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On the Stratigraphy of the Sog Valley in SW Iceland

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CONTENTS

INTRODUCTION AND ACKNOWLEDGEMENT

In connection with the erection of a hydroeletric power plant at the waterfalls Neðri Fossar (Lower Falls) in the river Sog in SW Iceland there has been an exellent opportunity to study the sequence of rocks in that area. The powerhouse is built underground in the rock; the shaft and outlets together give a vertical section of about 46 m through the rocks. The discharge tunnel offers a horizontal section nearly half a mile long.

As a preparatory research, a number of boreholes were made by diamond core drilling in the area. The interpretation of the cores gave an initial idea as to the sequence of the rocks.

In the surroundings of the river Efra Sog between Lake Thingvallavatn and Lake Úlfljótsvatn, also several boreholes have been drilled for the purpose of investigation.

Last but not least, there are several outcrops accessible for field observations, both in the gorge of the river and in its surroundings, completing the picture obtained by the borehole investigation and the studies in the subterranean sections.

A number of geologists have visited the area and done more or less detailed investigations. Besides Thoroddsen (15), who published a geological map of Iceland, Kjartansson (8) made a general survey and published a decription and a geological map of the Árnessýsla region. In 1934 Hannesson (5) surveyed the Efra Sog area and in 1938 (6) the waterfall Ljósafoss and its surroundings. In 1945—46 Hannesson and Thorarinsson investigated the Neðri Fossar area and mapped a number of boreholes. Their report (7), given to the Direction of The Sog Hydroelectric Power Development is not as yet published. Einarsson (3) has undertaken a number of excursions in the area and its surroundings and collected his results in a summary on the geological history of the Þingvellir — Sog area and its connection with the stratigraphy of SW Iceland in general. Neither has this report been published. Besides these, the author's studies of bores, shaft and tunnel, and the completion of field studies in the area, may be mentioned.

The drilling was done to see whether the rock formations were favourable for subterranean constructions. It was done on the initiative of the Sog. H. P. D. and performed by the Well Drilling Dept. of the State Electricity Authority (with the exception of borehole No X at Ljósafoss which was drilled by the Well Drilling Dept. of the Reykjavík Hot Water Supply). The drilling in the Neðri Fossar area began in 1946 and ended in the early spring of 1949. The drilling in the Efra Sog area was carried out in 1951 —1952.

In the autumn of 1947 an experimental tunnel was driven near the outlet of the planned discharge tunnel. The experimental tunnel disclosed some unknown geological features and thus was valuable for the interpretations of the bores. In the beginning Professor S. Thorarinsson made the interpretations of the bores, but in the autumn of 1947 the author was appointed as consulting geologist in geological and geotechnical questions at the Sog H. P. D. and then took over the interpretations.

The author wishes to express his gratitude to Mr. Steingrímur Jónsson, Director General of the Sog H. P. D. for his vivid interest and broad views on not only the practical but also the theoretical problems involved in the author's work. He also is indepted to Mr. Jónsson for making the publication of this paper economically possible. He also wishes to thank the engineers of Sog H. P. D. for good and instructive cooperation. Superintending engineer Ingólfur Ágústsson, 1st engineer Pétur Aðalsteinsson, his wife, and other personal stationed at Sog he thanks for exellent hospitality and helpfulness. A special mention goes to the late Managing Director Ágúst Guðmundsson for ever so many services rendered. To the Drilling Manager, Mr. Guðmundur Sigurðsson for exellent and skilful service. To Superintendent Folmer Östergaard, C. E. and his wife for splendid hospitality and friendship. Also to the contractors Chief Engineer Kaj Langvad and his staff of engineers for valuable and fortunate cooperation. Acknowlegdements are due to Mr. Jóhann Jakobsson, C. E., for the petrological analysis done, and to Dr. Earl Ingerson, U. S. Geol. Survey for correcting linguistic errors in this manuscript. Mr. Stefán Egilsson has made all thin sections needed, and Miss Guðrún Ágústsdóttir the final copies of the drawings. Special acknowlegdement goes to Prof. Noe-Nygaard, Copenhagen, who on a visit to the area located the first striated boulder found in the moraine of the Írafoss gorge. The author is indebted to Dr. V. Okko of the University of Helsinki and to Stud. Geol. Þorleifur Einarsson, Reykjavík, for investigating the sand layer at the exit of the tunnel and the tephra layer in the tunnel on pollen and plant fragments. To Prof. S. Thorarinsson the author owes thanks for including this paper in Acta Naturalia. He also takes this opportunity to express his appreciation for the geological interpretation of bores carried out by Prof. Thorarinsson.

THE DOLERITE

The landscape is thoroughly modified by glaciation. The predominating landscape forms are soft slopes and moores, covered by heath vegetation.

The outcrops are for the most part located in the river gorge, on lake shores and in ravines. Here and there on the slopes the bed rock breaks through the cover of moraine and soil. Naked cliffs may also be found on the very top of the hills and where the wind has blown away the soil from the slopes.

At the 80 m level a bed of violet-gray coarse grained basalt, the so-called dolerite, occurs. It is visible on the slope west of Írafoss and on both sides of Lake Úlfljótsvatn. These dolerite outcrops represent the glaciated remains of effusive series, some 50—100 m thick (3 and 4) covering wide areas in SW-Iceland.

According to Kjartansson (8) the dolerite in the area represents two separate formations of different age. Even Hannesson (6) maintains, that the dolerite originates from at least two different streams, one on each side of the Lake Úlfljótsvatn. Einarsson (3) interprets all the dolerite occurrences in the area as belonging to the same formation or series of eruptions. His arguments are as follows:

1) The base of the dolerite over the entire area is at about the same altitude.
2) So far as can be determined, the base of the dolerite is always the same, an old palagonite breccia, in places covered by gray conglomerate, probably tillite.

According to Einarsson, the dolerite was erupted in the *first* interglacial period, but denuded and smoothed out by the following glaciations.

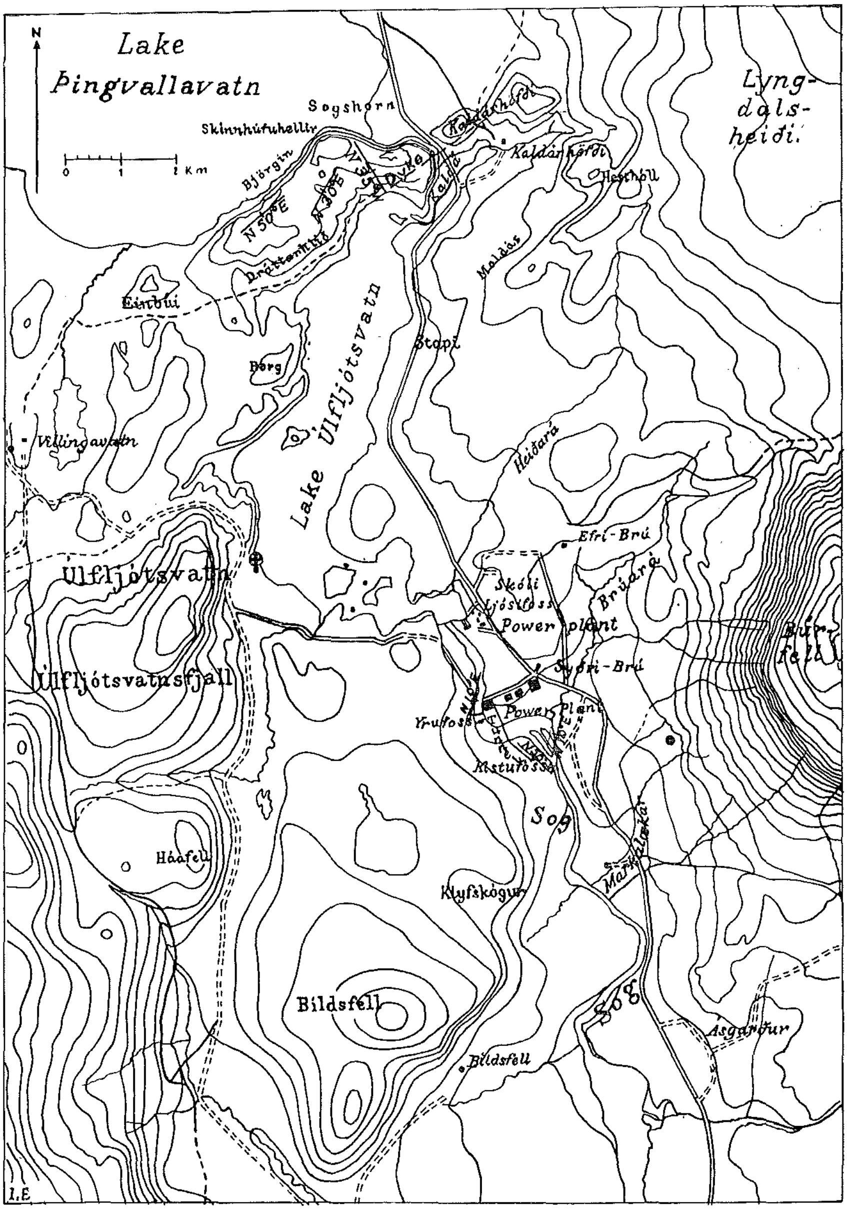

Fig. 1. Topographical map of the Sog Valley with tectonic fissure lines. Drawn from the Ceneral Staff map, Sheet 37.

