basalt, this breccia proved to be one of the most markedly morainic accumulations encountered in the course of my wanderings. Towards the base it is very stony, with big, blunted blocks, none of which, so far as I saw, showed any distinct striæ. A little higher up in the bed, however, any number of striated stones appeared—blocks of a compact, black basalt, exhibiting the finest glacial polish one could wish to see. The rock contained also some boulders of what I took to be morainic breccia of a different colour. A comparatively small portion of the breccia was of a brown colour, and contained slightly subangular stones. This brownish-coloured rock reminded me of certain "palagonite-breccias" which I had supposed were of volcanic origin. On a narrow shelf of basalt, projecting from below the breccia, distinct ice-markings were observed, the direction of the striæ being N. to S. There can be no doubt that this characteristic morainic deposit rests upon a striated surface. Mr. P. Lýdsson, who visited the place later in the autumn, informs me that on the east side of Búrfell a sheet of moraine, which he thinks is the same bed as that just mentioned, can be seen resting on a very thick basalt, underneath which occurs a brownish-yellow moraine. He has sent me a finely glaciated stone which he extracted from the latter.

Unfortunately I did not succeed in climbing to the top of the mountain, and I had no time to attack it from the north. The grey moraine which, as I have said, rests on a striated surface, seems to be overlaid by at least 200 feet of basalt. Probably the united thickness of the beds above that striated surface is about 700 feet.

According to Dr. Thoroddsen, a red breccia appears on some of the highest parts of Búrfell. Of the nature of that breccia, however, I can say nothing.

The lowest rock I observed in Búrfell was a breccia of morainic

aspect, capped by a layer of glaciated basalt at a height of 100 feet above the river. Save for its colour, which is more decidedly grey, this rock reminded me of the lowest breccia of Skeljafell already described. Like it, too, the lower breccia of Búrfell appeared to contain no indubitably striated stones. The base of the mountain advances nearer to the river here than elsewhere, and I did not forget the possibility of the breccia having been brought, by subsidence, into its present position. It is remarkable, however, that the lower breccias differ always, more or less, from the upper beds. Although the former have a morainic character, yet they seldom or never yielded striated stones, while the reverse was the case with the upper breccias.

The grey-coloured indurated ground-moraine (100 feet thick) in Búrfell is conspicuous from a considerable distance, and dips gently towards the north. It seems to be continued in Skeljafell to the north. The moraine that underlies the conglomerate of that mountain occurs at a somewhat higher level, probably owing to the existence of transverse faults. I am inclined to think that the 100 feet moraine of Búrfell corresponds to the lower moraine of Bringa, and to the middle moraine (80 to 90 feet thick) of Midfellsfjall.

Imperfect though they be, I hope that these notes on the mountains that flank Thjórsárdalur will suffice to show that this district—long famous for its scenery, volcanic phenomena, and archæology—is of no little interest likewise from the point of view of glacial geology.

On the way back to Reykjavík a few additional observations were made, of which the following may be mentioned. Hestfjall is an isolated mountain rising out of the lowland at a bend of the river Hvítá. Near the ferry of Árhraun the rocks on the river consist of morainic breccia with blunted stones, but no striated stones were seen. This breccia seems to be the lowest rock of Hestfjall, which at that locality consists chiefly of brown, stratified tuff. A little to the north of the mountain I noted low rocks of a grey breccia, containing striated stones. Rocks of a similar breccia were also seen near Kidjaberg, to the west of Hestfjall, and in one place post-glacial marine deposits were observed resting on a striated surface of indurated moraine.

Hellisheidi is the name of a highland tract which rises precipitously above the country to the east and west. It is clearly of the nature of a "Horst," and the lower land to the west of it is largely covered with lavas which exhibit ice-worn surfaces. The main road from Reykjavík to the southern lowland traverses this tract. A short distance from Hveradalir (the valleys of the hot springs) a steep rock on the roadside consists of breccia, in which I found a distinctly striated stone. Probably further investigation will show that the breccia of Hellisheidi is largely of glacial origin.

The observations which I shall now mention relate to glaciations of a more recent date than those whose records are seen in the so-called "palagonite-breccias."

