NATIONAL ENERGY AUTHORITY
Department of Natural Heat

# INFRARED IMAGERY OF TORFAJÖKULL THERMAL AREA

by

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Reykjavík, January 1969

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ABSTRACT

An interpretation of IR-imagery of a part of the Torfajökull high temperature area in South Central Iceland is given. The IR-imagery obtained by IR-scanning technique in Aug. 1968, consists of 4 strips running almost parallel in WSW-ENE direction across the western half of the Torfajökull area. Information gathered during previous field trips and conventional airphotos provided a basis for interpreting the IR-imagery.

A short account of the geology and morphology of the area is given. Various tonal contrasts of the IR-imagery and their causes are discussed. Finally geological phenomena displayed by the IR-imagery are described. It was found that hydrothermal features are splendidly manifested on the IR-imagery, but it was not possible to identify them as to type. Thus interpretation of the IR-imagery has supplied valuable information on the distribution of hydrothermal features in a remote area hitherto inadequately known. Areas of different moisture content also showed up by different tones, which might be of use in ground water studies. Relating to other geological phenomena the IR-imagery seems to be much inferior to conventional airphotos.

Further interpretation work possibly includes an isothermal map of the thermal area and an estimation of the actual size of steaming ground-important parameters pertaining to the total outward transport of heat by the high temperature area.

CONTENTS

## FIGURES

# 1 INTRODUCTION

Torfajökull-area refers to a rhyolite massive approximately 400 km$^2$ in size located in South Central Iceland. In the western part of this area is located the largest and most intense high temperature area in the country. Prior to 1966 very scant and incomplete data was available on the geology, hot springs and solfatara fields of the region. During three successive field seasons (1966-1968) however the Dept. of Natural Heat of the National Energy Authority organized reconnaissance trips into the area and some three weeks in total were spent there collecting information on the geology and distribution of hot-springs and steamfields and a great number of samples of water, gas and rocks were taken.

Information gathered during those trips provided a basis for interpreting imagery obtained by airborne infrared scanning in Aug. 1968. The infrared program was jointly sponsored by the National Energy Authority of Iceland, U.S. Geological Survey, Infrared Physics Laboratory of the University of Michigan and the Air Force Cambridge Research Laboratories, Cambridge, Mass. The efforts of Dr. J.D. Friedman (U.S.G.S.) and Dr. R.W.Williams (A.F.C.R.L) who conducted the infrared work in Iceland are greatly acknowledged. Writing of this report was supported by the U.S.G.S. under contract No. 14-08-001-11348.

Fig. 1 shows the area covered by the infrared imagery in relation to the high temperature area and the rhyolitic rocks.

# 2 INTRODUCTORY REMARKS ON THE GEOLOGY AND MORPHOLOGY OF THE TORFAJÖKULL-AREA

## 2.1 Bedrock

The bedrock of the area consists mainly of three different rock types. These are in order of age from oldest to youngest rhyolites - hyaloclastites - postglacial lava flows.

## 2.11 Rhyolites

The rhyolites are extrusive in origin. They form a coherent massive which is bound by abruptly rising slopes and surpasses the surrounding country by some 300-400 m in elevation. Some smaller domelike or conical hills, the highest more than 200 m, are situated on the rhyolitic plateau. Two sectors have been strongly affected by erosion, i.e. the area to the south of Laugahraun up to Torfajökull and the area south of Hrafntinnusker. There the rhyolitic plateau is deeply cut by numerous ravines and gullies forming a true badland topography.

The rhyolites almost certainly consist of many different eruptive units. Although our investigations did not go far into elucidating this question we confirmed the existence of several different flows, domes ignimbrites and rhyolite breccias. The rhyolites are light coloured, greyish, yellowish or pink rocks, often with redbrown stain due to oxidation of pyrite.

So far, the age of the rhyolites is unknown, but since they underlie the hyaloclastites (2.12) an age greater than the last glacial stage is almost certain.

## 2.12 Hyaloclastites

The rhyolite plateau is bound on all sides by hyaloclastites which form NE-SW-trending ridge- or cone-shaped mountains 100-400 m in height. These rocks invariably overlap the rhyolites at their contacts. The hyaloclastites have been produced by subglacial fissure (ridge) or central (cone) eruptions most probably during the last glacial stage. Some patches of hyaloclastites were found within the rhyolite plateau in the vicinity of Laugahraun (Suðurnámur, Bláhnúkur) and near the juncture of Hamragil and

Jökulgilskvísl. To the northwest of the rhyolite-plateau and overlying it in part are numerous short ridges in Reykjadalir and the great hyaloclastite mass of Mógilshöfðar.

The hyaloclastites are mostly basaltic in composition. They are dark brown in colour, and very fine grained, with the coarser breccias and pillow lavas exposed only where eroded to some extent. Silicic varieties of hyaloclastites also occur. The hyaloclastites of Mógilshöfðar and Sátubotnar have the composition of basaltic andesites. Rhyolitic varieties are found in Bláhnúkur and also east and south of Kirkjufell. The rhyolitic hyaloclastites are much lighter in colour than the basaltic ones except black pitchstone bodies which are usually associated with the silicic hyaloclastites.

