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Origin of the Basic Tuffs of Iceland

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INTRODUCTION

Some Critical Remarks on the Development and Present State of the Geology of Iceland.

The study of the geology of Iceland was opened with the well-known travels of Eggert Ólafsson and Bjarni Pálsson during the years 1750 — 1757.

In the following one and a quarter centuries the accumulation of knowledge went on very slowly. The country was visited at long intervals by scientists who mostly spent only a few weeks or months in the island, and owing to the great difficulties of travelling could visit only a few limited areas.

When considering the achievements of this period, the general state of affairs in Geology must naturally also be borne in mind. But at the close of this period considerable knowledge had nevertheless been gathered relating to the geology of the country. There was above all the recognition of the country being almost entirely built up of volcanic rocks, and a realization of a great number of interesting problems which are represented by the wealth of volcanic phenomena of the country.

But systematic research was entirely wanting. Such work was begun by the Icelander Þorvaldur Thoroddsen with the financial support of the Icelandic Parliament.

Thoroddsen made systematic travels through most of the country during the years 1882 — 1898 with the aim of a pioneer geographical and geological survey.

His work has been an invaluable foundation for later, more specialized work, the more so as this indefatigable worker put all emphasis on the collection of data.

Thoroddsen described the distribution and mutual relations of what he assumed to be the three main formations of the country, viz. the Basalts, the Palagonite Formation, and the Dolerites.

Yet, Thoroddsen could not devote himself to more specialized work, and this classification of the rocks was not parallelized by, and founded on any extensive microscopical petrographical work.

No wonder, therefore, that he came to no clear conception of the nature of the chaotic Palagonite Formation, and that his distinction of Basalts and Dolerites by their general appearance in the field resulted in some confusion as such a distinction must be based on extensive petrographical research.

Thoroddsen built up the following system:

The oldest formation of the country is plateau basalts with a thickness of at least 3000 m containing beds of a flora, which according to O. Heer is of Upper and Lower Miocene.

In the Pliocene or earlier, this plateau was heavily faulted, and was covered, mainly through violent eruptions of ash, by tuffs and breccias with a thickness of many hundreds of metres, especially in an irregular zone across the country from NE to SW.

This „Palagonite Formation" was in turn covered by Plateau Dolerites to a depth of 300 — 400 m. These are the „Older Dolerites" of Thoroddsen.

This zonal tableland was in turn broken down and through the following erosion the main features of the modern topography were modelled. But still preceding the Ice Age a number of shield-volcanoes were formed, pouring out large floods of the „Younger Dolerites". During the following Ice Age, which Thoroddsen considered to have been of unbroken continuity, the topography was only slightly affected.[1])

This system of Thoroddsen's was questioned very soon, as another Icelander Helgi Pjetursson (now Dr. Helgi Pjeturss) in 1900 announced the discovery of moraines embedded in the Palagonite Formation.[2]) The conclusion then was that this formation was of Quaternary age.

In the next decade this author collected a wealth of material on moraines, occurring not only in the Palagonite Formation, but also in the presumably Miocene plateau basalts of Middle Northern Iceland, in the plateau of Mt. Esja in Southwestern Iceland, and in many other localities. Furthermore, Pjeturss' discovery of arctic Mollusca below Plateau Dolerites and palagonite tuffs in the Snæfellsnes peninsula seemed to place his main conslusions — the building up of the uppermost part of the basalt plateau and the vast younger rocks in Quaternary times — beyond any doubt. Nevertheless some difficulties have been felt in connexion with this system, although at the present time it is generally accepted.

Thoroddsen accepted Pjeturss' moraines as genuine, but he never accepted his system as a whole, as is clearly seen in his compendium of 1906.[1]) As a compromise, he put the moraines into the uppermost part of the Palagonite Formation. This view is, however, not compatible with the acceptance of the moraines as genuine, but it is nevertheless of interest to notice that Thoroddsen at last, with reference to Pjeturss' work, assumed the youngest part of the Palagonite Formation to be of Quaternary age.

Before Pjeturss, K. Keilhack[3]) had already in 1883 found conglomerates of a morainic appearance in the Palagonite Formation, but refrained from the assumption of a glacial origin:

„und so gross ist die Ähnlichkeit mit der Structur der recenten Endmoränen, dass man nur bei Erwägung des tachylytischen Bindemittels dieser Conglomerate und der darüber lagernden Hunderte von Metern mächtigen Complexen von Basalten und geschichteten Tuffen sich des Gedanken erwehren kann, dass diese völlig structurlosen Massen Producte der Gletschertätigkeit sind."

In a much later paper, however, Keilhack abandons this hesitant attitude and fully accepts Pjeturss' interpretation of the old conglomerates.[4])

G. G. Bárðarson in 1929 emphasized the enormous bulk of the Quaternary strata of Iceland as compared with those of Scandinavia. He concluded that certain glacial strata in Snæfellsnes must be very early Quaternary „and it is doubtful whether simultaneous glacial strata are found in other countries."[5])

It is of interest to notice here the changing opinions as to moraines embedded in the top of the basalt plateau at Fnjóskadalur in Middle Northern Iceland.

In the original report[6]) on old moraines in this area in 1905, Pjeturss assumed a Middle Tertiary age for these moraines because of their apparent relation to the Pliocene Mollusca of Tjörnes. These moraines, as well as the accompanying basalts, are, however, according to Pjeturss, very similar in appearance to those in Hreppar in Southern Iceland, but there the conglomerates were considered as a proof of the Quaternary age of the Hreppar rocks. This apparent inconsistency does, however, not appear in the final formulation of Pjeturss' views in 1910, where every moraine is considered of Quaternary age.[7] In 1905, however, Pjeturss thought it obvious that the Fnjóskadalur moraines are older than the Pliocene of Tjörnes and it does not appear that it has been shown directly that the relation is the reverse.

L. Hawkes thinks it quite obvious that the Fnjóskadalur sediments are older than the Pliocene of Tjörnes.[8] But Hawkes denies the existence of moraines at Fnjóskadalur where reported by Pjeturss. On the other hand J. Líndal reports that he has found a number of moraines in the mountains in question.[9]

The existence of moraines in these localities seems thus to be somewhat doubtful. But what about the age of these sediments? If they are older than the Pliocene of Tjörnes and are genuine moraines, then Pjeturss' time-scale is entirely upset and we have got a Tertiary glaciation of Iceland.

But Pjeturss system as a whole appears to be so well-founded that it cannot be upset by this. The obvious answer to the difficulty just mentioned would be that the moraines at Fnjóskadalur, if genuine, must be younger than the Pliocene of Tjörnes. Some geologists, however, believe that the Pliocene is younger than the "moraines" and this is therefore still an open question. But it seems a priori improbable that the answer to it can seriously influence Pjeturss' system as a whole.

An apparent weakness of the system, which L. Hawkes has already pointed out is the tremendous work of modelling the fjord landscape of Northern and Western Iceland which according to the system was carried out during part of the Quaternary period. But this is perhaps no real weakness. According to Pjeturss there is no escape from the conclusion that an enormous erosion was carried out in Quaternary times, and this seems to be in accordance with the view of some Norwegian geologists that the Norwegian fjords are of Quaternary, even Middle or Late Quaternary age. Pjeturss' main arguments, obtained in Snæfellsnes, are, it must be admitted, very strong and seemingly also those derived from the moraines at Hvalfjörður, where a striated floor of the moraines is also reported. —

I have in the foregoing pointed out some difficulties which arise in connexion with Pjeturss' system, but they all seem to be of no great importance, and it would therefore seem that to-day we have arrived at a fairly true general picture of the geology of the country. Yet, what this analysis shows is only that our present unsatisfactory state of knowledge does not reveal any marked inconsistences in the system. To believe, however, that the system therefore must be correct would be to shut one's eyes to the real state of knowledge of Icelandic geology of to-day. I have already mentioned that the classification of the basalts does not rest on microscopic work to any great extent. Secondly, the interpretation of the old conglomerates as moraines likewise *rests entirely on their macroscopic character* Yet, the general system depends largely on the interpretation of these conglomerates. The vast masses of basic tuffs which occupy a place of crucial importance in the geology of the country are nearly untouched by petrographical methods and the dominating Basalt areas are even macroscopically little known.

The nature of Pjeturss' conglomerates has however in spite of the unsatisfactory research, for a long time been considered as a settled question. Similarly the origin of the basic tuffs (Palagonite Formation) is now believed to be pretty well understood. *It is therefore necessary to state emphatically that the present views are unsatisfactorily founded and should be thoroughly revised.*

Several years ago I pointed out the need for a preliminary survey of the country and a revision of certain important questions. In the meantime I have worked on such a program and I believe that it is justifiable to publish the conclusions so far arrived at.

The key to the geology of Iceland is in my opinion to be sought in the Basic tuffs, their origin and age. Consequently they will be considered first. Then I shall attempt a discrimation of the different suites of plateau basalts and lastly the erosional features of the plateau and their age will be considered with special reference to the valleys and fjords of Northern Iceland.

In connexion with this work I stayed for several months in the Geological Department of the University of Glasgow. Needless to say, the access to the rich collection made by Dr. G. W. Tyrrell and M. A. Peacock of Icelandic rocks was of great value to me. I am also greatly indebted to Dr. Tyrrell for his advice and for putting his manuscript on Icelandic basalts at my disposal. I also acknowledge my great debt to Prof. A. E. Trueman and Dr. J. Weir, for valuable discussions and substantial help.

1. PREVIOUS STUDIES ON THE BASIC TUFFS

The so-called Palagonite Formation of Iceland is a rather vaguely defined assembly of brown or grey volcanic tuffs, breccias and conglomerates, which constitute a large part of Iceland. These rocks may be dominating in one region and whole mountains are made of them, in another layers of this material alternate with basaltic lavas.

It has been generally agreed upon that these peculiar rocks are predominant in certain large areas of the country, viz. in an irregular zone stretching across the centre of the country from NE to SW. All the main mountains in that zone are built up of such rocks as well as,partially, the lower ground. There is further a separate area of palagonite tuffs, namely the peninsula of Snæfellsnes. On both sides of the main zone lie high, heavily dissected areas of predominantly basaltic plateau lavas. These enclose Middle or Lower Tertiary lignite and are generally supposed to be mostly remnants of an old basalt plateau.

There is thus in the main a "palagonite area" filling a wide gap between the two "basalt areas".

In the view of early workers on Icelandic geology the Palagonite Formation was older than the Basalt Formation.

Þ. Thoroddsen on the other hand came to the opposite conclusion. According to his opinion a central zone of the Tertiary basalt plateau had sunk, the gap being filled by the Palagonite Formation. In his own words: "Die älteren Geologen waren der Ansicht, dass die Palagonitbreccie im grossen ganzen älteren Ursprungs als der Basalt wäre, während die späteren Untersuchungen vollständig bestätigt haben, dass Tuffe und Breccien jünger sind, dass der sich quer über das Land erstreckende Brecciegürtel später gebildet wurde als das Basaltplateau, dass letzteres in der Mitte gesenkt und durchbrochen ist, was eine grossartige vulkanische Tätigkeit veranlasste, die wahrscheinlich früzeitig im Pliozän begann und sich durch die Eiszeit bis auf den heutigen Tag fortsetzt". (Island, p. 288). And further: "Die Unterlage (of the Palagonite Formation), die ursprüngliche gesenkte und zerbrochene Basaltplatte, muss sich wahrscheinlich unter dem ganzen Breccieterrain befinden und von den Basaltgegenden gegen O und W durch terrassenförmige Brüche getrennt sein."

G. Bárðarson in his Icelandic text book of geology[10]) accepts the main conceptions of Thoroddsen that the Palagonite Formation fills a gap in a sunk central zone of the old basalt plateau. Fig. 1 which is reproduced from his book, shows his and Thoroddsen's scheme.

The distribution of the Basic Tuffs in the areas where they are most prominent is extensively dealt with by Thoroddsen in his "Ísland", and is shown on his geological map. As to the "Basaltformation", it must be remembered, however, that Thoroddsen did not accomplish more than a few ascents of its high mountains and his knowledge of it was bound to be rather fragmentary. Thoroddsen points out that layers of "Palagonite breccia" are occasionally embedded in the „Basaltformation". In reality such material is very common in the "Basaltformation". The result is that Thoroddsen's and Bárðarson's views as to the relation between a Palagonite Formation and a Basalt Formation are far from the truth.

The picture envisaged by the present author will be presented in the concluding chapter. —

The origin and nature of the Basic Tuffs have always been one of the main problems in Icelandic geology and it has occupied some well-known scientists such as v. Waltershausen. R. Bunsen and A. Penck.

Sartorius v. Waltershausen, who brought the matter up for discussion, ascribed the formation to submarine chemical alteration of basaltic volcanic ashes, through which a brown or yellow substance, the palagonite should be formed.

On the other hand, it was clearly expressed

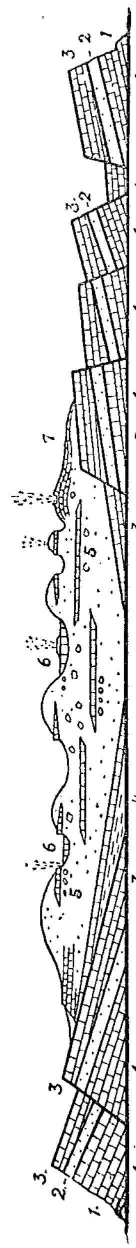

Fig. 1. — Geological structure of Iceland according to G. G. Bárðarson. An E—W section looking south. 1. Older Basalts. 2. Lignite. 3. The Younger Basalts. 4. Pliocene of Tjörnes, covered with basalt. 5. The palagonite Formation with intercalated layers of basalt and dolerite, filling the supposed great gap across the centre of the country. 6. Surface lavas. 7. A dome and young lavas of dolerite.

by Al. Penck that the Icelandic Palagonite tuffs consist of fragments of isotropic yellow glass, sideromelan, which were superficially and sometimes wholly altered by hydration into a brown anisotropic or isotropic substance, palagonite.[11])

According to Penck, sideromelan and the opaque tachylyte cannot be distinguished chemically, and his conclusion was that they are essentially identical. Therefore, Penck considered the Palagonite tuffs to be simply a common loose product of volcanism, altered by hydration. ("Sideromelan, ein vulkanischer Auswürfling").

Thoroddsen rejected v. Waltershausen's reasons for a submarine origin of the formation. In his view, based on extensive field work, there is "keine Veranlassung vorhanden, etwas anderes anzunehmen, als dass die Bildung von Tuffen und Breccien auf trockenem Lande bei Ausbrüchen über dem Meere vor sich gegangen ist." (Island, p. 291).

On the other hand Thoroddsen had no clear conception of the mechanism of these eruptions. The difficulty of some of the problėms facing him is seen from the following passage:

"In längeren Profilen werden bisweilen zahlreiche grosse, eckige Felsblöcke über grosse Areale unregelmässig ausgestreut, angetroffen, und es ist nicht leicht zu begreifen auf welche Weise das Ausstreuen dieser grossen Basaltblöcke stattgefunden hat; vorausgesetzt dass dieselben von Vulkanen ausgeworfen sind, liegt die Vermutung nahe, dass die Explosionen der Vorzeit ungleich kräftiger als die gegenwärtigen waren. An einzelnen Stellen können diese Blöcke durch Schuttströme und in den neueren Tuffen durch Gletscher und Gletscherläufe ausgetreut sein, aber im grossen ganzen sind die Verhältnisse noch recht rätselhaft". (Island, p. 290).

In the main Thoroddsen, however, believes clearly in an explosive origin of these masses, although he is very well aware of the hopeless confusion the formation presents on closer observation and the many problems it creates.

The conception of the origin of the formation was, however, again to be greatly altered.

In 1899 H. Pjeturss brought forward the view that certain peculiar grey conglomerates embedded in the formation were of glacial origin, and in the following decade this author discovered such conglomerates containing striated boulders and sometimes resting on a striated floor in a considerable number of localities in the formation. He furthermore discovered that the palagonite tuffs of Snæfellsnes rest on sediments containing arctic molluscs.

The remarkable idea was now conceived that the Palagonite tuffs were the result of sub-glacial eruptions during the Quaternary period, whereas Thoroddsen had put them in the Pliocene.

A petrographic study of the basic tuffs in Iceland was published by M. A. Peacock in 1926.[12]) According to Peacock a clear distinction between tachylyte and sideromelan should be made, the latter most probably being the result of an ultra-rapid chilling which was "sufficiently drastic to inhibit the facile separation of opaque ores and thus to produce translucent sideromelan". (l. c. p. 67). In Iceland this chilling was, in Peacock's opinion, caused by the Quaternary ice beneath which the eruptions were to have taken place.

These conclusions of the Peacock's are, however, erroneous and this must be made quite clear as they have not only been made the basis of later work in Iceland but are also widely quoted and used in the literature on basic tuffs elsewhere. As a matter of fact it is a theoretically unsound hypothesis that the absence of opaque ores in the basic glass is indicative of ultra-rapid chilling. And it is a demonstrably wrong assumption, as the observations, to be described in this paper, show beyond doubt that sideromelan may be formed by slow cooling.

And this should a priori have been expected. It is well-known from the glass industry that glass may easily be formed by relatively slow cooling and the same must be expected for natural glasses. An interesting verification of this are the well-known post-glacial streams of obsidian in Iceland. The emphasis laid by Peacock and later authors on the factor of rapidity in the formation of glasses is certainly misleading.

It is, in other words, erroneous to believe that Peacock's microscopic studies of the Basic tuffs in Iceland indicate a sub-glacial origin of the glasses. These studies are a most valuable investigation of the alteration of the glass but they leave in reality the question of its origin unanswered. The only argument decisively in favour of the sub-glacial origin is Pjeturss' interpretation of the old conglomerates, but these are still unsatisfactorily investigated and even though we accept Pjeturss' view we are still far from proving the sub-glacial extrusion of the tuffs.

The last phase in the study of our basic tuffs centered around the eruption of the sub-glacial volcano Grímsvötn in Vatnajökull in 1934. It was thought that this eruption might throw some light on the formation of the Palagonite tuffs and expeditions were undertaken, among others by Dr. N. Nielsen.