River Sog and its valley are younger than the dolerite. Later glaciations have scoured the valley into the dolerite, and the river is of the same age as the basin of the Lake Þingvallavatn i. e. late Glacial.

Einarsson's arguments can be accepted with the exception of the age relations, which are discussed below. Along the Heiðará gorge the dolerite can be followed nearly continuously from Lake Úlfljótsvatn to the dolerite shield Lyngdalsheiði without any sign of discontinuity. In view of the immense extension of the dolerite and the few doleritic centres of eruptions hitherto found, it seems most probable that the dolerite on both sides of river Sog and Lake Úlfljótsvatn not only belongs to the same formation, but also emanates from the same volcano, Lyngdalsheiði.

In this paper the dolerite is used as a horizon marker. The rock units underlying the dolerite are called predoleritic, and those covering it postdoleritic (12).

THE PREDOLERITIC SECTION

Field observations

The oldest rocks accessible to field observation are found on the banks of the river Sog a short distance downstream from Kistufoss. The rock is basalt covered by a tillite-like gray conglomerate, which is overlain by brown palagonite tuff. These rocks are then covered by late glacial or postglacial deltas. The same basalt appears in the canyon of the waterfall Kistufoss. Between Kistufoss and Írafoss the river flows on top of it, and the Kistufoss-canyon is localized by a zone of tectonic fissures cutting the basalt. The basalt in the walls of the cataract is columnar in structure, with high and thick columns.

At the waterfall Írafoss is found the same sequence of rocks as mentioned before. First the gray conglomerate and then the basic tuff up to the top of the cataract. An uppermost layer, found at the west side of the waterfall, is a breccia with sharp-edged blocks of a black, very dense and fine grained basalt embedded in tuff. Farther upstreams this breccia is not found, but similar breccia appears at a somewhat higher level behind the farmhouse Syðri Brú.

A short distance above Írafoss a 3—4 m thick layer of basalt constitutes the uppermost rock east of the river. At Ljósafoss a layer of columnar basalt appears at the same level. No tectonic disturbances have been observed in the area, and the basalt occurrences, especially that at Ljósafoss, reminds one of the basal part of a normal effusive basalt.

Preparatory Investigations

The diamond core drillings were for the most part concentrated along a direct line between the planned powerhouse east of the head of Írafoss and the exit of the planned tunnel which discharges into the river at the 25 m level. Also some bores were drilled on a line perpendicular to the main line, and besides that, two bores were drilled near the Ljósafoss power plant.

The geological interpretation of the cores was fraught with difficulties, especially in the beginning, when the geologist had not gained sufficient training in his technique. It was a relatively easy job to determine the boundaries between rock units of different mineralogical composition from studies of the washings and core fragments obtained. The main difficulties were involved in distinguishing between tillite, basalt and agglomerate, as their lithological composition is practically the same. The drilling rate and core-loss gave valuable information. Also, there might be a certain petrological heterogeneity observed in the core fragments obtained from conglomerate and tillite.

Normally the uppermost zone of an effusive basalt layer has high porosity, causing considerable loss of the core. In such a case the scanty porous core fragments indicate the properties of the rock. The compact and dense rock of the lower parts of such layers promotes an even rate of drilling and minimal loss of core. If the basalt is extraordinarily disintegrated by cracks and fissures, it is easily misinterpreted as a tillite.

Fig. 2 shows the interpretation of bore No. XIII as compared to the shaft near by. The top of the solid rock is interpreted as a moraine bed, but really belongs to the basalt bed B No. I. The uppermost part of that basalt layer is heavily split up and disintegrated, causing a relatively big loss of the core which leads to that misinterpretation. On the map of the bore the basic tuff is divided into three different sections. Studies in the shaft revealed a rough stratification of the tuff, but there is no apparent reason of dividing it into seperate units. As to the surface of the basalt layer B No. II, it can be noted that the core suffered heavy losses. However, it was all mapped as belonging to the basalt bed, with the reservation that it might either represent the blocky

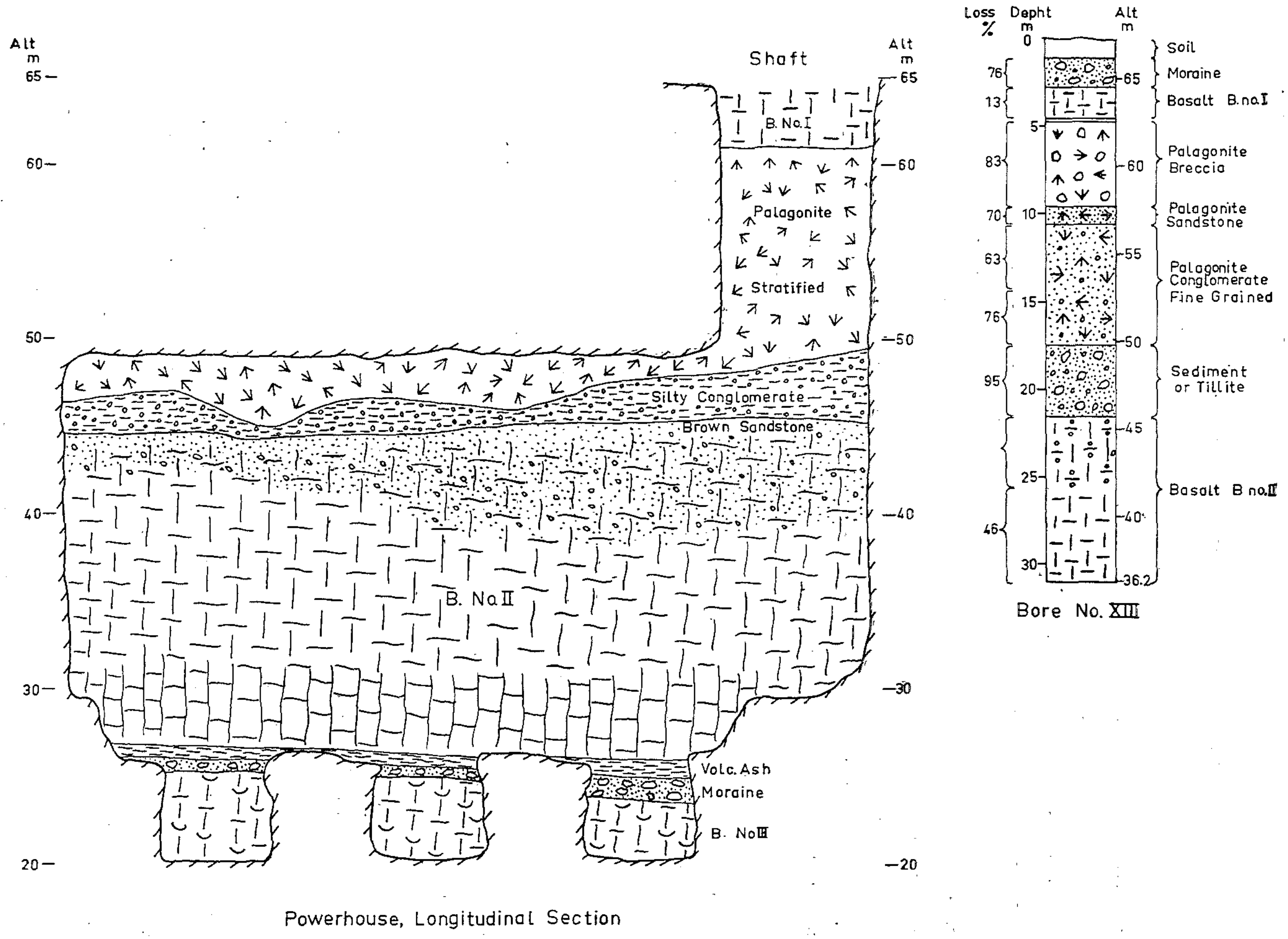

Fig. 2. The rock series in the shaft and powerhouse as compared to the interpretation of bore No. XIII.

surface layer of a lava bed, or even a clastic rock containing boulders in finer grained matrix.