## 2.13 Postglacial lava flows

Postglacial lava flows are widely distributed in depressions and valleys to the north, south and west of the rhyolite plateau. Several lavas of intermediate to rhyolitic composition lie within a 5 km broad zone crossing the area near its NW-border.

The composition of the lavas varies between basaltic and rhyolitic, and composite lavas may be found too (Walker 1964). The surface morphology of the lavas and the steepness of their margins vary with their silica content. The most viscous lava forms a steep-sided "staurücken" as high as 130 m above the surrounding located about 1 km to the north of Frostastaðavatn.

The margins of the other rhyolitic flows attain heights of some 20-50 m. The surface of the rhyolitic flows is extremely uneven and blocky being made of black obsidian with strings of pumiceous greyish rock.

The basalt lavas have a more even surface and much lower margins. Aa-type lavas are not present except Laufahraun (andesitic) on the southeastern margin of the area.

The youngest of the lavas are historic in age (i.e. less than 1000 years old). The Veiðivötn - Ljótipollur - Námshraun - Laugahraun - Hrafntinnusker - row was presumably erupted during a single eruptive episode shortly after the settlement of Iceland. And Hrafntinnuhraun is believed (Thorarinsson 1967) to have formed during the 12. century.

## 2.2 Covering by loose material

Actually the bedrock is concealed to a great extent in this area. Two types of loose deposits are most abundant i.e. tephra and fluviatile sediments.

### 2.21 Tephra

There are numerous tephra producing volcanoes within and in the vicinity of the Torfajökull area. Notably in the northwest sector - the same area as covered by the IR-imagery - is this cover of tephra so thick, that the bedrock is completely masked except on the tops of hills where it has been blown off or in gullies and on precipitous slopes and rough lava surfaces. The tephra is of diverse origin. Black or dark grey basaltic ash mostly phreatic in origin is abundant. White rhyolitic pumice is very thick north of Frostastaðavatn and east of Hrafntinnuhraun near local eruptive sources. Perhaps most abundant, however, is tephra produced by numerous eruptions of the volcano Hekla. The composition of the Hekla layers varies from basaltic to rhyolitic and their colour accordingly from black to white and the thickness of individual layers may exceed 1 foot. The whole of the area is uniformly covered by the Hekla 1845 layer that was carried mainly to the east of the volcano. This layer is thickest in the western part of the Torfajökull-area, nearest to the volcano (c.f. fig. 3). The 1845 ash is rather coarse grained and brown in colour except near the base where it is light coloured, Near Hrafntinnuhraun and just north of the rhyolite massive it is about 1 foot thick on level surfaces. The tephra layers, of course, have been much redeposited by blowing or washing away from high peaks and steep slopes and accumulating in depressions and grooves of the blocky lava surfaces. The total thickness of ash on level surfaces attains somewhere between 1 and 5 m, the minimum thickness being towards the east.

### 2.22 River gravels, lake sediments, terraces

River gravels, lake sediments and terraces constitute another type of loose surface deposits abundant in the area. These are most common near the Jökulgilskvísl and its tributaries. But also near Tungnaá on the northeast border and around Markarfljót and its tributaries on the southeastern border of the area. The river gravels are mostly made up of coarse rhyolite debris which is very light coloured.

The lake sediments have formed within depressions in the area following its deglaciation. The lakes were dammed up between hyaloclastite ridges (some also by postglacial lava flows) but have been emptied subsequently due to erosion of the damming thresholds. The lake sediments consist of clay and sometimes crossbedded gravels on top, but being very old they are usually covered by ash.

### 2.23 Screes

Screes made up of rhyolitic debris are amazingly rare in the area, the only good examples occurring within the area represented on the IR-imagery being Kirkjufell in the northeast and Laufafell in the southwest.

### 2.24 Rock slides

Rock slides have occurred in various places throughout the area. The downward transported masses appear as thick piles on the slopes underneath a precipitous scar.

### 2.25 Vegetation

Vegetation is negligible in the Torfajökull area. The ash and lava covered ground may be regarded as an edaphic desert (Schwarzback 1964) due to the permeability of the volcanic material and strong wind moving the loose ash over the ground. Small oases however occur where conditions are favourable. The high plateau itself is practically without vegetation. North of the Torfajökull area some of the hyaloclastite mountains are vegetation covered in their higher parts, where not affected by "sand"-storms.

## 3 TONAL CONTRASTS OF THE IR-IMAGERY AND THEIR CAUSES

The tonal contrasts of the IR-imagery depend on the intensity of heat radiation which in turn depends on the relative heat emission (emissivity) and temperature of the surface rocks.

The IR-imagery was obtained from 10.000 feet altitude at night between 00.27 and 01.35 thus almost eliminating visual radiation and sensing IR-radiation alone. According to the calendar for 1968 sunset in this region was at about 20.00 h and darkness at about 21.00 h on the 24th of August. Darkness is assumed when the sun is $6^{o}$ below horizon.

Effects of heating of the surface by solar radiation during the previous day may have influenced the tone of the IR-imagery although 4-5 hours passed from sunset until the images were taken. The sky was not quite clear and on the easternmost image some anomalies result from clouds. The quality of the images is elsewhere good but the scale is much greater in the direction of flight than perpendicular to it and thus the images appear somewhat distorted. This is due to the infrared scanning technique.