No conclusive results as to the formation of "palagonite breccia" were obtained on that occasion. But two years later it was assumed by Nielsen and Noe-Nygaard that no material resembling the "palagonite breccias" or tuffs was formed at the eruption. Nevertheless, these authors accept Peacock's view, with some specifications: "Palagonite breccia", in their opinion, is not formed by violent explosions of the Grímsvötn type, but more probably by "slow" eruptions beneath the ice-sheet through which they are unable to break.

This new theory is, however, not easily understood. If, as the authors believe, sideromelan is formed by ultra-rapid cooling, why should it be more readily formed by a slow eruption than a violent one? And as to the arguments for this new version of the theory of sub-glacial origin of sideromelan a "slow" sub-glacial eruption will always be difficult to establish and up to the present time no such eruptions are known with certainty. But these specifications of the theory are also unnecessary as it was shown by Tom F. W. Barth[13]) that the ash thrown out by the violent eruptions of Grímsvötn in 1934 and in 1922 did consist of porphyritic sideromelan. And this is actually the sole argument for the subglacial origin of the Basic tuffs which was derived from these eruptions of Grímsvötn. In the last chapter I shall consider these eruptions more closely.

Nielsen and Noe-Nygaard find that field studies in the Palagonite Formation of Southern Iceland are suggestive of the (still hypothetical) slow subglacial eruptions, but as yet only a preliminary report of their work is available.[14]) In this report a general theory of the Palagonite Formation is put forward. According to this theory the formation is the result of glacial and inter-glacial volcanism, i. e. pyroclastic material and lavas, and the work of the different agents of denudation during the varying conditions of the multiple Quaternary Ice Age.

I shall now turn to my own observations. It will be seen in the course of the discussions that the glacial theory of the formation of sideromelan is incapable of explaining a number of observations and a new theory will be framed which appears to be directly suggested by the observations.

2. TINDAFJÖLL

We begin with a brief orientation of the Tindafjöll area which lies between the rivers Markarfljót and Eystri-Rangá in Southern Iceland. It may be broadly described as a very gently dipping plateau or a part of a dome with grey basalts at the surface, rising from 600 m at the southern edge above the farms Barkarstaðir and Múlakot to 750 m. in the centre, where many irregular mountain peaks, mostly of palagonite breccia, rise above the plain.

This plateau has been cut by the Markarfljót whereby good profiles have been opened in the steep slope of Fljótshlíð. In a profile at Barkarstaðir Thoroddsen has mentioned alternating lavas and palagonite tuffs and also two main layers of conglomerate, indicating considerable erosion and rest of volcanic activity. According to Pjeturss striated boulders are easily found in these structureless conglomerates and accordingly he considers them to be moraines. Thus the whole massif should be of Quaternary age.

I ascended the plateau at Múlakot 5 km. west of Barkarstaðir.

The lowest horizon is here a small outcrop of a rather loose brown tuff. In a thin section (243) it is seen to consist of angular fragments of unaltered sideromelan with an average diameter of 0,5 mm. Some of the fragments enclose phenocrysts of plagioclase. Separate fragments of bytownite are also fairly abundant and olivine occurs sparsely. These crystals were most probably originally enclosed in the glass. Dark glass is also abundant, containing a greater number of phenocrysts than the translucent variety. The whole mass is cemented by zeolites. This tuff can have suffered no or very little transportation, except through the air.

Covering this tuff we find 4 lavas of a porphyritic grey basalt with thin partings of scoriae, the total thickness being 15—18 m. A thin section from the second lowest lava (245) is very rich in phenocrysts of bytownite and augite but olivine is sparse. The base is very fine-grained. The other lavas are nearly identical with this one, and the magmas of the lavas and the tuffs seem thus to be closely related.

Covering these lavas is a thick layer of a structureless conglomerate with an abundance of rounded blocks, large and small, in a compact dark-grey matrix. It has all the appearance of Pjeturss' old moraines and is possibly identical with Pjeturss' lower moraine at Barkarstaðir. Beautifully striated boulders are also easily found here.

Yet, comparing the different boulders we find that their striae are always *largely parallel* and strike along the mountain slope, as if made by a late glacier creeping down the valley of the Markarfljót — as undoubtedly they are. By chance the boulders could not be put in such position in a moraine, but protruding out of the hard conglomerate they would be striated in such a way by a late glacier of the Markarfljót valley.

I was not able to detect a single stone in the conglomerate which I considered to have originally lain in it as a striated boulder, and in my view a proof of the morainic nature of the conglomerate is lacking.

The conglomerate is covered by a very coarse breccia consisting mainly of unworn blocks of a porphyritic basalt, containing unusually large phenocrysts of plagioclase in great abundance.

Parts of a lava of the same basalt are also seen and the breccia in all probability represents the crumbling of this lava, which probably was heavily jointed and easily broken down (cf. later).

Higher in the section occurs a confused mass, which in the main consists of irregular sheets of this same porphyritic basalt, and the first regular lava sheet, still of the same kind of basalt, is not met with until we reach the edge of the escarpment, 230 m. above sea level.

To reach the edge of the main plateau mentioned at the outset, we have now to walk up a gently sloping terrain with but very little barelaid rock. Not until reaching the brook Merkiá at a height of about 400 m, could I follow clearly the volcanic series again.

We find here a porphyritic lava similar to those at the base of the series. It is covered with many thin strata of sediments: a brown sandstone with veins of bog-iron, a darker stratified sandstone with thin layers of white rhyolite-pumice and a layer of very coarse sandstone. These strata are all of nearly the same composition, namely subangular fragments of sideromelan and a few worn crystals of plagioclase (bytownite-labradorite) and augite, which appear to be phenocrysts originally enclosed in the glass. These sediments are most probably wind-blown sideromelan "ash", thrown out by some nearby volcano. They do not on the other hand suggest any appreciable period of volcanic rest and weathering.

There yet remains to be mentioned one of the strata, not thicker than 1 m, a dark-grey conglomerate with small rounded pebbles of basalt. This conglomerate has all the characteristics of Pjeturss' moraines, with the exception that no striated pebbles were found. Its position suggests moreover that it might correspond to Pjeturss' higher moraine at Barkarstaðir.

Studying a thin section (256) I was, however, rather surprised to find that the groundmass of this conglomerate consists mainly of worn fragments of palagonite and dark glass, although worn grains of basaltic lavas and an abundance of minute fragments of plagioclase and augite are also present.

The material of this conglomerate, so markedly morainic in appearance, is thus mainly of a glassy nature, not exactly what one should expect to find in a groundmoraine embedded in a series of basaltic lavas. Furthermore a consideration of these thin glassy sediments as a whole does not suggest the existence of a glacier as a creative agency.

I think it is more natural to consider the conglomerate and the sediments as a whole as a link in the volcanic series rather than a break, especially a break of such magnitude as a glaciation. In my view the conglomerate may represent a volcanic mud flow but this question will be discussed in more detail later. This assumption is in accordance with the absence of structure, the wearing of the material, and its composition, and even the eventual presence of a few more or less indistinctly scratched stones would, I think, hardly be very surprising.

Walking up along the brook we again meet with a grey basaltic lava and a similar conglomerate as before, and this is probably higher in the series as no dislocations could be seen. Yet this is not quite clear. At last we arrive at a deep terminal gorge eroded by the brook into an enormous basaltic layer of a thickness no less than 100 m.

It forms the edge of the main plateau. This lava is a dark, extremely fine-grained basalt, which by consolidation has been jointed in such a way that it is almost wholly built up of innumerable cubes or polyhedrons with an average size of about 1 — 2 dm^3. Only near the top of the lava is this peculiar jointing replaced by vertical columns.

At a few places the lava encloses patches of brown palagonite.

This lava is obviously very easily broken up and we have already met with a breccia which probably results from the breaking up of a lava of this kind.

We have now reached the edge of the plateau. Here we find regular columnar lavas of a light coloured porphyritic olivine-basalt. (260) shows a few macrophenocrysts of bytownite and scattered microphenocrysts of bytownite, augite and olivine, in a very fine-grained groundmass.

The plateau rises very gently towards the central parts and individual lavas cannot be discerned, but everywhere in the surface we find the same kind of grey, porphyritic fine-grained basalt.

In the central part this basalt is covered by hills and high peaks of brown volcanic breccia and tuff, and according to Thoroddsen rhyolite also occurs here.

Near Vörðufell, one of the lower outer hills, the volcanic breccia (257) contains fragments of dark vesicular glass with microphenocrysts of plagioclase and augite, this glass being enclosed in a *compact* groundmass of somewhat altered sideromelan, which also encloses phenocrysts of olivine. This groundmass does not appear to have ever consisted of fragmental glass, it has clearly consolidated from a melt as a *compact glassy mass*. The melt then contained fragments of vesicular glass as well as crystals of olivine and during consolidation a great number of small crystals were formed. This relation of glass within glass is of great interest and we shall find it again in other localities.

Brown tuff, (258) which is also found here, consists on the other hand of small fragments of glass and is probably blown to the place as "ash" whereas we must assume that the compact glass of (257) results from a neighbouring extrusion of magma.

I was not able to detect any signs of a glacier with which this breccia might be connected and proofs of its sub-glacial origin are certainly lacking.

As a result of this study I have come to the conclusion that the whole mass of Tindafjöll presents an unbroken volcanic series of certain peculiar characteristics, built up without any great change of magma (the rhyolite of the peaks of Tindafjöll is not considered here) in a relatively short period, for there is no sign of a prolonged denudation.

Early and especially in the last phase of acticity the magma consolidated as translucent glass, whereas it formed fine-grained crystalline lavas in the middle of the period. At that time, however, somewhere else sideromelan was produced, probably as ash, and blown by the wind to our locality. Also mudflows occurred as a volcanic phase, consisting mainly of glass fragments. In one case we have observed what may be a transition from a crystalline to a glassy consolidation.

As to the formation of sideromelan no signs of a connexion with ice are visible.

On the other hand the peculiar, thick lava at the edge of the plateau points to a quite different explanation, for this lava indicates that the same magma consolidated in three different ways without any detectable direct influence of glaciers, namely with columnar jointing, block jointing, and as a mass of brown glass, and significantly enough the patches of brown glass are surrounded by lava and have therefore hardly been in contact with a chilling agency.

This observation suggests that the formation of sideromelan is to be considered as dependent on certain physical properties of the magma rather than being caused by external chilling agencies. The same suggestion is derived from the breccia at Vörðufell. Ice may be assumed to cause the formation of minute glass fragments, but it can hardly produce a compact mass of glass. Or what about the two generations of glass, the one enclosed in the other? It is at least not naturally accounted for by glacial influence.

We have, however, at this stage still too scant a material to enter into a further discussion of the possible modes of formation of sideromelan.

3. EYJAFJÖLL

This is a neighbouring plateau crowned by the snowcapped recent volcano Eyjafjallajökull. It is separated from Tindafjöll by the valley of Markarfljót and it may be more correct to consider the two complexes as a single one dissected by the river. Yet, this is a question wich I shall not further discuss here. We are concerned with the composition of this second complex which is a volcanic series closely similar to that of Tindafjöll.

At the farm Hvammur I made a closer study of the series.

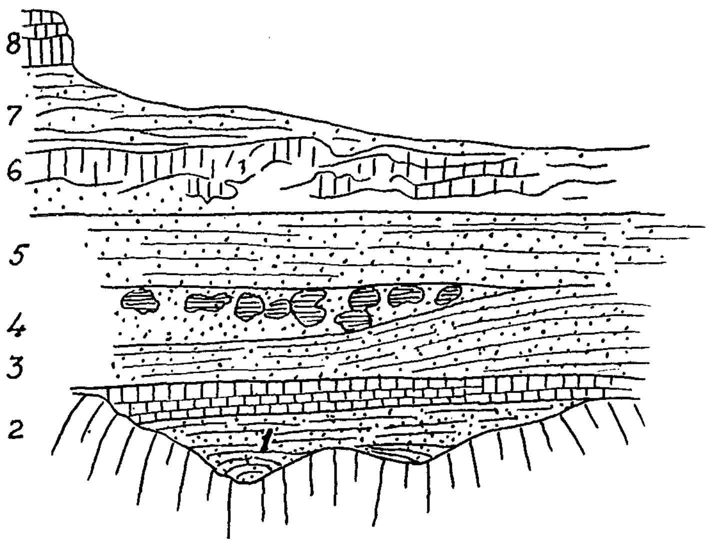

Fig. 2. — Section in the Palagonite Formation at Hvammur (Eyjafjöll). Total height about 200 m. Basalt lavas, brown tuff and breccia. Further explanation in the text.

The lowest visible horizon is a thick layer of stratified light brown volcanic tuff and breccia (1). The layer is mostly of fine grain, but strata of scoriae are also abundant, and rounded, worn pebbles may be found.

The strata are undulating in such a way as to suggest the action of wind as a dominant factor in the deposition of these sediments. In a thin section (261) we find that the tuff is composed of subangular and rounded grains of translucent, rather porous glass, enclosing small crystals of plagioclase and augite and a fair amount of relatively large phenocrysts of the same minerals.

Besides this glass fragments we find a fair amount of separate subangular and rounded crystals of the two minerals of the same size as the larger group of phenocrysts, and it is clear that they are of the same nature: broken out of the glass during the transport. The small size of worn grains suggests again the action of wind.

The groundmass (262) of the breccia may be called identical with the described tuff.

These layers are covered by a 2 m thick red sandstone and conglomerate consisting of pumice, scoriaceous material and glass fragments and is most probably of explosive origin, and partially windblown.

Next are some lavas (2) of a fine-grained porphyritic grey basalt the heat of which has reddened the sandstone below. Then again we have brown tuff and breccia similar to those at the base of the section (3). These sediments are covered by a peculiar, thick layer consisting of unworn cubes or polyhedrons of dark, very fine-grained basalt, about 1 dm^3 in size, in a brown matrix.

This layer reminds one of the thick lava at the head of the brook Merkiá, the main difference being a far greater amount of brown matter at Hvammur.

This matrix is seen in thin section (268) to consist of a *compact mass of brown translucent glass.* No glass fragments are seen in the slide.

Another slide (266) of a brown matter enclosed in a lava cavity at the same place shows again a compact mass of sideromelan enclosing phenocrysts of bytownite and some augite.

The nature of this layer is clearly very different from that of the lower breccias and tuffs. While these layers consist of transported fragments we have here a material which shows no signs of transport. This has not been a watery mixture of lava blocks and glass fragments. Nor are there, as far as I can see, any direct signs of the molten lava having been in contact with a chilling agency. It is, I think, clear that this layer represents a lava flow that consolidated at its present place partly as a "cube lava" and partly as a compact, yet irregularly jointed mass of translucent glass.

Above this breccia there is again a thick layer of brown tuff, obviously transported, and lastly there are several lava banks of a light porphyritic basalt up to the edge of the plateau.

Above the edge such lavas are everywhere in the surface of the plateau, up to the central regions. Here the plateau is surmounted by hills, probably of fragmental material, but because of fog I was unable to study these hills closer.

This series is thus built up of alternating layers of fine-grained porphyritic lavas and tuffs which consist mostly of translucent brown glass fragments, most probably being blown to this place. There is only one layer of glassy material which is in its place of formation, a compact yet heavily jointed glassy mass with angular blocks of an extremely fine-grained lava, representing a peculiar mode of consolidation of a lava flow.

The series appears to have been built up in a relatively short time, without any great change of magma, and there is in particular nothing to suggest that the alternation of crystalline and glassy eruptive products was parallelized by such major external events as a radical change of climate or of sea-level. I have found nothing to suggest that the whole series is not built up on ice-free land.

In our section there is no conglomerate which might suggest the idea of a moraine, although such a conglomerate has been mentioned by Pjeturss in the continuation of this series at Fit, a short distance west of Hvammur. No striated boulders were, however, found there by Pjeturss.

A locality with striated boulders is according to Pjeturss near Varmahlíð, som distance east of Hvammur. But whatever the nature of these conglomerates may be, their occurrence dos not influence the interpretation of the section at Hvammur.

A moraine with numerous primarily striated boulders I found on the edge of our plateau above the farm Núpur, close to Hvammur. This moraine is younger than a heavy dissection of the plateau, but it is older than the formation of the precipitous southern slope by which the plateau is now cut. Now, this slope is certainly not the work of post-glacial marine erosion, it is much older.

This shows that our plateau is of considerable age and dates at least far back into Quaternary times.

Let us now take a more general survey of the whole series as it is seen in the long precipitous slope of the plateau. We see that the main character is everywhere the same as in Hvammur, from Seljaland at the western limit, to Raufarfell some 25 km. to the east: a pile of nearly horizontal layers of brown tuffs or breccias and ordinary lavas. In the west the brown tuffs show a clear predominancy over lavas. In Steinafjall which is nearer to the present centre of the complex the lavas are, on the other hand, not less prominent than the tuffs. I could discern 5 or 6 separate layers of brown tuff or breccia interbedded between lavas. This repeated alternation, occurring no doubt in a relatively short period, is of interrest as an argument against parallel major external events.

With increasing distance from the centre of the complex, east of Raufarfell, the lavas, however, not only dwindle but become quite negligible. The entire complex is here built up of piles of brown fragmental material.

This fact possibly means that the main centre of eruptions was at the site of the present volcano, Eyjafjallajökull. In its neighbourhood the lavas were piled up, whereas to greater distances only the finer fragmental materials was carried (blown). It is in this connexion interesting that in the Westmann Isles, just off the coast, finer fragmental glassy material builds up the larger mountains, although coarser material and basalt, probably intrusive, are also abundant.

The material of the thick piles of brown tuff all the way from Raufarfell to Vík in Mýrdalur seems to have suffered considerable transportation. A thin section (289) of tuffs at Vík (taken from the hill on which the church stands) is, I think, rather typical. It shows larger and smaller worn grains of translucent and black porous glass, enclosing a number of small needles of plagioclase. The finer mass is altered and faintly birefringent. . .

Following the main road east of Vík it was not before the Kerlingardalsheiði some 10 km east of Vík, that I noticed tuffs of a different character and a more primary appearance, and we may here have reached the domain of a new volcanic centre.