The drillings revealed a thick bed of dense basalt (B No. II) between 20 and 40 m above sea level. The landscape covered by the lava apparently was of low relief, the greatest difference in altitude of the lower surface of the basalt was about 12 m as found in the 10 borehole-profile of c. 1,5 km length. This information obtained by the drillings was of great technical value, since the discharge tunnel leading from the power plant had to run between the 20 and the 30 m level. Thus it became evident that the tunnel should for the most part run in the bottom section of the lava bed and at its lower contact.

The information about the rock series below B No. II gained by the drillings was rather fragmentary and vague. In order to get further information on this rock and its mechanical properties, an experimental tunnel was driven into the rock below the basalt.

Immediately underneath basalt B No. II was found a thin layer of black sand, contaminated by organic matter. Underneath the sand lies a c. 3 m thick bed of gray clastic rock on a thick basaltic layer, B No. III.

Description of the rock units

B No. III. The lowest unit concerned is a thick layer of basalt, B No. III. This basalt flow constitutes the floor and the lower parts of the walls of the discharge tunnel at both ends. The basalt is aphanitic and macroscopic phenocrysts are rare. In sections it is columnar, but most of it is split up into small pieces more or less slaggy, which give the bed a breccia-like appearance. However, no alteration is observed, and fractured faces look quite fresh. The surface layer of the lava is eroded away down to the compact rock. The contructions do not go through it, but according to the drillings the thickness of the bed is variable. Microscopically, phenocrysts of labradorite, augite and basaltic olivine are observed, both single crystals and in clusters.

Moraine. The clastic bed covering B No. III has the appearance of a moraine; no other interpretation seems plausible. The bed consists of an assembly of assorted boulders of different size and degree of rounding; embedded in a silty matrix of minute rock

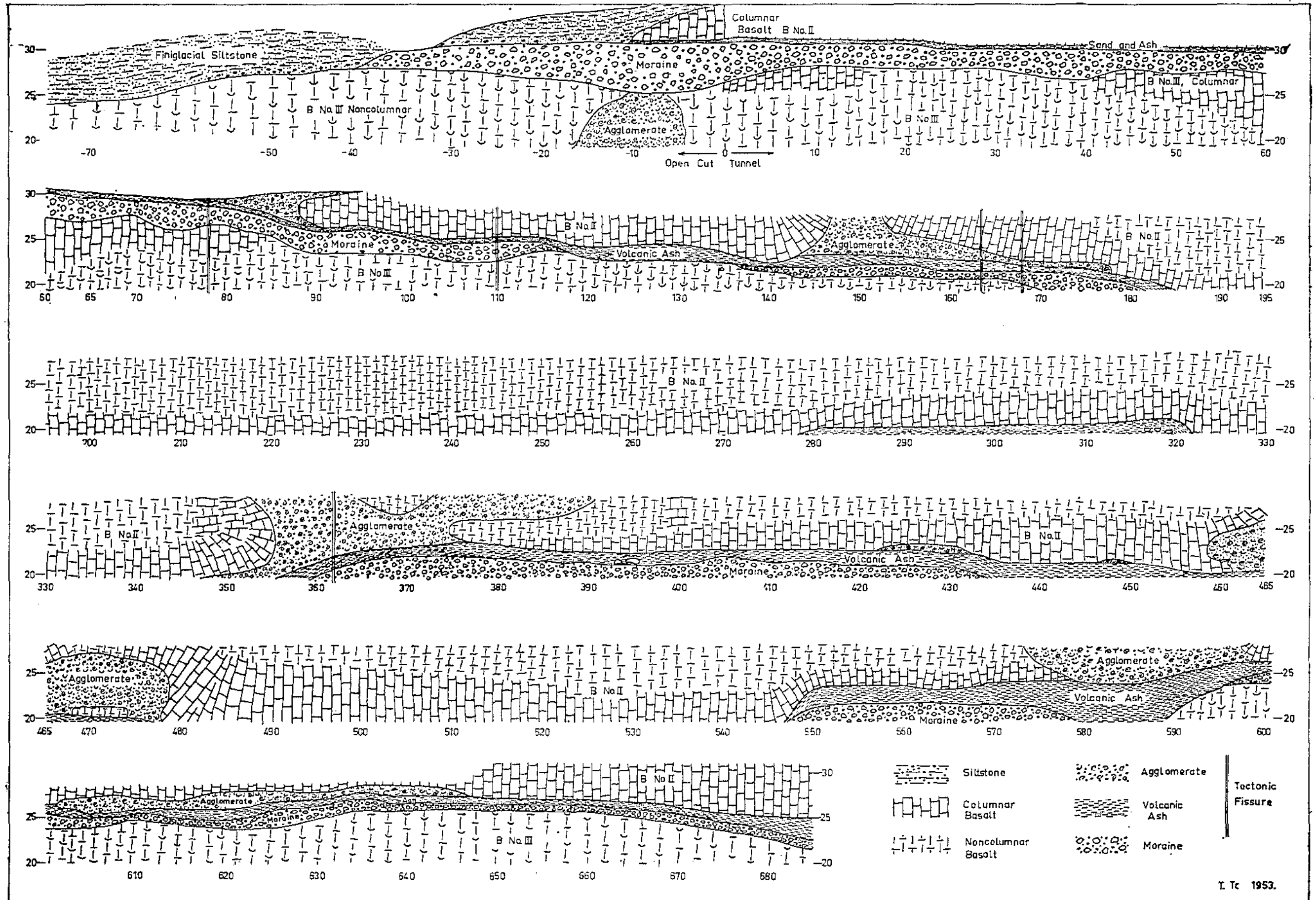

Fig. 3. Geological section along the discharge tunnel.

fragments and crystals. The bed is compressed and stands without support in the walls of the tunnel. It is not cemented to any perceptible extent, and no mineralization is observed.

The origin of the predoleritic clastic beds is of great importance for the determination of the age relations of the rock formations.

The gray conglomerates in the so-called Palagonite-Formation of Iceland have been interpreted by Péturss (12, 14) as indurated moraines, and his theories are still commonly accepted. Recently this explanation of the gray conglomerates has been doubted by Einarsson (1), and it is suggested that they are formed by volcanic mud flows. Therefore there is reason to discuss somewhat further the two alternatives in connection with the clastic bed in question.

1) The surface layer of the underlying basalt is eroded, and the contact between the clastic bed and the basalt is intimate. Cracks and crevices in the surface of the basalt layer are filled by material belonging to the clastic bed. This fact indicates that the eroding factor acting upon the basalt is the clastic bed itself.
2) Volcanic glass occurs in such trivial quantities that it may all come from the surfaces of lava beds and agglomerate zones eroded by a glacier. A volcanic mud flow caused by an explosive eruption should be expected to be mixed with magmatic explosion products to a greater extent than is found here.
3) The boulders observed in the clastic bed all belong to a similar type of rock, — a dense, aphanitic basalt, not rich in phenocrysts, like the basalt B No. III. In a volcanic mud flow most of the allogenic material is derived from the walls of the vent. In that case a certain heterogeneity in the petrographic character of the clastic material can be expected. The homogeneity of the boulder material rather speaks for a short transported moraine than for a mud flow.
4) Striated boulders are not found in spite of considerable search. The boulders exhibit smooth rounding but no signs of catastrophic rolling. In view of the fact that the boulder material is homogeneous and all of similar hardness, the absence of striae does not exclude the possibility of its morainic character.