## 3.1 Conspicuous dark and light tonal contrasts

4 types of geologic objects produce a marked tonal effect on the IR-photograph. Dark effects are produced by:

1. Snow field and glaciers
2. Dry depressions filled with sediments of high moisture content and hence evaporative cooling.

### 3.11 Snow fields and glaciers

The reason for the snow fields and glaciers showing up dark is obvious and needs no further comments.

### 3.12 Sediments of high moisture content

The dry depressions covered by sediments with high moisture content probably derive their low thermal radiation from the effect of evaporative cooling. Experiments by SHOCKLEY & others (1963 p. 272) clearly indicate a decrease in infrared radiation with increasing moisture content of the investigated samples. This effect can be seen on the low terraces on either side of the Jökulgilskvísl up to Norðurnámsver. These terraces consist of coarse gravels but their surface has been coated with a thin veneer of silt and clay which has inundated them during great floods of the Jökulgilskvísl. Moss and sparse grass is thriving on these terraces, but Norðurnámsver is a boggy grasscovered oasis.

The "evaporative cooling effect" is also very clear west of Markarfljót in the westernmost part of the area covered by the IR-imagery (c.f. fig. 4). Also there terraces made up of ancient lake sediments are present. In Reykjadalir they are known to consist of varved clay covered by thick ash deposits. Probably similar conditions are to be found in the other localities which have not beed visited yet.

Sediments such as gravels or volcanic ash which is completely soaked with water do not show this effect. (c.f. later in this report, 3.2)

## 3.13 Lakes, river courses and gullies

Light effects are produced by:

1. Lakes, river courses and gullies
2. Hydrothermal features

The reason for lakes and river courses showing up light is because of their great thermal radiation, which is perhaps mainly due to their relatively high summer temperatures and also the high relative heat emission of water. It was observed that the numerous gullies cutting the slopes of hills and valleysides appear in a marked light grey tone independant of their disposition towards the sun, indicating a high thermal radiation from their bottoms. This effect probably is due to water seepage along the bottoms of the gullies.

## 3.14 Hydrothermal features

IR-imagery has already been used sucessfully in evaluating inaccessible or little known thermal areas (Miller 1966, Shilin and Komarov 1968). The possibility of detecting various hydrothermal phenomena is evidenced also by these papers as well as papers by McLerran 1964, Chaturvedi and Palmason 1967, Miller 1968. It is however evident from these papers that the use of IR-imagery is very limited when identifying various types of hydrothermal features. But in connection with ground surveys it becomes a most valuable guide.

The distribution of hydrothermal features is splendidly manifested on the Torfajökull IR-imagery. They appear as white spots often with fringed margins unlike the lakes and rivers which have clear cut margins. The unsharp boundaries of the hot areas are probably due to the gradual decrease in temperature avay from a solfatara field.

The hot spots revealed by the IR-imagery provide us with some very valuable information supplementing our previous field reconnaissance in a most appropiate manner. In fact many new hot spots were detected when studying the IR-photographs, some of which however need checking in the field. The hydrothermal features cannot however be identified as to type.

Some disadvantages are met with when locating the hot spots, because of the few recognizable field marks which can be used for their location. However by carefully comparing such field marks as river courses and snowfields on conventional aerial photographs and the IR-imagery the accurate location of many was assured. In other instances, the configuration of hot areas as mapped in the field could be recognized on the IR-photos and additional hot spots in their vicinity could be located with good approximation. Fig. 2 presents a map of the Torfajökull area showing the hydrothermal features without distinction as to type according to field data and complementary additions from the IR-imagery, marked accordingly.

### 3.2 Light grey tone produced by water soaked sediments

A marked light grey contrast is produced by the water soaked gravel plains along Markarfljót and Jökulgilskvísl and their tributaries. This effect is however not equally pronounced all over the outwash plains, some parts show the same grey tone as the surroundings and some are much darker giving the image a mottled appearance. This is probably due to the different water or moisture content of the gravel plains. Where they are completely soaked with water they show up light. The dark effects probably are related to places where clay or silt has been left on the gravels after an occasional flood. There evaporative cooling may be effective. Dry gravels where ground water stands well below the surface do not show the warm or cold effects.

The basin of a temporary lake northeast of Tjörvafell (Fig. 5) appears light grey on the IR-imagery probably because of a high groundwater level. At the lowest point this depression may have contained shallow water when scanned, since it appears in a grey tone intermediate between that of nearby lakes and the rest of the lake basin.

## 3.3 Slope effect produced by different solar heating during daytime

In the NE-part of Run 1 (Fig. 5) some dark contrasts are to be seen mostly elongated in NE-SW-direction. On closer inspection these areas of low thermal radiation were found to represent steep slopes facing NW. The same effect can be seen on Run 2 at the SE corner of lake Frostastaðavatn and in the walls to the west and southwest of Ljótipollur and Blautaver. The situation at Ljótipollur where the opposite wall appears light gray proves that this tonal contrast must be produced by the limited or lacking solar radiation received by slopes facing NW and north during the previous day contrary to the slopes facing southeast and south which may have retained some of the solar heat received during daytime (Strangway & others 1964, Lattman 1963).

The slope effect is prominent in the hyaloclastite ridge area of Reykjadalir, where the SE slopes appear light but the NW-slopes dark. This may be seen also in Brandsgil east of Laugar (Run 3) and equally well in numerous gullies of Jökultungur (Run 4) and Ljósártungur (Runs 2 and 3). Precipitous cliffs facing southeast, south and southwest show this effect particularly well.