This brown tuff or coarse sandstone is also in a thin section — (290) which is taken near the highest part of the road — very different from the transported tuffs to the west. This slide consists entirely of angular fragments of fresh translucent yellow glass, enclosing a number of the usual phenocrysts. The shape of many of the larger fragments suggests that hardly any transport can have occurred, the fragments being a veritable network of glass. In some cases also, neighbouring fragments seem to fit so well into one another as to indicate that the fragmentation took place on the spot. The unarranged admixture of large and small fragments indicates that they did not settle from the air. This tuff seems either to represent a lava flow that consolidated entirely as glass which on cooling crumbled into innumerable pieces or perhaps more likely it is a volcanic sandflow spreading out over a limited area around the vent. There are no signs of a tumultuous motion as might be expected if a chilling glacier had produced this glass.

4. SÍÐA AND FLJÓTSHVERFI

The volcanic series of Tindafjöll, Eyjafjöll, and Mýrdalur are continued to the east and north. They extend to the Skeiðarárjökull in the east and at least beyond Þórisvatn in the north. In all this area previous authors speak of the Palagonite Formation, and it is described as being in many ways quite similar to Tindafjöll and Eyjafjöll.

The formation is cut by the coastal plain in an escarpment of sometimes appreciable height and here many excellent sections can be studied and the section of the series followed uninterruptedly over large distances. The character of the series is everywhere the same, a succession of very fine-grained lavas with columnar and polyhedrous or block jointing and brown breccia to fine brown and greenish tuffs, and the brown material is always composed of translucent brown or yellow glass and its alteration products: the darker palagonite, and the white zeolites. As far as I have been able to detect, no signs of noteworthy interruptions of the volcanism are present nor are there any unmistakable signs of ice as an important factor in the formation of the brown glass. But here we are able to make many interesting observations of sideromelan on an original layer which lead to a fuller understanding of its formation.

I shall now describe some observations more closely.

In Síða, between Skál and Þverárnúpur the edge of the escarpment is made up of lava with block jointing, then below follows a brown layer of breccia and brown matter which further down turns into a lava of block jointing. Protuberances, not apophyses, extend from the lava up into the brown matter in such a way as to show clearly the genetic unity of both. We have here clearly a lava flow that consolidated both as a very fine-grained lava and as a brown compact matter containing a varying amount of lava blocks.

The brown matrix of the breccia is in a thin section (286) seen to consist of marginally altered angular fragments of sideromelan enclosing a few phenocrysts of plagioclase and olivine. A great abundance of zeolites and a little calcite occur as cement. There are both large and small fragments of glass, a common size being 5 mm, and I think there can be no doubt that they have resulted at this place from the crumbling of a compact mass of glass, but did not creep forth as a watery mass of fragments. Thus the interpretation of this section seems clear: A very thick lava flow consolidated partially as fine-grained lava and partially as a mass of glass which broke into pieces because of internal tension.

Among the glass fragments in the slide two exceptionally large ones are of special interest. They are mostly opaque, but partially translucent and then indistinguishable from the neigbouring fragments of sideromelan. The two varieties of basic glass, tachylyte and sideromelan, are thus found in contact, and a sharp contact at that with each other.

Proceeding westwards the brown breccia increases in the section and at Foss the over 100 m high escarpment is nearly wholly made up of this breccia: Angular lava cubes or polyhedrons in a brown matrix and it closely resembles the breccia described at Hvammur. At Foss the matrix (287) is very similar to (286). Some of the glass fragments are here again partially opaque. The fragments are on the whole large, up to 10 mm, and there is no sign of a comminution of them as would result from transport. In some cases neigbouring fragments seem to fit into one another, indicating that they were not transported, either as "ash" through the air or as a mud flow, but represent a crumbled thick mass of glass. The exceptionally thick lava flow simply seems to have consolidated partially as translucent glass, not because of some chilling external agency, but because of its own properties.

Underlying the series is at Breiðabólstaður a grey conglomerate which I assume to be a mud flow.

At Kirkjubæjarklaustur the whole escarpment, over 100 m high, is made up of brown tuffs in which fragments of lava and scoriae occur, especially near the top. Lower, this tuff contains large fragments of glass and unworn pebbles of lava of the size of a fist. A thin section (281) from a specimen taken at the small waterfall shows large angular fragments of sideromelan and a fragment of opaque glass, with enclosed phenocrysts. Some zeolitic matter occurs as cement. Another thin section (282) from the top of the series west of the farm contains large (about 5 mm) beautiful augular fragments of sideromelan, laterally altered. Smaller fragments are wholly altered into birefringent palagonite. Zeolites are abundant as cement and cause a whitish appearance in the hand-specimen. As at Þverárnúpur we find fragments which are partially opaque.

The breccia is some distance west of the farm covered with a layer of a grey conglomerate, closely resembling the old "moraines". Yet no striated stones were observed, and the thin section (283) reveals that this layer is not different from the previously described grey conglomerates. The matrix consists mostly of glassy fragments, some large but most of them very small, and a few fractured crystals of plagioclase, olivine and augite, and this is in my view most naturally explained as a mud flow.

If we compare (283) on the one hand, with (281) and (282) on the other, the main difference is that in the former the large mass consists of very small glass fragments whereas in the latter the average size of the fragments is much larger. This is easily understood when it is considered that in one case we have most probably a flow of a wet mixture of fragments, in which grinding and comminution of the fragments must be assumed, whereas in the other case the conclusion seems inevitable that a (very thick) lava flow consolidated partly as a mass of glass which afterwards crumbled into innumerable fragments — because of inevitable tension in the glass. In (283) we see the effect of a long transport of a mass of glass fragments, an effect which is absent in (281) and (282).

A characteristic feature of the volcanic series here in Síða is the vast extent of the layers of breccia. It appears as if we had the same thick layer of breccia and lava of block jointing all the distance from Þverárgnúpur to Kirkjubæjarklaustur or even to Skál, over a distance of 25 km. At least the extension is so large that an extrusion beneath an ice-sheet seems to be quite out of the question. This extension is however easily understood if a fluid magma flowed over the area and consolidated in this peculiar way. —

Above the edge of the scarpment of Síða the land rises gently inwards and the rough oblique plain is surmounted by two high roughly dome-shaped mountains, the Kaldbakur and the Geirlandshraun.

Two rivers, Geirlandsá and Þverá have cut deep gorges into the roots of Kaldbakur. The roots of the mountain are here similar to the section already described. In the lower gully of Þverá we see volcanic breccias such as that described before, lavas with block jointing and columnar grey porphyritic basalt. Higher up along this river, below the so-called Berjafit a succession of many such porphyritic lavas is seen. Above these lavas is a thin layer of a grey conglomerate and then comes a typical block lava.

From now on we ascend the steep slope of the mountain and in it we observe a few ordinary lava flows but mostly "block lava". On the large surface of the mountain are also either "block lavas" or remnants of more ordinary lavas of a porous grey porphyritic basalt. A peculiar feature of these porous lavas is that *their vesicles are filled with a loose mass which to the naked eye resembles humus but is in reality fragments of sideromelan.* Thus in the midst of lavas sideromelan is formed in the vesicles and here quite certainly without the influence of ice or any other chilling agency.

We have already described Kaldbakur as a somewhat irregular dome. This dome rises above a vast, also somewhat uneven, i. e. eroded tableland, the southern section of which we have studied between Þverárnúpur and Kirkjubæjarklaustur. But the plain extends also northwards, until it meets quite abruptly a ragged ridge of mountains which extends in the here usual tectonic direction SW—NE from Torfajökull to Vatnajökull. These mountains are according to Thoroddsen and Nielsen[15]) built up of Palagonite breccia. Their tectonic origin is emphasized by Nielsen. Many of the mountains are flat-topped and steep-walled and it seems likely that they are an uplifted part of the larger plateau surrounding Kaldbakur and Geirlandshraun.

The idea presents itself that these two domes are in reality ancient volcanoes, and thes was already suggested by Thoroddsen. Kaldbakur lies on the very active volcanic line which is marked by Grímsvötn, Hágöngur, and Rauðhólar, but more direct evidence is also available. The western slope of Kaldbakur from about 600 m down to about 400 m elevation is covered by a thick layer of a brown mass with scattered blocks of dark basalt. On the surface we observe low elongated ridges stretching down the slope, as if the material had flowed downwards. This layer is but little dissected, and only at the lower end did I see a good section of it, about 30 m thick. It is stratified with the general dip of the slope. At the bottom we have scoriae and a mixture of irregular lava blocks and the usual brown matrix, the percentage of the matrix increasing rapidly a short distance from the bottom and then remaining constanet. In thin section (280) the brown matrix is seen to consist of *compact* sideromelan, such as we have formerly found in the breccia at Hvammur. It is clear therefore, that a very thick and no doubt viscous lava flowed down the slope and consolidated mostly as glass.

It is very difficult to assume a subglacial lava flow in this case and the thickness of the compact, although naturally jointed glassy mass, is incompatible with the conception of an ultra-rapidly chilling agency.

This breccia at its lower termination rests on a grey hard conconglomerate of morainic appearance. I "managed" to find a striated block standing out of the hard matrix, but I considered the striae to be possibly of a secondary nature, i. e. made by a glacier creeping down the slope after the hardening of the conglomerate. In my view this predominantly glassy conglomerate, resting on crystalline basalt lavas, is a mud flow. The grey basalts on which the conglomerate rests are of just the same kind as those mentioned on the east side of the mountain, which also are covered by a similar conglomerate. We thus most probably find the same mud flow on both sides.

Descending further down the slope we find lavas of block jointing, columnar lavas and at the bottom of the series a thick layer of breccia which may be identical with that of Kirkjubæjarklaustur.

We now proceed further eastwards to Fljótshverfi where a section at Núpsstaður shall be mentioned. The lower part consists of lavas of the usual grey basalt covered by a layer of conglomerate of well worn pebbles and boulders. No striae were found. Then follows a very thick interesting layer. At the bottom it is a columnar dark basalt, soon turning into block jointing with an abundance of yellow matter and still higher containing patches of brown glassy material. Here again is a lava flow which consolidated partly with columnar, partly with block jointing and partly as glass and zeolites.

On the top af this peculiar layer we have a thick layer of fine brown stratified tuff which is made of worn grains of translucent glass and thus is no doubt of distant origin. Covering this at the edge of the escarpment are again some lavas of grey porphyritic basalt.

The perpendicular wall of the over 600 m high Lómagnúpur east of Núpsstaður is built up in a similar way although ordinary lavas are here in less abundance than at Núpsstaður, except at the top of the series.

5. SOME GENERAL CONSIDERATIONS

With Skeiðarárjökull we have reached the eastern limit of this wide area of the Palagonite Formation. An isolated small area of similar rocks is the complex of Öræfajökull which is separated from Fljótshverfi by the mountains around Morsárdalur which are built up of older dipping lavas, a different kind of basalt with intercalated altered tuffs and breccias.

The main area here considered from Tindafjöll to Fljótshverfi is a vast, dissected plateau built up of horizontal layers of:

1. Grey porphyritic very fine-grained lavas.
2. Brown tuff of worn grains of translucent porphyritic, often very porous yellow glass and opaque glass which probably were thrown out by explosive eruptions and carried to and fro by the wind over wide areas.
3. Brown tuffs of angular fragments of sideromelan which have not been transported at all and seem either to represent lava flows which consolidated wholly as glass and vere split up into innumerable pieces or they represent what may be called a volcanic sandflow of glass fragments.
4. Peculiar basic lavas which partly consolidated as an extremely fine-grained dark basalt with columnar and block jointing and partly as translucent glass which may be compact or split up into relatively large fragments. In some cases the basalt is predominant, in other cases the glass. These lavas are mostly exceptionally thick and seem nevertheless often to extend over relatively wide areas. There is no indication of a tumultuous motion or explosion from contact with a chilling agency.
5. Occasionally sheets of indurated grey glassy conglomerates occur in the series.

The whole plateau series appears to be built up on ice-free, dry land in a relatively short period, so as to leave but very limited space for the destructive forces. The magma appears to have changed very little during the volcanic period as indicated by the phenocrysts but it consolidated in many different ways. This difference, as we have pointed out, it is very difficult, not to say impossible to ascribe to external chilling agencies. It must be sought in somewhat changing physical properties of the extruded magma and in the concluding chapter we shall be able to point out a simple and natural explanation of the different modes of consolidation.

Here we shall enter further into the question of the grey conglomerates, which hitherto have generally been assumed to be moraines.

We have emphasized their largely glassy composition, a fact which was originally noted by Keilhack. This holds also in cases where the conglomerates rest on crystalline lavas. It is further important to notice that blocks or pebbles of brown tuff or breccia are extremely rare in the conglomerates. At any rate I have not noticed such blocks. Hence it is rather unnatural to assume that the material of the conglomerates derives from the breaking down of tuffs or breccias.

Now as to striated stones contained in the conglomerates two facts must be kept in mind. The first is the phenomenon of secondary striation. These hard conglomerates are just in such a condition that boulders protruding out of them may be striated by glaciers without much danger of being loosened and carried away. On the other hand, post-glacial weathering would suffice to wipe out eventual striae on the fine matrix of the conglomerates and yet in most cases permit the striated basaltic boulders to remain in place. This phenomenon, it seems, has aroused little notice and it might be suggested that the striae detected on boulders in the conglomerates are partly of this nature.

The other fact is the notorious scarcity of striated boulders in the assumed old moraines. Observers often remark that by a thorough search they managed to find one or a few striated stones. And this scarcity should be further accentuated if secondary striae are taken into account.

The significance of this scarcity of striated stones struck me especially as I walked across one of Iceland's well-known sandar, the Breiðamerkursandur. From the eastern part of this sandur the glacier Breiðamerkurjökull has retreated since the beginning of this century, and here nearly every, if not every stone of the size of a human head or larger which I looked at, was very clearly glacially striated.

This may be an exceptional case, but nevertheless, I think that the occurrence of striated blocks in Pjeturss' "moraines" is so rare as to call for a special explanation. I think the question is legimitate, wheth er the reported striation of such a small percentage of boulders in the conglomerates is not more naturally explained by some other agency than glaciers.

It must be borne in mind that a glaciation has a great many effects besides striation. A sheet of conglomerate occurring in the midst of strata of a different material, or which do not point to the presence of glaciers at all, can hardly be accepted as a proof of a glacial condition or as indicating a general glaciation of a whole country, simply because of the presence of occasional, striated, or what is possibly just as correct, scratched stones.

In such a case the possibility of another explanation of the scratches should be considered. The composition of the conglomerates I have studied in the area considered and their relation to other strata have suggested to me that an entirely volcanic origin is the most natural explanation.

Eruptions of such material as the conglomerates consist of, are not unknown. A quite similar material is known in theTertiary volcanic series of e. g. the Faroes, Scotland and Ireland.

In these series we find, according to A. Geikie and others, beds of volcanic conglomerates and breccias, interbedded between the basaltic layers. Sometimes these conglomerates consist mostly of coarse blocks, "more commonly however, the dirty-green or dark brown granular matrix exceeds in bulk the stones embedded in it"[16])

Of still more interest, on account of their unequivocal meaning are, however, the infillings of volcanic vents, the so-called necks.

The neck of Maclean's Nose, with a cross section of 1000 x 300 yards, contains blocks of all sizes up to eight or ten feet in diameter. "By far the largest" number of the blocks are "varieties of basalt, slaggy and vesicular structures being especially conspicuous. There are also large blocks of different porphyries and felsitic rocks". "All the stones are more or less rounded and are wrapped up in a dull-green compact matrix of basalt-debris. There is no stratification or structure of any kind in the mass." (l.c. 106)

The largest neck mentioned by Geikie is the one in the valley of Strath in Skye.

There seems no reason to doubt that the mass occupies part of the site of a single volcanic funnel, which was almost two miles in diameter. "This agglomerate is a coarse tumultuous assemblage of blocks and bombs, embedded in the usual dull dirty-green matrix. Among the stones, scoriaceous, vesicular, and amydaloidal basalts are specially abundant." "Towards the end if not from the beginning of its activity, its discharge consisted mainly of dust and stones". (l c. p. 108 — 9).

In the Faroes 8 or 9 necks are now known and I quote here from Walker and Davidson's description of these necks[17]).

"In most cases the vents are wholly filled with a volcanic agglomerate formed of both rounded and angular fragments of basalts of different petrographic types, frequently scoriaceous and invariably much decomposed, ranging in size from minute particles up to masses 2 feet in diam. Sometimes the ashes are bedded, dipping towards the middle of the section; sometimes there is no trace of stratification" (l. c. p. 873).

In the neighbouring and related volcanic series a material has thus been erupted which is in many respects similar to that of our conglomerates, the eruption of rounded blocks being especially interresting.

Of special interest is also a comparison with the volcanic tuffs of Schwaben in Germany.[18]) They are very similar to the British occurrences and like these are thought to be of purely volcanic (explosive) origin. But contrary to what appears to have been the case in Britain they have for some time been considered to be of glacial origin and only by a thorough research has it been proved that they are in no way genetically connected with ice. Branco quotes e.g. the following passage from Deffner: "Den Nachweis, dass auch dort alle Erscheinungen dafür sprechen, dass Gletscher die vulkanischen Auswürflinge (des Gebietes von Urach) mit dem anderen Gesteinsschutt zusammengeschoben und in jenen sonst unerklärlichen Schutthügeln angehäuft haben . . . . muss ich mir für einen anderen Ort vorbehalten" (l. c. p. 563). And Branco himself writes: "Mehr wie einmal ist mir selbst bei der Untersuchung unserer merkwürdigen Tuffbreccien, unserer gewaltigen Schuttmassen aus Weiss-Jura und der durch diese wie jene gebildeten Berge im Vorlande der Alb, der Gedanke vor die Seele getreten, ob hier nicht doch das Werk von Gletschern sich verrate". (l. c. p. 564). Further on he asks "ob nicht von den Alpen oder vom Schwarzwald her ein Gletscher diese Massen gebracht habe, welche hier das Bild norddeutscher oder gewisser alpiner Moränen vor seinen Augen auftauchen lassen". But Branco proves that these masses are purely volcanic and have in spite of their appearance nothing to do with ice-work.

