NOTE:

The typewritten "Đ" = Icelandic "Đ" (soft th).
" "đ" = Icelandic "ð" (").
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THE GEOLOGY OF VIĐEY, S.W. ICELAND: A RECORD OF IGNEOUS ACTION IN GLACIAL TIMES.

by

MARTIN A. PEACOCK, B.Sc., L.R.A.M., Carnegie Research Fellow,

University, Glasgow.

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I. INTRODUCTION.

1. OPPORTUNITY AND REASONS FOR A DETAILED SURVEY.

At the commencement of the 1924 geological expedition to Iceland, which was conducted by Dr. G.W.Tyrrell and the present writer, aided by a grant from the Carnegie Trust, the author took advantage of his earlier arrival in Iceland by devoting his time to a detailed survey of Viðey, a small island which lies three miles E.N.E. of Reykjavík. His interest having been aroused by a study of the curious rock specimens which Mackenzie collected from that locality in 1810 (author, 1925), the writer intended at first to make only a rapid examination of the island in order to ascertain their field relations, and , if possible, to determine their mode of formation.
A day's field work, however, convinced him that a more protracted survey would be amply repaid, and this was accordingly undertaken; during two days, out of the total of ten which were devoted to this work, the writer enjoyed the invaluable

assistance of Dr. Tyrrell.

The opportunity of constructing a large-scale geological map was offered through the kindness of Mr. Eggert Briem, the owner of the farm on Viðey; Mr. Briem, who possesses a unique blue-print of the original Danish ordnance survey of Viðey on the scale of 1 : 5,000, with a vertical contour interval of 2 m., provided the writer with every facility for tracing this map. The tracing thus obtained forms the topographic basis of the geological map accompanying this paper.

2. PREVIOUS WORK ON VIÐEY.

Mackenzie collected 20 specimens from the neighbourhood of the farm house on Viðey, and the appendix to his "Travels in Iceland" (1812) contains some notes on the appearance of these specimens, and their relations in the field.

Bunsen gives analyses of two basaltic rocks from Viðey in a lengthy paper on the chemical characteristics of the Icelandic volcanic rocks (1851, pp. 202 and 265).

Penck, in the course of an extended paper on palagonitic and basaltic tuffs, has described a palagonite-tuff from Viðey (1879, pp. 512-513).

Keilhack mentions the palagonite-tuffs of Viðey in connection with the view which he once held that the Palagonite-Formation of Iceland was older than the Miocene Basalt-Formation (1886, p. 390).

Rosenbusch quotes analyses of a palagonite-tuff from Viðey, and of the contained "sideromelan" fragments, but fails to indicate their source (1910, p. 407).

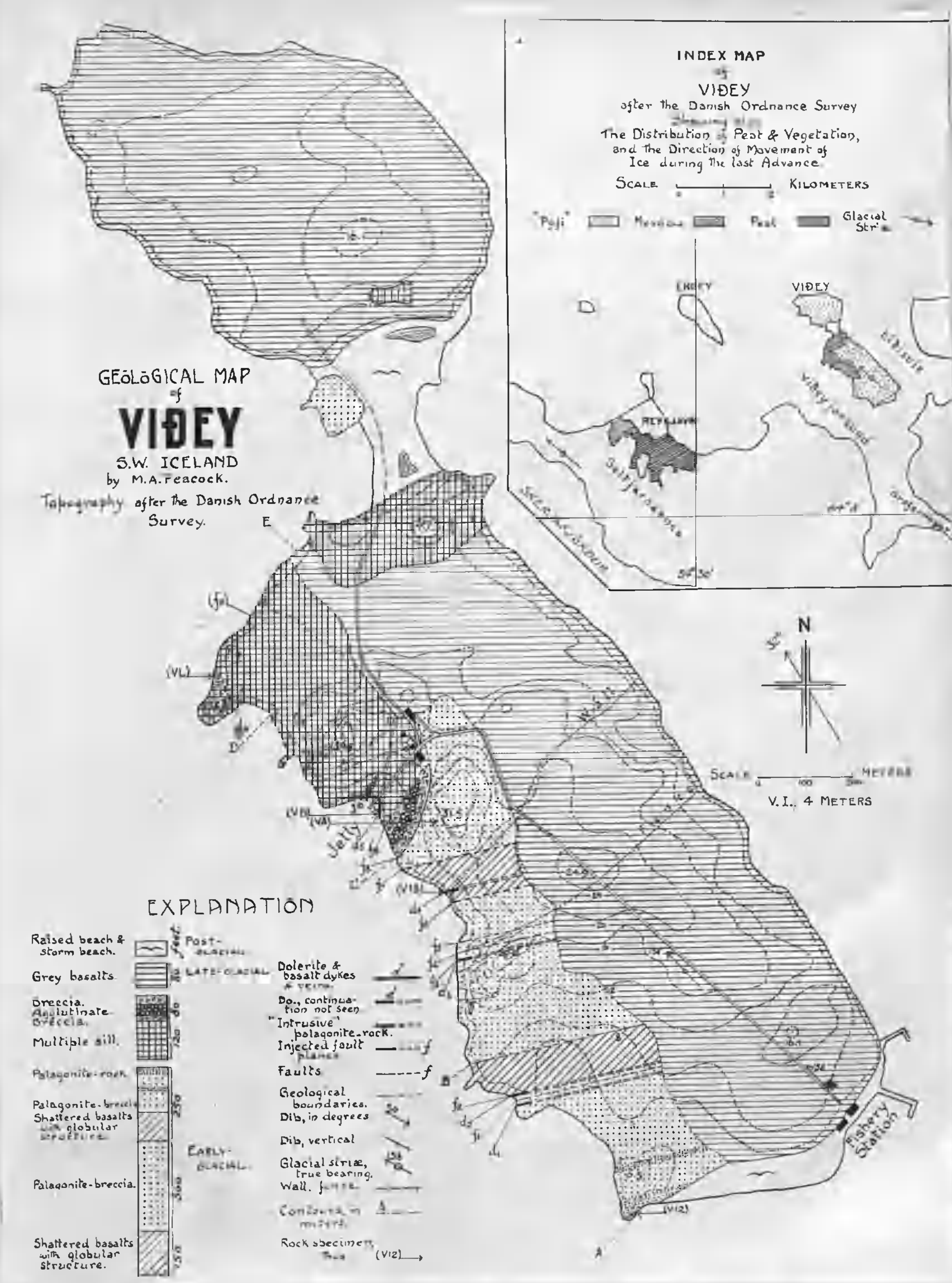
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Fig. 1 .

Thoroddsen, on his geological map of Iceland on the scale of 1 : 600,000, indicates Viðey uniformly with the colour devoted to the Pre-glacial Basalt Formation; in connection with columnar structure he twice refers to Viðey in his "Island" (1906, p. 249).

Pjeturss, who originally regarded an agglomerate-like rock on Viðey as a Pre-glacial vent* (1910, p. 6), now looks on it as a "dislocation breccia"**.

The present writer recently described and figured one of Mackenzie's specimens of palagonite-tuff from Viðey (1925, pp. 309-310, and Pl. IV., Fig. 8), and also a palagonite-dolerite from the same locality (*ibid*, pp. 285-286, and Pl. III., Fig. 4).

* "Füllung eines tertiären Ausbruchkanals."
**This was the view which Dr. Pjeturss expressed to the writer in June, 1924.

II. TOPOGRAPHICAL AND GEOLOGICAL OUTLINE.

1. TOPOGRAPHICAL OUTLINE.

Viðey, with a length of 2 miles and an average width of ½ mile, lies 3 miles E.N.E. of Reykjavík with the direction of its greatest length occupying a N.W.-S.E. position. The island divides into two unequal portions, the smaller, northern portion being connected to the larger portion to the south by a narrow isthmus. The island is a low table-land with an almost continuous, precipitous coastal scarp which is followed with little deviation by the 8 m. contour line. Rising from this low plateau are a number of knolls, the highest of which are 31.5 m . point, 200 yards S.E. of the farm house, and 30.5 m. point lying about the same distance to the W. of it; less conspicuous are 29.0 m. point, near the junction of the fence with the S.W. shore, and 20.1 m. point on the S.E. side of the is~~muth~~thmus.

2. GEOLOGICAL OUTLINE.

The following five formations, in ascending order, can be distinguished: 1. The Palagonite Series, 2. The Multiple Sill, 3. Breccia and "Agglutinate", 4. The Grey Basalts, and 5. Late-glacial and Recent Deposits.

The Palagonite Series consists of a double, descending sequence of palagonite-breccia with associated palagonite-rock, globular basalts, and fine-grained, shattered basalts. This series has been greatly disturbed by faulting, and has been extensively injected by igneous bodies of various dimensions.

By far the greatest of these intrusions is the multiple sill which intruded the palagonite series in ~~at least~~ two acts; that part of the palagonite-series which originally overlaid, the sill has been removed by erosion.

At the only visible junction between the sill and the palagonite series a fault-rock is found, the breccia and "agglutinate", which was formed during relative movement between the sill and the palagonite series at a stage when the former had not yet completely consolidated. This is the rock referred to by Pjeturss (p. 4).

The above rocks are overrun by a sheet of grey basalt whose original connection with the extensive grey basalts of

Reykjavík is at once apparent; the grey basalts are undisturbed and not injected.

At the S. end of the island, and on the isthmus, are found Post-glacial or Recent beaches, while the greater part of the whole island is covered with soil and vegetation.