The two sets of striæ of which I have several times spoken are not uncommon in the region to the east of Stóra Laxá, and seem to occur between Hvítá and that river, but west of Hvítá, in the district of

Biskups-Tungur, they were not observed. The system having a direction mainly S. is everywhere seen to be the older. The trend of the younger set varies a few degrees on both sides of W. The older striæ are beautifully preserved on what are lee-sides with respect to the westward movement. I have already mentioned some of the localities where these two sets of striæ are seen, and shall only add that on the hill called Krókholt south of Hlídarfjall, and on every bare rock for a long way south of it, the two systems can be distinctly observed. We may note, for example, how the back of many a rocky ridge is striated from east to west, while the flanks are fluted from north to south.

Deflection was more characteristic of the younger than of the older system of striæ. This fact, taken in connection with the greater degree of erosion that accompanies the older system, seems to show that the southward moving ice-sheet was more important or thicker than the other. That the thickness of the latter, however, was by no means inconsiderable is shown by the fact that the ice has flowed right across well-marked inequalities of the ground—traversing ridges and hollows alike.

Certain observations made near Reykjavik tend to confirm me in my opinion that Iceland has experienced more than one general glaciation after the outpouring of the doleritic lavas. At Sudurnes—the farthest westward projecting point of the peninsula, on which is situated the town of Reykjavík—a greyish-brown ground-moraine with striated stones, nearly as completely indurated as many of the "palagonite-moraines" described above, can be seen resting on striated dolerite. About 1½ feet from its base the moraine becomes finer-grained and harder, and the surface of this harder portion is distinctly smoothed and striated. About 1½ feet higher there seems to be another striated floor overlaid by more stony moraine (4 to 5 feet). Throughout the whole morainic series much triturated shell-débris occurred. The moraine is washed by the sea at high water.

Loose débris of glacial origin is usually scattered over the dolerite around Reykjavík, but nowhere else save at Sudurnes have I seen the dolerite covered by a moraine of the kind described. Judging, however, from the occurrence of loose blocks, patches of a similar rock will probably be found at Øskjuhlíd (hill near Reykjavík) and at Valhús near Sudurnes, and elsewhere.

Especially interesting was a glaciated lava-stream observed at several places in the neighbourhood of the farm of Vatnsleysa, about two miles (Dan.) south-west of Geysir. By far the greater part of this lava-stream is concealed under marine deposits and peat, etc., but it is exposed on the river Tungufljót; and about an hour's ride north-west of Valdavad, where the river is forded, a considerable stretch of highly glaciated and boulder-strewn lava is to be seen on the east side of the river. This doleritic lava is the only glaciated lava-stream known to me, resting on apparently marine deposits, which closely resemble those so commonly met with in the southern lowland. The superposition of striated lava upon gravel and clay can be observed on both sides of Tungufljót, but it can be studied most satisfactorily in the eastern wall of the ravine below the waterfall—which, it may be added, owes its origin to this

superposition. The surface of the sedimentary deposit underlying the lava is very uneven; in places the lava even descends to the river, while elsewhere the sedimentary strata attain a visible thickness of hardly less than 20 feet. At their contact the two rocks are kneaded together in a most remarkable manner, and small pebbles are enclosed in the lava, which towards its base presents a honeycombed aspect, containing in the very irregular cavities a red, earthy matter. The following section may be given:—

	Feet.
d. Glaciated lava, ...	3 to 4
c. Sand and gravel, undisturbed, . .	8 to 10
b. Laminated clay, folded and contorted, .	4 to 5
a. Laminated clay, undisturbed, . .	4 to 6

The clay (*a*, *b*) is somewhat indurated and the stratification very well marked, darker and lighter-coloured layers alternating. The dolerite (*d*) is here very thin, having apparently been ground away by the ice down to its undermost vesicular layer. The direction of the striæ is SSW. to SW., and no traces of an E. to W. system were observed.