An interesting feature is the different degree of roundness of the blocks. Those derived from the younger formations of the area are angular while the older rocks such as granite are more rounded. "Es ist das sehr erklärlich; denn letztere hatten einen viel längeren Weg im Ausbruchskanale zurückzulegen als erstere" (l. c. p. 504) .In a long explosion pipe we may thus expect an advanced rounding of the blocks, a conclusion which seems well worth considering in connexion with the Icelandic conglomerates. To make the analogy with the Icelandic conglomerate even more complete the blocks of granite sometimes show polished surfaces. The explanation of Deffner is this: "Entweder konnten die Stücke dadurch abgeschliffen werden, dass sie, in die Tuffmassen der Kraterausfüllung eingebettet, mit diesen im Kraterkanal auf- und abstiegen und sich dabei an einem härteren Gestein abrieben, bis sie endlich einmal umkanteten und eine neue Seite zum Abreiben darboten. Oder konnten sich auch die Stücke in den Kraterwandungen festklemmen und hier durch die vorbeipassierenden Auswürflinge in gewissen Richtungen glatt geschliffen werden" (l. c. p. 506).

As a further possible analogy to our conglomerates we shall now consider the Early Basic Breccias in Yellowstone Park, which are thought to be of Miocene or Oligocene age. A discussion of these masses by C. N. Fenner will be quoted here at some length[19]).

"In places they form deposits several thousand feet thick, some of which are composed chiefly of fragmental material, whereas others have many basaltic lava-flows intercalated.

On first acquaintance with these great deposits two features are likely to attract attention. In the exposures revealed on the precipitous mountain sides the strata have a nearly horizontal attitude for mile after mile . . . and many of the beds are made up largely of rounded boulders of great size. What was the means by which transportation and distribution of this material were effected? To one who has chiefly in mind the ordinary text-book illustrations of volcanoes, showing the inclination of beds and the general structure of such typical volcanoes as Vesuvius and Etna, and recalls descriptions of the conditions of extrusion that gave rise to these structures, these two features seem difficult to explain.

Although the structures of Vesuvius and Etna are typical of certain forms of volcanic extrusion, geologists have had impressed upon them forcibly within recent years that other volcanoes that may be considered equally typical depart widely from these in the manner of distribution of their ejecta.

Probably volcanic processes of several kinds were responsible for the building up of the thick beds of basic breccia in Yellowstone Park.. We should not suppose that the ordinary explosive ejection of blocks and lapilli was lacking here. The deposits in Mount Washburne and Sepulcher Mountain, for instance, are close to vents, and a portion,at least, was explosively ejected. Probably in general this process was an important factor. This, however, would tend to heap up material close to the vents, and if these accumulations remained undisturbed, we should hardly have the miles of horizontal strata or the rounded boulders that we see.

The formation of the spine of Montagne Pelée, and the accompanying avalanches of clastic material that occasionally burst forth from it in the form of nuée ardentes, have called attention to a type of eruption that has since been recognized as of common occurrence. It is now generally accepted that in such cases very viscous lava is pushed up from a vent in the form of spines, domes, or plugs. At intervals, shattering explosions occur, which disrupt portions of the mass and cause it to rush down the slopes. Continued evolution of gas from the shattered blocks is believed to be an important factor in maintaining mobility, and these streams of fragmental material, carrying large boulders, have been known to continue their course for miles after reaching gentle grades.

By a variation of this process a new element is introduced. In the volcanoes of Java especially, but also in other regions, the waters of the crater lakes have been involved in eruptions, and widespreading mud-flows have resulted.

Though the evolution of magmatic gases or the presence of water from crater lakes has been definitely recognized as involved in these flows, and must have greatly increased mobility, in other instances boulder-flows of great magnitude have occurred in which only a modicum of water or mud seems to have been present as a lubricating agent, and yet an astonishing facility of movement has been exhibited. A well-known instance is that of the eruptions of Bandai San, in Japan, in 1888. This has been attributed to a subterranean explosion, by which a part of the Mountain, of enormous magnitude, was upheaved and set in motion. It flowed down from the Mountain into the lowland, and covered an area of more than 25 square miles.

At the time of the eruption of Mount Katmai, several great boulder-flows or landslides occurred, whose only connection with the eruption seems to have been that the accompanying earthquakes served to start in motion masses of rock that had been in an unstable condition. One of these flows came down the canyon of Mageik Creck and covered the flat floor of Katmai valley over an area estimated at two miles by three-fourths of a mile".

"The roundness of the boulders in the Mageik Creek Slide gives the impression that the material set in motion must have been an old glacial accumulation. Material of that kind may have been involved, but observations on another slide indicate that this is not necessarily the case.

A few miles away, a section of steep lava-cliffs on the lower slopes of Mount Katmai fell away, and formed a dam across Katmai River at the upper entrance to Katmai Canyon. This dam persisted for several years, and impounded a lake several hundred feet deep over a wide area. When it gave way, a large part of the dam was swept by the flood through one-half to two miles of narrow canyon and spread out over the floor of the Valley at its lower end. The pounding and grinding undergone by the boulders seem to have been equivalent in their rounding effects to those produced on the ordinary boulders of river-channels through hundreds of years of stream-action.

In making application of these various observations to the conditions of accumulation of the Basic Breccia series of Yellowstone Park, and to many occurrences of thick beds of tuffs and breccias in other regions, the point that it is desired to bring out is that a vigorously active volcano forms a structure in which conditions of instability of large masses of rock are likely to occur repeatedly. Material from the interior of the earth is brought to the surface in great quantity and has to be disposed of. Violent ejection is one means of doing this, but evidently this is only one of the forms that manifestations take. Plugs and domes of viscous material are frequently protruded, which are likely to undergo shattering explosions. Katmaian eruptions (extrusion of a sand-flow) may occur. Lavas are poured out, which may be so liquid as to spread for miles but may approach in viscosity that of the plugs, and congeal on steep slopes in unstable positions. Whether an inner explosion shatters a protruded mass and starts it in a motion, or whether there is simply the breaking away of a somewhat watersoaked cliff, perhaps accompanied by loose ejecta that have accumulated on slopes, the masses set in motion have an ability to move in their lower courses for long distances over gentle grades in a manner that is difficult to conceive but that is attested by abundant evidence. Landslides of such origin may temporarily impound rivers, and the resulting floods may effect a rounding of boulders and their transportation for many miles. Even torrential rains may have a similar effect." (l. c. p. 237—239).

From these descriptions it is clear that sheets of conglomerates and breccias as a secondary product of certain not very uncommon types of volcanism may be formed under non-glacial conditions and this fact should not be overlooked in a discussion of the volcanic series of Iceland.

On the contrary, the reader will already have recognized that these types of volcanism are of crucial interest in the study of the Palagonite Formation as a whole.

A certain feature of eruptions of this type which does not appear in the previous quotations is the filing effect of a nuée ardente. This is of great interest with respect to the fact that the Icelandic conglomerates in some cases rest on a filed floor which has hitherto been considered as an especially clear proof of their morainic nature.

To give here some impression of the filing effects of a volcanic blast a discussion of the outburst of the Lassen Peak in California on May 19, 1915 will be quoted[20]).

By this blast a dense forest was swept away over a large area and a mudflow, caused by the melting of a considerable amount of snow in the slopes of the volcano, ran for a distance of 7—8 miles. The mud flow consisted of ash falling during the eruption and of large and small blocks. "It was, however, not the mud flow but a volcanic blast of terrific power (nuée ardente) and moderately high temperature, heavily charged with dust and rock fragments, delivered at a low angle in an east-northeast direction down Lost Creek Valley, which cleared the valley of its immense trees and indeed of every movable object for more than 4 miles" (p 21). "Before May 19 the valley of Lost Creek is reported by the Forest Service to have contained 5,000,000 feet of standing timber (original forest), much of which reached the diameter of 3 to 5 feet. After that date the bottom of the valley was swept like a floor, and was left without stumps or roots to indicate its previous forest cover. It was hard to find even a pebble in that area greater than a few inches in diameter. In the lower reaches of the valley this floor still carries its covering of baked mud flow, sometimes 2 or 3, sometimes 5 or 6 feet deep, and it is only when one arrives at the far end of the devastated region that the disposition of the boulders from the summit and the timber which once covered the valley begins to be evident. Here are giant trees broken and twisted into fantastic groups, with here and there a boulder weighing up to 15 tons or more. As stated above this cleaning-out of the timber cover of the valley was not accomplished in the first instance by the mud flow, because the valley walls are clean far above any point reached by the mud. It requires hardly more than a glance, however, to show what the agent must have been, for higher up on the inclosing sides of the valley, a little at the side of the main axis of the blast, we find the forest trees down but not removed, and in particular we find them lying in parallel rows for nearly 2 miles, with their tops pointing uniformly away from the crater". "Another interesting observation may be made in the outer zone at side of the blast. Most of the trees which line these corridors were uprooted, but some were broken off a few feet above the ground instead. The standing stumps of such bear unmistakable, direct evidence of the bombardment which they received. Without exception, their bark is gone on the side toward the mountain, while fully retained on the protected side. Similarly, the exposed wood on the side toward the mountain is completely peppered with fine sand, oftentimes driven in for a considerable fraction of an inch. Indeed, as one nears the source of the outburst the intensity of this bombardment was that of a fierce sand-blast which rounded off the stumps themselves." (p. 22—24).

It would seem a very reasonable conclusion that a blast laden with sand and rock fragments such as this one would file and scratch the surface of a basaltic lava and create a surface which locally might show striking similarities to a glacially striated surface. Furthermore, it would not be surprising to find in a subsequent mud flow a low percentage of scratched blocks.

Summing up, we see that the Icelandic conglomerates possibly have analogues of volcanic origin, either consisting of directly erupted material or of material which was worked and deposited as a secondary phase of eruptions of a certain type. As will be more clearly seen later there is every reason to pay especial attention to this type of volcanism when studying the volcanism of Iceland. Yet, it must be kept in mind that these conglomerates, interpreted as moraines, have played a dominant role in Icelandic geology for a long time. We shall therefore have to consider directly some well-known localities of the supposed moraines.

6. HVALFJÖRÐUR

This area in S.W. Iceland presents many interesting and important features. Above all the conception of a non-glacial origin of the grey conglomerates can here be put to a very hard test, perhaps the hardest test it is likely to be out for.

Here, at the head of Hvalfjörður, near to the farm Botn are to to be found two of Pjeturss' classical localities of "Early Quaternary Moraines". They were discovered and described by Pjeturss in 1904[21]).

In these localities the morainic nature of the described conglomerates is, it seems, especially convincing for the reason that not only did Pjeturss find striated stones in them, but the conglomerates in Austurgil and at Glymur, he reports, rest on a very clearly striated floor of basalt.

We shall now pay special attention to the sections which contain these interesting conglomerates. I had no difficulty in finding either of these sections from Pjeturss' description.

The section in Austurgil. Below a thick pile of grey fine-grained porphyretic basaltic lavas we have the section shown in Fig. 3 (c.f. Pjeturss' Fig. 6, l.c.).

The section is as follows:

1. Dark amygdaloidal basalt.
2. A dark conglomerate in an advanced state of decomposition.

I could not find any glacially striated stones and I think that in this state of the conglomerate it is impossible with any safety to decide upon glacial striation of the contained rounded stones.

Pjeturss reports that striated stones are easily found, which is contrary to my observation and I cannot accept his interpretation of this conglomerate as a moraine.

3. A lava of amygdaloidal basalt.

4. Conglomerate with rounded pebbles of basalt, not larger than a fist, in a brownish matrix. This conglomerate is not a chaotic mass but somewhat stratified and there are alternating layers of conglomerate and thin stratified layers of fine-grained brown tuff. Pjeturss asserts that striated stones are easily found in this conglomerate, yet I could not detect any stones with clear glacial striae. Scratched stones may be found, but certainly they do not prove the conglomerate to be a moraine.

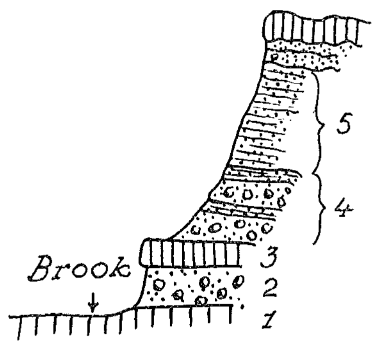

Fig. 3. — Sediments in Austurgil. Explanation in the text.

The matrix of this conglomerate, in thin sections (362 a) and (362 c), is seen to consist mainly of yellow faint polarizing glass although there is also an abundance of minute fragments of undeterminable crystals, and worn grains of basalt and opaque glass are scattered throughout the matrix. The yellow glass does not consist of distinguishable fragments but appears as a compact cement. The strata of tuff intercalated with the conglomerate consist of rounded grains of opaque glass and of grains of an extremely fine-grained lava in a rather sparse groundmass of a brown amorphous substance.

The stratification as well as the composition of this conglomerate seems to fit in very badly with the hypothesis of a moraine and as already stated, I could not find glacially striated stones in it.

This composite conglomerate is directly covered by:

5. Many thick layers of brown tuff or mudstone, greenish coarse sandstone, and at the top a coarser brown tuff.

All these strata consist to a high degree of fragmental translucent glass. The lower brown tuff (363) consists of small rounded grains of a black fine-grained lava, separate crystals, so large that they were no doubt originally phenocrysts, and yellow glass.

The green sandstone (364) consists mostly of rounded and subangular grains (average diam. 0,3—0,4 mm) of greenish palagonite, dark glass, and separate crystals of augite, olivine and plagioclase, obviously phenocrysts from the glass. No lava fragments are seen in the slide. The grains are cemented by palagonite, zeolites, and calcite. The topmost layer of brown tuff (365) differs from (364) by coarser grain, angular shape of the glass fragments, and the presence of worn grains of lava. It is the dominating brown palagonite that determines the colour.

These sediments are covered by a number of grey, fine-grained, porous lavas of basalt.

These strata as a whole do not suggest a glaciation. They are simply a volcanic series like those described in the previous chapters. A striated floor of the conglomerate (4) can hardly change that conclusion. Yet, we shall consider this striation closer.

The surface of the lava (3) is very clearly filed as stated by Pjeturss, elongated grooves and striae are unmistakable and there is much resemblance to a glacially filed surface. Also, there is no doubt that this surface goes under the conglomerate.

On the other hand the conglomerate does not lie directly on the lava surface (cf. Fig. (4) which is a section at right angle to the striae). The surface of the lava is covered with a 1 cm thick layer of soft yellowish clay. Then comes a loose mass of fragments of a hard brown amorphous or glassy substance, evening out the grooves of the lava surface. The lower surface of the conglomerate that rests on this loose mass consists of the same amorphous substance.

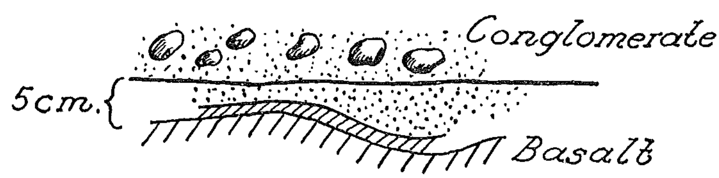

Fig. 4. — Lower contact of grey conglomerate in Austurgil. See text.

I cannot see any possibility of accepting this as the contact of a moraine and its floor. On the other hand the interpretation of this contact is far from being clear. This much is clear that the grooves of the lava-surface were filled up before the deposition of the conglomerate and it seems most probable that the high temperature of the mudflow, which in my opinion, the conglomerate represents, metamorphosed the underlying sediments.

The section at Glymur. Fig. (5) is a reproduction of Pjeturss' Fig. 4 (l. c.) showing the section at the waterfall Glymur. It shows a series of alternating basaltic lavas, brown tuffs, and conglomerates. Only the highest part of the section is accessible to close observation and here the main interest concentrates on the layers f, g and h. According to Pjeturss g is a grey conglomerate containing worn and striated stones and resting on the striated surface of the lava f, and it is hence assumed to be an especially clear case of a moraine.

Now in a thin section (374) from the bottom of this conglomerate the hard groundmass is seen to consist mainly of *angular fragments of isotropic brown glass,* only occasionally altered. Fragments of olivine, augite and plagioclase are present, probably phenocrysts, as they also occur as such in the glass fragments. The brown stratified tuff h (375) which rests directly on the conglomerate consists almost exclusively of small fragments of yellow glass, only very few fragments of crystals being seen.

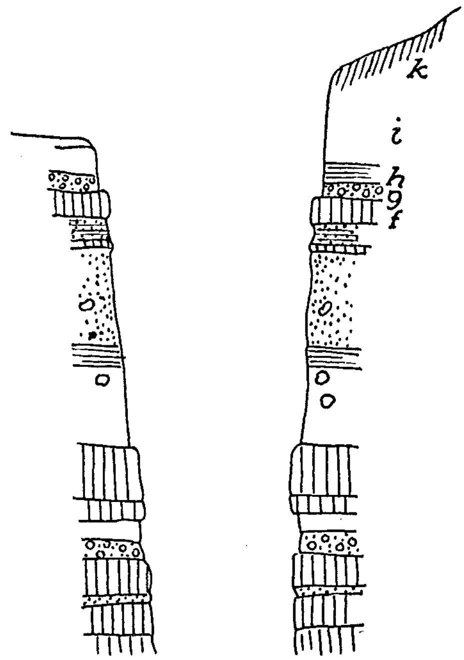

Fig. 5. — The gorge of Glymur (After Pjeturss, l. c. Fig. 4.)

These layers are certainly no ordinary products of a glaciation and a very strong evidence would be needed to prove their morainic nature.

As to glacially striated pebbles I cannot endorse Pjeturss' statement that these are easily found. There are scratched, rounded stones which, however, prove nothing. In a mud flow, as e.g. in an avalanche, the pebbles might be scratched like this.

There is, however, the striation of the surface of the lava f, which might be a strong evidence of glaciation.

This striation is very clear, but it is not of any great magnitude as the original flow structure of the lava surface is at many places clearly seen and it is further of interest to note that the flow direction of the lava was the same as the direction of the striae. The surface is in spite of the filing rather rough and there is only a remote resemblance to the polished surfaces left by the late Quaternary glaciation in this country.

If this lava surface was filed by a glacier, that glacier must have been thin or ineffective and to assume a general glaciation of the country on account of such glacial work is in my opinion impossible. But there is a further fact to be taken into account which is decisively against glacial action. This is the extra-ordinary contact of the conglomerate and the lava. The conglomerate does not touch directly the lava surface, but there is left an open space of 4—5 mm between them. Out of the conglomerate protrude small pebbles and on these as on innumerable pillars rests the conglomerate.