III. DESCRIPTION OF THE FORMATIONS.

1. THE PALAGONITE SERIES.

The palagonite series occupies an irregular belt on the S.W. shore. The series terminates at the N.W. end against the breccia S. of the farm house; at the S.E. end it is covered by raised beach, while to the N.E. it is overrun by the grey basalts. Although actual contacts between the palagonite series and the grey basalts were never seen, the mutual boundary was determined, with only a small possible error, by surface outcrops. Where the boundary is dotted, outcrops are lacking, and its position was determined by the nature of the soil surfaces and the covering vegetation. Surfaces overlying the palagonite series are even, and bear a comparatively green grass, on account of the greater age of these rocks and their more friable nature; while the soil surface overlying the grey basalts reflects the blocky nature of these younger and less decomposed rocks, and the grass it carries is distinctly less green, and has a habit of growing in clumps. The boundaries between the individual members of the

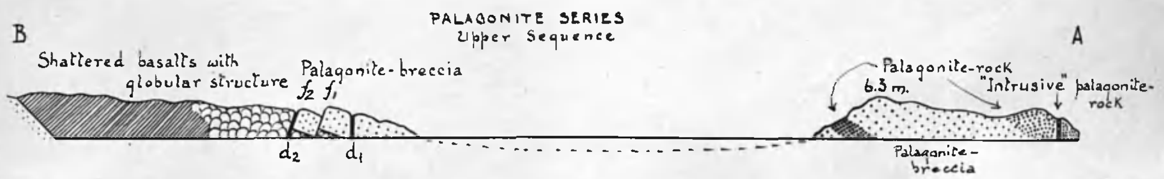

Fig. 2 . - Section along the S.W. shore of Viðey, between the points A and B on the map, Fig. 1 .

series are less distinct; their apparent parallelism, as indicated by the trend of some of the dykes and one accurately measured direction of strike, has been idealised on the map. The nature and structure of the palagonite series is best seen in the S.W. shore section; a detailed account of this section, illustrated by a continuous diagram, will therefore be given.

The bluff headland which forms the southern extremity of the island (Figs. 1 and 2) is built of a friable, dark-brown tuff, which, from subsequent microscopic examination, it was decided to designate "palagonite-rock", from the homogeneous nature and highly palagonitised condition of the vitreous fragments which constitute it. In the field it weathers into rounded masses which are traversed by a rude system of joints from which no certain bedding direction could be deduced. Cutting the brown palagonite-rock at the southernmost point, and in a line with the fishery station, is a vertical, greatly shattered , dyke-like body about 2 feet thick, of a rock which is essentially similar to the mass which it intersects; this rock is mapped as "intrusive" palagonite-rock, but the conjecture that it represented a palagonitised, originally coherent intrusion, was found, on microscopic examination, to be erroneous. Just below 6.3 m. point the brown palagonite-rock merges gradually into an almost black, vitreous rock which is indistinguishable from the "intrusive" palagonite-rock just mentioned.

At the southernmost point the brown palagonite-rock is almost free from included blocks, but as 6.3 m. point is approached angular included basaltic blocks appear in great numbers, varying in size from that of a fist to 4 feet in diameter. One specimen, taken near the S. point, is a dense, black basalt, while near 6.3 m. point the prevalent type is a dense, matt-blue basalt with a few glassy felspar microlites, and a similar vesicular basalt in which the steam cavities are filled with minerals.

Proceeding N.W. along the shore the tuff changes somewhat in character; in addition to being charged with large angular basaltic blocks, as is seen in Pl. I Fig. 2 , which is reproduced from a photograph taken on the shore 350 yards N.W. of the S. point, it contains a host of black, vitreous fragments of highest velvety lustre, and of an average size of 2 mm. This rock will therefore be designated palagonite-breccia to distinguish it from the palagonite-rock of the S. point.

A few yards farther N. the palagonite-breccia passes into fine-grained, shattered basalt with occasional globular structure. The inclined plane of junction has been cut by a fault (f_1), while a few yards farther N. another fault (f_2) brings the palagonite-breccia against the globular basalts; a few yards S. of f_1 the palagonite-breccia has been cut by a sinuous dyke (d_1) of coarse basalt, 2 feet in thickness, while f_2 has been injected by a 4 foot dyke (d_2) of a compact, blue, fine-grained basalt of conchoidal fracture.

The palagonite series so far described is thus composed of a sequence of palagonite-breccia associated with palagonite-rock, and underlain by fine-grained basalts with globular structure; these two members follow conformably in the field, and entirely lack the features of a surface lava flow.

Still continuing N. (Fig. 3) the shore section reveals persistent palagonite-breccia which has now developed a well-marked bedding direction; the bedding-planes, which at the same time are joint-planes, divide the rock into massive, rounded slabs which dip to the S. with a fairly consistent inclination of 35 degs. As 20.2 m. point is approached a massive, irregular body of globular basalt appears beneath the palagonite-breccia. This association continues, and is thrice repeated by a series of four step faults (f_3, f_4, f_5, and f_6) whose downthrow side is to the N; the plane of f_3 has been invaded by an irregular basaltic vein d_3. This succession represents a second and distinct sequence which is older than the one first described.

To the N. of f_6 shattered basalts are again found; these appear to be the down-faulted continuation of the basalts which form the base of the first sequence. They show sporadic globular structure, and are cut, in the vicinity of the junction of the farm wall with the shore, by a coarse dolerite dyke (d_4) a specimen of which is indistinguishable from the dolerite of the multiple sill.

The globular basalts, on which the palagonite-breccia rests conformably, are characterised by the spheroidal structure

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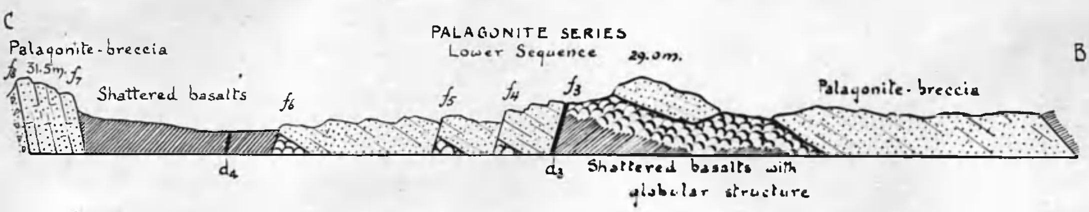

Fig. 3 . - Section along the S.W. shore of Videy, between the points B and C on the map, Fig. 1 .

which is associated with pillow-lavas. As the Videy examples are certainly not lavas, the writer prefers to apply to them the purely structural term globular basalt, especially as this term was used by Johnston-Lavis to describe precisely the same rock, related in the same way to palagonite-breccia, at Reykjanes, S.W. Iceland (1895, p. 445). The globular areas vary from 6 inches to 4 feet in diameter, each area being bounded by a vitreous skin about 2 inches in thickness; the vitreous shells of adjacent globular areas coalesce to form a continuous meshwork which is brought into relief by the action of differential erosion. Internally the spheroids are jointed into rude, radial columns, and also, to a lesser degree, into concentric shells; both the interiors and the vitreous skins are somewhat vesicular.

As we continue northwards from f_6 it becomes manifest, by the increasing severity of the shattering which the basalts have suffered, that a centre of disturbance is being approached. At f_7 the shattered basalts are faulted against a great block of palagonite-breccia in which the bedding-planes, which are defined by layers of enclosed blocks, stand vertically, while the direction of strike bears 78 degs. true. In addition to appearing in the continuous section just described, the palagonite series is represented by two small, irregular blocks which were caught up by the sill, and which are exposed 100 yards N. of 12.8 m. point. Surface exposures do not further elucidate the structure of the palagonite series.

Outcrops of palagonite-breccia are observed on the rising ground surrounding 29.0 m. point and 31.5 m. point, and there is also a flat-domed exposure of the same rock on the W. side of the isthmus; exposures of the associated globular basalts and shattered basalts were not seen.

Any estimate of the thickness of the palagonite series is attended by serious difficulties; the chief of these are the total absence of bedding direction in the basalts, the lack of consistent bedding in the breccia, and the severe dislocation to which the whole series has been subjected. On the stretch between the first appearance of the breccia north of f_2 and its termination at f_6, a distance of 325 m. at right angles to the measured direction of strike, the dip of the palagonite-breccia is fairly constant; allowing for the faulting the thickness works out at 300 feet. The thickness of the globular and shattered basalts may be roughly estimated at 150 feet, giving 450 feet for the total thickness of the older sequence; the younger sequence of the S. end is much less massive, and to it a total thickness of 250 feet may be attributed. Thus the total thickness of the palagonite series may be of the order of 700 feet.

2. THE MULTIPLE SILL.

The rectangular areas surrounding 30.5 m. point and 20.1 m. point S. of the isthmus, and the small exposure N. of it, are occupied by rocks which differ completely from those described above. The boundaries between these areas and the grey basalts are clearly defined by surface exposures, and changes in the soil surface and vegetation; the short boundary between the sill and the breccia and agglutinate, and between it and the palagonite series, is less clearly observable, and is indicated by a broken line.

Returning to the shore section (Fig. 4), at the northern boundary of the breccia and agglutinate we find massive columns of vesicular dolerite which are tilted southwards from the vertical to the average extent of 30 degs.; they continue with uniform inclination until we reach the wedge of agglutinate just N. of the jetty. A few yards S. of the jetty the massive basal columns are cut by a vertical doleritic dyke (d_5) which is 20 feet thick, and displays perfectly developed horizontal columns. The planes of contact between this dyke and the basal columns of the sill have been injected by tachylytic veins, while the dyke itself has been bisected vertically by a similar injection. The dyke has not disturbed the regular inclination of the basal columns, and Thoroddsen probably had this case in mind when he wrote: "Es kommt vor dass Basalt- oder Doleritlagen mit Säulenstruktur von Basaltgängen durchsetzt sind, ohne dass deshalb die Säulen sich im geringsten verschoben haben (Videy, Stapi)" (1906, p. 249).

Occupying the area between the vertical dyke and the breccia to the S. of it, and resting on the basal columns, is found a mass of columnar basalt of complex radiate structure; this mass is probably not unconnected with the vertical dyke. The rock constituting both is fine-grained and compact com-

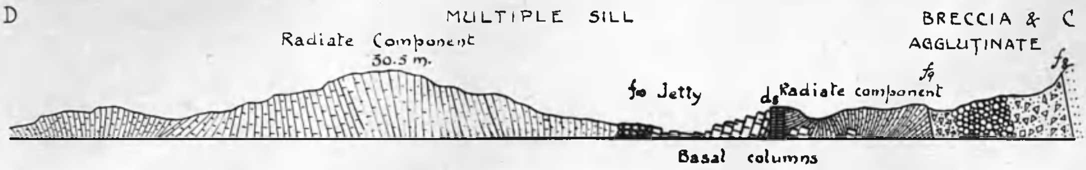

Fig. 4 . - Section along the S.W. shore of Videy, between the points C and D on the map, Fig. 1 .