## 3.4 Mottled appearance of the youngest lava flows

Lava flows having an extremely rough surface such as Námshraun, Laugahraun and Dómadalshraun produce a tonal contrast of a mottled appearance with both dark and light contrasts. Sometimes individual lava ogives and ridges thus become recognizable on the IR-imagery and the lava margins show up very light where they face a southerly direction. The Norðurnámshraun is in some places characterized by numerous small kettle holes which show up light grey on the IR-imagery, whereas the smooth parts of the surface of this lava appear a little darker.

The mottled tonal effect can be explained like the slope effect of the lava margins by the solar heat retained by surfaces exposed directly to the sun during the previous day. The roughness of the lavas offers good opportunities for solar radiation to fall on exposed dark rock surfaces under low angle of incidence. A similar mottled apperance is observed in the hyaloclastite-area near Kýlingar and Tungnaá (Run 3). This is again due to the hyaloclastite topography with its uneven surface of small hills, mounds and pinnacles.

## 3.5 Greytone of the ash covered high plateau

Apart from the variations mentioned the high plateau appears in a monotonous greytone. Since it is so thickly covered by tephra rhyolites, hyaloclastite ridges and postglacial lava flows all appear in the same tone. Only Hrafntinnuhraun makes a difference being the youngest and least covered lavaflow in the area. This lavaflow, although half of it lies in the dark region near the margin of the image, shows a somewhat mottled appearence due to the rough surface, the ogives and lavaridges of which still project well out of the ash cover.

# 4. DISCUSSION OF GEOLOGICAL PHENOMENA DISPLAYED BY IR-IMAGERY

It seems that the IR-imagery does not reveal any significant geological phenomena in this particular area, except the hydrothermal features. Most if not all tonal contrasts could be explained either by the different water content of the surficial beds or by solar heat stored in the rocks since daytime. The pattern of the hydrothermal features alone deserves further discussion from a geological point of view.

## 4.1 Vestur-Reykjadalir

The solfatara fields of Vestur-Reykjadalir (Fig. 4) are located in an area characterized by NE-SW-trending short hyaloclastite ridges. The most intense solfatara fields are located near the Markarfljót river itself and along one of its tributaries farther west. The IR-imagery does not give the impression of distinct linear trends in the distribution of the hydrothermal features in this area. However, with regard to the NE-SW-trending fissures in the area it is suggested that three rows of solfatara fields in the ground between river Markarfljót and its tributary are confined to hidden faults. The westernmost solfatara fields of Vestur-Reykjadalir are likewise situated within the hyaloclastite ridge area. The hydrothermal features detected on the IR-imagery lie there in an area of extensive hydrothermal alteration seen from some distance but not checked further in the field, since it apparently was "cold". The IR-imagery clearly shows that this was incorrect.

The second feature is located in a deep gully near the jeeptrack. This gully trends SW-NE and continues NE into the volcanic fissure through which the westernmost rhyolitic lava was erupted. It may thus represent a fault.

## 4.2 Austur-Reykjadalir

There are two major solfatara-groups in the Austur-Reykjadalir along the uppermost reaches of river Markarfljót. The Austur-Reykjadalir-valley system is divided by a large hyaloclastite ridge trending NE-SW. The more westerly group (Rauði hver group) lies west of this ridge extending in ENE-WSW-direction across the Markarfljót up to the edge of an old postglacial rhyolite lava flow south of the river. The second group (Stóri hver group) shows a very distinct WNW-ESE elongation for about 1500 m (Fig. 6) which may well represent a fault. Another fault with the same trend probably lies some 500 m farther north.

An isolated hot area was detected on the IR-imagery to the east of the Stóri hver group and some weak light contrasts east of the main spot, which is almost certainly due to a hydrothermal feature, need checking in the field before final conclusion.

## 4.3 Hrafntinnusker

Extensive solfatara fields occur around the postglacial and probably historic rhyolitic lava flow of Hrafntinnusker, being most intense to the south and west of it, where individual solfatara groups almost coalesce to form a more or less continuous area of hot ground, somewhere near 2 $km^2$ in size.

The limited time at our disposal during the field reconnaisance trips did not allow for a detailed mapping of this solfatara area except near the outskirts of it where the solfatara groups were less crowded together. The IR-imagery makes it however possible to map the solfatara pattern very exactly also in the central area where they are most numerous and densely crowded. Fig. 7 shows a map based on IR-imagery interpretation of a part of the Hrafntinnusker solfatara area on a somewhat larger scale than Fig. 2.

The solfatara fields south of Hrafntinnusker were not visited in the field. No linear trends can be detected in the distribution pattern of the solfataras in the Hrafntinnusker area. However it is evident that a major broad zone of intense hydrothermal features extends from Kaldaklofsfjöll in a northwesterly direction to include the Hrafntinnusker field and even the Vestur-Reykjadalir field too. Assumption about a deep seated infrastructure such as a ring fracture may be involved to explain the distribution of thermal fields in the Hrafntinnusker region, but they remain merely speculative.