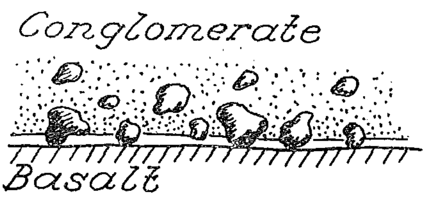

Fig. 6. — Lower contact of conglomerate at Glymur. See text.

This peculiar contact is hardly that of a moraine and its bedrock, but it is on the whole not easily understood. It seems the most probable theory that an originally high temperature of the mud might in some way be the cause (a layer of steam?).

Thus, as far as I am able to see, Pjeturss' interpretation of these conglomerates in Austurgil and at Glymur is not convincing. The interpretation pays no attention to the composition of the matrix of the conglomerates or to the accompanying volcanic products, or the peculiar contacts. On the other hand it stresses too far the occurrence of scratched pebbles as indicative of glacial action. And as to the striated floor, other possible agencies such as wind erosion, the erosion of a volcanic blast (note that at Glymur the flow direction of the lava is that of the striae), and of the mudflow itself, are left out of consideration.

There is no conclusive proof of glacial action; on the contrary, there are many factors against such an interpretation.

General aspects of this area. The mountains at the head of Hvalfjörður are, if we leave for the present Hvalfell and Botnssúlur out of consideration, eroded out of an extensive plateau, built up of slightly eastward dipping layers. This plateau is built up of alternating layers of grey fine-grained, porous porphyritic basalt lavas, beds of glassy tuffs, the glassy fragments sometimes showing no sign of longer transport, sometimes being probably wind blown,

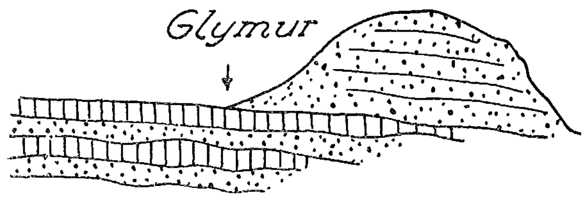

Fig. 7. — Section of Hvalfell from the south, showing the mountain as a remnant of a thick cover of stratified tuffs.

and a few beds of conglomerates of volcanic origin. Hvalfell and Botnssúlur are two immense piles of brown tuffs or breccias resting on this composite series. The thickness of these piles is well over 300 m both in Hvalfell and in Botnssúlur. Especially in Hvalfell there is a clear stratification, with the same general dip as that of the composite series below. It is clear, that both mountains are only remnants of an extensive cover of pyroclastic material and it seems also clear, that this cover was laid down before the tectonic period which is evidenced by the general dip. In both mountains these tuffs are covered with lavas of ophitic dolerite which is entirely different from the lower basalts. These lavas of dolerite probably covered originally much larger parts of the main layer of brown tuffs.

Above the edge on the western side of Botnssúlur at a height of about 900 m there is what appears to be a relatively recent flow of fragmentary brown glass, flowing out over the present edge of the mountain. The tuff is of very fresh appearance and clearly distinct from the tuffs of the mountain itself. In a thin section (380) this tuff consists of fresh angular fragments of pale yellow sideromelan of 1—2 mm diameter. These fragments are highly charged with phenocrysts of plagioclase and some olivine (20 — 30 % crystals). The fragments are embedded in a rather sparse groundmass of comminuted sideromelan and its phenocrysts. There is no indication of porosity of the glass. (379) is a grey tuff below (380) from the main mass of the mountain. It is similar to (380), the main difference being a slight porosity of the glass and a few fragments of porous dark glass.

A brown tuff (378) lower than (379) is perhaps more typical of the main mass of the mountain. It differs from (380) by the fact that every fragment of sideromelan is lined with a narrow brown rim of palagonite and the fragments are completely cemented by this palagonite and an appreciable amount of zeolites. Phenocrysts are fewer than in (380) and there is some porosity as in (379).

There is no indication of a notable transport of these glass fragments. Further, the absence or low degree of porosity seems to indicate that these tuffs are not the result of explosive eruptions. Most probably they either represent lava flows consolidating entirely as glass and crumbling into pieces on cooling or, what seems more likely, they are streams of a mixture of glass fragments — erupted sandflows.

The dolerite on the top of the mountain in hand-specimen closely resembles the dolerite of Reykjavík as remarked by Thoroddsen. In thin section (391) it is practically identical with the ophitic dolerite of Reykjavík.

There remains to be mentioned an interesting feature in the mountain slope some 100 m east of Austurgil. This is a stream of breccia running down the slope. It consists of dark lava fragments of distorted forms and a matrix of brown matter of varying percentage. In thin section (369) this matrix is seen to have orginally been a somewhat porous unfragmented mass of sideromelan containing a few phenocrysts of olivine. A great deal of the glass is now altered into faintly birefringent palagonite, only scattered patches of unaltered sideromelan being left. This is clearly a lava flow consolidating partly in a fine-grained form and partly as massive glass, and as far as I can see this flow ran down the present side of the valley and should thus be relatively recent.

7. MIDDLE NORTHERN ICELAND

The high mountainous area on both sides of Eyjafjörður was earlier considered to be built up of a Tertiary Basalt Formation. According to Pjeturss' system, however, the higher reaches of these mountains consist of Quaternary rocks, as we have already mentioned in the introductory remarks. It has often been stated, among others by Paijkull, Kjerulf, Thoroddsen and Pjeturss that the basalts crowning these mountains are light-coloured and porous and very similar in appearance to the basalts of Southern Iceland, but it was not until Pjeturss' discovery of grey conglomerates of morainic appearance in the basalts of the North, i. e. at an elevation of about 700 m in the mountains of Fnjóskadalur, that a Quaternary age was assumed as for the rocks of Southern Iceland.

But quite apart from the question of age which according to our previous discussion of the grey conglomerates in the South cannot with certainty be based on a glacial interpretation of the conglomerates, it seems nevertheless a sound assumption that there is a close relationship between the volcanic series of the South and that forming the highest reaches in the mountains of Middle Northern Iceland. In fact, the volcanic plateau which we have studied from Tindafjöll to Fljótshverfi is not only continued in the region of Hreppar, to the west, but also without a disturbance of any notable magnitude to the north between Hofsjökull and Tungnafellsjökull, to the high ground of Middle Northern Iceland. The country is essentially a slightly inclined plateau with an elevation of about 4 — 500 m in Southern Iceland, 6—700 m south and east of Hofsjökull, 7—800 m north of Hofsjökull, then rising almost imperceptibly to 11—1200 m around Djúpidalur and Fnjóskadalur (here heavily dissected), attaining its greatest height of about 1500 m. around Glerárdalur near Akureyri. Thence it declines again down to about 1100 m or lower around Ólafsfjörður and Fljót. The rocks forming the uppermost part of a thickness of several hundred meters of this large plateau are the same in the south as in the north and there is no reason why they should not be considered as parts of the same formation. We shall now consider several sections in Northern Iceland.

Head of Eyjafjörður. In the eastern, about 700 m high slope of the valley of Eyjafjörður opposite Hafrárdalur I could distinguish 4 or 5 separate layers of brown tuff alternating with banks of basalt, but I have had no opportunity to make any closer study of these layers. On the opposite side of the valley, in the gully of the river Hafrá, there are just above an elevation of 340 m, i. e. below a pile of at least 700 m of basalt lavas, two layers of brown tuff, the higher one being 30—40 m thick. In the alluvial cone of the river we find an abundance of pebbles of tuff which no doubt are derived from these layers. In a thin section (592) of one of these pebbles we find worn grains of dark porous glass, yellow translucent glass, a few separate crystals of plagioclase which clearly are phenocrysts of the glass, and a few grains of basaltic lava in a predominating groundmass of birefringent palagonite. The vast majority of this rock is worn, probably wind-blown sideromelan, now a great deal altered.

Staðarbyggðarfjall on the eastern side of Eyjaförður just south of Akureyri has a height of 1200 m. It is almost entirely built up of lavas (of basalt) but we find also two layers of brown stratified tuff (when ascending from the farm Uppsalir). The lower at 680 m above sea level is 5—6 m thick. A thin section (400a) is nearly identical with (592), described above, but the alteration is still more advanced in (400a). (400b) from another substratum shows an abundance of large worn crystals of plagioclase (diam. 1—2 mm), a few crystals of olivine, several grains of dark glass enclosing large phenocrysts of plagioclase — all in a yellow faintly birefringent altered groundmass. Judging from their size the separate crystals are no doubt phenocrysts from the glass, either from the dark variety or the sideromelan which must have been the mother substance of the groundmass.

Somewhat higher, at 700 m, there is the second layer, 12—15 m thich. There are many separate substrata of different coarseness, and some enclose worn fragments of scoriae, but in other respects the material is the same as in the lower layer. Slide (401a) is very similar to (400a) but unaltered sideromelan occurs in addition. (401b) is also very similar to (400a) and (401c) must be described as identical with (592).

Kirkjufell at Öxnadalur. (Ascending a large gully near the farm Engimýri). A composite lava of columnar and block jointing and breccia of dark basalt cubes in a brown glassy matrix of the usual kind we have often described occurs at an elevation of 500 m, i. e. below a pile of 800 m. From an elevation of 450 m to about 800 m the section consists of fragmental material, either tuffs or breccias and conglomerates of a very heterogeneous appearance. It is likely that they are mostly of purely volcanic origin and that they may be caused by a type of volcanism represented by the British necks. But here we cannot enter into a discussion of these large and complicated masses. Only a few features may be mentioned. The dark-brown matrix (416) of the above- mentioned breccia consists of a granular mass of faintly polarizing translucent glass with phenocrysts of plagioclase, augite, and olivine. The larger glass fragments show flow structure but the smaller ones usually do not.

A thin vein (418) of brown matter traverses the fragmental masses below this breccia. It consists of a compact mass of palagonite enclosing broken crystals of plagioclase and augite and scattered fragments of porphyritic opaque glass.

At an elevation of 600 m there is an apophysis (423) of a compact faintly polarizing palagonite containing again fragments of crystals and dark glass which in some cases is very heavily charged with phenocrysts of plagioclase.

These occurrences of brown translucent glass can, I think, in no way be connected with glaciers, and also in another respect they are of great interest.

They show that sideromelan is found down to the lower parts of the basalt plateau, but the higher parts of the plateau enclose Tertiary lignite and petrified tree trunks. A short distance to the east of Kirkjufell, at Glerárdalur, these fossils are found in the basaltic series at an elevation of 1050—1100 m, and here, in the ridge between Reithólar and Hlíðarskál, I found several separate layers of sideromelan tuff in the series directly underlying the fossils. *Thus, already in Tertiary times, perhaps early in that period, sideromelan was formed in Iceland.*

Ljósavatnsskarð. In the 800 m high northern slope of the pass of Ljósavatnsskarð, following the brook near Sigríðarstaðir, we have the following layers of brown tuff which is probably mainly wind-blown sideromelan.

1. At 500 m, thickness		10 m.
2. — 540	—	several meters. In a thin section (464) we find perfectly rounded grains of translucent yellow glass mostly altered, opaque glass, and a few rounded grains of lava and crystals of plagioclase, all cemented by a yellow birefringent alteration product.
3. — 580	—	several m. This tuff rests on a fresh lava surface with very clear flow structure — an indication of the rapidity with which the series was built up[22]). A thin section (466) of this tuff is very similar to (464) except that no lava grains occur.
4. — 615		Yellow mudstone.
5. — 650		Brown tuff.
6. — 710		Brown-yellow tuff.

The material of these tuff layers is clearly transported, probably produced by explosive eruptions occurring somewhere else during the piling up of these series of basalts. But primary sideromelan may also be found here, i. e. eruptions of such a material also occurred in this area.

At an elevation of 260 m I found a narrow vein of brown matter traversing a basalt lava, this being no doubt of igneous origin. Yet, in a thin section (450) it is seen to consist of perfectly worn grains of translucent yellow glass, dark glass, and some crystals of plagioclase and grains of lava, also rounded.

The similarity of this matter and the stratified tuffs in Staðarbygðarfjall, Hafrárdalur and those higher in the present section is so great that one may feel some hesitation as to the secondary position of these sediments. They might certainly be derived from a material that was erupted in the worn condition.

At an elevation of about 420 m in our gully we find further primary material. This is a 10 m thick dyke of the same compact brown matter as that of the described vein. From this dyke apophyses are sent into the walls sometimes surrounding blocks of basalt breaking from the walls (Fig. 8). Towards the top the brown matter is horizontally stratified and this part has probably been carried into the fault from above. A thin section from this part is very similar

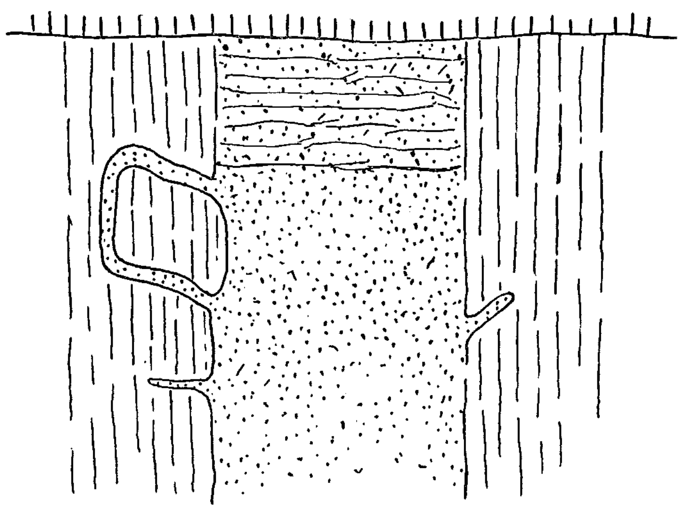

Fig. 8. — A dyke of glass fragments in north side of Ljósavatnsskarð.

to (400b), containing grains of glass and worn crystals of plagioclase and olivine. (457) from the dyke itself is somewhat different. We find a considerable number of rounded grains of opaque glass in a yellow translucent, faintly polarizing granular groundmass. But it is difficult to discern whether this groundmass was originally compact sideromelan or not. It is not possible to find sharply-defined grains of sideromelan. The separate rounded grains of opaque glass show that no ordinary hot lava was erupted but either a colder fluid or perhaps more probably a wet mixture of glass fragments.

In the *southern slope of Ljósavatnsskarð* we find also, as might be expected, several layers of brown glass intercalated between the basalt lavas, but here we find also layers of the usual grey conglomerates. They have been mentioned earlier and interpreted in the traditional way as "obvious signs of glaciation"[9]).

There are also other features of interest to be found here,

I ascended to the edge of Stóradalsfjall at Kambur, the edge being at about 850 m above sea level. A litle east of Kambur I found the following section at the edge of the escarpment, Fig. 9:

1. Lavas of grey fine-grained basalt.
2. Wind-blown sand and gravel.
3. Grey basalt.
4. Sediments, 4—5 m thick.
5. Grey dolerite.

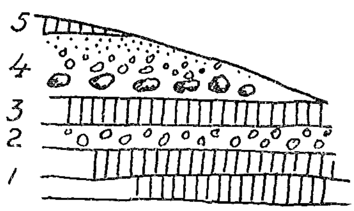

Fig. 9. — Sediments in south side of Ljósvatnsskarð.

The sediments (4) consist of brown mudstone at the top, then brown tuff and at the bottom greyish conglomerate with large boulders of basalt on which I was not able to detect any striae. The matrix of the conglomerate consists of worn grains of basalt and fine basalt debris, but no distinct fragments of glass are seen in the slide (438a). The tuff (439) consists of perfectly rounded grains (at least down to a diameter of 0,1 mm) sparsely cemented by palagonite. The grains are of opaque glass, basalt, and yellow translucent glass in that order of abundance and this material is most probably wind-blown.

Of interest is the fact that the conglomerate is traversed by a number of more or less vertical veins of brown matter of a thickness of several centimeters. These veins (slide 438b) which obviously are of volcanic nature consist of a structureless mass of minute fragments of brown translucent glass, opaque glass, and a relatively few very small fragments of crystals.

As to the coarse structureless conglomerate I can see no reason why it should necessarily be interpreted as a moraine, although at a glance it looks like one. In my view it is most probably a volcanic product, extruded as a mixture of fragmental material and it reminds us of the British necks.

We now follow the edge of the escarpment eastwards to a point a short distance east of the highest point of the escarpment.

The interesting section here found is most probably the one observed by J. Líndal (l.c.). Beneath several basaltic lavas there is the following series of varied sediments of a total thickness of about 40 m. (Fig. 10).

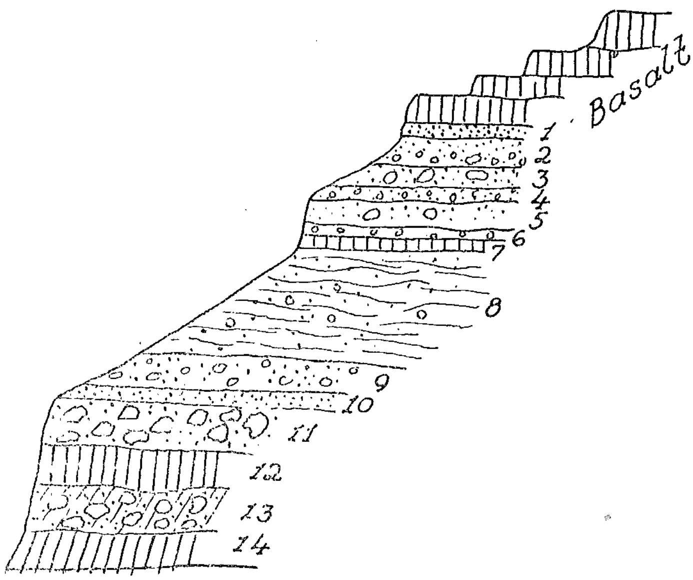

Fig. 10. — Main sediments in southern side of Ljósvatnsskarð.