On the left bank of the river, a short distance above the waterfall, laminated clay overlies the striated lava. This succession, however, is not actually seen in the section to be described, as the bottom of the clay is not exposed. There can be no doubt, however, as to the relative position of the beds, for only a few minutes' walk down stream the lava in question occupies the bed of the river. The clay seen above the waterfall has a visible thickness of 8 to 10 feet. Rounded stones occur in the soil above it. This clay is softer than that underlying the lava, and is very well stratified. Towards the top and the bottom the layers are violently contorted—a structure which is rendered very apparent on account of the several layers being differently coloured. The disturbed portions are separated by a few feet of totally undisturbed clay (see fig. 6).

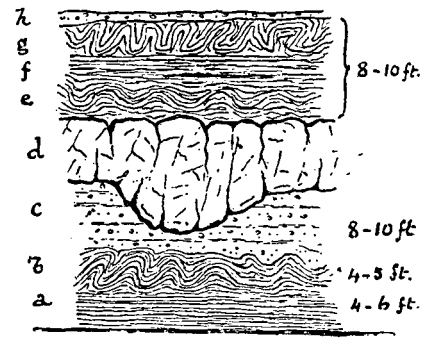

FIG. 6.—DIAGRAM SECTION ON TUNGUFLJÓT.

a. Clay-beds, horizontal: *b.* Disturbed beds of sand, etc.: *c.* Horizontal beds of sand and gravel: *d.* Lava with glaciated surface: *e.* Contorted clays: *f.* Undisturbed clay: *g.* Highly contorted beds: *h.* Gravelly subsoil.

Such disturbances—though rarely, if ever, so striking as here—were commonly observed in sections of the "post-glacial marine deposits" of the southern lowland. Sometimes, too, striated boulders, and in one case a completely angular block, with remains of balani attached to it, were found imbedded in the post-glacial clays. These phenomena would seem to indicate the existence of icebergs or rafts in the post-glacial sea. And seeing that the deposits underlying the glaciated lava on Tungufljót closely resemble those of unquestionable marine origin, one is naturally led to infer a similar

origin for them, and to conclude that the contorted structure referred to may be due to the action of floating ice.

As indicated above, the clay passes upwards into sand and gravel, while the lava rests upon the uneven surface of these deposits. These facts lead one to infer that the lava was erupted after elevation of the sea-floor had taken place. If this has been the case then it would follow that the land must have been submerged and re-elevated subsequently to the outflow of the glaciated dolerite. But for this lava, which has protected the underlying soft beds, we might never have had any record of these interesting oscillations of level. The lava in question seems to accommodate itself to the form of the ground in a more intimate manner than the "pre-glacial" dolerite of Reykjavík, and possibly, therefore, it may be of more recent date. But as I do not know, even approximately, how far it extends, I am unable to offer any opinion upon the question of its probable age.

In the summer of 1897 I observed near Godhavn in the island of Disko, Greenland, a well-developed terminal moraine, indicative of a more severe glaciation than that now obtaining in the island; and a lateral border-moraine which bears testimony to still more marked glacial conditions, and is demonstrably older than the terminal moraine.[1] Possibly these morainic accumulations are not moraines of retreat, but represent glaciations corresponding in age to those which have left their markings on the above described dolerite of Stangarfjall.

III. A Few Conclusions.

I shall not be surprised if this account of the occurrence of glacial deposits and striated rock-surfaces in connection with the "palagonite-formation" of Iceland is received with incredulity. For myself, I could hardly believe the evidence when I first encountered it, and tried to explain it in every possible way other than by glacial action. But the glacial origin of the "breccias" could not be gainsaid. Not only did they present a characteristically morainic aspect, but they yielded numerous well-striated stones, and in places were found to be resting upon grooved and striated rock-surfaces. If the observations I have here recorded be accepted as fairly trustworthy, we cannot avoid the conclusion that glacial deposits, hitherto unrecognised as such, are largely developed in Iceland, or at all events in that part of the island which I have critically examined and referred to in these pages.