Volcanic ash (tephra) and sand. The thin sand layer between the moraine and the basalt B No. II gradually gets mixed with volcanic ash (tephra) along the tunnel section, and has become nearly pure ash some 100 m from the exit of the tunnel. The banded ash seems to be fluvial. Its bulk is rather basic, with dark-green and light-gray layers alternatively. A 15—20 cm thick horizon of white ash is observed.

A sample of the sand, taken at the exit of the tunnel, was investigated for pollen by Dr. V. Okko in Helsinki. Besides some remains of plant tissues of which one with certainly belongs to Sphagnum, and others probably to Equisetum and Carex, one pollen of Betula and a fragment of Pinus-pollen was found. Both of these pollens were filled with a black dust, which indicates that they really belong to the sample and have not entered it by contamination in the laboratory. One species of fresh water diatom was also found.

Another sample of the tephra layer displaying some fragments of plant tissues was taken in the discharge tunnel some 170 m from its exit. The examination of four preparations (24×32 mm), carried out by Þorleifur Einarsson, gave the following results:

Pollen:			
7)	Salix	15	
	Betula	2	
	Pinus	1	(fragment)
2)	Cyperaceae	78	
	Gramineae	17	
	Rosaceae	5	
	Arméria	1	
	Caryophyllaceae	4	
Spores:			
	Equisetaceae	12	
	Lycopodiaceae	1	

With exception of the Pinus this flora indicates rather cold climatic conditions. Only two Pinus pollens were obtained and both of them are worn and fragmentary in contrast to the other pollens obtained, which all were found to be in a good condition. Thus the Pinus pollens most probably are of secondary origin and might be derived from older rock formations.

Single, rounded boulders of considerable dimensions were found in the ash. The boulders are always located at the bottom of the ash layer, but it could not be determined whether they were in direct contact with the underlying moraine.

Table I.

	Banded ash from the Tunnel	Light ash from the Tunnel
N		1.50—1.51
SiO_2	41.25%	67.03
FeO	5.93	2.30
$H_2O\div$	7.20	1.17
H_2O+	9.89	4.97

Ceteris paribus the hydration and devitrification of a volcanic glass depends on its age. Other factors affecting the rate of hydration are the grain size, the chemical composition and the geophysical conditions suffered by the glass.

The basic ash in the tunnel is far more hydrated than the acid one; also its cementation is farther advanced even though incomplete.

B No. II. The basalt layer B No. II is petrologically similar to B No. III with the exception of the phenocrysts, which are not detected macroscopically. Under the microscope, however, the same phenocrysts as in B No. III are observed. The rock is quite fresh both in a mineralogical and structural sense. The bed can be divided into three sections. The bottom section is characterized by pentagonal columns, arranged perpendicular to the cooling surfaces. The contacts with the middle section are distinct. The dimensions of the columns are variable in different places. Columns 4—5 m high and 60—80 cm in diameter are common, but a height of 7—8 m and diameter exceeding 1 m are found. The middle section consists of noncolumnar or cryptocolumnar rock, split up into sharp edged blocks of 15—25 cm in diameter. On approaching the surface, this section runs into the surface section, which is characterized by air bubbles, cracks and crevices filled by silt and sand. At the very surface are found „Staukuppen“, and heaps of vesicular blocks suggestive of a postglacial blocklava.

In driving the tunnel, numerous zones of volcanic agglomerate were found in the basalt; the bottom columns can be followed around the agglomerate zones, and in places the agglomerate is intruded by the compact basalt. The underlying tephra layer is not noticeably disturbed, but lumps of the ash are found scattered about in the agglomerate. The agglomerate consists of blocks of vesicular and porous basalt irregularly heaped up. The space between the blocks is filled by mud and silt. The origin of the agglomerate zones most probably is due to explosions in the lava prior to its consolidation.

The two lowest basaltic layers, B No. III and B No. II, are rather congruous in their chemical composition as well as in their appearance. As compared to the analyses of the postglacial lavas in

Table II.

Basalt bed B No. II, discharge tunnel. Anal. Jóhann Jakobsson.

	Wt. %	*Mol. quot.*	*Norm*					*Niggli-values*
H_2O^-	0.06			Or	5.36			qz = - 21.7
H_2O^+	0.67	37	F	Ab	25.50	52.01		si = 111.1
SiO_2	47.35	788		An	21.15			fm = 48.7
TiO_2	2.86	36						al = 18.9
Al_2O_3	13.65	134	Σsal				52.01	c = 24.2
Fe_2O_3	2.27	14		Wo	8.05			alk = 8.2
FeO	13.76	192	Di	En	3.33	16.18		ti = 5.07
MnO	n.d.			Fs	4.80			p = 0.13
MgO	5.03	125	Hy	En	4.85	12.00		h = 5.22
CaO	9.63	172		Fs	7.15			k = 0.164
Na_2O	3.00	48.5	Ol	Fo	3.10	8.50		mg = 0.362
K_2O	0.91	9.5		Fa	5.40			o = 0.081
P_2O_5	1.17	8		Ap	2.67			c/fm = 0.50
	100.36			Mt	3.27			
				Ilm	5.46			
			Σfem				48.08	
			Or:Ab:An = 10.3 : 49.0 : 40.7					

Table III.

Basalt bed B No. III, discharge tunnel. Anal. Jóhann Jakobsson.

	Wt. %	*Mol. quot.*	*Norm*				*Niggli-values*
H_2O-	0.07		Or	3.93			qz = - 22.0
H_2O+	0.90	50	F Ab	23.61	51.49		si = 106.0
SiO_2	46.26	770	An	23.95			fm = 49.4
TiO_2	2.97	37					al = 19.0
Al_2O_3	14.04	138	Σsal			51.49	c = 24.6
Fe_2O_3	5.20	32.5	Wo	9.50			alk = 7.0
FeO	11.30	157	Di En	5.00	18.65		ti = 5.1
MnO	n.d.		Fs	4.15			p = 0.55
MgO	5.64	140	Hy En	6.25	11.48		h = 6.9
CaO	10.11	180	Fs	5.23			k = 0.135
Na_2O	2.81	45	Ol Fo	2.00	3.70		mg = 0.390
K_2O	0.68	7	Fa	1.70			o = 0.180
P_2O_5	0.61	4	Ap	5.67			c/fm = 0.50
	100.59		Mt	1.36			
			Ilm	7.55			
			Σfem			48.41	
			Or:Ab:An = 7.6:45.8:46.6				

the Skjaldbreið area (16), the chemical difference between these two lava groups is obvious. The content of iron, titanium, soda, potassium and even phosphorus is considerably higher, whereas the magnesium, calcium, and aluminium content is lower than in the Skjaldbreið lavas. Especially the high iron content is remarkable.

The calcium content of the phenocrysts is in good harmony with the analyses of both groups. In the calcium rich Skjaldbreið lavas the phenocrysts are intermediate bytownite, but in the Sog lavas they are intermediate labradorite, or some 20% lower in anorthite than those of the Skjaldbreið lavas.

Sandstone. The irregularities of the surface of the basalt layer are smoothed out by a thin layer of brown sandstone, probably formed as quicksand blown into a lava field. The sandstone consists of a heterogeneous material; subangular crystal fragments, much volcanic glass, mostly basic and opaque grains, probably tachylite. The cementation of the sandstone is surprising. A single test revealed compressive strength of 95 kg cm^2.

Moraine. The sandstone is covered by a silty, gray conglomerate. The rounded cobbles of the conglomerate seldom exceed 10 cm in diameter, but larger boulders were found at the surface of the conglomerate bed, cemented into the overlying tuff. The conglomerate strongly suggests a long transported moraine. The cobbles exhibit the elongated form characteristic of the materials of moraines which have been transported long distances. Rare striated boulders are found in the gorge of Írafoss.

In its lithological character this bed is very like the lower moraine with the exception of some pebbles of an extremely black and dense basalt not found in the first moraine.

In the shaft and powerhouse at Írafoss this bed is 2—4 m thick, but in bore No. XII on the slope south of the powerhouse it is not observed at all. In borehole No X, located approximately 15 m SW of the SW-corner of the powerhouse at Ljósafoss, the bed is some 15—16 m thick, resting on the seemingly undisturbed lava surface of B No. II, as is the case at Írafoss. In bore No. IX situated east of the river some 150 m S of the powerhouse at Ljósafoss, it is at least 20 m thick. In that borehole the porous surface layer of B No. II is not observed.