1. Fine-grained brown breccia. The thin section (443) is very interesting. It shows large fragments of brown sideromelan, heavily charged with phenocrysts of plagioclase and olivine, and a great abundance of microlites. These fragments are embedded in an abundant base of compact, somewhat fractured sideromelan of a lighter colour and, remarkably enough, this glass is wholly devoid of phenocrysts and microlites. It is clear, both from the fractured condition

and the fresh appearance of the brighter sideromelan and the absence of phenocrysts, that it is not an alteration product of the darker glass. This layer simply represents a magma that flowed out on the surface and consolidated as glass and was very heavily charged with an "older generation" of somewhat different glass.

The difference in colour is very clear and the limit sharp. But the margin of the darker colour is not the same as that of the respective area containing phenocrysts and microlites. These crystals also occur in a sharply limited zone with the lighter colour around every darker fragment. In this zone the crystals are sometimes arranged parallel to the margin whereas no fluidal structure is seen in the darker glass. In this zone even olivine is unaltered. This zoning has clearly nothing to do with alteration but the fragments of the older glass were laterally melted and changed in composition.

We shall not here discuss the significance of this relation of glass within glass which I have found at several places. But it may be pointed out that the magma or fluid that was extruded can hardly have been kept fluid by high temperature but more probably by a high content of gases which on rapid escape left a highly viscous mass, unable to crystallize.

2. Brown tuff or sandstone attaining the coarseness of gravel at the bottom. The main mass (444) consists of a chaotic mixture of minute grains of opaque glass, brown glass, and crystal fragments and on the whole it is closely similar to the vein (438b). On the other hand this is very unlike a sandstone as the separate grains are indistinctly limited. I think it most likely that the layer was formed by extrusion of a type represented in the above mentioned vein.

3. Conglomerate of grey clay with scattered well-worn pebbles. This is a structureless mass of morainic appearance, although, in my view, it is not a moraine. Scratched pebbles may be found but they do not prove a morainic nature of the conglomerate. The grey groundmass (445a) consists of rounded grains of basalt, opaque glass and basalt debris. Translucent glass may be found but it is extremely sparse. A peculiarity of this conglomerate is, however, large and small patches of a pink homogeneous amorphous clay of very irregular boundaries, often with long protuberances into the surrounding mass. This layer is in my opinion a volcanic mud flow.

4. Conglomerate.

5. Grey conglomerate in every respect similar to (3).

6. Conglomerate and breccia. At the top the stones are rounded, but with increasing depth they become more and more angular and increase in size and at the bottom the breccia merges into

7. a basaltic lava. There is clearly a genetic relation between the lava and the conglomerate, the latter probably resulting from the breaking up and weathering of the lava.

8. Many strata of brown tuff with beds of greater coarseness.

9. A coarse breccia, large boulders, somewhat worn.

10. Brownish stratified tuff.

11. Again a coarse breccia. Large boulders, very little worn, in a grey structureless matrix (447), which consists of rounded grains of basalt, dark glass and translucent yellow glass. I suppose this groundmass is an erupted mud flow such as represented by the vein (438b), which flowed over the lava (12) whose surface was already broken up into large blocks. So the blocks were incorporated in the mud.

13. Palagonite breccia: blocks of dark basalt in a brown matrix and it is clear in the field that this is a primary volcanic product. A thin section (448) of the brown matrix shows this nevertheless to be composed of granular brown translucent glass, some grains of opaque glass and moreover some rounded grains of ophitic olivine-dolerite, and a few worn crystals of plagioclase. This breccia results, it must be assumed, from the outpouring of fragmental material.

We shall lastly mention an important section near *Klambrasel.* The Langavatnsheiði east of Langavatnsdalur in Þingeyjarsýsla is a part of a volcanic plateau rising about 180 m above the floor of

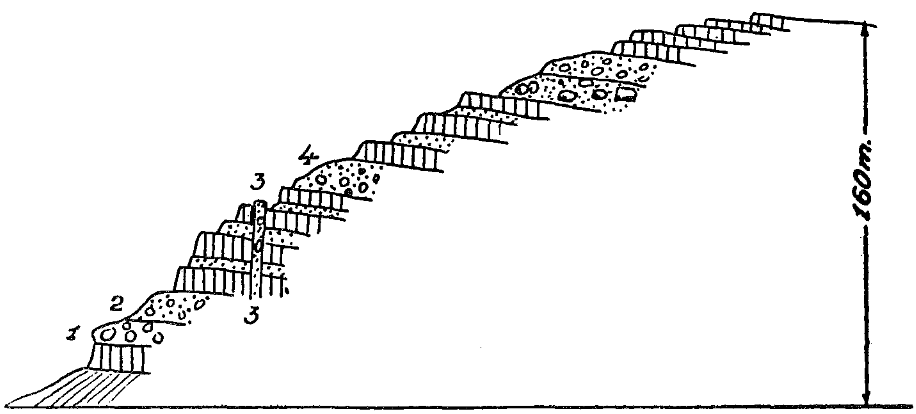

Fig. 11. — Section at Klambrasel showing a dyke of coarse fragmental material.

the valley. It is of the same character as the plateau we have been considering and is no doubt a part of the same plateau. A short distance south of the farm Klambrasel a brook has opened a section of this series, Fig. 11.

Resting on the lowest visible lava is a conglomerate, about 2 m thick, consisting almost exclusively of porous, scoriaceous stones in a very sparse cement. This is probably a directly erupted material. It is covered by a conglomerate of well-worn pebbles in a grey matrix which has some horizontal jointing as seen by its form of weathering and its breaking into flakes. Beyond that, the mass is entirely without structure and of the common moraine-like appearance. I could find no striated stones and in a thin section (528) the matrix is seen to consist of large and small fragments of porous opaque glass, small fragments of brown translucent glass, fragments of very fine-grained lava, and a brown amorphous palagonite filling all interspaces and it is at least doubtful whether this palagonite is an alteration product and not of a primary origin. This conglomerate thus has all the appearance of being a volcanic product and not a moraine.

Higher in the section there is a similar grey conglomerate of a thickness of 5—6 m. The relatively few stones it contains are not larger than 10—15 cm. but mostly much smaller. The groundmass (534) consists again of rounded grains of a very fine-grained basalt, opaque glass and a few grains of brown translucent glass.

A short distance below this layer the basaltic lavas are traversed by a "dyke" which is seen in both walls of the gorge. Its thickness is about 1 m and it consists of a chaos of worn and angular blocks of basalt of a diameter up to ⅓ m. The grey matrix (533) is of subordinate abundance and consists of rounded grains of a very fine-grained basalt — also fewer grains of a coarser basalt — opaque glass, and sideromelan, the glass being of a high percentage. Thin apophyses extend into the walls of the fault and the dyke is beyond doubt of volcanic origin.

Although this material is coarser than the grey conglomerate higher in the section, it is typical of the grey conglomerates, both as concerns the condition of the boulders and the composition of the matrix, and the dyke renders perhaps the clearest proof of the volcanic nature of the conglomerates.

8. THE YOUNGER BASIC TUFFS

In the Tindafjöll complex we observed a pile of brown tuffs and breccias covering the main plateau of alternating lavas and layers of fragmental material. Obviously this pile is a remnant of a more extensive thick cover. At Hvalfjörður we similarly found that Hvalfell and Botnssúlur represent remnants of a very thick pile of brown fragmental material, directly covering the series of composite composition.

Similar masses of palagonite tuffs are of great extent in other parts of Iceland and, in fact, form the main mass of the Palagonite Formation. The whole mountain range from Cape Reykjanes to Langjökull is mostly built up of this material. Furthermore Hofsjökull is a similar pile resting on the composite plateau which we described as running from Southern to Middle Northern Iceland. The same may be said of all the separate mountains to the north of Vatnajökull: Dyngjufjöll, Herðubreið, Herðubreiðarfjöll, Bláfjall, Sellandafjall, Gæsafjöll, Lambafjöll, and last but not least the vast pile of Hólsfjöll covering an area of about 3500 km^2. At many places it is seen that this thick cover rests on a series of alternating lavas of grey, mostly fine-grained and porous porphyritic basalt, and layers of brown glassy material.

On a great many of these remnants there is, as on Botnssúlur, a relatively thin cover of ophitic olivine-dolerite. In many cases also the craters which produced this dolerite are still preserved, even in a fresh condition, and in one case, on Skriða, I have found that the last flow from such a crater consists entirely of glass, mainly sideromelan.

It is clear that at least a part of these fragmental masses are very young and large parts of them are demonstrably separated from the composite series by a long interval, as the tuffs of Hólsfjöll and the breccia masses of Ingólfsfjall among others which rest discordantly on the lower series. We may therefore distinguish this thick cover as the Younger Tuffs of relatively late origin. In Snæfellsnes a thick pile of tuffs overlies beds with arctic molluscs as found by Pjeturss and we may assume that the Younger Tuffs are mostly or wholly of Quaternary age.

In spite of this their origin need not be directly connected with glacial chilling and in fact the arguments found against that theory are partly derived from observations of these younger masses and are equally valid for them as the older tuffs. But it is probable that some of the youngest tuffs were extruded beneath ice-sheets.

The younger tuffs deserve a detailed treatment but it would carry us beyond the limits of this work. Here only a few features can be described.

Skriða is a 1006 m high mountain north of Laugarvatn in S. Iceland. The surrounding country is about 600 m high and above this the mountain is in its steep slopes seen to be built up of fragmental,

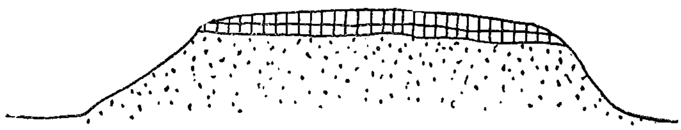

Fig. 12. — The mountain Skriða. Loose brown tuff and breccia covered by lavas of grey basalt.

mostly glassy material up to the edge at about 850 m. Here we find several lavas of fine-grained grey porous basalt, forming a gently sising shield in the centre of which there is a large and deep crater. This crater has no doubt produced the basaltic lavas, but what is of more interest is that its last eruption produced a stream of pure sideromelan. As shown in Fig. 13 the coarse, brown, largely stratified layer of tuff which extends from the edge of the inner crater, has overflowed the eastern and northern rim of the outer crater from which it spread out over the eastern slope of the gentle dome, in just the same way as would a usual lava flow. I think it is impossible to escape the conclusion that this material also flowed calmly from the crater out over the dome, either as a magma which consolidated as glass, or as a wet mixture of glass fragments. In

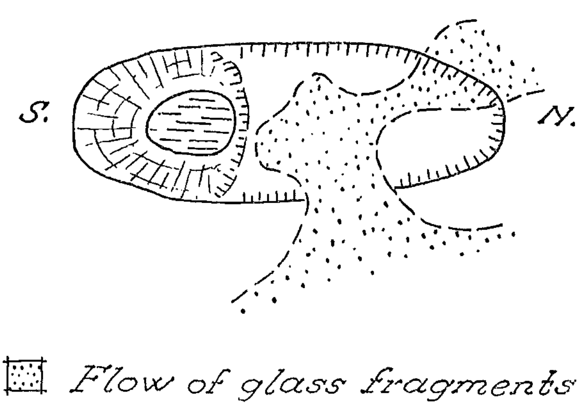

Fig. 13. — A sketch of the crater on Skriða.

thin section (198) we find a number of angular fragments of fresh sideromelan enclosing phenocrysts of olivine, in a predominating groundmass of comminuted sideromelan. The glass fragments are rather porous and there is flow structure in some of them which is absent in others. On account of this slight heterogenity and the abundance of comminuted matter I think it is clear, that the tuff did not reach the surface as a fluid magma, but as a calmly flowing wet mixture of glass fragments.

Hólsfjöll. Of wide occurrence in the vast masses of fragmental material occupying N. E. Iceland between Melrakkaslétta and Vatnajökull is a peculiar whitish tuff. Thoroddsen mentions this and also points out the occurrence of a similar variety in the Fiskivötn area. The mountain Haugur is largely built up of this tuff and from that area I have studied a thin section (83). It consists of grains of brown translucent glass enclosing a number of phenocrysts of plagioclase. All interspaces between the grains, the contours of which are seldom clearly seen because of the advanced state of alteration, are filled with white zeolites and some calcite which causes the whitish appearance of the tuff.

Another slide from the top of Þjóðfell (68) consists of fragments of porous yellow glass, enclosing a number of phenocrysts of plagioclase and olivine. The glass shows mostly flow structure and is very much altered and mostly birefringent. There is also one fragment of opaque glass. The vesicles of the glass and the interspaces are largely filled with calcite. The heterogenity and whole appearance of the slide indicate an explosive eruption of this matter, or more generally, an eruption in the solid fragmental state. Slide (71) from the top of Kjalfell, west of the farm Möðrudalur, is of nearly the same composition as (68) except that augite also occurs as a phenocryst and that the alteration of the very porous yellow glass has proceeded much farther, only a very few fragments being wholly isotropic.

This tuff of Kjalfell is of interest for comparison with other altered tuffs. Thick masses (up to 300 m) of green tuffs occur down to the lowest visible horizon of the basalt plateau of Esja and in the old basalts in Suðursveit in Eastern Iceland. A slide from Esja is in many respects very similar to (71) only more altered and it is difficult to decide whether this alteration product is derived from sideromelan. But the comparison with (71) makes it very likely. It is probable, therefore, that sideromelan was found among the oldest rocks of the country.

I have described the younger tuffs of Hvalfell and Botnssúlur as remnants of a wide cover. In the same way plateaus as Gagnheiði, Ármannsfell, Laugarvatnsfjall, Miðdalsfjall and the base of the ice-cap Langjökull are clearly parts of one or more larger plateaus. The same is true of the separate plateau mountains of NE-Iceland. It may be tempting prima facie to assume that there was originally a continuous cover of tuffs over large parts of the country. Yet, such a plateau cannot at present be reconstructed with any certainty and the possibility remains that there were originally several separate plateaus of tuffs. In that connexion the youngest group of tuffs and breccias is of interest.

This group occurs as very young heaps of fragmental material which have been piled up on volcanic vents or as narrow ridges built up along volcanic lines. Of the former type are the tuff heaps in the valley Hítardalur in Snæfellsnes, of the latter type are Jarlhettur, and Fagradalsfjall, at Langjökull. Along the same volcanic line occur the more isolated heaps Kálfstindur, Högnhöfði and Rauðafell. Of the same nature are Klukkutindar, and probably also Kálfstindar, and many smaller heaps along the western main fracture line of Hengill,such as Reykjafell. A small flow of such material some 3 km. south of Kolviðarhóll is of post-glacial age. The central part of Vífilsfell is a large body of fragmental material thrust up in a half-fluid state. Eldey and most of the Westman Isles are also of this origin.

In the examples mentioned the internal flow structure and often the original smooth streamlined surface of the heaps are seen and it is clear that these masses were thrust up to the surface as a very viscous body of fragmental material.

Sometimes the heaps have very steep and even overhanging sides and it seems difficult to account for this except by the aid of an ice-wall. The elevated structures, on the other hand, seem hardly compatible with subglacial conditions.In the tuffs heaps near the farm Hítardalur I found glacially striated stones which are clearly foreign to the tuffs, and the tuffs rest on a perfectly fresh glacially striated floor. These facts indicate that the tuffs in this case were extruded beneath an ice-sheet.

In the same way as the youngest tuffs are produced by large bodies of fragmental material directly erupted the somewhat older "plateau tuffs" are at least partly built up of immense floods of such material. There may then have been several separate plateaus of this kind.

9. SUMMARY AND GENERAL CONCLUSIONS

For a full understanding of the Palagonite Formation the general geological structure of Iceland is of importance. The picture here given is partly gained through the here described studies, partly as far as new conceptions are concerned, it had to be based on studies which are intended to form the subject of a separate paper. This picture is as follows:

The fundament of Iceland is an extensive thick plateau which has suffered considerable disturbances, its surface lying at different levels in the various parts of the country. East of Bárðardalur as far as Vopnafjörður it has an average height of 200—400 m. At Bárðardalur there is a major dislocation, as first pointed out by Thoroddsen, yet it is only marked in the north. West of Bárðardalur as far as Skagafjörður the plateau lies much higher, 900—1500 m. Yet in the southern part this area, it dips gently to the south and runs uninterruptedly to Southern Iceland, where it terminates abruptly in Hreppar.

In Western Iceland the plateau has a height of 1100—1200 m in Skarðsheiði, declines gently towards the east, reaching a medium height at the head of Hvalfjörður.

The higher parts of this plateau are built up of basaltic lavas, almost exclusively a grey, fine-grained porphyritic rather porous basalt, and layers of brown glassy tuffs and breccias, and an occasional layer of grey conglomerate. As a further feature of the lavas must be added that their vesicles are very often filled with a loose mass of sideromelan fragments.

Near Akureyri, Tertiary lignite and petrified trees are embedded in these higher parts of the plateau series. The lignite at Illugastaðir in Fnjóskadalur and at Árbær in Skagafjörður also occur in these higher reaches and most probably a number of other known localities for lignite are situated in the higher parts of the plateau.

Glassy tuffs and breccias with sideromelan as the main constituent were thus formed early in the geological history of Iceland — long before the Quaternary period. Volcanic tuffs are also found on the lowest visible horizons in the fundamental basalt plateau as e. g. in Esja and in Suðursveit in S. E. Iceland, and it is at least probable that these altered tuffs contained sideromelan.

Wide areas of this plateau are covered with a thick layer, up to 500—600 m, of brown tuff and breccia, mainly consisting of sideromelan, but also of opaque glass and scoriae, and very fine-grained blocks of lava. These piles of fragmental material are only erosional remnants of a wider cover, which certainly was originally of a far greater extent than to-day.

Many of these remnants of the old cover carry a layer of ophitic dolerite lavas. Often there are fresh craters in these lavas. At Búlandshöfði, in Snæfellsnes, a thick pile of brown tuffs and breccias rests on beds with arctic molluscs.

We have therefore a good reason to assume, that the main cover of fragmental material is of Quaternary age, probably Early Quaternary.

Still younger are the fresh flows of tuff on Kaldbakur and Skriða and the heaps of fragmental material piled up on vents and fissures ranging even into post-glacial times.

We must at this stage point out the main difference between this conception of the geological structure of Iceland and that of earlier authors, especially that of Thoroddsen.