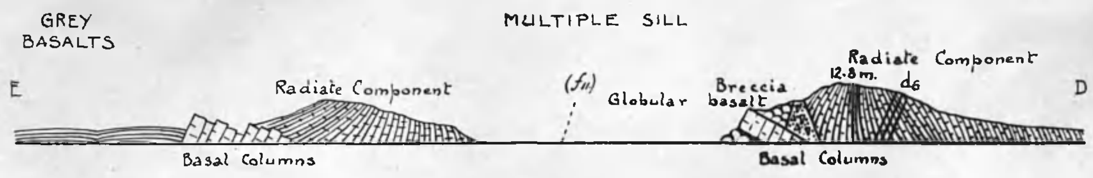

Fig. 5 . - Section along the S.W. shore of Videy, between the points D and E on the map, Fig. 1 .

pared with the vesicular dolerite of the basal columns, but, on microscopical examination, its dissimilarity to the coarser rock was found to be almost solely textural. The sill is therefore a multiple one, consisting of two components, the older basal columns and the younger radiate component, which are structurally different but petrographically comparable.

To the N. of the smaller agglutinate exposure the upper, radiate component reappears; the columns constituting it increase in width as 30.5 m. point is approached, specimens of the rock revealing a corresponding coarsening of grain. At 30.5 m. point the intrusive body reaches a vertical thickness of 100 feet, while the rock is distinguishable from the dolerite of the basal columns only by its lack of vesicles. Proceeding northwards the radiate component is seen to continue, showing variations in column diameter accompanied by considerable variations in the orientation of the columns; this is particularly well seen at 12.8 m. point (Fig. 5) which is built of finely curved, radiating columns. On the S.E. side they are cut discordantly by three parallel injections (d_6), one foot thick, of dense blue basalt with tachylytic margins.

On the N. side of 12.8 m. point, wedged between the radiate component and the sloping surface of the basal columns which reappear at this place, is found an irregular mass of breccia and globular basalt. The breccia contains angular blocks which reach 4 feet in size; blocks of dense blue basalt are the commonest variety, while blocks of the dolerite of the sill are less frequent. The mass of the globular basalt presents an irregular triangle some 6 feet wide, which is accompanied by a smaller outcrop underlying the basal columns. Near the plane of contact between the basal columns and the globular basalt the dolerite of the former becomes suddenly fine-grained and then tachylytic in the space of 2 inches, thus showing that the sill intruded the globular basalt, and is therefore younger than the palagonite series of which the globular basalt is a conformable member.

A few yards farther to the N.E. the radiate component of the sill reappears, and soon terminates unconformably against another outcrop of the basal columns which again show their persistent inclination to the S. These columns rise rapidly to a height of 20 feet, and then terminate against the grey basalts which will be described later.

The visible thickness of the sill is 120 feet; in this estimate 20 feet are ascribed to the basal columns, and 100 feet to the radiate component.

3. BRECCIA AND AGGLUTINATE.

In the shore section (Fig. 4) these rocks occupy a short stretch bounded to the S. by the vertically standing palagonite-breccia, and to the N. by the southern margin of the sill; on the surface they occupy an ill-defined, arcuate area.

At the S. end of the shore exposure the rock is a breccia consisting of large, angular boulders of a coarse, vesicular dolerite the same as that which constitutes the basal columns of the sill, bedded in a scanty sandy matrix. Proceeding northwards, the nature of the enclosed blocks changes; in addition to dolerite blocks, which reach 2 feet in diameter, there appear smaller blocks of dense blue basalt, earthy palagonite, slaggy basalt with minerals, and velvety palagonite chips, the matrix consisting of the same materials finely comminuted.

About 20 yards N. of the junction with the vertical palagonite-breccia the agglomerate with which we are now concerned passes without real break into a rock to which Dr. Tyrrell has given the name agglutinate. Weathered masses of this rock have a surface of subangular protuberances which vary from 1 inch in diameter to cobble size; they all consist of the dolerite of the sill. On attempting to loosen a block with the hammer, it as often breaks through as comes away entire. When a block is detached it is seen to have presented moderately plane and smooth faces to adjacent blocks, and to have cohered to these entirely without the help of matrix. A few yards N. of the jetty is found another small wedge of agglutinate which again consists of cohering dolerite blocks without matrix.

While fully agreeing with Pjeturss that the breccia and agglutinate S. of the jetty are not to be explained as the filling of a vent, the writer thinks that the "dislocation-breccia" explanation does not fully meet the requirements of the case unless we make one important stipulation. The cohering dolerite blocks of the agglutinate were certainly derived from the margin of the sill; if dislocation took place at a time when the sill had fully consolidated, the formation of the agglutinate could be explained only by assuming that the heat generated during the period in which dislocation took place was sufficient to render the blocks torn from the margin of the sill plastic and cohesive. Instead of making this somewhat unlikely assumption, the writer is disposed to think that the dislocation was concurrent with the formation of the sill, or at any rate took place late in the consolidatinn period, and that the train of events ~~were~~ was somewhat as follows.

In the act of intrusion the dolerite magma tore away masses of the palagonite-breccia which it intruded, and incorporated them in its margin; cooling proceeded until the edge of the intrusion reached a plastic condition while the interior of the mass was still freely mobile. Faulting, which may have been initiated at this point by the release of underground support, or which may have commenced with the act of intrusion and have continued up to this stage, broke away parts of the semi-rigid edge of the intrusion and kneaded them into spheroidal masses; a slight rise of temperature, caused by this kneading action, sufficed to render the semi-rigid units plastic and cohesive, thus producing on cooling the matrix-free agglutinate.

4. THE GREY BASALTS.

With the name "Doleritformation" Thoroddsen designated the grey, ophitic, olivine-bearing lavas which occupy large areas in the S.W. and elsewhere in Iceland. Recognising the unsuitability of this term, which suffers in German the inappropiate contraction to "Dolerit", Pjeturss has abandoned it in favour of "Grey Basalts", the grey colour being the most striking feature of these ultrabasic lavas. Pjeturss' term will be used in the field description.

With exception of the areas already described Videy is covered by a massive sheet of the grey basalts. The positions of the boundaries between the grey basalts and the older formations has already been given, together with the evidence on which they were determined, and their probable accuracy. The shore affords excellent, continuous sections, and surface exposures are numerous. The rock is remarkably uniform throughout, handspecimens from extreme ends of the island being indistinguishable. It is characterised by a coarseness of grain sufficient to permit the macroscopic recognition of felspar, augite and olivine, together with a minute vesicularity which may partly account for the grey colour and the ease with which it breaks under the hammer.

Structurally the grey basalts, which are Late-glacial in age, have close affinity to the more recent lavas. Sections sometimes show an approach to columnar structure, but more frequently a system of joints has developed dividing the rock into blocks which approximate in shape to that of a keystone. Individual joint blocks often measure a yard each way, while their bounding surfaces are always slightly convex or concave. The significance of this system of jointing was not appreciated until later in the summer when Dr. Tyrrell and the writer examined the magnificent sections through Post-glacial lavas at Þingvalla. In the Allmannagjá, the greatest of the straight gaping fissures in which these sections are produced, a series of successive basaltic flows may be seen in which the surface of each flow is defined, not by a straight line, but by a series of flat arches which are the sectional counterpart of the flat-domed surfaces presented by a lava of this structural type. The interior of one of these arches is seen to consist of a surface layer of small, rude columns arranged radially like the bricks in a brick arch, while the massive interior of an arch is traversed by radial and concentric joints dividing it into keystone-shaped or wedge-shaped blocks. The grey basalts on Viðey are therefore considered to belong to the flat-domed lava type (Icel. "helluhraun"), the surface layer of small columns having been removed by denudation, leaving only the keystone-jointed interiors*.

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* This structural resemblance between the Late-glacial grey basalts and the Post-glacial basalts was noted by the writer in a recent paper (1925, p. 324) in which it was shown that the lavas of the two periods are also closely related chemically.
~~the lavas of~~

The base of the grey basalt escarpment is always deeply buried in a great heap of recently fallen joint blocks. The ease with which degradation takes place in the grey basalt cliff is due to the wide spacing of the joint planes producing correspondingly wide gaps between adjacent blocks, and thus ensuring their complete detachment one from another. The grey basalts on Viðey differ from their Post-glacial structural analogues in the following respect; whereas the average thickness of a "helluhraun" flow, as seen in the Allmannagjá, is perhaps 10 feet, the Viðey escarpment, apparently representing the section of a single flow, reaches a height of 40 feet in the N. part of the island.

The grey basalts on Videy show no signs of disturbance by earth movements, nor have they suffered igneous injection. Their total thickness may be estimated as 80 feet, the 24.9 m. spot-level, near the junction of the fence with the road, being the highest level above the sea reached by these rocks.

5. LATE GLACIAL AND RECENT.

Glacial Markings:- On Videy, as elsewhere in Iceland, surface outcrops of the grey basalts are sometimes ideally moulded by ice action, and carry series of striae whose direction can be accurately measured. That these markings date from the last total glaciation is clearly appreciable on an excursion from Reykjavík, situated on striated grey basalts, to Þingvalla, wich lies on structurally and chemically similar lavas whose original ropy surfaces are untouched by ice.

In the road, near the fishery station at the S. end of Videy, is a fine glaciated outcrop of the grey basalts; it carries a series of well-defined striae which run N.W. at 138 degs. true. Four hundred yards N.W. of this outcrop is a similar exposure bearing striae which run in precisely the same direction. This direction agrees with the direction of extension of Videy itself, and of the neighbouring physical features: Engey, Videyjarsund, Grafarvogur, Seltjarnarnes and the Skerjarfjörður (See Index Map, Fig. 1). The direction of the movement of ice, as measured above, is also in good agreement with the direction of the glacial striae on the mainland as recorded on Thoroddsen's geological map.

Peat and Vegetation:- The narrow belt of low ground running E. and W. between 30.5 m. point and 20.1 m. point is occupied by a peat moss. The peat is cut and dried for fuel, and in trenches is exposed to a depth of 6 feet.

The remainder of the island is covered with grass the nature of which appears to be intimately connected with the particular type of rock underlying the soil on which it grows. The grass covering the grey basalts is a poor variety which has a habit of growing in clumps, and is locally called Þýfi. These clumps have the shape of a deep, inverted bowl averaging 2 feet in diameter; they lie so closely together that progress on foot is rendered difficult. The poverty of the grass is due to the freshness of the underlying rock, while the formation of the clumps is best explained as the result of the action of frost in sorting and piling up the stones in the shallow soil. Hawkes has dealt with this subject in a recent paper (*Geol. Mag.*, 1924, pp. 509 and 511).