It is possible that there is a caldera within the Torfajökull massive and the probable location of it is shown on the map (Fig. 2). This suggestion is based largely on topographic evidence. However the proposed caldera includes most of the hydrothermal features, except Vestur-Reykjadalir and the associated hydrothermal alteration. Large outcrops of rhyolitic tuffs and breccias of pyroclastic origin are known to exist within the proposed caldera. There is however more geological work needed to check this idea.

## 4.4 Area around Laugahraun

While the thermal areas described above are characterized mainly by steaming ground with little flow but occasional mudpools and water filled pits and also sometimes carbonaceous springs the region near Laugahraun displays in addition numerous hot springs with a considerable discharge of chlorine rich water. However as mentioned before the IR-imagery cannot distinguish between different types of hydrothermal features.

The hot springs and solfataras near Laugahraun form some dispersed small groups around the main field near the eruptive source of Laugahraun. Most of this area was investigated thoroughly in the field and the IR-imagery did not reveal new hot spots except some in the upper reaches of Grænagil and also three large spots in Stóra Brandsgil. NE-SW-trending alignments of the hydrothermal features near the source of Laugahraun related to faults visible in the field, can be seen also on the IR-imagery. A very strong anomaly results from the Landmannalaugar hot springs, the discharge of which has been estimated to correspond to some 70 l/sec of 100°C. Even Námskvísl into which this water flows, can be identified as abnormally warm down to its junction with the Jökulgilskvísl.

### 4.5 Eastern flank of Reykjafjöll and upper course of Jökulgilskvísl

Run 4 of the IR-imagery only shows the northern margin of the great thermal field east of Reykjafjöll and thus reveals little beyond what was known from field study. However a new small thermal field is evidently present west of Jökulgilskvísl in a side gully not well seen from the main valley. Also according to the IR-imagery the hot springs below Hattur seem to be distributed over a larger area than recognized during field study.

## 5. CONCLUSIONS

The IR-imagery of the Torfajökull area is particularly useful in mapping hydrothermal features expecially in the less accessible parts of the area. Continued IR-scanning of the area would reveal changes in the surface pattern of the thermal activity.

We think it worth while to scan the area from a lower altitude for a more precise estimate of the actual size of the steam fields, an important parameter pertaining to the total outward transport of heat by the high-temperature areas in general. Another parameter of great importance which might be inferred from IR-imagery is an isothermal map of the thermal area, but this has still to be done.

The IR-imagery did not reveal any important tonal contrasts which could be related to differences in the lithology of the bedrock. Topographic features giving tonal contrasts are better studied on conventional airphotos.

The IR-imagery might prove useful in determining areas of high moisture content in soil and alluvial depostis, and thus prove useful in hydrologic studies.

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| Mkv. 1:250.000 | ORKUSTOFNUN TORFAJÖKULL Jarðhitasvæði | 9.12'68. K.S/EK. Tnr. I J-Torfajökull Fnr. 8652 |
|---|---|---|

Fig I.