As I have had only a glimpse, as it were, into this very promising field of glacial research, I shall not attempt to deal with the glacial succession in Iceland. That must be left for future investigations to determine. Nevertheless there are several conclusions which seem to me obvious enough. Of these the most important in my opinion is that which has reference to successive glaciations. The facts advanced show that Iceland has experienced more than one glaciation before the ejection of the doleritic lavas and their subsequent smoothing and grooving by

[1] *Meddel. om Grönland*, vol. xiv., 1898, p. 297-301.

ice. How many separate glaciations the morainic breccias bear witness to is uncertain. But the repeated occurrence of four separate sheets or beds of morainic breccia seems to render it not improbable that there have been just as many separate glaciations during the accumulation of the so-called palagonite-formation. Even if we discard the evidence furnished by the lowest breccias (in which, it will be remembered, that notwithstanding their morainic aspect, no striated stones occurred), we have still the overwhelming evidence of glaciation supplied by the higher morainic breccias. But whether these indurated ground-moraines represent three, four, or more glaciations, one or other of them must represent the epoch of maximum glaciation in Europe. The glaciation which left the older system of markings on the dolerite of Stangarfjall is of course of later date and may possibly represent the Mecklenburgian stage (Geikie) of Northern Europe, and the "first post-glacial stage of glaciation" of the Alps (Penck). It seems more than probable that a change of climate, corresponding to that which in the Alps depressed the snow-line about 3000 feet, would bring about the total glaciation of Iceland. Indeed, a much less important change in the climatic conditions would suffice to do this. It is therefore quite possible that the younger system of striæ marking the surfaces of the dolerites may be contemporaneous with that re-advance of cold conditions which produced the local glaciers of the "Lower Turbarian stage" of Scotland, and those of the "Second Post-glacial stage" in the Alps.

[The second striated horizon in the moraine of Sudurnes (if it be not a striated pavement) may possibly indicate a third "post-doleritic" glaciation, but until additional evidence be forthcoming, this isolated observation must be left out of consideration.]

So far as I know, all that has been written on the glacial period in Iceland refers to the minor glaciations which supervened after the ejection of the doleritic streams of lava. I say minor glaciations even although the country appears during those stages to have been totally ice-covered. But the mass of the "palagonite-moraines" is so very much greater than that of the loose accumulations of the later glaciations, that we may reasonably infer that the former are the products of much greater ice-sheets. Moreover, the conditions of erosion and accumulation during successive glaciations seem to have differed at the same localities. Further, when we remember that the whole region throughout which the palagonite-formation occurs has been extensively fractured and consequently has experienced many subsidences—and when we reflect that all these important deformations of the land-surface took place subsequent to the accumulation of the uppermost morainic breccias, we are led to suspect that the area over which the older glaciations prevailed may have considerably exceeded that which now exists. Probably conclusive evidence on this point may be obtained by studying the directions of the oldest glacial striæ all over the country, and more especially in the north. Unfortunately, however, the striæ in question are not very likely to be accessible in many places.

It would probably also be of great interest to determine the relations of the pliocene shell-beds near Húsavík, North Iceland, to the "tuff- and

breccia-formation." As I have obtained a grant from the Carlsberg Fund, Copenhagen, to enable me to continue these investigations, I hope to do so on the lines here indicated.

About 5500 square miles of the total area of Iceland are at present covered with glaciers.[1] The country, therefore, would seem to be in a state of glaciation comparable to that obtaining in Scotland during the fourth glacial epoch as defined by Professor Geikie. Now, if Iceland were to be once more totally glaciated, should we term that final ice-invasion a separate stage of glaciation, or merely an oscillation of the existing glaciers? Would the present inhabited condition of Iceland be considered an inter-glacial epoch, or merely a stage of temporary glacial retreat?

Such consideration must be kept in view when we are discussing whether the old ground-moraines described in this paper have been laid down by an oscillating ice-sheet or during separate glacial epochs.

In Búrfell two bottom-moraines are separated by 150 to 200 feet of basalt on the striated surface of which the upper moraine reposes. Possibly, however, that basalt does not mark the lowest inter-glacial horizon.