The grass growing on the soil derived from the older rocks on the island, the palagonite series and the multiple sill, is rich and green, and entirely free from the clumps described above; this grass is mowed and dried for fodder, while the Þýfi affords but poor grazing, and can hardly be cut. The fertility of the soil on these rocks is a result of their greater age, and their shattered and decomposed condition.

Raised Beach and Storm Beach:- A raised beach of small, uniform, well-rounded grey basalt shingle extends back some 50 yards from the high water mark of the S. shore; its landward boundary approximately coincides with the 2 m. contour*.

* When drawing the geological map alternate contours, 2 m., 6 m., 10 m., etc. of the original blue-print, were omitted.

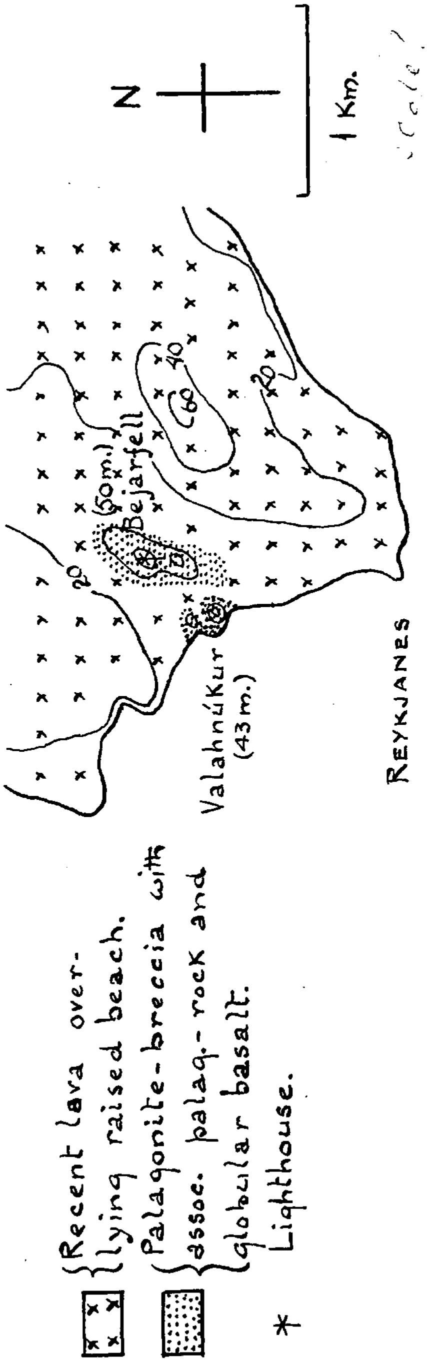

Fig. 6. - Sketch-map of Reykjanes, S.W. Iceland, showing an inlier of the palagonite series overrun by recent lava.

The possibility of this being a storm beach is precluded by the fact that Viðey receives complete protection by the mainland from all winds except those coming from the west and north-west.

The shingle covering the isthmus has more the characters of a storm beach; close to the high-water line, and parallel to it, on either side of the isthmus, the pebbles are banked 6 feet high, while centrally, between these shingle banks, the beach is depressed 3 feet below high-water level.

IV. CORRELATION AND AGE OF THE PALAGONITE SERIES.

Whereas the geological evidence on Viðey suffices to determine the relative ages of the formations, it is inadequate as a basis for the determination of their absolute ages. The identity of the striated, grey basalt sheet with the Late-glacial grey basalts of the Reykjavík district is certain, but to arrive at the age of the older palagonite series we must consider the evidence in other localities where comparable rocks are exposed.

1. REYKJANES.

A complex association of palagonite-breccia, palagonite-rock, and fine-grained basalts with globular structure, disturbed by dislocation, copiously injected, and otherwise closely corresponding to the Viðey succession, is found surrounding the lighthouse at Reykjanes, 35 miles S.E. of Reykjavík (Fig. 6). Johnston-Lavis has partly described this locality, and has advanced an hypothesis to explain the globular structure of the basalts (1885, p. 445). Dr. Tyrrell and the present writer encountered the locality in June, 1924, and the following condensed description is extracted from their joint journal.

The Bejarfell (50 m., the present site of the lighthouse) is an inlier of palagonite-breccia associated with palagonite-rock and globular basalt, and surrounded by a Post-glacial basaltic lava flow; it thus corresponds with the upper sequence of the Videy palagonite series. The Valahnúkur (43 m., the site which the lighthouse occupied in 1885, and from which it was removed on account of extensive recent landsliding) is seen, on the N.W. face to consist of 90 feet of globular basalt overlying palagonite-breccia dipping N.E. at about 30 degs.; on the S., seaward face the relations of palagonite-breccia and globular basalt are complicated, and the mass is traversed by many irregular injections of basalt varying from 6 inches to 20 feet in thickness. The base of the Valahnúkur is covered by sandy raised beach which is indurated by the still younger recent basaltic lava. The Valahnúkur globular basalt thus corresponds with the base of the upper sequence of the Videy palagonite series, while the conformably underlying palagonite-breccia is the counterpart of the rock forming the topmost member of the lower Videy sequence.

Thus the rocks of the two localities are strictly comparable; as regards age, the only inference that can be made is that the Reykjanes rocks are older than the raised beach, being separated from it by an unconformity of unknown extent.

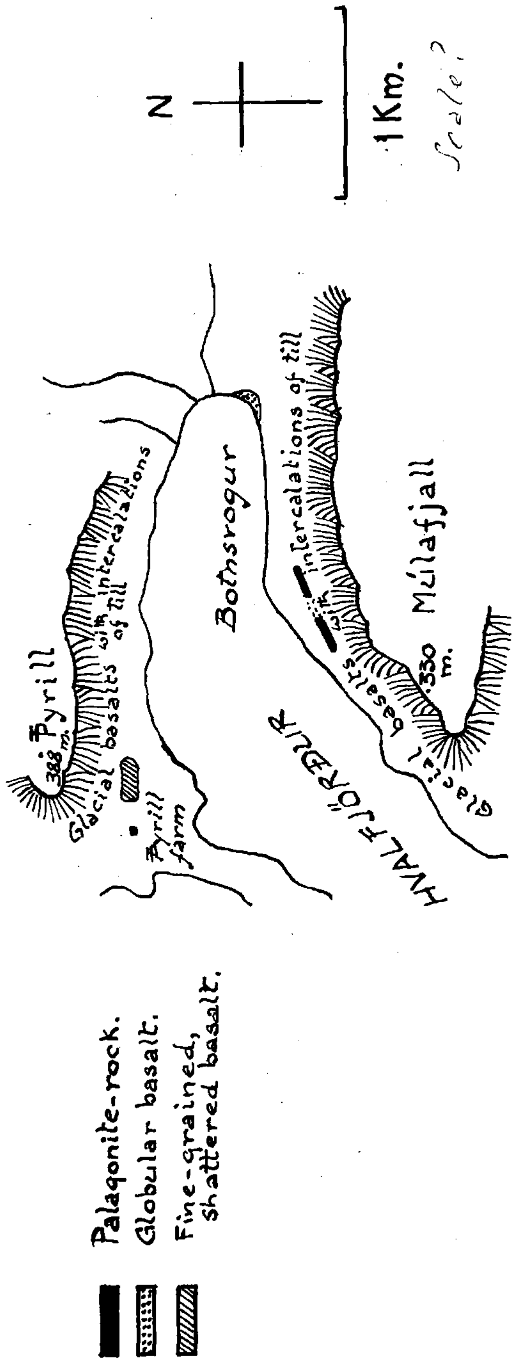

Fig. 7 . - Sketch-map of the head of the Hvalfjörður, showing members of the palagonite series immediately beneath basalts of Glacial age.

2. BOTNSVOGUR, HVALFJÖRÐUR.

On the S. shore of the Botnsvogur (Fig. 7), the eastern extremity of the Hvalfjörður which is 25 miles N.E. of Reykjavík, at a distance of 1 mile from its head, and 60 feet above sea-level, a bed of palagonite-rock 30 feet thick was found. This bed is overlain by a series of basalt flows forming the Múlafjall towards the top of which two massive beds of glacial till are intercalated. The palagonite-rock agrees strikingly with the palagonite-rock of the upper Viðey sequence.

At the head of the Botnsvogur, ~~100 yards E. of the farm Þyrill~~ at sea-level, an exposure of globular basalt was observed; from its position relative to the outcrop of palagonite-rock this globular basalt appears to be the counterpart of the globular basalt of the upper Viðey sequence.

On the N. side of the Botnsvogur, 300 yards E. of the farm Þyrill, a prominent scarp of fine-grained, shattered basalt was observed; the absence in this mass of the structural features of lava, and the resemblance which it bore to the shattered basalts of Viðey, struck the observers at the time and is specifically recorded in their journal. The rocks overlying this exposure are basaltic lavas with massive intercalations of glacial till.

The glacial intercalations in the basalts of the Hvalfjörður region were either not observed or were misinterpreted by Thoroddsen who included them in the Miocene Basalt Formation. That Pjeturss fully recognised the sigificance of the tills is seen from the following: "in den älteren quartären Basalten, wie z. B. am Hvalfjord, vorkommen" (1910, p. 7).