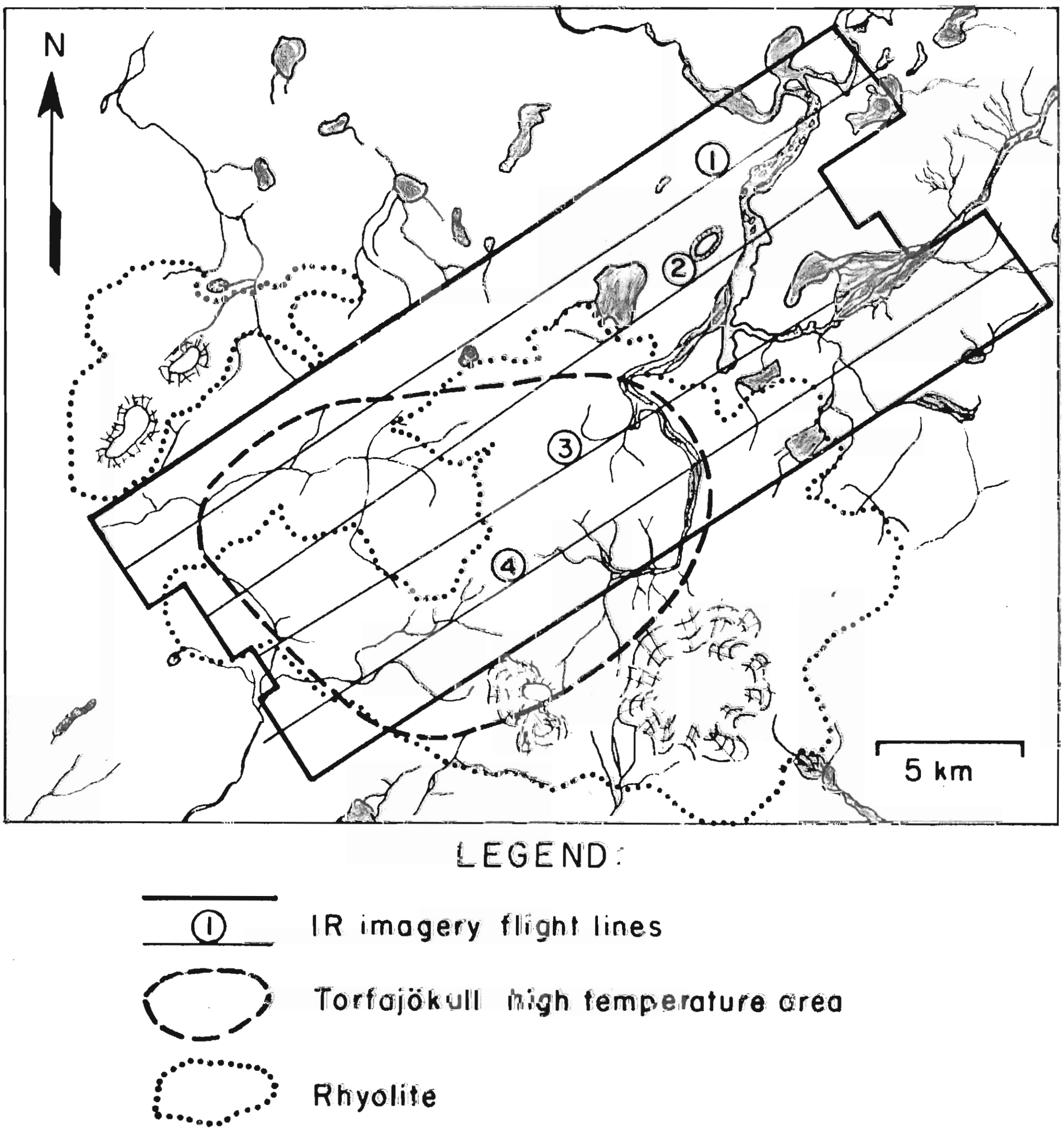



Fig. 1. Index map showing the position of IR-flight lines.