To the next succeeding inter-glacial horizon probably belong the conglomerates of Stangarfjall, Bringa, and Hagafjall, which are supposed to be of fluviatile origin. Perhaps also the columnar dolerite of Stangarfjall should be included here. The existence of those conglomerates at such heights and so far inland suggests at least a very considerable oscillation of the ice-sheet. Moreover, we must not forget that the conglomerates in question are buried underneath masses of various volcanic products. [While some of the old gravel-beds may well represent old river-channels, in other places, as in Hagafjall and Bringa, they had more the character of lacustrine deltas or *cônes de déjection.*]

The next interval between two glaciations is that marked by the so-called "pre-glacial dolerites," which henceforward cannot claim to be more than inter-glacial. "At the time these pre-glacial lava-beds were laid down, the country had pretty much the same essential contours that it has at present."[2] But when the uppermost of the "palagonite-moraines" (as in Berghylsfjall and Hagafjall) were laid down, the relief of the country as we have seen differed greatly from that which now obtains. In the interval of time that separates these morainic breccias from the eruption of the later lavas, the most radical changes in the contours of the country had been effected, chiefly perhaps by subsidence. The southern lowland of Iceland cannot date farther back than this inter-glacial epoch.

It is not improbable, indeed, that the essential contour-lines or surface-features of the whole island, so far as these are older than the later outflows of dolerite, came into existence during this inter-glacial epoch. We cannot tell at what particular stage the later dolerites were erupted, but we know that the changes of relief which were effected during the inter-glacial stage in question were very much greater than those which

[1] Thoroddsen, *Explorations, etc.*, p. 42.
[2] Thoroddsen, *Explorations, etc.*, p. 35.

have taken place since the outflow of the doleritic lavas. And yet these lavas have been glaciated more than once, and we do not know how long they had to wait for their first glaciation.[1]

We seem therefore justified in coming to the conclusion that the two glaciations in question have not been the result of comparatively insignificant oscillations of an ice-sheet, but were really separated by a protracted period. The very occurrence indeed of the inter-glacial streams of lava over such great areas suffices to show how extensively the ice-sheet melted away. It seems to me highly probable, that *all* the so-called "pre-glacial" lavas are in reality inter-glacial.[2]

Furthermore, the evidence leads to the inference that the time which has elapsed since the last ice-sheet disappeared from the southern lowland of Iceland, is very short as compared to the inter-glacial epoch that intervened between the first of the glaciations experienced by the dolerites, and that next preceding it.

Whether the supposed marine deposit which underlies the glaciated lava on Tungufljót dates back to the closing stages of the inter-glacial epoch just mentioned, or whether it ought rather to be ascribed to an interval separating the two glaciations which are represented by the two systems of striæ upon the surfaces of the later dolerites, future investigations must be left to determine.

No doubt many additional conclusions are suggested by the observations recorded in this paper, but I do not care to consider these at present. As already stated, the chief object of this paper is to point out that there exists in Iceland much hitherto unsuspected evidence of former glacial action. I am indeed sanguine enough to think it is not improbable that the records of the glacial period have been more fully preserved here than elsewhere. For it is obvious that the conditions for the protection and preservation of glacial deposits have been with us somewhat exceptional. While in other lands, free from volcanic activity, each succeeding ice-sheet has partly destroyed and partly covered up the deposits of its predecessor, in Iceland the moraines have been greatly sheltered by the products of volcanic eruptions which overlie them. Moreover, crustal movements have contributed directly towards the same end by placing the old moraines beyond the reach as it were of succeeding glacial invasions. Not improbably, too, some rocks of the "tuff- and breccia-formation" may be due to the direct interaction of volcanic and glacial forces.

The important part played by volcanism as a conservator of the Icelandic glacial accumulations is evidenced by the fact that the "tuff- and breccia-formation" is mainly confined to that belt of the country which has continued to witness volcanic activity ever since Tertiary

[1] So far as I am able to judge, the columnar dolerite overlying the conglomerate of Stangarfjall is not to be confounded with "the pre-glacial dolerites" but belongs—together with the underlying conglomerate—to the next preceding inter-glacial epoch. It is also clear that at the time this rock was formed, the relief of the country was widely different from the present, what is now the top of a mountain-ridge being then the bottom of a river-channel.