The underlaying soft sandstone still preserved and the undisturbed lava surface of B No. II are not compatible with a long and severe glaciation. A short transgression of a glacier seems to be the most plausible explanation of the origin of this moraine bed.

Basic tuff. The next layer is a 10—15 m thick bed of roughly stratified basic tuff. The lower parts of the tuff bed are highly altered or „palagonitized" and green from chloritization. The fragments of sideromelane are rather dark and high in index of refraction (N=1.62). Impregnations of calcite are found. The uppermost part of the tuff bed is less altered. At the top it is interbedded with three layers of sand and silt, 5—10 cm thick.

B No. I. The topmost rock horizon in the shaft at Írafoss, the basaltic layer B No. I, looks macroscopically somewhat coarser than the underlaying basaltic beds. Microscopically it is observed however, that it is practically as fine grained as the other predoleritic basalts, but texturally somewhat looser, which results in a coarser fracture. The interstices between the minerals are filled with an isotropic or diffusively polarizing mass, yellowish-brown in colour. The intensity of the brown colour is variable. Probably it is due to an iron-rich groundwater percolating in the rock near the surface. Most commonly the refringence is c. 1.51 (leucite?) for white light, but increases with the intensity of the brown colour. The isotropic material also is observed in B No. II and B No. III, but there it is commonly colourless or faintly brown.

At the base of the slope of Ljósafoss, at the same level as B No. I at Írafoss, a layer of columnar basalt occurs. This basalt is of the same type as the basalt beds already described, and probably belongs to the same flow as B No. I.

The Ljósafoss Tuff. The slope of Ljósafoss is built up by basic tuff, rather fine grained and homogeneous. The alteration of the sideromelane is not so advanced as in the tuff layer at Írafoss, and the green colour characteristic for the thin sections of that tuff is not observed here. The vesicles are lined with a vermiculite like mineral with a positive elongation, probably celadonite.

Pillow Lava. At the head of the waterfall Ljósafoss, the tuff is cut by a pillow lava of rather coarse grained and vesicular basalt. As to the grain size it is comparable to the dolerites, but the ophitic texure is not so pronounced as in the compact dolerite. The type of basalt represented by B No. I, II and III is obviously passed and the forerunner of the dolerites has appeared on the scene.

Moraine. The contact between the pillow lava and the compact dolerite on both sides of Lake Úlfljótsvatn behind the falls is not accessible for observation. This does not affect the results of the present investigation, since the moraines under the dolerite are, also in the vicinity of lake Úlfljótsvatn, confirmed by several geologists. A tillite-like gray conglomerate has also been observed by the author below the dolerite at the Fossá gorge c. 2 km south of the farmhouse Úlfljótsvatn.

Tectonic Systems in the Neðri Fossar area

The tectonic systems have been studied both in the field and on aerial photographs. In the Neðri Fossar area the main tectonic direction is c. N10°E (7). No dislocation has been observed along this line, but the river bed and other morphological elements are affected by zones of tectonic fissures. Thus the Kistufoss gorge is cut into the basalt along a tectonic zone, which continues N10°E, followed by the Brúará gorge. Fissures running in that direction cut the tuff at the head of Írafoss. There the river has eroded deep channels along the fissures into the soft tuff.

Other tectonic systems suggested (7) are N75°E, i.e. the direction of the river between Írafoss and Kistufoss, and N50°W, which tectonic direction might appear in the course of the river in places south of Kistufoss.

The fissures observed all run in the N10°E-direction. For the most part they are closed, appearing as narrow seams of light pink clay in the dark rock. Fissures belonging to this system were observed in a late glacial or early postglacial gravel when a trench was cut through the slope east of Írafoss. Thus this tectonic system might be still active on a minute scale.

During the trenching of the open cut in front of the discharge tunnel, tectonic fissures running N50°W appeared both in the basalt and in the sandstone covering the basalt. In the sandstone the fissures are so narrow that they were not observed until blasting was begun. The tectonic system N75°E may be represented by a c. 35 cm wide cleft crossing the tunnel below the river. This crevasse, which is so filled up by silt and mud that it does not cause any leaking in the tunnel, has not been observed in the river bed, but might be hidden there under sand and gravel.

THE POSTDOLERITIC SERIES

Stapi—Moldás

The sequence of rock units overlying the dolerite is more difficult to follow than that of the older ones. The complete series is not found in a single cross-section, and therefore the interpretations have to be based on observations on scattered outcrops. Normally, the dolerite is covered by rather fresh basic tuff, but tillite-like, gray conglomerates occur also. In Stapi on the east side of Lake Úlfljótsvatn, a brownish tuff-conglomerate covers the dolerite. On Moldás east of Stapi, the top of the ridge consists of similar tuff-conglomerate containing striated pebbles of basic tuff, whereas a tillite-like gray conglomerate appears in a terrace on the northern slope. North of Stapi, at the waterline of Lake Úlfljótsvatn, globular basalt interfoliated by sideromelane is observed, but its relation to the dolerite is not known.

Dráttarhlíð—Kaldárhöfði

At the mouth of the stream Kaldá in Lake Úlfljótsvatn a gray moraine-like conglomerate with dolerite pebbles is found at a higher level than a dolerite outcrop in the inlet near by. Similar conglomerate of morainic character containing dolerite pebbles is found in Þúfnanes between Lake Úlfljótsvatn and the juncture of the river Efra Sog with the lake. The moraine bed dips gently to the west and disappears under the igneous rocks of Dráttarhlíð at the level of about 81 m c. 400 m west of the inlet. There the moraine bed reaches down to the level of c. 60 m, resting on basic tuff (Fig. 4).