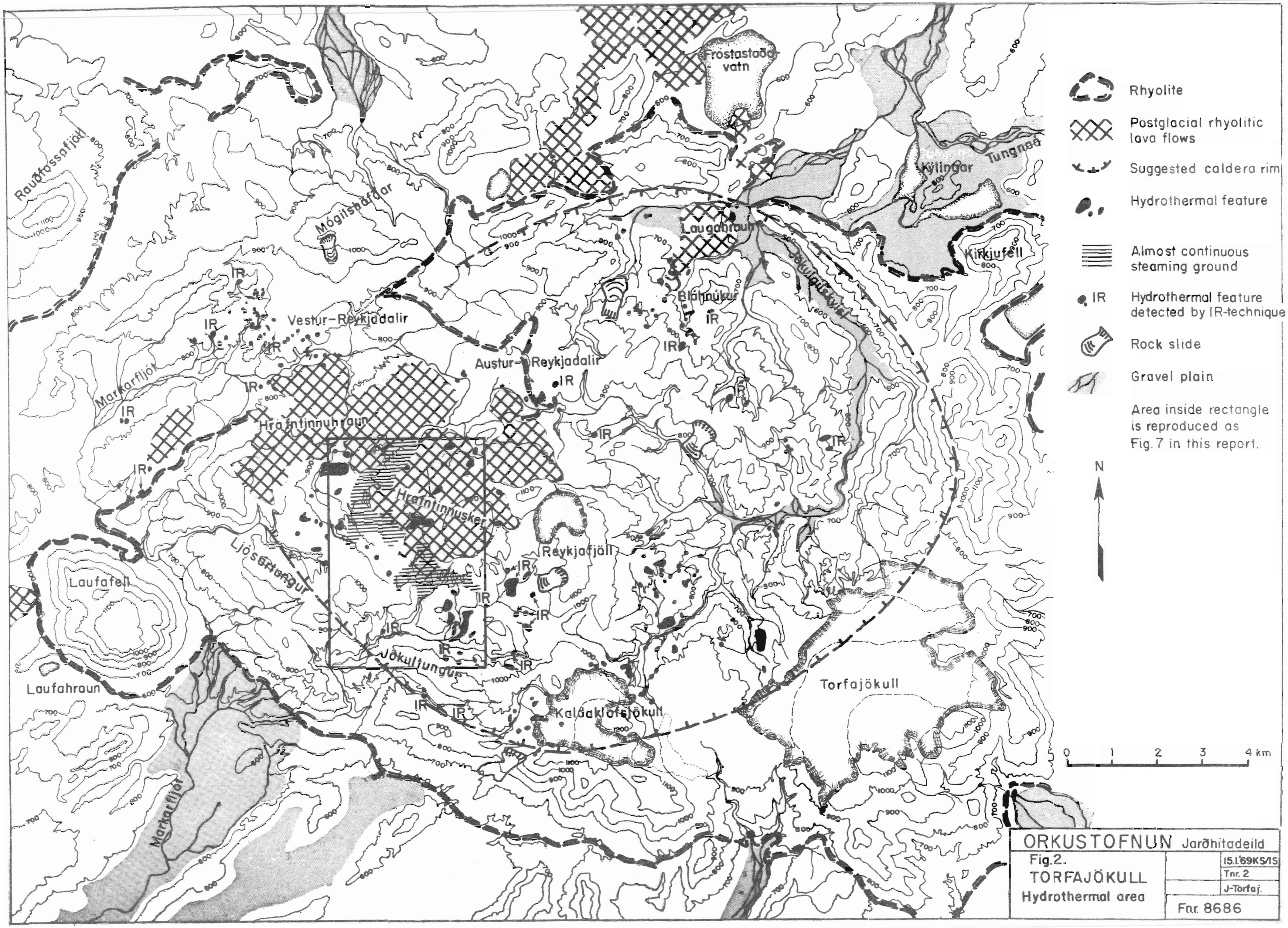


Fig. 2. TORFAJÖKULL Hydrothermal area

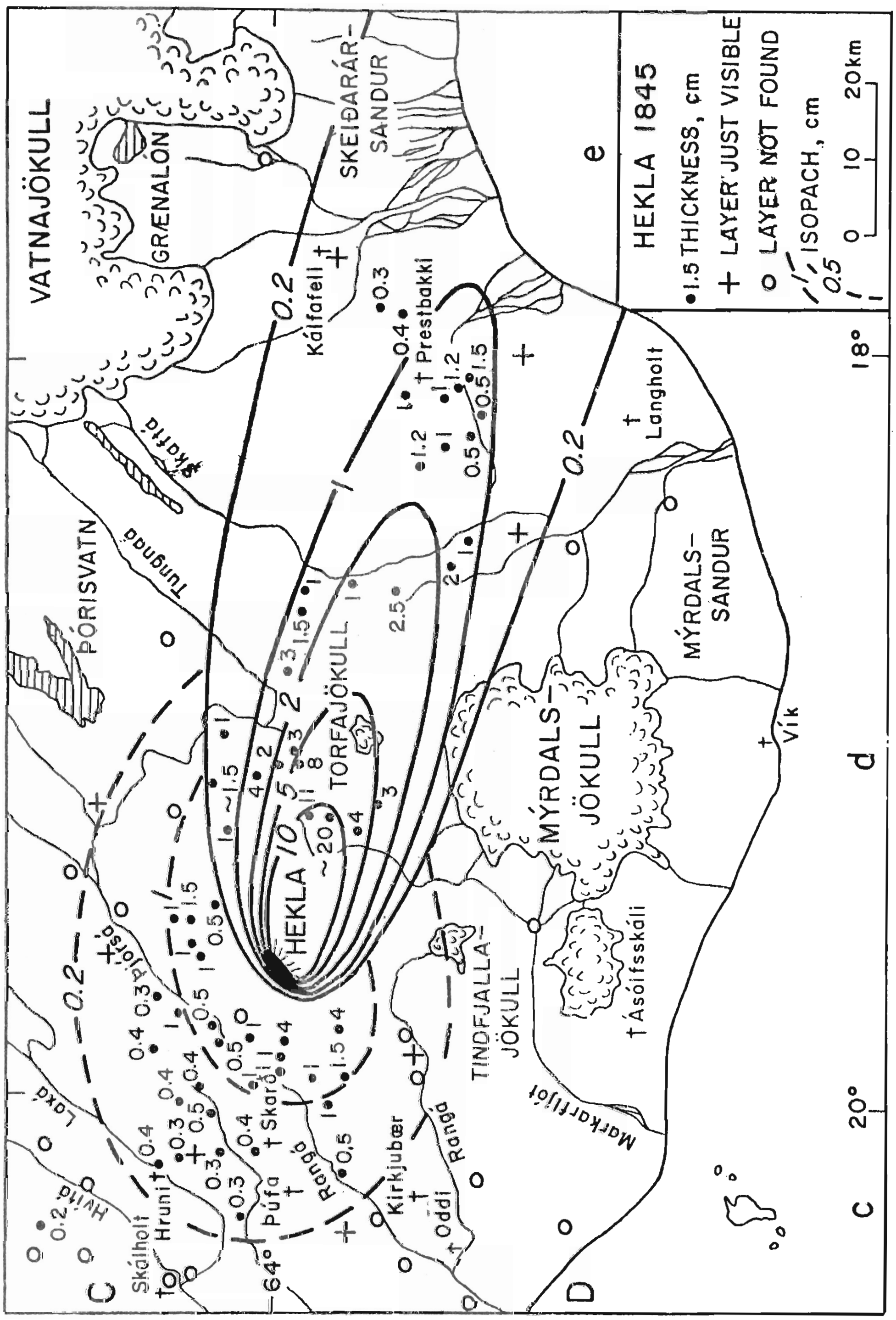
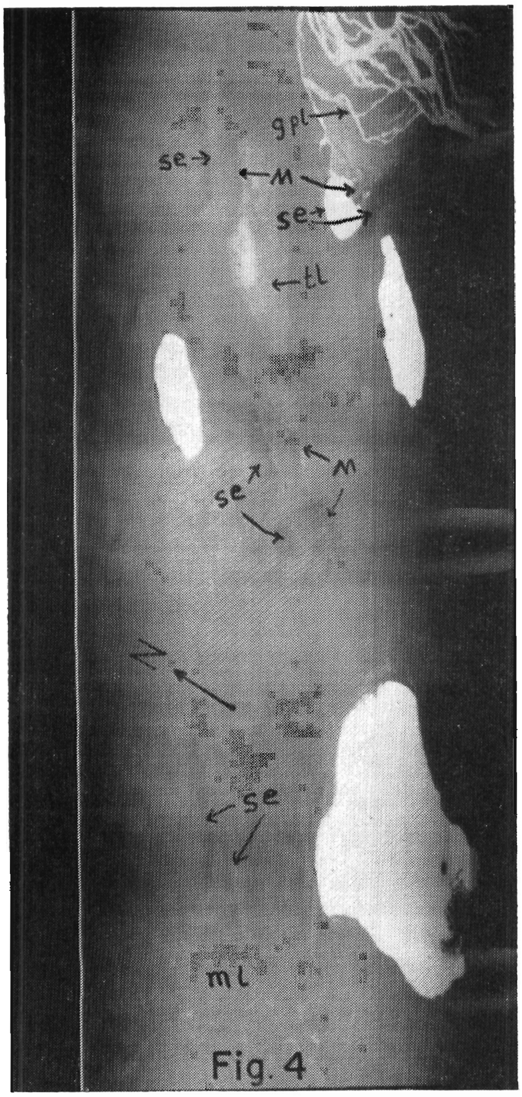
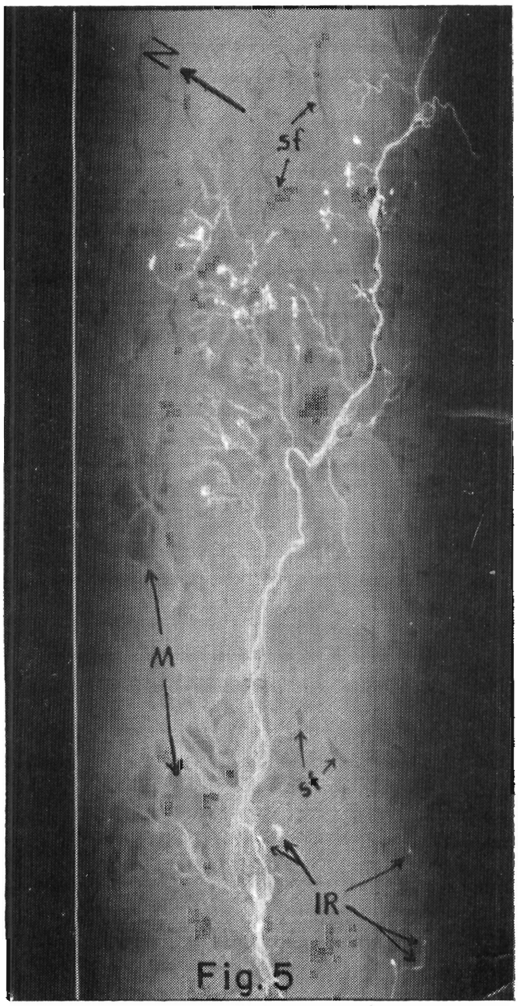