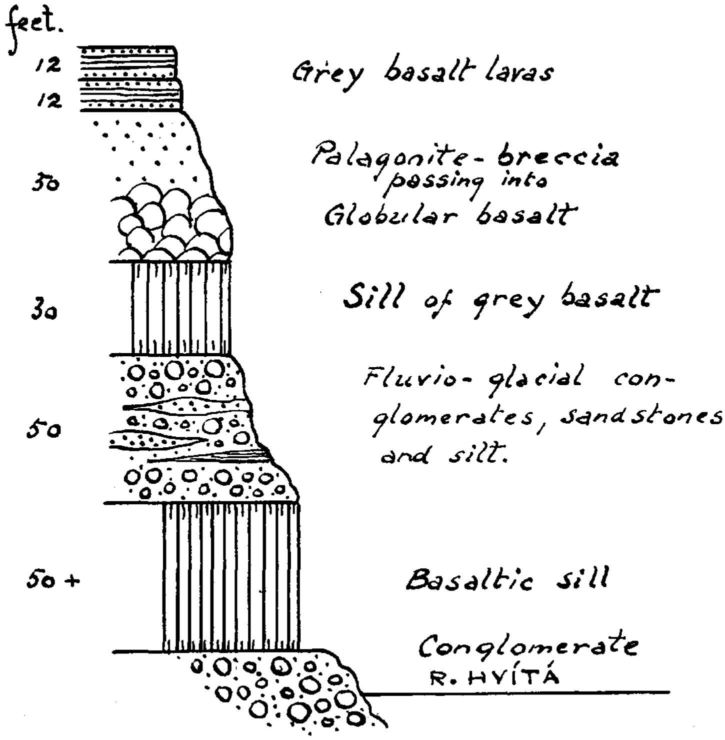

Fig. 8 . - Profile of the W. wall of the gorge of the Hvítá, immediately below Gullfoss, showing the palagonite series resting on glacial sediments, and overrun by the Late-glacial grey basalts.

Thus we have a complete correlative of the Videy palagonite series immediately and conformably underlying a series of glacial basalts; unless the tills in these basalts represent the very earliest glaciation, we may infer that the underlying palagonite series is itself Early-glacial in age.

3. GULLFOSS ~~AND THE HVÍTÁ (ARNESSÝSLA) BASIN.~~ 87

Immediately below the famous waterfall Gullfoss, which lies 5 km. distant on the landward side from the line of highest submergence as mapped by Thoroddsen, the Hvítá enters a magnificent gorge 2½ miles long, with vertical walls exceeding 200 feet in height. In the western wall (Fig. 8), at the head of the gorge, and immediately below the fall, the following succession was observed. At the top there are two flows of grey basalt about 12 feet in thickness; these basalts are seen in the immediate neighbourhood to be highly glaciated. Below these appears a bed of palagonite-breccia with an estimated thickness of 50 feet, which in its lower parts passes gradually into basalt with well developed globular structure. Below this lies a 30 foot sill of grey basalt, fairly dense throughout, and particularly so towards the contacts. The sill rests on 50 feet of typical fluvio-glacial sediments, conglomerate with rounded pebbles, occasional layers of sandstone with a few streaks of pebbles, and at least one lenticle of laminated silt, the whole showing current bedding on a large scale. Below these sediments appears another massive sill, at least 50 feet thick, which rests on a conglomerate forming the bed of the river. Here we have resting on glacial sediments an excellent correlative to the Videy succession.

From the foregoing we may draw the following conclusions: (1), that the association of globular basalt with palagonite-breccia is significant, rather than fortuitous, and that the former always underlies the latter; the apparent reversal of this order at Reykjanes is to be explained, as on Videy (p. 9), as the result of the lower member of an upper binary association resting conformably on the upper member of a similar lower association; and (2), that this rock association in the correlated areas, ~~was formed~~ and therefore also in Videy, was the result of igneous activity in Early-glacial times.

V. PETROGRAPHY.

1. PALAGONITE-BRECCIA AND PALAGONITE-ROCK.

It is proposed to reserve a fuller discussion of the palagonite-bearing rocks until the completion of an investigation of all the rocks falling into this category which were collected on the 1924 visit to Iceland. At present the writer wishes to consider only the evidence which bears on the following points: firstly; Given the requisite conditions, will palagonitisation take place in any basaltic glass, or are only certain basaltic glasses susceptible to this form of alteration? and secondly; Does further investigation of the occurrence and appearance of palagonite glass support the suggestion recently made by the writer, namely that, in addition to its usual occurrence in tuffs, in deep-sea deposits, and in certain dolerites and basalts, palagonite glass may represent extrusive or intrusive, vitreous, basaltic bodies which were originally coherent, and to which the term palagonite-rock might appropriately be applied? (op. cit., p. 309). Incidentally to the first inquiry a value for the H_2O content of the products of palagonitisation was obtained.

a. Hydrotachylyte the Parent of Palagonite. The rock which offers the best opportunity for studying the material which has suffered palagonitisation is a palagonite-breccia in which the alteration process has only partially attacked the vitreous fragments constituting the rock, and in which the unaltered portions are sufficiently large to permit of their mechanical separation. The specimen VA, taken at a point 100 yards S. of the farm (see Fig. 1), has accordingly been chosen for description and discussion. Its appearance agrees closely with Penck's description of a palagonite-tuff from Viey (1879, pp. 512-513), and the analyses of a Viey palagonite-tuff and of the contained "sideromelan" fragments quoted by Rosenbusch (1910, p. 407) appear to have been performed on a comparable rock; the specimen of palagonite-tuff from Viey which the writer selected for description from Mackenzie's collection (op. cit., pp. 309-310, and Pl. IV., Fig. 8) differs slightly from the rock to be described.

The rock is composed of black, angular, vitreous fragments which attain a diameter of 1½ cms.; these fragments have smoothly curved boundaries, and are bedded in a reddish, fibrous matrix. In section (Pl. I., Figs. 1, A; 1, B) three types of fragments may be observed; firstly, pale-brown, slightly vesicular, entirely homogeneous and isotropic fragments which are entirely free from microlites, and which, except for this last property, closely resemble the unaltered core of the palagonite nucleus of a manganese nodule from the South Pacific figured by Murray and Renard (1891, Pl. XVII., Fig. 3); secondly, dark-brown fragments which are traversed by opaque flow-bands, or are dotted with minute ore specks; and lastly, fragments of totally opaque tachylyte. The first stage of palagonitisation is marked by the presence of bright-yellow, bleached borders surrounding all the translucent glassy areas, and completely replacing the smaller of these. It is significant that in the case of the second and third types of fragments the bleaching has left the opaque bands and the ore specks intact, proving that the bleached borders indeed represent an alteration of the margins and not an addition to them, that palagonitisation does not attack glasses which are opaque due to the solution or separation of magnetic iron, and that the homogeneous, translucent condition of the first type of fragment is a primary one, and not a result of the palagonitisation process.

The outer borders of the bleached margins pass into a finely-fibrous, yellow-red, birefracting mineral, while the remaining interspaces are filled by a zeolite to which neither Penck nor the present writer was able to give a name. It is a colourless, isotropic in small fragments and very nearly so in larger pieces; it forms a mosaic of equidimensional grains which possess one good cleavage; it is insoluble in HCl, and has a refractive index which lies definitely between 1.520 and 1.530; and finally, an examination of its flame spectrum revealed persistent lime bands, potash lines for one second, soda continuous but not in great amount, and cesium absent. The standard tables catalogue no mineral with these properties; the accession of potash to analcite, which agrees in some respects with the Videy zeolite, would result in an increase of its refractive index to some value greater than 1.487 (Larsen), and the Videy mineral might therefore be an impure potash analogue of analcite; the available amount is, however, too minute for quantitative determinations.

It was shown that palagonitisation proceeds only in primarily translucent basaltic glasses, and in seeking for a cause for this condition of the glass a primarily abnormally high water content at once suggested itself. In the analysis given by Rosenbusch (<u>loc. cit.</u>) the water content of the unaltered fragments ("sideromelan") is 4.23 per cent; to verify this a piece of the specimen VA was coarsely ground, and small chips of glass, which showed by their clean, lustrous surfaces that they were derived from the unaltered cores, were separated, and their loss on ignition estimated*; the result, 4.38 per cent, is in good agreement with the H_2O value of the older analysis. Washington's Tables (1917) contain four "superior" analyses of tachylyte whose average H_2O value is 1.13 per cent. It is evident that the translucent glass with which we are here concerned differs from tachylyte in possessing a much greater H_2O content, and it is proposed to designate it "hydrotachylyte" in

* The error involved in taking "loss on ignition" as representing "H_2O" is in this case negligible.

in preference to von Waltershausen's "sideromelan", which, apart from being practically obsolete, appears to be less accurately expressive than the proposed name.

From the above it appears that palagonitisation does not take place in the normal, almost anhydrous tachylytes which are characteristically opaque due to the solution or separation of magnetic iron, but attacks only hydrous, translucent basaltic glasses which may be called "hydrotachylyte".

b. The Water Content of the Products of Palagonitisation.

Given the H_2O content of the whole rock, i.e. the unaltered hydrotachylyte together with its alteration products, the H_2O content of the unaltered hydrotachylyte, and also the relative proportions of the two constituents, the H_2O content of the alteration products may be calculated. The H_2O content of the unaltered hydrotachylyte was 4.38 per cent; an estimation of the loss on ignition of the whole rock gave 10.61 per cent, while the average relative proportion of hydrotachylyte was 46.8 per cent*. These figures give 16.1 per cent for the H_2O content of the palagonitisation products. For the same constituent Bunsen obtained 17.85 from the palagonite-rock from Seljadalr, Iceland; Steiger obtained 17.02 in palagonite specks in a gabbroid diabase from Holyoke, Massachusetts; Teall recorded 16.80 in palagonite specks in a basalt from Franz Joseph Land; and the present author found 16.21 in an

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* This was obtained in the following way which depends on the assumption that the specific weights of the constituents are alike; two areas of the slide were photographed and the complete circular photographs weighed. The hydrotachylyte areas were then cut out, weighed, their proportions to their respective complete photographs calculated, and the average of the ~~spective~~ two results taken.

almost completely palagonitised rock from Krisuvík, Iceland (op. cit., p. 312, analyses I, II, III, and H' respectively).

c. The Nature of Palagonite-rock. A typical example of palagonite-rock was found as a dyke-like body cutting the palagonite-tuff of the southernmost point of Viðey (Figs. 1 and 2). If palagonite can replace originally coherent, vitreous basaltic bodies, we would expect that this example, with its apparently intrusive relations, would supply the ideal case.