Thoroddsen speaks of Middle Northern, North Western and Eastern Iceland as „Basalt regions" in which brown tuffs and breccias sporadically also occur, intercalated between the lavas. Southern and Central Iceland, on the other hand, is a „Palagonite region" in which basaltic lavas occur intercalated between the brown tuffs and breccias, the higher percentage of fragmental material in Southern Iceland than in the "Basalt regions" thus leading to a splitting of one and the same plateau series. Thoroddsen found that the Palagonite Formation is younger than the Basalt Formation. What he really discovered was, that the thick cover of fragmental brown material is younger than the composite basaltic masses of Middle Northern Iceland and the Eastern fjords, i.e. it is younger than our composite series, but thereby he does not prove, that the composite series of Southern Iceland is younger than that of e. g. Middle Northern Iceland.

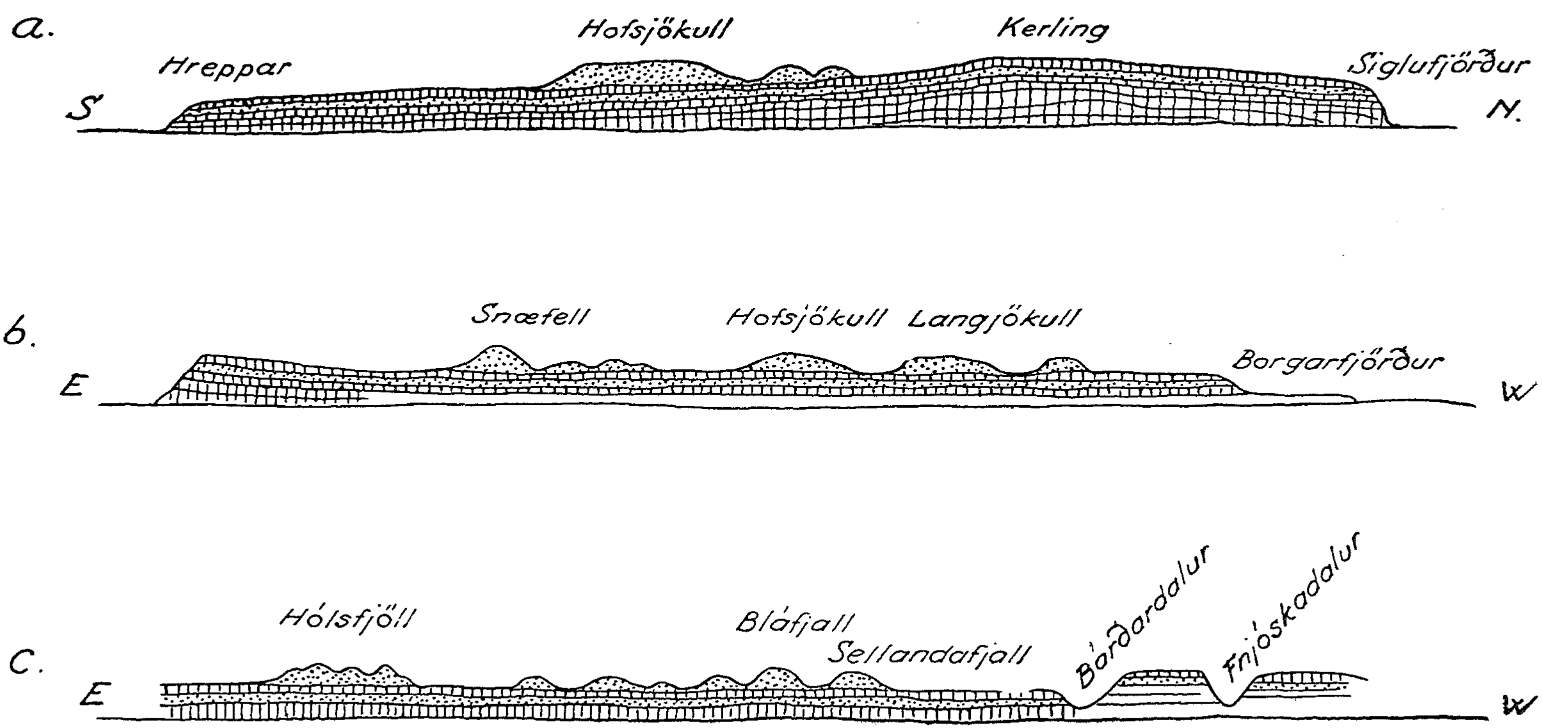

Fig. 14. — Schematic sections through Iceland to show the extent of the composite plateau series and its relation to the Younger Tuffs. Line c is parallel to b, but about 100 km. farther to the north.

We have tried to make it clear that the composite plateau of Northern Iceland extends with a gentle dip, but without any notable break to Southern Iceland and that the composite series at both places are the same.

It follows from this, that the large gap in the "Basalt plateau" right across the country which Thoroddsen assumed, and which should be filled by the Palagonite Formation *does not exist.* The dislocation of Bárðardalur does not reach far into the centre of the country, it is already imperceptible far to the north of Kiðagil. We may also state, although we have not considered the Eastern Fjords in this paper, that only parts of this area are separated from the rest of the plateau by dislocations. The composite plateau has a medium height from Central to Eastern Iceland.

A "Palagonite Formation", filling a major gap between blocks of of a "Basalt Formatation" is therefore a conception which must disappear from Icelandic geology.

But also the term Palagonite Formation should either disappear or its meaning be entirely changed. In the first place there is in principle no difference between the composite rocks of the "Palagonite area" and the upper parts of the series of the "Basalt areas". They are only at a somewhat different level. The old distinction between Basalt and Palagonite areas must therefore be dropped in the usual sense.

And secondly the thick masses of pyroclastic material which no doubt are responsible for this devision into two formations, do not only occur in the "Palagonite area" but are found also in the other areas, e. g. Esja, Tröllafjall and Hlíðarfjall near Akureyri, and Dyrfjöll in Eastern Iceland.

We therefore cannot distinguish a "Palagonite Formation" in a certain area, but instead the general picture is, that Iceland is essentially a part of a larger plateau built up alternately of basaltic lavas and basic pyroclastic material.

The disturbance of this plateau as well as the different stages of destruction of the main layer of fragmental material in different parts of the country are the main reasons for obscuring this simple picture. It may be concluded that the formation of the vast masses of pyroclastic material is in no way connected with a major sinking of the central part of the fundamental plateau.

The Formation of the Basic Tuffs and Breccias. The observations described in this paper lead to a certain conception of the formation of the volcanic rocks in question. They definitely point to a certain type of volcanism which only in later years has been recognized and has hitherto not been considered in studies of Icelandic volcanism. On account of the general acceptance at present of the view that the Icelandic pyroclastic masses are inherently linked with sub-glacial conditions, it has, however, been neccessary to devote much space to a discussion of that theory in order to demonstrate its failure to explain the observed facts. We shall now put together the main facts which either weaken or directly contradict that theory.

There is first the interpretation of the grey conglomerates as moraines which we have rejected on the following grounds:

1. The glacial striae of boulders embedded in the conglomerates are at least in some cases of secondary origin.

2. Primarily striated pebbles are certainly very rare, conspicuously rare for the conglomerates to be interpreted as moraines.

3. The series as a whole in which the conglomerates occur do not suggest a glaciation.

4. The matrix of the conglomerates consists largely of glass fragments, also when resting on a floor of crystalline lavas.

5. In the cases of a striated floor, it was seen that the striation is hardly or not of glacial origin.

6. A dyke of the same material as that which makes up the conglomerates was found, as well as several volcanic veins of material containing worn grains of glass and lava, and it was pointed out, that the volcanic necks of N-Britain, the Faroes and Schwaben consist of a similar chaotic, worn material as the Icelandic grey conglomerates, and have in some cases great resemblance to moraines.

7. The conglomerates form a part of a volcanic series, built up without any notable interruptions of denudation, and are most naturally understood as a link in the series and not as a break of it.

8. The composite series in which the conglomerates occur encloses lignite and petrified trees and the conglomerates are no doubt of Tertiary age.

On the basis of these points we interpret the conglomerates as being entirely of volcanic origin — mudflows either directly erupted by volcanic vents or formed as a secondary product of certain eruptions. This conception applies to all the conglomerates mentioned in this paper, among which are found classical, and some of the most convincing cases of Pjeturss' "moraines".

The real moraines of Iceland are, as far as known to the present writer, not in any way connected with the sideromelan of the composite plateau series. They might and probably do occur with younger glassy masses, but such cases have no influence on the interpretation of our observations.

With the rejection of Pjeturss' interpretation of the grey conglomerates the glacial theory of the formation of the pyroclastic masses loses its main support. But the most direct evidence against the theory is that observation fails to reveal facts which decisively point to an ultra-rapid cooling, whereas we find many facts pointing to the reverse: Thick masses of compact sideromelan, sideromelan infillings of vesicles in lavas and patches of this glass in the middle of very thick lavas, among other evidences.

The common occurrence of microlites, especially of plagioclase, in the sideromelan is also a fact which should be noted, as it not only shows that there has been no "ultra-rapid" cooling but also that the "separation of opaque ores" is generally not so facile as assumed by Peacock.

The observations indicate that we are concerned with that type of volcanism which is characterized by low temperature of the magma, high viscosity and high water content. Extremely thick fine-grained and partly glassy lavas are the clearest indication of high viscosity and as to the other factors they are evidenced by the general porosity of the rocks and their porphyritic texture, the phenocrysts often being of very high percentage.

It is pretty clear that a magma may be fluid enough to flow in a large mass, yet, at the same time be too viscous to crystallize markedly in the time at disposal, and in that way masses of glass would be formed. This is, for instance, clearly evidenced by the post-glacial lavas of obsidian in Iceland. These lavas have spread out with considerable fluidity, yet, without any sign of an exceptionally rapid cooling, they have solidified as glass.

Crystallization in a melt becomes extremely slow when the viscosity is higher than 10^4—10^5 c.g.s. But the melt then flows with ease. Glass is blown at a viscosity of 10^7 and even at a viscosity of 10^{10} a thick mass flows perceptibly. Take for instance a layer of the thickness of 50 m on a slope with the inclination 10°. Let h be the thickness, y the distance of an element of the fluid from the bottom, v the velocity of this element, η the viscosity, ϱ the density of the melt, and g the acceleration of gravity. Then we have by steady flow, disregarding the influence of walls

$$\varrho g (h - y) \sin 10^\circ = \eta \frac{dv}{dy} \quad \text{or}$$

$$v = \frac{g \varrho}{\eta} y (h - y/2) \sin 10^\circ$$

and at the surface of the flow

$$v_{max} = \frac{g \varrho \sin 10^\circ}{\eta} \frac{h^2}{2}$$

With the figures assumed we find v_{max} = 23 m per hour. With a viscosity of 10^8 the velocity is 2,3 km per hour, but crystallization would be imperceptible unless the melt was kept at a constant temperature for a very long time.

But the water content of the lava is a factor which determines some main characteristics of this type of volcanism and it is easily seen how it favours the formation of glass.

Qualitatively the effects of the gas content in a magma on its viscosity are well-known. Quantitative data are, however, scant and such directly relating to our basic magmas are not available. Data on melts of other composition are, however, significant and may suffice for the present purpose. Dry melts, the one of composition Na_2Si0_3 and the other of Na_2Si0_5 have been compared in the Geophysical Laboratory of the Carnegie Inst. of Washington with the same melts under a steam pressure of 200 Atm. In the first case the liquidus was lowered by 175° C and in the second by 165° C, on account of the absorbed water content.[23]) Transferring these figures into viscosities we might expect that the basic magmas would under similar conditions retain fluidity at 100—200°C below the corresponding point for a dry magma.

The temperature interval of crystallization for a melt of the composition of e.g. augite is only 30—40°C and it is hardly very different for the here considered magmas. Our wet magmas will then be able to retain fluidity at a temperature far below that interval. When the steam pressure is such a magma is suddenly lowered during extrusion the magma will become too viscous to crystallize. This glassy consolidation may be effected before or during extrusion or it may occur after some flow on the surface of the earth, depending on the temperature. In this way we may understand that in some cases streams of glass fragments are extruded and in other cases a viscous magma which comes to rest on a steep slope or builds exceptionally thick layers, partially or wholly glassy.

To this picture must be added the factor of explosiveness which will prevail in such cases where the pressure of the magma is released very suddenly. Explosive eruptions will then result and the magma is thrown up into minute pieces of glass. Deep explosions will in some cases tear away pieces from the wall of the volcanic funnel and a mixture of glass fragments and blocks, more or less worn off, may be extruded to produce a mudflow of morainic appearance.

It has been shown by G. W. Morey[24]) how extreme vapor pressures may be developed in a relatively cold and viscous magma. When such a magma absorbs water, rapid crystallisation will be inaugurated on account of the lowering of the viscosity, but thereby the vapour pressure is enormously increased and devastating explosions may be the result.

In this way the terrific volcanic blasts of the Peléean type have been explained. Allen and Day[20]) explain the explosive activity of the Lassen Peak as due to a high vapour pressure in a cold and viscous magma. It is assumed that surface water reached a very viscous magma mass and was absorbed in it. The resulting decrease in viscosity would cause a sudden onset of crystallization through which the vapour pressure was increased. The pressure would continue to increase until the roof of the magma chamber yielded. Then the magma would be thrown up as fine-grained ash.

Eruptions of this type would reasonably be expected to have occurred in Iceland, and we pointed out in an earlier chapter that to them must probably be ascribed the striation which is found in a few places in connexion with the conglomerates, and some of the sheets of conglomerate may also reasonably be explained as mudflows caused by such volcanic blasts. And even to-day such eruptions occur in Iceland.

Beneath two of Iceland's ice-caps are buried very active volcanoes, Katla in the Mýrdalsjökull, and Grímsvötn in Vatnajökull. In both cases the eruptions solely produce ashes (disregarding possible great amounts of water) and cause devastating floods of meltwater(?), generally known as "jökulhlaup". The eruptions occur at roughly regular intervals, especially in the case of Grímsvötn, where the period is about 10—12 years. It appears to have been generally assumed that the ice sheet is the direct cause of the peculiarities of these eruptions, especially that the splitting up of the magma into minute pieces of glass (sideromelan) is caused by the contact of the magma with ice or meltwater. And in turn this "sub-glacial" origin of sideromelan has been thought to illustrate the origin of the Palagonite Tuffs. But this is really a very unlikely assumption, and moreover directly contrary to observation. The effects produced when a lava flows over swampy grounds or into a lake are pretty well known. The resulting material is either a heap of scoriae or pillow lavas. A splitting up of the entire mass of lava into minute glass particles does not appear to be on record. In the case of Grímsvötn we might understand that a heap of scoriaceous material was piled up around the vent and a small percentage of the magma split up into ash particles. But to explain by the chilling influence of the ice how the magma is in fact totally split up into ash does not appear to rest on rational foundation.

The eruptions of Grímsvötn are, on the other hand, easily understood on the same basis as those of Lassen Peak. They are caused by the water which the ice-cap or more directly the large crater lake gives off to the magma chamber. This water leads, in the way mentioned above, to an extremely high vapour pressure which after having gathered force for a sufficient lapse of time results in an explosive eruption and a splitting up of the entire magma extruded into minute pieces of glass.

Thus these modern eruptions point to the same mode of formation of basic glass as the studies of the ancient tuffs. They are not produced by a chilling agency but result from certain physical properties of the magma itself, namely low temperature and a large content of water.

On this basis the tuffs and the accompanying porphyritic fine-grained basalts may now be classified genetically as proposed below.

1. The temperature of the magma is so high that with the percentage of gases it still retains it is still fluid after extrusion. The result is the ordinary fine-grained porphyritic grey lavas.

2. The temperature is lower and the melt is very viscous, at least after having reached the surface of the earth, in spite of the gas it still retains. Yet, it has still fluidity enough to flow in a thick stream. The decrease of pressure from bottom to surface in the flow, local differences of gas content, and the continued loss of gases from the lava mass may have conspicuous effects on the mode of consolidation. A composite lava is formed, consisting of three more or less distinct, roughly parallel zones, viz. columnar, very fine-grained lava, a lava of block jointing, and pure, mostly fragmental glass. The predominance of one zone or another varies from case to case, and all degrees of variations from an entirely crystalline lava to pure glass will be possible. Most often the columnar zone is at the top and the glass at the bottom, but the order may be the reverse.

3. The melt, probably after losing some of its gases and while still losing gases flows on the surface in a thick, very viscous flow and becomes entirely glassy. Somtimes a compact, although more or less jointed mass of glass is formed, more often, however, the glass, on cooling, crumbles into a mass of porous fragments.

4. At a still lower temperature the magma consolidates to glass already on its way up to the surface on account of the loss of gases, and a mixture of glass fragments and gases flows out of the volcanic vent. A typical exemple of this is the flow on Skriða (p. 55). and it seems to have a modern representative in the sandflow of the Valley of Ten Thousand Smokes.[25]) The young heaps of fragmental material (Jarlhettur, Hítardalur etc.) are also of this type.

This phase might also be explosive and was probably often so. The main volume of the Younger tuffs in Iceland is probably of type 4, especially sandflows and breccia flows.

5. Deep explosions and a tumultuous whirling of glass fragments and pieces from the wall rock produce a mixture of worn glass fragments and more or less rounded blocks and pebbles. This mixture seems to flow rather quietly to the surface of the earth, the blocks then getting scratched and even faceted as was the case in Swaben.[18]) On extrusion this porridge may have considerable mobility thus giving rise to layers of grey conglomerates which are of markedly morainic appearance.

In some cases, as in the dyke in the north slope of Ljósavatnsskarð (p. 48) and in the veins in the southern escarpment of that pass, foreign blocks are absent, and we get mainly rounded grains of glass. Many of the horizontal layers in these mountains as well as in those of Eyjafjörður may have resulted more or less directly from such eruptions. In the dyke of Klambrasel (p. 53) on the other hand the percentage of foreign blocks is high, which is also often the case with the sheets of conglomerates.

This type is clearly characterized by a very low temperature of the magma and is therefore closely related to the Peléean type of volcanism which may also be expected to have occurred and may reasonably have had such effects as the striation sometimes observed in connection with the grey conglomerates.

6. A separate type is represented by the layer (1) of Southern Ljósavatnsskarð (p. 50) and a similar layer of Leirhafnarfjöll (not described in this paper) and (257) of Vörðufell (p. 18). The melt extruded contained a great amount of fragments of porphyritic sideromelan of an earlier generation. Here the temperature most probably was very low and fluidity was maintained by a high content of water.