With the exception of the postglacial lava at Miðfellshraun, the

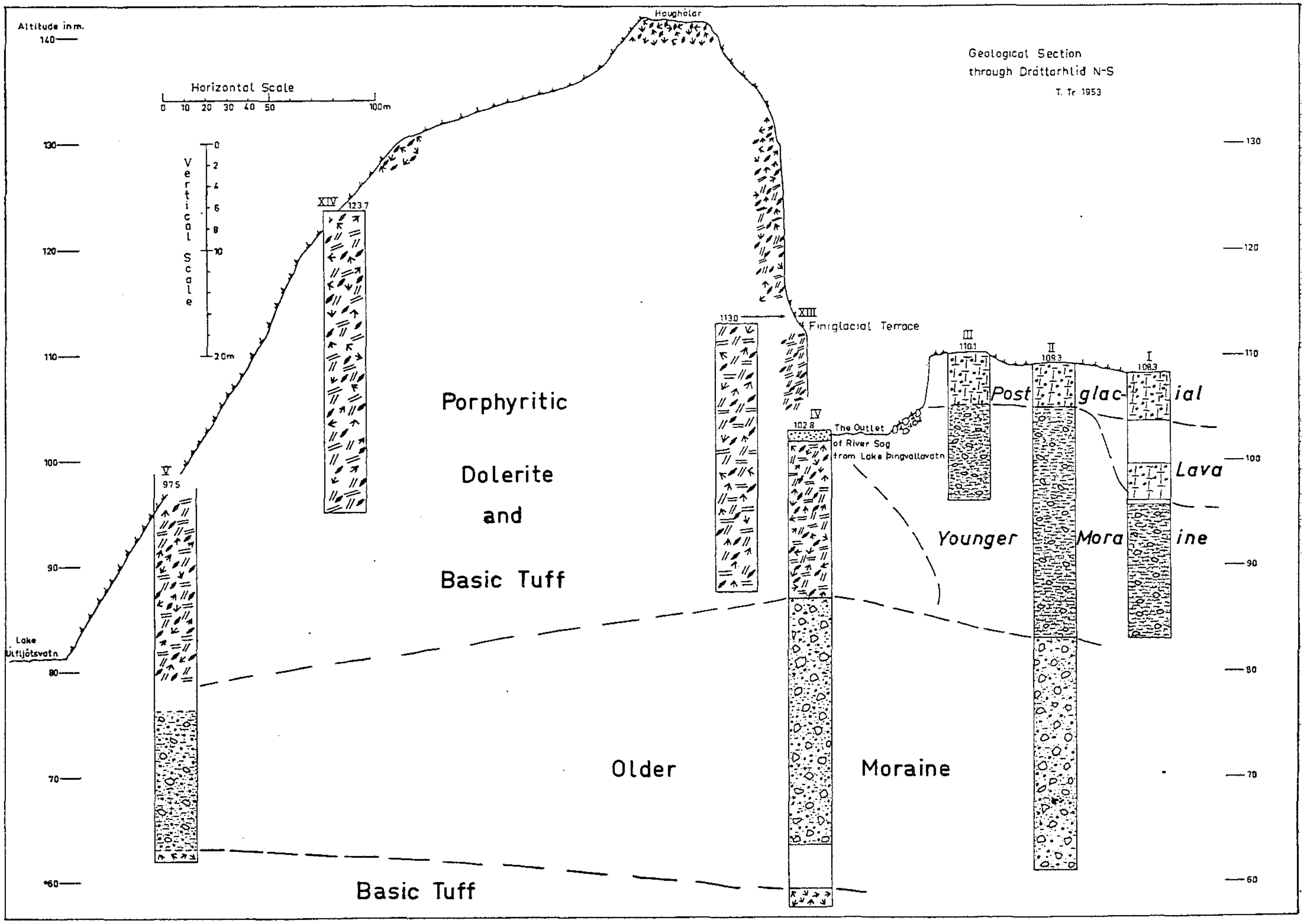

Fig. 4. Geological section through Dráttarhlíð.

tuff ridge Dráttarhlíð—Kaldárhöfði represents the youngest unit in the igneous series in the Efra Sog area. In spite of its soft rock, the glaciation has not modified the ridge to the same extent as the other hills in the surrounding, and its relief reminds one of the other young tuff ridges in SW-Iceland. Nevertheless on its highest points dolerite boulders are found, indicating that the entire ridge has endured a glaciation, and in places the surface rock appears to be tillite mixed with tuff.

With the exception of the tillite-like heaps, the rock in the ridge is a heterogeneous mixture of dolerite porphyry and basaltic tuff, which also is porphyritic. The porphyry predominates at the lower levels, but the tuff is more abundant in the upper part of the ridge. In places the porphyry is of globular structure. In the gorge of river Efra Sog, at a place called Borgardalur, the porphyry is suggestive of a homogeneous, intrusive body, displaying horizontal columns like a dyke. The abundant phenocrysts consist of pea-size plagioclase crystals and rarely of olivine. The phenocrysts in the tuff are coated with a thin film of black basaltic glass.

Microscopic studies reveal that the plagioclase crystals are of the same composition both in the porpyry and the tuff, basic bytownite and anorthite. This extremely porpyritic type of dolerite and tuff is rare in the Quaternary rocks of Iceland.

The tuff is relatively fresh and the larger sideromelane grains do not reveal significant signs of hydration. On the other hand the fine ground sideromelane acting as a ground-mass in the tuff is mostly hydrated. The tuff is cemented by a colourless or faint yellowish, fibrous mineral of low refringence and negative elongation. A minor quantity of calcite is also observed as a secondary mineral.

There is reason to think that the porphyry and the tuff are comagmatic. The porphyry might represent the feeder dyke and minor intrusions into accumulated pyroclastic material derived from the same eruption.

The intrusive character of the dolerite porphyry is distinctly revealed in Dráttarhlíð at the shore of Lake Úlfljótsvatn a short distance from the inlet of Efra Sog. There the stratified moraine and a thin tuff layer are tilted against a cliff of globular porphyry (Fig. 6). The cliff probably represents the continuation of the Borgardalur dyke.

Drillings. In the two deepest boreholes in Dráttarhlíð, Nos. IV and V (Fig. 4), basic tuff is found at the bottom of the bores. In bore No. IV the tuff is brecciated. The cavities in the breccia are more or less filled up with glacial clay, and the remaining cavities are coated with a thin crust of zeolite, probably chabasite. Calcite is also found.

At the bottom of the bore No. V is found stratified tuffaceous siltstone. A fissure in the siltstone is filled by a clay of faint pink colour, as are the tectonic fissures at Írafoss. These two boreholes reach down to the 60 m level, or some 20 m deeper than the normal bottom level of the dolerite.

As there are no evidences of dislocations in the area, most probably the dolerite is eroded away. Hence the tuff at the bottom level should be of predoleritic age. It is of especial interest that the zeolites are formed later than the impregnation of glacial clay in the brecciated tuff. Probably the formation of the zeolites and calcite is due to a short period of slight thermal activity in connection with the volcanism giving rise to the porphyry and tuff of the ridge Dráttarhlíð—Kaldárhöfði.

Postglacial Basalt. A postglacial basalt lava covers large areas north and east of Lake Þingvallavatn. The shield-volcano Skjaldbreið has yielded most of the lava masses, but the lava east of the lake is erupted from a crater row east of the mountain Hrafnabjörg (17). The lava has flowed between Miðfell and Lyngdalsheiði and filled the gorge of the river Efra Sog, between Dráttarhlíð and Kaldárhöfði, in two separate floods. A narrow tongue of the first flood has advanced down to Lake Úlfljótsvatn. In the present canyon a moraine is found below the lava near the outlet from Lake Þingvallavatn.

Tectonic Systems in the Efra Sog area

The tectonic systems are best studied on aerial photographs in combination with field observations. The locally predominating morphological features trend N35°W. Tectonic fissures running in that direction are rare, but numerous ridges and depressions follow that direction, among others a part of the canyon of Efra Sog.

The strike of the fault lines of the Þingvellir depression, which direction is also the prevailing elongation of the young tuff ridges near Lake Þingvallavatn, c. N30°E, is represented by fissures in the tuff and other morphologic elements in the area.

The Dráttarhlíð—Kaldárhöfði ridge does not coincide with the general trend of the other young tuff ridges above mentioned. Its axis of elongation runs toward the dolerite shield Lyngdalsheiði, or N50°—57°E, and its feeder channel in Borgardalur seems to run in the same direction. Tectonic fissures determining the face of the cliff Björgin trend the same way. Furthermore the steep south wall of the dolerite ridge Borg and the tuff hill Moldás are elongated in this direction.

That the tectonic direction predominating in a limited area trends towards the centre of the interglacial shield volcano Lyngdalsheiði is propably not a mere coincidence. It might indicate that the Dráttarhlíð—Kaldárhöfði volcanism represents the last phase of the activity forming that volcano.

SUMMARY AND CONCLUSIONS

The profiles investigated run as follows:

Dráttar-hlíð—Kaldár-höfði	Recent lava. Moraine and tuff-conglomerate, probably tillite. Porphyritic tuff and dolerite porphyry. Moraine. Basic tuff.
Stapi—Moldás	Tuff-conglomerate, probably tillite. Moraine. Tuff-conglomerate, probably tillite. Dolerite.

Ljósafoss, Írafoss, subterranean constructions	Dolerite. Moraine (not observed at Ljósafoss). Pillow lava, doleritic. Basic tuff. Dense basalt (B No. I). Basic tuff. Moraine. Sandstone, lava surface. Dense basalt (B No. II). Volcanic ash. Gray conglomerate, probably moraine. Dense basalt (B No. III).

The age of the Quaternary dolerites in Iceland has been subject to different opinions. All geologists concerned join in the opinion that these are of interglacial age. Péturss (13, 14) considers their age to be late Quaternary, most probably from the period before the last interglacial period, and claims to have observed at least four separate tillite horizons older than the dolerites. Péturss' opinion has been generally accepted until few years ago, when Einarsson brought forward a new theory on the age and origin of Icelandic basic tuffs, and the stratigraphic position of the dolerites. According to Einarsson the dolerite is extruded in the first interglacial period, and the predoleritic basic tuffs therefore are preglacial.

In the renewed discussion Noe-Nygaard (10) reports indurated moraines found south of Vatnajökull. He is fairly well in line with Péturss when he reports at least four such horizons separated by basalts of plateau character.

The moraines in the discharge tunnel and the shaft are new links in this chain of arguments.

In the postdoleritic series in the Sog area there are evidences for two moraines separated by basic tuff (Dráttarhlíð), and at least two seperate tuffaceous horizons separated by a moraine (Stapi—Moldás). For the age determination of the dolerite it therefore is a question of major importance, if the tuff can be formed and indurated during a glacial period.