The handspecimen (V12) is a homogeneous, dark-brown rock which fractures readily, revealing a vitreous, resinoid surface; the fracture is quite irregular, however, never approaching the conchoidal fracture of glasses. The rock further shows numerous specks and threads of a yellowish zeolitic material, and also a few, very small crystals of clear felspar. In thin section this rock is seen to be an exceedingly fine-grained version of the palagonite-rock just described, with certain differences. It contains the same variety of vitreous fragments, but in this case their maximum size is about 1 mm. Whereas in the previous rock the boundaries of the fragments were smooth curves and vesicles were comparatively rare, in the present case the vitreous particles are highly vesicular and their boundaries are typically embayed. In this respect the fragments are similar to those constituting the thin red tuff parting recently figured by the writer (op. cit., Pl. IV., Fig. 10). The vitreous fragments occasionally contain a microlite of fresh plagioclase or greenish pyroxene, but more often these minerals appear as detached, broken crystal fragments in the cementing material. As before, palagonitisation has resulted in the formation of yellow, bleached glass, the finely-fibrous, yellow-red, birefracting mineral, and finally, the almost isotropic zeolite; on account of the smallness of the original vitreous particles palagonitisation is highly advanced, the proportion of unaltered, translucent glass being very subordinate. There can be no doubt that this rock with its heterogeneous constituents, its "Aschenstruktur" and its detached and broken crystal fragments, is a true tuff, and not the result of alteration of an coherent intrusive body. Its intrusive field relations may be explained by postulating a fissuring of the country rock, followed by, or caused by a blast or exposion of steam laden with fine volcanic dust which eventually completely filled the fissure.

In applying the name "palagonite-rock" to denote a palagonitised, originally coherent basaltic body, to one of Mackenzie's specimens (R253, op. cit., pp. 311-312, and Pl. IV., Fig. 9) the writer was governed by its appearance in section of which he wrote the following: "In this case one cannot well distinguish individual glass fragments, but the specimen rather gives the impression of a continuous mass of glass,". The advanced state of decomposition of this rock, a result of its situation in the heart of the still vigorously active solfataric region of Krisuvík, lends uncertainty to the observation. Emerson re-examined two large specimens of the classic Seljadalr palagonite, which although described by Bunsen as a flow of glass, was figured by Rosenbusch as a typical "Palagonitfels" or "Aschentuff" (1910, Fig. 66); he came to the following conclusion: "they seem to me to be not clastic in any proper sense, but to be portions of a flow somewhat brecciated by steam explosion in place...The whole seems to me not a tuff, but a much-cracked glass," (1905, p. 122). In view of the similarity of both Rosenbusch's and Emerson's micrographs of the Seljadalr rock to the appearance of the writer's undoubtedly detrital palagonite-rock from Videy, it seems certain that the "Aschentuff" interpretation of Rosenbusch is the true one.

It thus appears that the conception of palagonitised coherent, vitreous, basaltic bodies, to which palagonite-rock might be applied, has not yet been justified; it does, however, seem desirable that the term palagonite-rock should be retained, as the equivalent of "Palagonitfels" of the older writers, to denote fine-grained, vitreous, basaltic tuffs in which palagonitisation has advanced to such a degree that the amount of unaltered glass is subordinate to the amount of the palagonitisation products, which so completely cement the whole as to give it a homogeneous, vitreous appearance.

2. THE GLOBULAR BASALTS.

The specimen VL was taken from the centre of a globular mass which was caught up by the sill, and which is exposed on the shore 100 yards N. of 12.8 m. point. It is a highly vesicular, very fine-grained basalt in which minute felspar microlites are the only macroscopically discernible crystalline constituents. In section these are seen to be labradorites without fluxional orientation. Brown augite is seen as minute intergranules, but more often in dominantly augitic, well-defined, curved cervicorn intergrowths with minute felspar needles; the production of this curved cervicorn structure may be connected with the mechanical strains involved in the formation of the globular structure. The vitreous base, in which these minerals appear in subordinate amount, is generally opaque; where it clears occasionally to a deep-brown translucency, it is seen to be charged with ilmenite needles. At the same time it has been attacked by palagonitisation with the formation of greenish, finely-fibrous, birefracting patches; this alteration is most noticeable in the glass which immediately surrounds the many vesicles. Olivine was not detected.

From the above two points emerge; the vesicularity of the rock, together with the occasional translucency of its vitreous base, indicates the magma from which it was derived was notably hydrated; and the absence of olivine, which feature the globular basalt shares with the vitreous fragments of the associated palagonite-breccias, indicates that both these rock types are derived from a magma saturated with respect to silica. Recently the writer showed that the available analyses indicated that the Icelandic eruptives fall into two series, a Pre-glacial series, in which the basalts are saturated, and therefore free from olivine, and an Inter- and Post-glacial series in which the basalts are undersaturated and carry olivine. The period within which this magmatic change took place was that which lay between the commencement of the deposition of the red Crag sediments at Tjörnes, N. Iceland, and the eruption of the grey basalts in Late-glacial times. The Early-glacial palagonite series, with its saturated rocks, appears to be a product of a continuation of Pre-glacial vulcanicity, and thus the period in which the magmatic change took place becomes narrowed down to that which lies between Early- and Late-glacial times.

It is fair to connect a magmatic change with major crustal disturbances, and a glance at the tectonics of S.W. Iceland will show that such a cause is not far to seek. It is well-known that the lowlands of S.W. Iceland were produced by the fracturing and sinking of great masses of the Palagonite Formation plateau, and that the grey basalts flooded this plane and were subsequently glaciated. It was not apparent, however, until Pjeturss (1900) found undoubted ground moraines in the breccia mountains, which are the relicts of the original plateau, that this extensive crustal disturbance took place between Early- and Late-glacial times, the very period for which we now have petrographic reasons for believing that a change in the magmatic sources took place.

3. THE MULTIPLE SILL AND THE COARSER DYKES.

Although varying somewhat in texture, and in the nature and extent of the mesostasis alteration, the rocks forming the multiple sill and the coarser dykes d_1, d_4, and d_5 are essentially similar, and are therefore probably contemporaneous, or nearly so. As the dykes d_1, and d_4 are younger than the palagonite series which they cut, it follows that the multiple sill is also probably younger; this agrees with the conclusion reached from field considerations (p. 14).

The writer recently described and figured one of Mackenzie's specimens from Videy (<u>op. cit</u>., pp. 285-286, Pl. III., Fig. 4) which now proves to have been taken from the basal columns of the multiple sill. It compares with four of the author's specimens taken from various points in the basal columns, and with the rock composing the dyke d_4. The conjecture that this rock "probably represents the hypabyssal equivalent of the ophitic (grey) basalts" (<u>ibid</u>, p. 285) was based on mineralogical similarity and on Mackenzie's insufficient field notes; in the light of the evidence now available, it must be regarded as unjustified. The rock was described as a coarse dolerite in which labradorite and augite, often ophitically related, were present in about equal amount; ilmenite appeared as an important accessory, while the once vitreous parts of the plentiful mesostasis were represented by fibrous, doubly-refracting, agate-structured palagonite. The characteristic presence of this last constituent induced the writer to propose the name "palagonite-dolerite" for this rock. An examination of a number of sections of the rock revealed two features which were not recorded in the above description; they are the presence of small relicts of olivine within certain of the palagonite areas, which in these cases do not exhibit the well-ordered agate structure, and the frequent, considerable curvature of the traces of the prismatic cleavages in the pyroxenes, accompanied by progressive extinction which in no

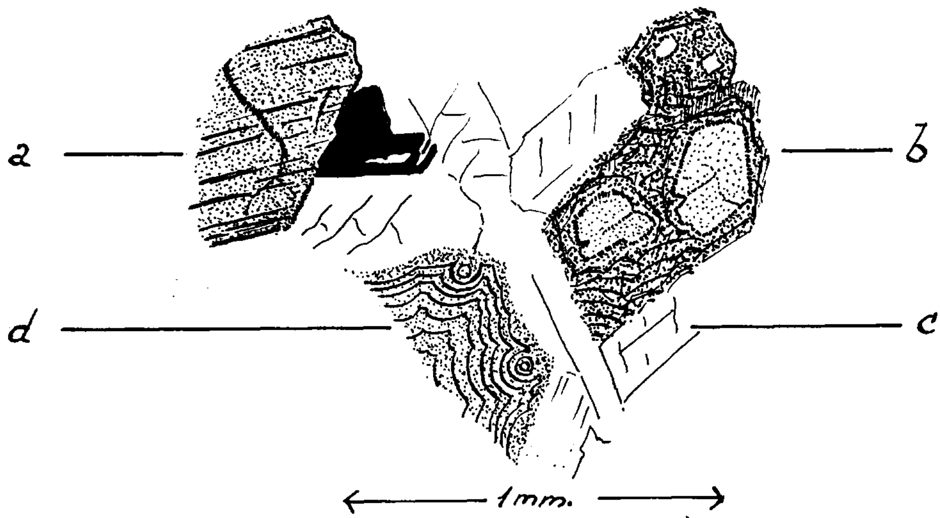

Fig. 9 . - An area from a section of the palagonite-olivine-dolerite from the basal columns of the multiple sill of Videy. a. - Augite. b. - Palagonite with olivine nucleii. c. - Labradorite. d. - Palagonite representing an aqueous, vitreous mesostasis.

way resembles that produced by twinning or zoning.

a. Palagonite after Olivine. An area of a slide of Mackenzie's specimen R220 from the basal columns is delineated in Fig. 9. To the left of a prism of labradorite is seen an area of reddish-brown, fibrous palagonite in which the fibres lie normally to the growth lines of a well-defined agate-structure. The writer regards this as palagonite replacing an aqueous, vitreous mesostasis in the manner already suggested by him (ibid, p. 315). To the right of the felspar crystal another area of palagonite is seen; it contains two larger and two smaller, optically continuous areas of olivine, and it differs from the first palagonite area only in that its fibrous agate-structure is less clearly defined. In this case palagonite is doubtless an alteration product of olivine, but its formation was probably preceded by the growth of a red serpentine such as replaces a ferriferous olivine.

b. Arcuate Augites. A typical arcuate augite is seen in Fig. 10 which is drawn from a section of the dolerite V13 of the dyke d_4. The cleavages are bent through 90 degs. and present smoothly curved traces except where they encounter a few transverse cracks; extinction is smoothly progressive, suffering only the slightest discontinuity at the transverse cracks. Ophitically enclosed plagioclase and ilmenite is perfectly undisturbed, showing no signs of bending or breaking. Distorted augites similar to these have frequently been noted by previous writers. Falconer describes and figures such augites from the quartz-dolerites of Linlithgow (1906, p. 140, and Pl. II., Fig. 3), and Thomas and Bailey have found them

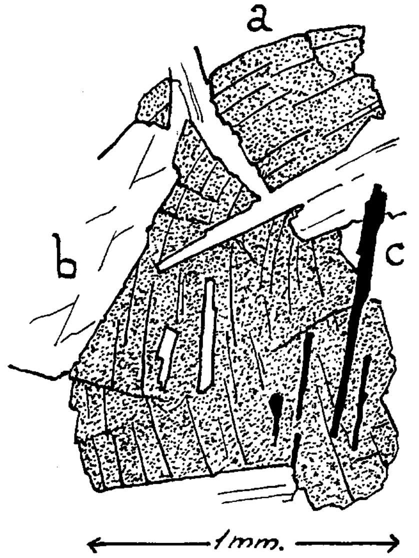

Fig. 10. - Mechanically deformed augite from the dolerite of the dyke d_4, a rock similar to that of the multiple sill, and very probably contemporaneous with it. a. - Arcuate augite. b. - Rectilinear, enclosed plagioclase. c. - Rectilinear, enclosed ilmenite.

in similar rocks from Mull (1924, p. 303). Falconer explains the curvature as a "mechanical deformation" resulting from "some movement in the igneous mass soon ofter the augite had crystallised out" (loc. cit.); this explanation is quite acceptable as Falconer regarded most of his augites as of early growth. Thomas and Bailey offer a similar explanation for this phenomenon in the Mull quartz dolerites: "...the crystals are sometimes curved and otherwise distorted...due to intercrystal pressure through the movement or withdrawal of the liquid mesostasis from the immediate neighbourhood" (loc. cit.).