[2] By means of the inter-glacial lavas it might perhaps be possible to ascertain whether the glacial covering of Iceland was less extensive at the time of their eruption than it is now.

times. It would certainly be astonishing if the "palagonite-moraines" were totally absent outside this belt, but such is not the case. From the maps and scientific communications of Dr. Thoroddsen, we learn that patches of the "tuff- and breccia-formation" occur at several places throughout the basaltic areas of Iceland. But with these exceptions, the areas referred to appear to have been stripped of their older moraines.

In the description of his travels in south-eastern Iceland in the summer of 1894, Dr. Thoroddsen remarks: "In the course of this journey it became clear that the palagonite-breccia to the north of Vatnajökull has a much greater extension towards the east than one had at first supposed. I have before shown that in the west of this country the great breccia-formation is younger than the basalt, and this is confirmed here, the breccia and tuff everywhere being found to rest on the basalt. . . . At several other places also small, thin patches of breccia can be observed overlying the basalt."[1] This is near the east coast. In the west of Iceland isolated patches of breccia resting on basalt also occur, as, for example, at Strútur, Vikrafell, and Sandfell. And seeing that the "tuff- and breccia-formation" likewise puts in an appearance, both in the extreme north and the extreme south of the country, we could hardly expect better evidence of the former wide extension of our glacial formation. But in the basalt regions, where the moraines were not protected by overlying volcanic rocks, they were naturally subjected to the repeated attacks of the ice-plough, while it is obvious that they could not escape the denudation carried on during inter-glacial epochs.

I have examined but a relatively limited portion of the area occupied by the "palagonite-formation," and it is conceivable that this formation may have a different character in the districts I have not visited. Even were this the case, however, it could not affect the evidence which I have adduced. But it is in a high degree improbable that the glaciations, of which the "palagonite-moraines" are the records, could have been restricted to those places only where these moraines are now met with. And, therefore, I fully expect to find that indurated ground-moraines will prove to be of common occurrence in other regions where the "palagonite-formation" has been detected.

In part proof of this I may mention that my friend Mr. Páll Lýdsson has met with what he takes to be a "palagonite-moraine" at several places in the narrow and deep valley of the Thjórsá called Gljúfurleit, about four or five (Danish) miles to the north-east of Búrfell. He makes special mention of a sheet of morainic breccia reaching a thickness of probably 200 feet, and resting on columnar basalt, the fine columns of which measure 30 to 40 feet in length. Again, turning to the literature of the subject, I find that the breccia of the Strútur, in the west of Iceland, is described by Thoroddsen as "of a greyish colour and poor in palagonite; only a few reddish-brown portions are seen; now and again also a fine-grained, stratified tuff."[2] Further, in a very

[1] *Dansk geograf. Tidskrift*, Bd. xiii. p. 203.

[2] Thoroddsen, "Geolog. Iagttag. paa Snæfellsnes i Island."—*Bihang till K. Svenska Vet. Akad. Handl.*, Band xvii. Afd. II., No. 2, p. 33-4.

interesting report on his travels in Vesturskaptafells-sýsla, South Iceland, in 1893, the same author gives a detailed account of the palagonite-formation. He remarks that in extensive exposures and long natural sections in the regions occupied by the tuff- and breccia-formation, the breccias over wide areas are sometimes crowded with very large, angular blocks of basalt irregularly distributed through the rock. "One may suppose," he says, "that the explosions by which fragments of such a size were scattered broadcast over areas so extensive must have been much more energetic and powerful than those which take place nowadays. It is conceivable also," he continues, "that the blocks may have been distributed by some other agency. But they give no indication of having been transported either by ice or water."[1] This description, so far as it goes, would apply very well to large portions of the section exposed in Sandá, but the breccia seen in that section is beyond doubt a true bottom-moraine.