The tuff conglomerate at Stapi contains many more or less rounded cobbles, but glacial striae are not found on the cobbles. On the SW-end of the Dráttarhlíð ridge, however, a little tuff hill is observed which does contain striated cobbles. This tuff hill is evidently younger than the dolerite, but its stratigraphic relations to the main ridge Dráttarhlíð are hidden by soil and vegetation. Farther east on the ridge some heaps of similar material, a gray tuff-conglomerate, is observed, but striated boulders have not been found there.

The conglomerate is obviously not formed in the same way as the volcanic complex of tuff and dolerite-porphyry constituting the bulk of the ridge. The contact between these two rock types is not clear, but the conglomerate seems to be related to the present surface. It might, as well as the Moldás conglomerate, be classified as „palagonite-moraine“ (12, 14), or as tillite, rich in sideromelane. The induration of such tillite in a relatively short time can be explained on account of its content of volcanic glass, which acts as a cement.

In 1847 Sartorius von Waltershausen (15) proposed the theory that the basic tuffs of Iceland are „in der Art eines hydraulischen Mörtels cementiert worden“. In view of the fact that the basic tuffs contain, in calcined state, all the components of a hydraulic cement, the suggestion of von Waltershausen is of major importance for the understanding of the origin and further development of the tuffs and their conglomerates.

If this theory is assumed, the understanding of several observed facts is facilitated. If a tuffaceous mass located at the bottom of a glacier can get indurated, there is a possibility that a series of tuff conglomerates interbedded with common moraines, like the Stapi—Moldás conglomerates, can originate during a single period of glaciation.

Turning to the age relations of the youngest dolerites in Southwest Iceland, it must be stressed that it is still an open question whether they were erupted in the last interglacial period or in an earlier interval in the Ice Age. The Fossvogur layers described by Péturss (13, 14), which constitute the strongest argument hitherto put forward for a postdoleritic interglacial period, might be formed during a minor interstadial or an oscillation in the last glaciation. The convincing evidence for the existence of such a period is still lacking.

As to the igneous tuff complex of Dráttarhlíð, it can not be proved whether it is extruded under glacial or interglacial conditions. However, some facts indicate its glacial origin:

1) After the formation of the Hengill mountains late in the Glacial Age (4), the glacier from the Langjökull — Thingvellir area found its way along the Sog valley between Lyngdalsheiði and Úlfljótsvatnsfjall. The ridge Dráttarhlíð—Kaldárhöfði lies as a threshold in the way of that glacier, and therefore an intense erosion of the ridge should be expected. Glacial boulders and tillite-like conglomerate are observed on the ridge, indicating that the glacier has gone over it, but the signs of glacial erosion on it are moderate. According to the borings the interglacial dolerite in the Dráttarhlíð area is eroded away. The tuff complex rests on a bed of slightly indurated moraine containing dolerite boulders. These observations agree fairly well. The tuff ridge has not endured any considerable glaciation, whereas its foundation rock has suffered a heavy erosion. The conclusion is that the tuff complex originated at the very end of the last Glacial period.

2) The hydration of the glass in the tuff is in its initial stage, which indicates a short age.
3) The appearance of the tuff complex is rather unlike the interglacial dolerites in general, which hints at some extraordinary conditions during its formation.

The field observations give evidence for the age relations of four seperate layers of basic tuff or tuff conglomerates of glacial or interglacial origin. As the rock series dealt with in this paper do not reveal any considerable signs of geothermal action, it can be assumed that the physical conditions to which this rock series have been subjected were rather homogeneous. Therefore it is of importance to observe that the alteration, i.e. the hydration and mineralization of the sideromelane increases markedly with the age of the tuff layers.

The Dráttarhlíð tuff, which is the youngest among the tuff beds, is well cemented although young and fresh. The colour of the sideromelane is relatively light, its hydration is at an early stage and the vermiculitic linings of the vesicles are at the very beginning and scarcely perceptible.

The postdoleritic conglomerate of Stapi is cemented in a similar way, and probably also the tuff breccia in bore IV in Dráttarhlíð. In both cases the hydration is somewhat more advanced than in the Dráttarhlíð tuff. The individual glass fragments consist of a core of light brown sideromelane and an outer fringe of a yellow, hydrated glass. The hydrated marginal zone is optically isotropic and a true devitrification of the glass is confined to the cementing mineral and a narrow fringe of celadonite (?) lining the vesicles in the glass. This celadonite lining seems to be somewhat more pronounced in the glass of the Stapi conglomerate than in the breccia.

Going back to the predoleritic series, the two tuff horizons are quite different in their alteration. The Ljósafoss tuff is of homogeneous character. The alteration of the sideromelane is more advanced as compared to the Stapi conglomerate, and the brown colour of the unhydrated glass is a shade deeper. The major part of the glass is hydrated, but the mineralization is for the most part limited to the vesicles.

The alteration of the uppermost part of the Írafoss tuff is similar to that of the Ljósafoss tuff. Farther down in this layer the alteration of the sideromelane is far more advanced, and resembles some tuffs of tertiary age familiar to the author. In this layer the remaining sideromelane is of a deep brown colour and far darker than in the younger tuff beds.

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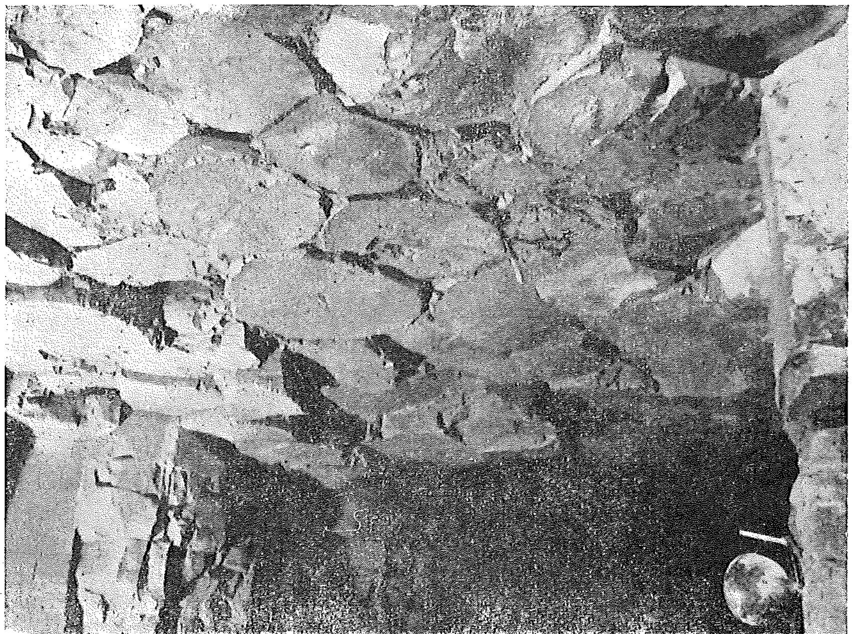

Fig. 5, plate I. The bottom columns of B No. III. Auxiliary tunnel at Írafoss. Photo T. Tryggvason.

Fig. 6, plate I. The doleritic porphyry dyke in Dráttarhlíð with tilted layers of moraine and tuff at its sides. Photo T. Tryggvason.

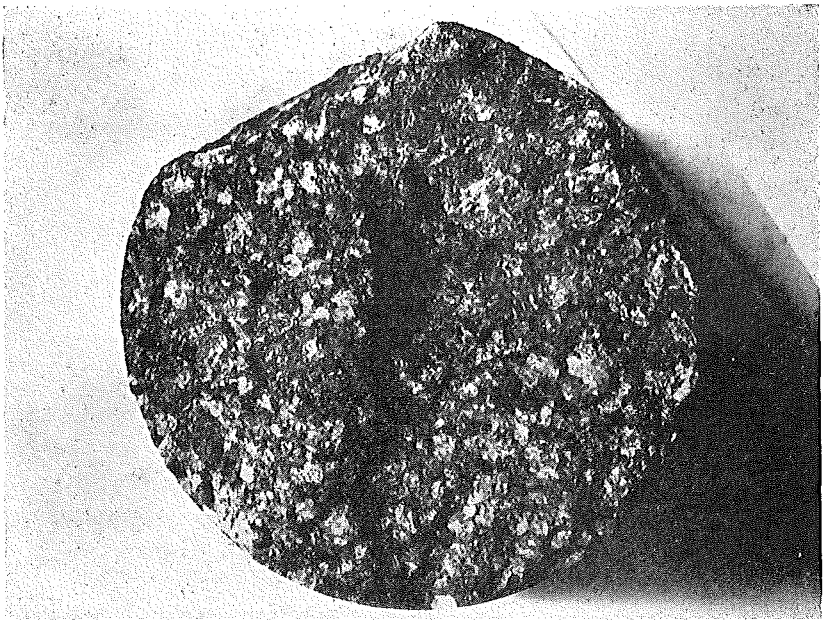

Fig. 7, plate II. Doleritic porphyry, Dráttarhlíð. Natural size.