Although the appearance of the present augites strongly suggests bending, an explanation involving mechanical deformation at first seems untenable on account of the absence of signs of deformation in the earlier formed, rectilinear ilmenites and felspars; the following analogy, however, may show that the objection is not valid. Given sufficient time, minute forces will produce notable deformation in highly viscous materials; a cork placed at the bottom of a vessel filled with cobbler's wax, will eventually float to the surface; a bar of the same material, supported in a horizontal position by its ends, will gradually assume a U-shape. In a composite experiment, in which a number of match-stalks are embedded centrally and longitudinally in such a bar of cobbler's wax, bending of the latter will take place without deformation of the match-stalks, provided the bending be sufficiently slow. Thus, in the case of these arcuate augites, the

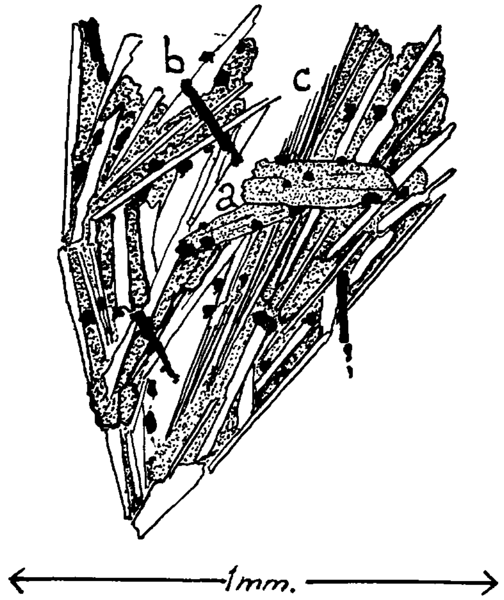

Fig. 11 . - Cervicorn structure in the mesostasis of the dolerite of dyke d_5. a. - Augite of the first generation. b. - Ilmenite of the first generation. c. - Extremely fine intergrowth of plagioclase and augite suggesting eutectic conditions.

writer believes that deformation commenced at a stage when ilmenite and felspar were fully formed and mechanically rigid, whereas augite had just developed its cleavage, and was not yet rigid. It is noteworthy that in order to explain the formation of the agglutinate the writer postulated just such a movement in the sill, accompanied no doubt by a similar movement in the contemporaneous dykes, at a late stage in its consolidation period (p. 16).

<u>c. Cervicorn Structure</u>. Specimens from the margins of the basal columns, from the radiate component, and from the dykes d_1, d_5, differ from the rocks just described in the following respects: they are finer-grained; the typical, bright, red-brown palagonite with occasional olivine relicts is replaced by greenish-black, almost opaque patches in the mesostasis, in which agate-like growth is discernible only with difficulty; ophitic relations between augite and felspar give way to an occasional approach to idiomorphism in basal sections of the pyroxene of the first generation, while the mesostasis tends to cervicorn structure with optically continuous felspar, indicating the earlier growth of the felspar.

Typical cervicorn structure is seen in the mesostasis of the dolerite (VB) of dyke d_5, and is delineated in Fig. 11. It consists of a sheaf-like intergrowth of felspar and augite in which repeated branching, resulting in secondary sheaves, has produced an antler-like growth. The felspar microlites of the individual sheaves are usually optically continuous, while the intergranular augite is not so; occasionally the intergrowth becomes extremely fine, suggesting eutectic conditions. Cervicorn structure similar to this, but consisting almost entirely of augite has been found in the quartz-dolerites of Mull, and has been described and figured by Thomas and Bailey (op. cit., p. 303, and Fig. 50, B).

Whereas the presence of olivine in a rapidly cooled rock cannot be regarded as proof that the parent magma was undersaturated with respect to silica, its presence in a coarse-grained rock, such as the dolerite of the basal columns, is sufficient proof of undersaturation. It thus appears that the multiple sill is consanguineous with younger, olivine-bearing grey basalts, that the period in which the magmatic change took place (p. 34) becomes further reduced to that which lies between the formation of the palagonite series and the time of its intrusion by the multiple sill and the attendant dykes.

4. THE GREY BASALTS.

Four specimens from different points of the grey basalts of Viðey were found to be mutually indistinguishable, and strictly comparable to the grey basalts of the Reykjavík district. Mackenzie's specimens from the grey basalts of this locality were recently fully described by the writer, and a new analysis of the coarsest-grained member of the series was submitted (op. cit., pp. 281-287, Tab. III., Anal. B, and Pl. III., Fig. 3). In a set of these rocks of varying grain size a well-defined, inverse relationship was observed between the proportion of olivine and the grain size of each member; i.e. the amount of olivine was found to be inversely proportional to the length of the period during which olivine had been permitted to react with the liquid (ibid, pp. 284-285). In accordance with this the Videy grey basalts are seen to bear a moderate proportion of olivine in keeping with their moderate grain size or cooling period.

The position which the new analysis occupied in the variation diagram indicated that these undersaturated, Late-glacial lavas belong to a series which is chemically distinct from the Pre-glacial series (ibid, Fig. 21, and pp. 327-328).

VI. THE VIDEY PALAGONITE SERIES A SUB-GLACIAL EXTRUSION.

1. CONDITIONS TO BE SATISFIED.

Before attempting to reconstruct the conditions under which the Videy palagonite series was formed, let us briefly recapitulate the facts which an hypothesis must take into account. (a) The palagonite series was a product of igneous action in Early-glacial times (p. 25). (b) The association of globular basalt with palagonite-breccia is significant, rather than fortuitous, and the former always underlies the latter (p. 25); the passage from the one to the other is sometimes gradual (p. 24), and therefore each was probably formed under similar conditions. (c) An occurrence of the palagonite series was found resting on glacial sediments at 690 feet above sea-level, 70 kms. from the coast, and 5 km. on the landward side of the line of highest submergence (p. 24). (d) Palagonite-breccia

is nearly always seen to be charged with a multitude of heterogeneous blocks which are angular, or only slightly rounded (p. 8).
(e) The magma which produced these rocks was notably hydrated (pp. 28, 33); in the hydrotachylyte fragments of the palagonite-breccia H_2O was largely retained in solid solution (p. 29); in the globular basalts and in the palagonite-rock it was largely released to form vesicles (pp. 32, 30).

2. DISCUSSION OF A SUBMARINE HYPOTHESIS.

Submarine eruptions, or eruptions in which the volcanic products fell into the sea, have often been suggested as the processes whereby both palagonite-tuffs and pillow-lavas have been formed, and undoubtedly this explanation is in many cases the correct one. The palagonitised hydrotachylyte cores of the manganese nodules described by Murray and Renard (1891, pp. 299 *et seq.*), which were found in mid-ocean, must have originated in submarine volcanoes; the non-vesicular nature of these fragments is the natural result of eruption at abysmal depths where the prevailing pressure is sufficient to restrain the escape of dissolved water-vapour, and to force the ejecta to consolidate in the hydrotachylyte condition. The Ballantrae pillow-lavas, in which the spaces between the spheroids are sometimes filled with calcareous matter, flinty shale, chert and jasper, are undoubted examples of lavas which have entered the sea. Submarine extrusion being an apparently attractive hypothesis to explain the formation of the palagonite series, and one which the critic is likely to range against the explanation to be offered presently, let us enquire whether it provides for the appearances detailed in the previous section.

When in 1845 Sartorius von Waltershausen first described his discovery of palagonite in the shell-bearing tuffs of the Val di Noto he was justified in pronouncing these tuffs a marine formation; two years later, on finding palagonite in Icelandic tuffs, both Bunsen and von Waltershausen adhered to the idea of submarine eruption in support of which they advanced amongst other evidence, the discovery of included shelly fragments. Thoroddsen tells us however that the Palagonite Formation is free from fossils, and that, in the cases where included shell remains are found, the palagonite-tuff is no longer in its original situation (1906, p. 291). Again, to provide for the retention of the high, primary water content of the Videy hydrotachylytes, and also their nonembayed and only slightly vesicular nature, submarine eruption at great depths would require to be postulated. The position of the correlated Gullfoss section, which is well above the line of highest submergence - a tolerably well-defined line in that locality - precludes submarine eruption, and _a fortiori_, submarine eruption at great depths. Furthermore, the included blocks in the palagonite-breccia of Videy argue against submarine extrusion; they are angular, or only slightly rounded, and are certainly derived from above, which is deduced from the fact that the globular basalts into which the palagonite-breccia passes downwards, were never observed to carry xenoliths. Were these blocks derived from the sea-floor, we should expect them to be well-rounded. There is no objection to applying a submarine extrusion hypothesis to the globular basalts _per se_, but, as these rocks appear to be but a special facies of the palagonite-breccia, and were therefore formed under conditions which did not differ materially from those which obtained during the formation of the breccia, and, as the above arguments tend to show that submarine extrusion will not account for the palagonite-breccia, this mode of formation is also regarded as an unlikely one in the case of the globular basalts.