POSTSCRIPT

After finishing the manuscript I had access to the detailed report of a part of the studies of Dr. N. Nielsen and A. Noe-Nygaard, referred to in this paper: Sub-glacial Volcanic Activity in Ancient and Recent Times (Studies in the Palagonite-System of Iceland. No. 1). By Arne Noe-Nygaard. Köbenhavn 1940. (Folia Geographica Danica. Tom. I. No. 2). The subject of this paper is "the form-complex within the system which we assume to be the result of sub-glacial volcanic activity" and which "plays a vital role quantitatively". The paper thus treats of the same main question as the present one but with a different outcome as its author firmly believes in the "sub-glacial extrusion hypothesis".

In the main text I have pointed out the flaws in this hypothesis and as far as I can see they are still inherent in the new paper. Yet it may be useful to comment specially on this paper.

Noe-Nygaard believes that to explain the formation of sideromelan the assumption of ultra-rapid chilling is inevitable. We have seen that this is not so and that the assumption does not conform to certain observations. Noe-Nygaard's paper, in my view, contains such observations: "The intrusive dykes in the breccia are particularly frequent in the cliff wall behind Kirkjubæjarklaustur. These dykes, which are very winding and irregular in their course, are coated with thick skins of sideromelan" (p. 36). But basic instrusives are usually not coated with sideromelan and this therefore rather speaks against ultra-rapid cooling as a vital factor, unless the ultra-rapid cooling of these intrusives is explained by some special hypothesis.

The question of the moraines is treated as usually. A number of cases is mentioned where the volcanic products are connected with moraines (tillites). But the interpretation of the hard conglomerates as moraines rests entirely on their macroscopic features, which are misleading. In one case Noe-Nygaard reports the microscopic character of a tillite. He finds that "the finer material comprises various more or less opaque particles and small pieces of mineral such as olivine, pyroxene, plagioclase, and zeolites" (p. 41). Stratified clay in the tillite "contains considerable quantities of sideromelan grains." This conforms well with the composition of the conglomerates which I assume to be of volcanic origin. Another case of a tillite mentioned in the paper is noteworthy:" Along the lower contact the matrix of the tillite is somewhat bleached, and the globular basalt directly adjacent to the tillite has a distinct glassy layer" (p. 14). We are thus expected to believe that a Quaternary ice-sheet crept over the loose "globular basalt" and deposited a moraine of some 3 m thickness without even scratching the glassy surface of the basalt. Moreover "besides its ordinary stones, the tillite includes large and small fragments of basalt-globes, often with areas of the glass coating preserved" (p. 14). Thus Noe-Nygaard seems to assume that the presence of striated stones proves the morainic nature of the structureless conglomerates, even in the face of strong evidence to the contrary and it is therefore certainly questionable whether he is right in his interpretations.

The assumption of ultra-rapid chilling and of a connexion of the eruptives with moraines represents the main basis on which the "sub-glacial extrusion hypothesis" rests. But some weight is also laid by Noe-Nygaard on a supposed sub-glacial eruption in Vatnajökull in 1934, as indicated by the breaking up and subsidence of a part of the glacier and by a great flow of water in the river Djúpá. As to the river the best local authority, Hannes Jónsson of Núpsstaður, confirmed to me, what is otherwise known, that the river is often very swollen during the summer and he had not the impression in the summer 1934 that the river was so unusually swollen as to warrant the assumption of an eruption in the glacier at its source. I believe that so long as no attempt has been made to parallelize the flood of the river with a cold weather period it has little bearing upon a supposed sub-glacial eruption.

Another fact that should be taken into account is, that if at the source of the river the extrusion of the loose masses of a palagonite breccia took place accompanied by the production of a great body of melt water, we might expect that the river carried away and deposited along its banks a perceptible amount of these eruptives. But nothing of the kind has been observed.

As to the subsidence itself, it extends, according to Dr. Nielsen, in his book Vatnajökull, over a zone 10 km long and a couple of km broad. It lies along the very active volcanic line of Grímsvötn and it occurred about 2 months after the great eruption of Grímsvötn in 1934. It might therefore be supposed that this disturbance of the glacier was in some way connected with the great eruption, without necessarily being caused by a sub-glacial extrusion, and when we learn from Nielsen's book that the disturbance extended right down to the margin of the glacier where nevertheless no signs of an eruption were seen, it would seem that the sub-glacial extrusion hypothesis is inadequate. On the other hand it seems a more simple explanation that earthquakes caused a slight run-off of this part of the glacier which lies on a sloping ground. By thorough studies it might have been possible to decide upon the cause of the disturbance, but unfortunately observations are scant and we are left to guess the best hypothesis.

This disturbance of the glacier is at any rate no proof of a "slow" subglacial extrusion and it can still less be used as a basis for a theory according to which the basic tuffs of Iceland are largely formed by "slow" sub-glacial extrusion.

Noe-Nygaard reports that he found the products of recent sub-glacial eruptions, i. e. globular basalt. But his deduction of this result is not convincing. First he shows clearly that in earlier post-glacial times the Vatnajökull was smaller than to-day. Thereupon he states that a globular basalt, which he assumes to be of recent age and lies outside the present margin of the glacier is of sub-glacial origin. Then we learn that "following the globular basalt in a southerly direction we find that it passes smoothly into a basalt without globular structure, but with pronounced columnar structure (irregularly orientated columns)" (p. 57). Then, a part of this lava might well be of sub-aerial or intrusive origin, and then, why not all of it? In short, the sub-glacial origin of this particular globular basalt is not derived from observations of the case itself, it is simply assumed on theoretical grounds, moreover, it would seem, in spite of the local observations.

Thus, all the main assumptions on which the sub-glacial extrusion hypothesis rests, are certainly disputable, and some are beyond doubt untenable.

In conclusion I may add that my critique of course in no way touches the valuable descriptions of rocks, we find in the paper. I might, however, point out some differences of terminology and conception between this paper and mine. What I term a lava with block jointing Noe-Nygaard seems always to call a globular basalt, and when he speaks of a breccia with basalt-globes which are more or less broken into pieces, I speak of a breccia with basalt blocks. By this terminology Noe-Nygaard is, it seems to me, emphasizing his belief that the primary form is always or mostly a globe or a pillow. Yet, in the facies I have described, the globular structure was nowhere so apparent as to be characteristic and there is no doubt that Noe-Nygaard overemphasizes the occurrence of the globular structure.

This may be understood when it is considered that the pillow structure is generally thought to be the structure of subaquaeous lavas and Noe-Nygaard believes that the rocks in question were formed under the influence of meltwater.

This naturally raises the question whether the pillow structure is a weighty argument for the sub-glacial extrusion hypothesis, as obviously assumed by Noe-Nygaard.

Most writers seem to assume the sub- aquaeous origin of pillow structure, but it should nevertheless be kept in mind that other explanations have been put forward and the theory of J. Volney Lewis seems well worth considering (Origin of pillow lavas. Bull. Geol. Soc. Amer. XXV, 1914, 591—664). According to Alb. Johannsen in A Descriptive Petrography of the Igneous Rocks, Vol. III, p. 278, "Lewis thought that neither the presence nor the absence of water can be predicted as particularly favorable to the formation of pillows. He assumed first that the lava was free-flowing and viscous, and that the supply of lava was not great, so that there was practically no movement. Under these conditions the front of the flow would cool, cracks would be formed at the front and sides, and from these new lava would come forth and form bulbous masses, which would cool with the formation of a tough membrane at the surface, and this would stretch by the pressure of the lava within until the increasing rigidity stopped it. Continued pressure would cause the formation of new "buds," and new lava would flow through a succession of pillows connected by short necks or necks of no appreciable length."

Now, the conclusion which I have arrived at in my paper, is that the magma from which the Icelandic rocks in question are derived, was relatively cold, and often very viscous and in that case the conditions required by Lewis were found. It seems to me that the Icelandic pillow lavas may be satisfactorily explained by Lewis' theory, and at any rate I think it will be admitted that the pillow structure is no conclusive evidence of a sub-glacial origin.

Of interest for comparison with my results is a paper by M. G. Hoffman on "Structural features in the Columbia River lavas of Central Washington (Journ. Geol. 1933. P. 184—195).

He describes lava structures which are quite similar to those described in my paper: "Throughout the Moses Coulee area many different kinds of basalt structures can be seen. Columns are thick and thin, have parallel walls or wavy outline, and few or numerous horizontal fractures. Many of the flows are not columnar, but massive and broken by widely or closely spaced joints. Some are irregularly fractured throughout and broken into odd-shaped blocks 6 inches to 1 foot in diameter. Several exhibit spheroidal weathering. Still others are largely or entirely ellipsoidal, and a few contain a large percentage of shattered basalt glass" (p. 184).

"All structural types grade into one another, some gradually and some abruptly. Here and there a lens of columnar lava is included within ellipsoidal or scoriaceous basalt. In a few places ellipsoidal lava grades upward into columnar basalt.

Four structural types were found which are gradational from ellipsoidal basalt to basalt breccias" (p. 188).

"Fuller . . . assumes that all the ellipsoidal lavas in the region were formed under water. . . . . Neither the studies of Lewis nor field evidence substantiate this assumption" (p. 191). Hoffman rejects the hypothesis of a subaqueous origin of the pillow lavas and breccias and other structures found here and concludes that these structures were formed without the chilling influence of water, which agrees with the results arrived at in my paper.

At last a remark on the difference between tachylyte and sideromelan may be made. It is clear that it is not caused by a different rapidity of cooling. I wonder whether it is not a sufficient explanation that tachylyte seems always to have been formed under the direct influence of free oxygen, either from the air or from groundwater, with a resulting rapid formation of magnetite, whereas sideromelan is formed without contact with free oxygen.

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It is herewith stated by the editor on the author's request that this paper was received in August 1944.

PLATES

EXPLANATION OF PLATE I.

Fig. 1. Breccia of Þverárnúpur. Slide 286, $\times 2.3$. The two largest fragments are mostly opaque glass, the others are sideromelan. Text p. 24.

Fig. 2. Same slide, $\times 7.1$. Illustrating the breaking up of the glass in situ.

Fig. 3. Same slide, $\times 7.1$. Illustrating the same as Fig. 2.

Fig. 4. Breccia at Kirkjubæjarklaustur. Slide 282, $\times 2.3$. Fragments of unworn sideromelan. Text p. 25.

Fig. 5. Tuff of Kerlingardalsheiði. Slide 290, $\times 14.5$. Text p. 23.

PLATE I

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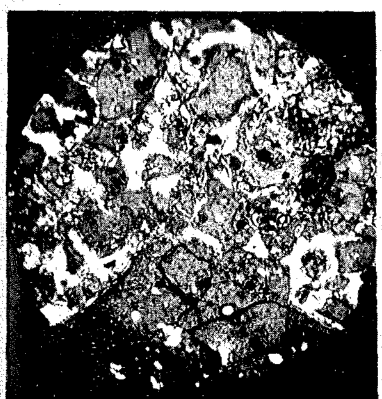

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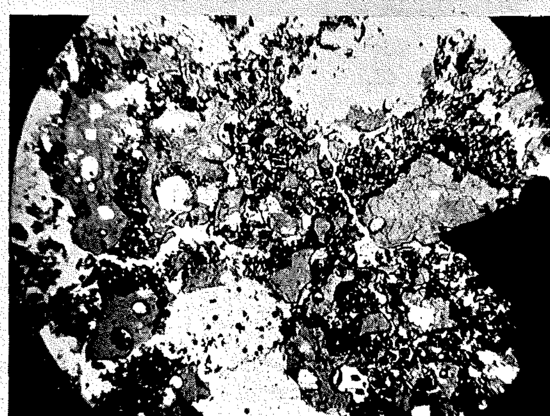


5

EXPLANATION OF PLATE II.

Fig. 1. Slide 450, ×7.1. Vein of worn grains, mostly of glass. Text p. 48.

Fig. 2. Slide 443, ×7.1. An example of older glass fragments within younger compact glass. Ljósavatnsskarð. Text p. 50.

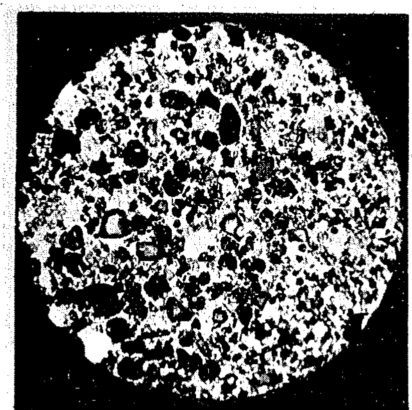
Fig. 3. Slide 369, ×7.1. Originally compact glass now much altered. Fresh patches are still left. Hvalfjörður. Text p. 44.

Fig. 4. Slide 198, ×7.1. Flow of glass fragments from the crater at Skriða. Text p. 56.

Fig. 5. Slide 380, ×7.1. Breccia of fresh sideromelan in Súlur. Text p. 43.

Fig. 6. Slide 379, ×7.1. Breccia in Súlur with marginally altered larger grains and completely altered smaller grains of sideromelan. Text p. 43.

PLATE II



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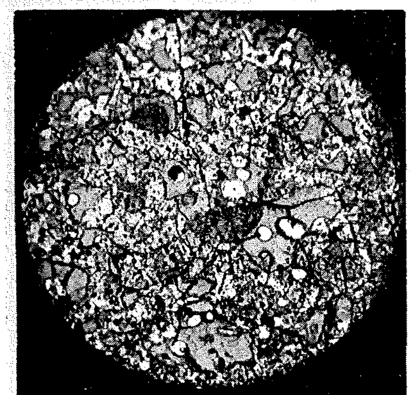

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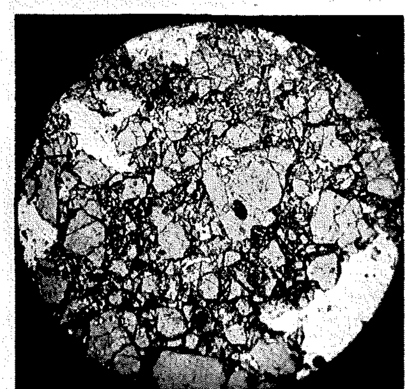

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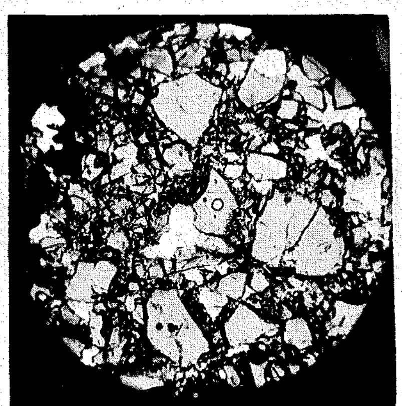

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EXPLANATION OF PLATE III.

Fig. 1. Slide 438b, ×7.1. Vein of brown tuff in Ljósavatnsskarð. Text p. 49.

Fig. 2. Slide 444, ×7.1. Brown tuff in Ljósavatnsskarð, probably extruded mud. Text. p. 51.

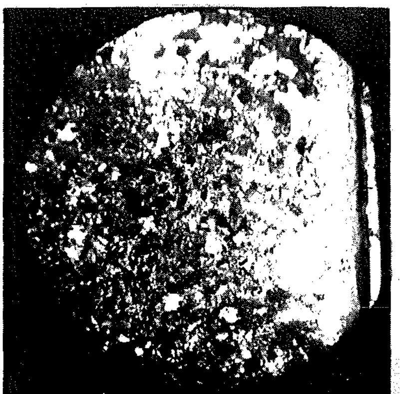
Fig. 3. Slide 448, ×7.1. Matrix of a brown breccia in Ljósavatnsskarð. Text p. 52.

Fig. 4. Slide 374, ×7.1. Matrix of conglomerate at Glymur. Text p. 41.

Fig. 5. Slide 362a, ×14.5 Matrix of the main layer of conglomerate in Austurgil. Text p. 39.

All photograps in ordinary light.

PLATE III



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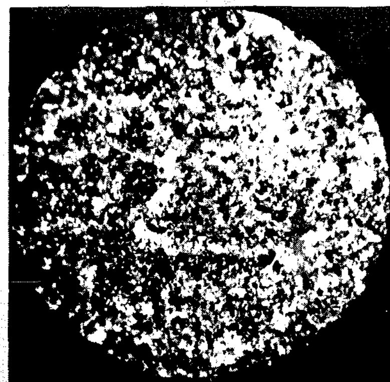

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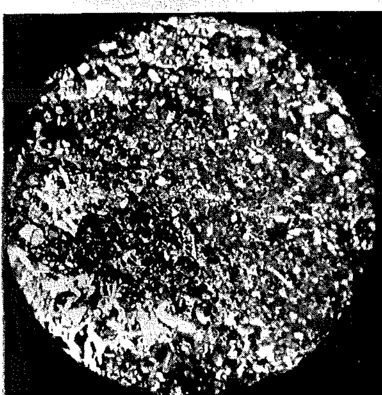

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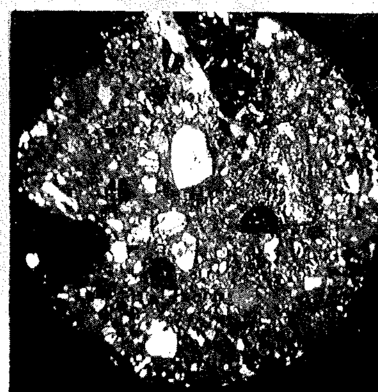

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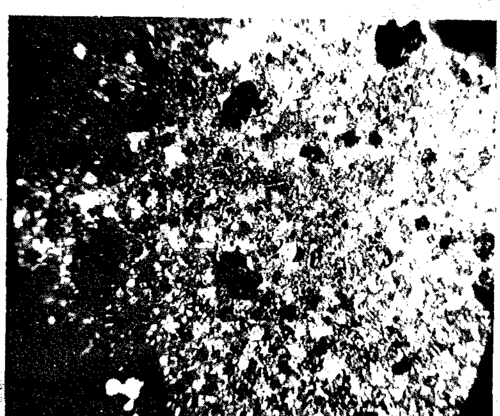

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