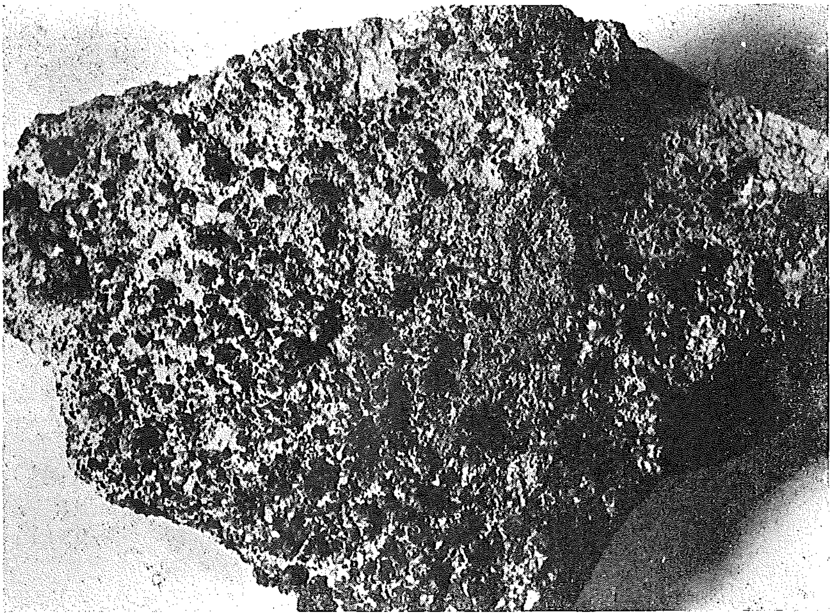

Fig. 8, plate II. The agglomeritic basic tuff of Dráttarhlíð. The weather surface is pock-marked with anortite crystals coated by basaltic glass. Natural size. Photo T. Tryggvason.

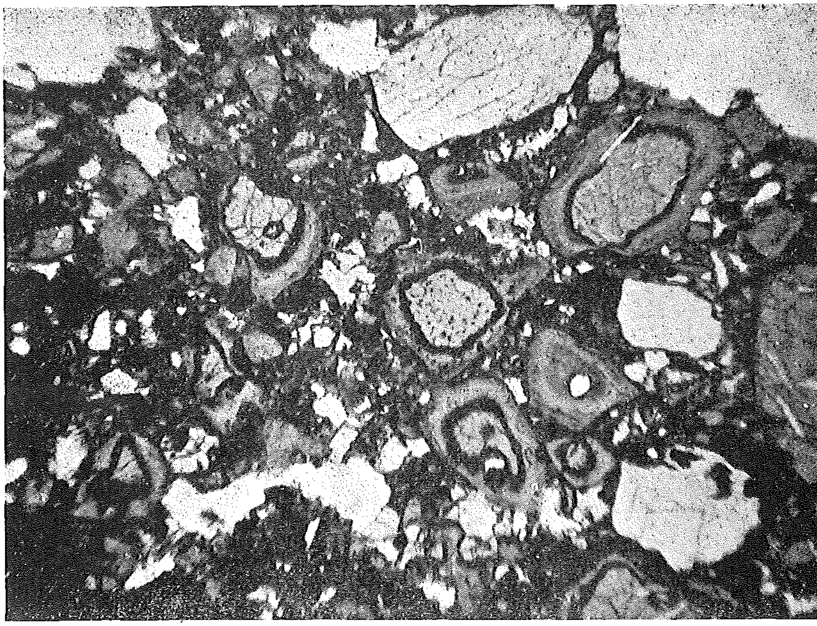

Fig. 9, plate III. Basic tuff-conglomerate at Stapi showing hydrated zones arond the sideromelane grains. x 45. Photo T. Tryggvason.

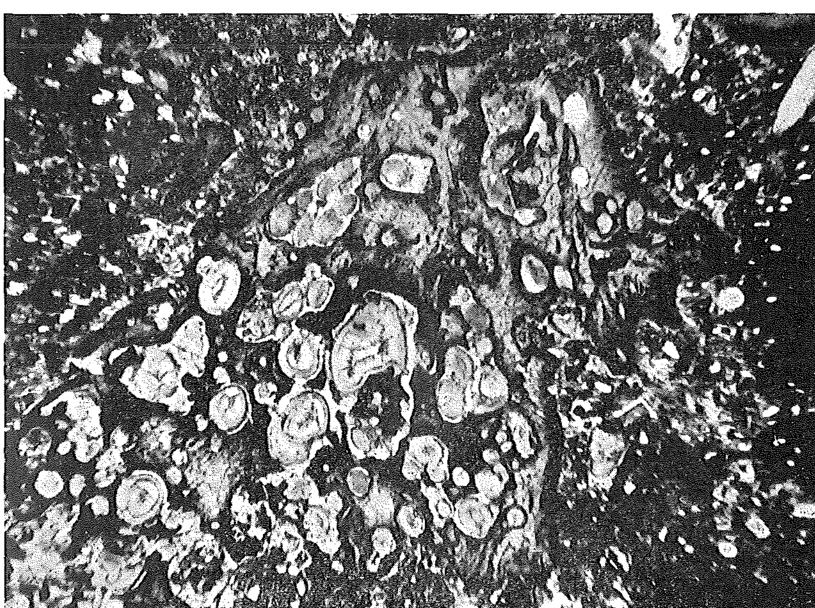

Fig. 10, plate III. Altered basic tuff from the shaft at Írafoss showing vermiculitic mineralisation inside the sideromelane grains. x 45. Photo T. Tryggvason.

Fig. 11, plate IV. Basalt B No. II. x 87. Photo G. Sigvaldason.

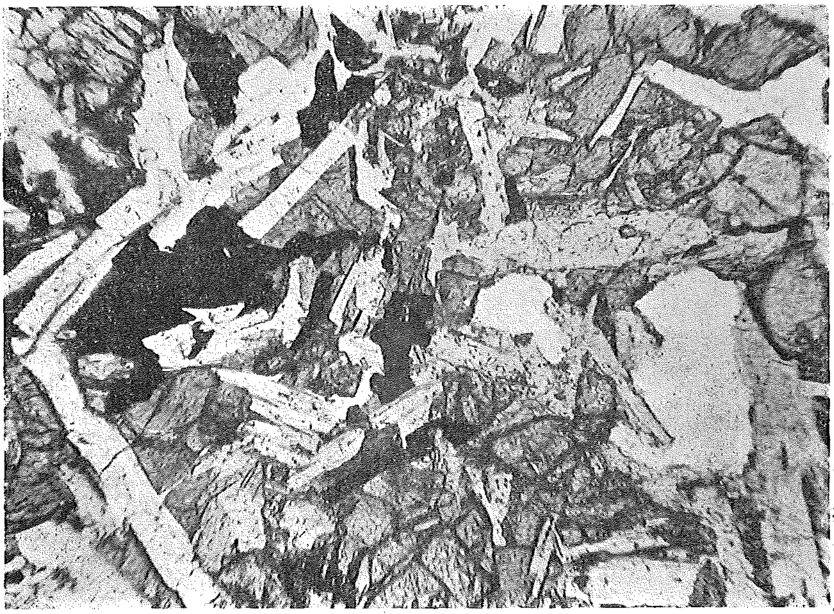

Fig. 12, plate IV. Dolerite, W-side of Lake Úlfljótsvatn. x 87.
Photo G. Sigvaldason.