3. THE SUB-GLACIAL EXTRUSION HYPOTHESIS.

From a consideration of all the evidence, the writer concludes that the Videy palagonite-series, a downward succession of palagonite-breccia with irregular intercalations of palagonite-rock, globular basalts, and fine-grained shattered basalts, were formed in Early-glacial times by a series of localised extrusions under the ice-sheet which then covered the country. As far as he is aware, this hypothesis has not previously been advanced to explain the formation of either the comparatively rare and localised occurrences of associated palagonite-breccia and globular basalt, or the immeasureably greater and wider-spread Palagonite-Tuff and -Breccia Formation of Iceland.

The following is the author's conception of the sequence of events in the formation of the Videy palagonite-series.

A basaltic magma, probably consanguineous with the normal, over-saturated, Pre-glacial basaltic magma, found egress at the base of a massive ice-sheet. Immediately vapourisation of the proximate ice or water took place, resulting in the release from the base of the ice-sheet of a multitude of heterogeneous, angular or subangular blocks; concurrently, that part of the magma coming in contact with the base of the ice-sheet, was quenched to form hydrotachylyte with its full initial complement of water vapour retained in solid solution. This rapid quenching resulted in the mass being traversed by a fine network of shrinkage cracks, while further impulses from below shattered the cracked mass into fragments whose maximum diameter is 1½ cms., and incorporated with them the released blocks from above. Thus were formed the smoothly curved boundaries and the network of fine cracks which the hydrotachylytes show under the microscope.

The absence of marked vesicularity and of "Aschenstruktur" in the hydrotachylytes indicates that approximate equilibrium was reached between the pressure of the generated steam and the restraining capacity of the ice-sheet. Whether or no the height of a column of ice which is theoretically required to produce a pressure approximately equal to that generated by steam in contact with basalt magma, is inordinately great, is of no consequence; the extrusion is regarded as originating from localised vents or comparatively limited fissures, ~~and~~ under which conditions ~~thus~~ the mechanical strength of the ice is added to the simple pressure due to its thickness, thus multiplying its restraining capacity many fold.

With the abeyance of the intrusive paroxysm the generated steam condensed, the bed of hydrotachylyte ejecta became waterlogged, and palagonitisation, whose initiation doubtless followed upon the disruption of the cracked intrusive body, proceded, aided by water and elevated temperature and pressure. Then followed another paroxysm which took much the same course as the first, the unconsolidated, waterlogged tuff-bed having a chilling and shattering effect similar to that of the base of the ice-sheet; and thus by repeated outbursts a massive blanket of hydrotachylyte breccia was accumulated and gradually consolidated by the pressure of the overlying ice-sheet and the cementing effect of the palagonitisation products which were being formed. During these later acts the breccia was occasionally fissured; the spaces produced by these fissures became regions of low pressure, and the induced blasts or explosions of steam laden with fine volcanic ash rapidly filled them with the fine-grained tuff free from larger particles, which now appears as palagonite-rock. Whereas the smoothly curved outlines and the almost non-vesicularity of the hydrotachylyte fragments were due to approximate equlibrium between the extrusive and the restraining forces, the "Aschenstruktur" and marked vesicularity of the particles of the palagonite rock were produced by the great disparity between the extrusive pressure and the void in the newly formed fissures.

With the increase of the rigidity of the breccia-bed, and the waning of the volcanic energy, the feebler outbursts had no longer sufficient energy to disrupt the overlying mass; generated steam served simply to arch the mass producing a flat-domed cavity which remained uncollapsed during the following cooling period, in which water percolated into it. At this stage the globular basalts were formed. The magma, emerging now with difficulty through restricted orifices, encountered the chilling effect of the accumulated water, and finally solidified as a mass of globular basalt; through the observations of ~~of~~ Tempest Anderson and the work of Johnston-lavis, Lewis and others the processes whereby "globular" or "pillow" structure is devoloped in the product of an extruded magma which is rapidly cooled, and at the same time constantly fed and urged forward by further liquid supply, is now well understood, and need not be further discussed. Johnston-Lavis examined the globular basalts at Reykjanes, a locality which was correlated with Videy on p. 21 , and expressed the view that the occurrence is the remenant of a submarine cone (1895, p. 445); in view of the presence ~~of presence~~ of the palagonite-breccia associated with these rocks, and ~~their~~ its probable similarity with the palagonite-breccia of Videy, to which a submarine extrusion hypothesis could not be appled, the writer considers it probable that the globulr baslats of Reykjanes were also formed by sub-glacial extrusion.

The accumulated extruded mass now assumed such a degree of compactness as to be almost impervious to water, and further intrusions from below solidified as normal, fine-grained basalts without the structural features of lava.

One point remains to be explained; quite apart from the repetition by faulting the Videy palagonite-series was seen to divide into two conformable and similar sequences, the members, and order of members of which are those dor which a mode of formation has been suggested. To expbain the formation fo the upper and younger sequence we must assume that after completing the cycle of events detailed above, volcanic energy increased greatly, and during an extrudive outburst of great violence succeeded in breaking through the whole mass of accumulated rock, encontered the base of the ice-shdeet which by this time was fully repaired and recharged with blocks, and re-enacted the events as suggested for the first sequence.

VII. THE GEOLOGICAL HISTORY OF VIÐEY.

We may now arrange in chronological order some of the salient inductions of the foregoing pages bearing on the geological history of Viðey.

In Early-glacial times the palagonite-series was formed by the sub-glacial extrusion of an oversaturated basaltic amgma which was consanguinous with the Pre-glacial magma; on its formation the palagonite series greatly exceeded its present thickness, and probably occupied a more evated position.

The extensive faulting, tilting and subsidence which the Palagonite Formation plateau of S.W. Iceland now suffered also affected Viðey; these movements gave vent to magma sources of a mildly undersaturated type resulting in the palagonite series being intruded by the slightly olivine-bearing multiple sill, and the coarser dykes. Then followed a period of erosion during which that part of the palagonite series which overlay the sill was removed.

During a Late-interglacial period, or a Late-glacial retreat, when Viðey was connected with the mainland, the lower-lying area of Viðey wsa overrun by a massive sheet of the markedly undersaturated grey basalts. This was followed by a final advance of the ice-sheet which moved seawards in a west-northwesterly direction, in conformity with the present-day topography. During this advance Videy was sufficiently depressed to separate it from the mainland with the formation of the Videyjarsund; with the final retreat of the ice the 6 foot raised beach of the S. end was formed. In Post-glacial and Recent times Videy escaped the volcanic activity which affected the greater part of the neighbouring Gullbringu Sýsla.

VIII. ACKNOWLEDGEMENTS.

In conclusion the writer wishes to record his indebtedness to the Carnegie Trust whose financial assistance permitted both the field work on Videy and the subsequent study of the collected material.

To Dr. G.W.Tyrrell, from whose invaluable assistance during part of the time devoted to the field work on Videy the writer has greatly benefited, and due to whose kindness the two photographs from Videy are herewith presented, the writer would express his sincere gratitude.

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EXPLANATION OF PLATE I.

Fig. I, A. - Palagonite-breccia (VA), taken at a point 100 yards S. of the farm on Viðey, showing negligibly vesicular hydrotachylyte fragments with non-embayed boundaries suffering marginal palagonitisation with the formation of isotropic bleached borders, a dark, spongy, fibrous, bi-refracting mineral, and a colourless zeolite (16 diameters).

Fig. I, B. - Another area of the same slide as the preceeding in which opaque flow-bands in the hydrotachylyte fragments are seen to be unattacked by palagonitisation (16 diameters).

Fig. 2. - Palagonite-breccia photographed from the shore at a point 350 yards N.W. of the S. point of Viðey; it is densely charged with angular basaltic blocks which, it is thought, are derived from the base of an ice-sheet.

Fig. 3. - Globular basalts photographed from the S.W. shore of Viðey at a point near the junction of the fence with the shore. The spheroids are defined by a vitreous skin, and a radio-concentric internal jointing.

PLATE I.

Fig. I, A.

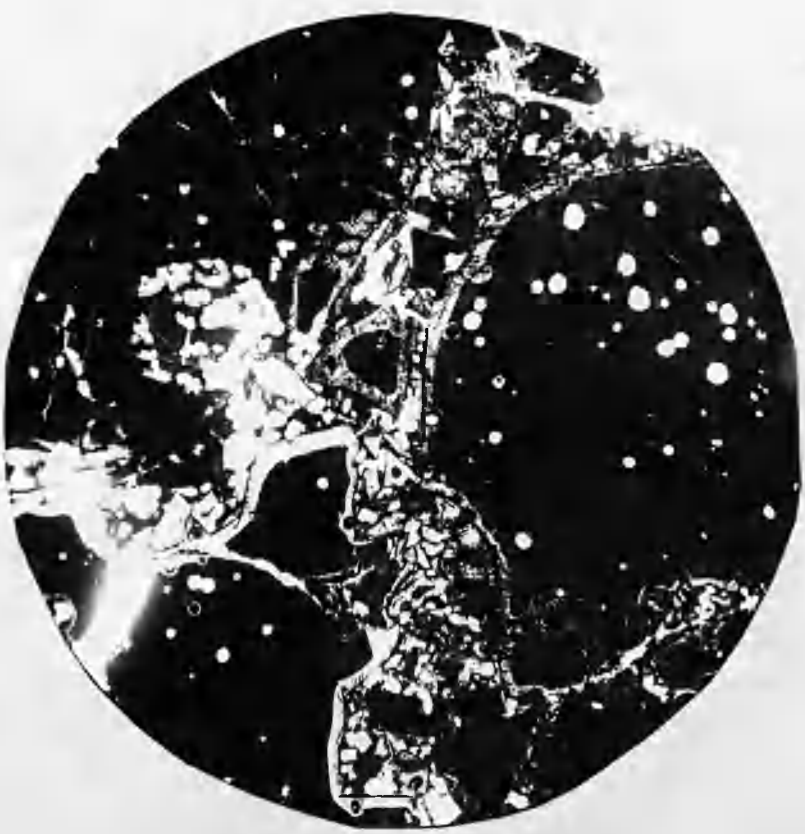

Fig. I, B.

PLATE I.

Fig. 2.

Fig. 3.