In 1883 the well-known German glacialist, Dr. K. Keilhack, visited Iceland and made a number of very valuable observations on the geology of the island. With reference to the conglomerates which occur in the south of the island, near the Eyjafjalla and the Mýrdalsjökull glaciers, he writes as follows:—"In many places in Southern Iceland the Miocene contains true conglomerates, in which occur blocks exceeding a cubic foot in size. The structure of these coarse accumulations reminds one of that of the Icelandic glacial formations, to which they have an extraordinary resemblance. One sees imbedded in a firmly cemented ground-mass blocks of all sizes lying higgledy-piggledy. And so greatly does the structure recall that of recent terminal moraines that it is only when we remember that the cementing material of the conglomerate is tachylytic, and that the overlying strata, hundreds of mètres in thickness, consist of a great succession of basalts and bedded tuffs, that we can avoid thinking that these completely structureless masses are the products of glacial action." Dr. Keilhack rejects the hypothesis that these "conglomerates" are deep-sea deposits, and is of opinion that they have either been accumulated along the coasts of a shallow sea, to which volcanic ejecta have been carried down in the form of rolled stones and fine-grained materials, or they are simply river-deposits, which, he thinks, is perhaps the more probable conclusion, seeing that the formation contains no traces of a marine fauna.[2]

In the report on his travels in Vesturskaptafells-sýsla, referred to above, Dr. Thoroddsen records some further observations on similar conglomerates, and remarks that "in these conglomerates, old and young alike, the boulders are rarely so well rounded as those of the rivers or the sea-beach; but they present," he continues, "a greater resemblance to morainic material which has been partly rounded by the action of glacier-brooks."[3]

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[1] *Dansk geograf. Tidskrift*, Bd. xii. p. 201.

[2] Keilhack, "Beiträge zur Geologie d. Insel Island."—*Zeitschr. d. deutsch. geol. Ges.*, Bd. xxxviii. (1886), p. 384-5.

[3] Thoroddsen, *Dansk geograf. Tidskrift*, Bd. xii. p. 203.

The rocks thus described by Dr. Keilhack and Dr. Thoroddsen seem to differ considerably from the conglomerates observed by me last summer. But the descriptions given by those authors[1] would apply very well to such a rock as the lower moraine of Bringa or to the 100 feet breccia of Búrfell, which, it will be remembered, rests upon a striated surface of basalt.

Dr. Thoroddsen does not agree with Dr. Keilhack in ascribing to these conglomerates a Miocene age, but is inclined to the opinion that they are much younger. According to him the conglomerates seem to have been accumulated not long before the glacial period and under wet climatic conditions.[2]

Although Dr. Keilhack was much struck with the morainic aspect of his conglomerates, he plainly rejects the idea of their glacial origin. I can hardly do so, for I have seen rocks which, so far as I can judge from the descriptions by Dr. Keilhack and Dr. Thoroddsen, are of similar character to the "conglomerates" examined by them, and yet the rocks I refer to rest upon a surface which is as distinctly glaciated as any of those I have seen along the margin of a modern glacier.

Although my conclusion as to the glacial origin of a part of the "palagonite formation" originated in the field, and was as far as possible from being suggested by anything I remembered to have read in works treating of Icelandic geology, yet I am quite willing to admit that the observations of Dr. Keilhack, referred to above, might well have formed the starting-point of some such theory—indeed, they might have done so any time within the last seventeen years.

Hitherto it has chiefly been volcanic Iceland which has received the attention of geologists. It is to be hoped that many will be able ere long to satisfy themselves by visiting our country that glacial Iceland is not less deserving of study.

In conclusion, I desire to express my heartiest thanks to those who have encouraged and helped me in my work, among whom I would specially mention Professor N. V. Ussing of Copenhagen. To Dr. Thoroddsen I am also indebted for his kindness in placing some of his journeying outfit at my disposal last summer. I am grateful, too, for the kindness which I have received from geologists and others since I came to Scotland. Professor Geikie and Messrs. Peach, Horne, and Goodchild of the Geological Survey have shown me much attention. I am also deeply indebted to Mr. A. Mackinnon, to Mr. W. Campbell of Tullichewan Castle, and last, but not least, to Mrs. Disney Leith of Westhall, who, among other things, was kind enough to help me with my English while preparing a part of this paper.

I shall only add that Professor Geikie has been good enough to revise my manuscript, and to help me over the difficulties which beset one who attempts to express himself in a language with which he is not thoroughly familiar.

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1 They make no mention, however, of striated stones as occurring in the conglomerates they examined.

2 *Dansk geograf. Tidskrift*, Bd. xii. p. 203.