Fig. 3. Isopach map of the tephra layer H 1845. Whole drawn lines are isopachs of the initial tephra fall, broken lines are isopachs of tephra deposited after the initial phase. Quoted from Thorarinsson 1967.



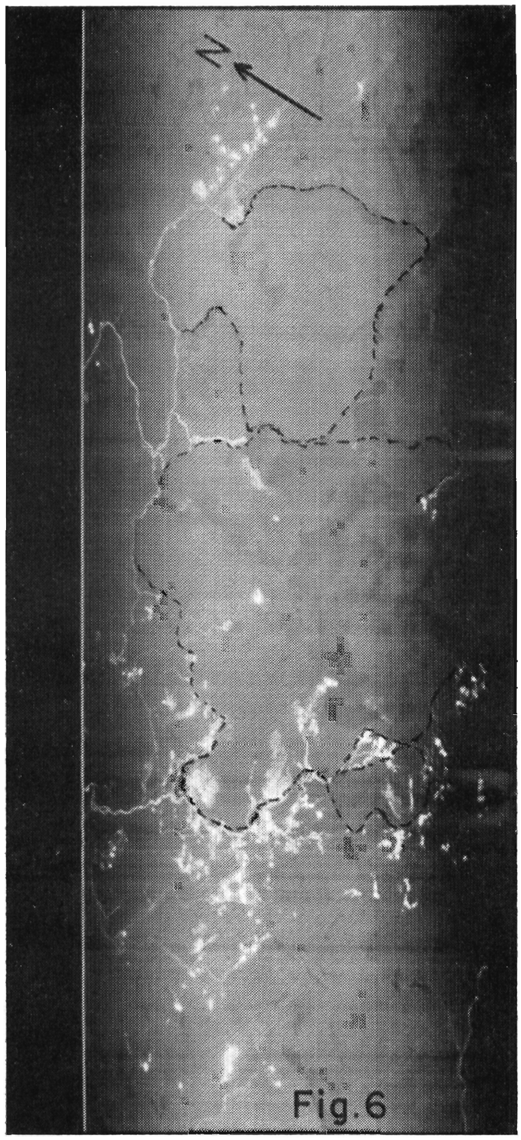




Fig. 4.

Part of Run 1 showing the area to the north and north east of Lake Frostastadavatn. Explanation: se = slope effect, gpl = gravel plain, ml = mottled lava, M = moisture, tl = temporary lake basin.

Fig. 5.

Part of Run 1 showing the Vestur-Reykjadalir. The white band is river Markarfljót. Hydrothermal features appear as white dots. Explanation: sf = snow fields, IR = hot spots revealed by IR—technique, M = high moisture content of alluvial deposits.

Fig. 6.

Part of Run 3 showing the intense hydrothermal activity around Hrafntinnusker. The outlines of the three Hrafntinnusker lavas are shown.

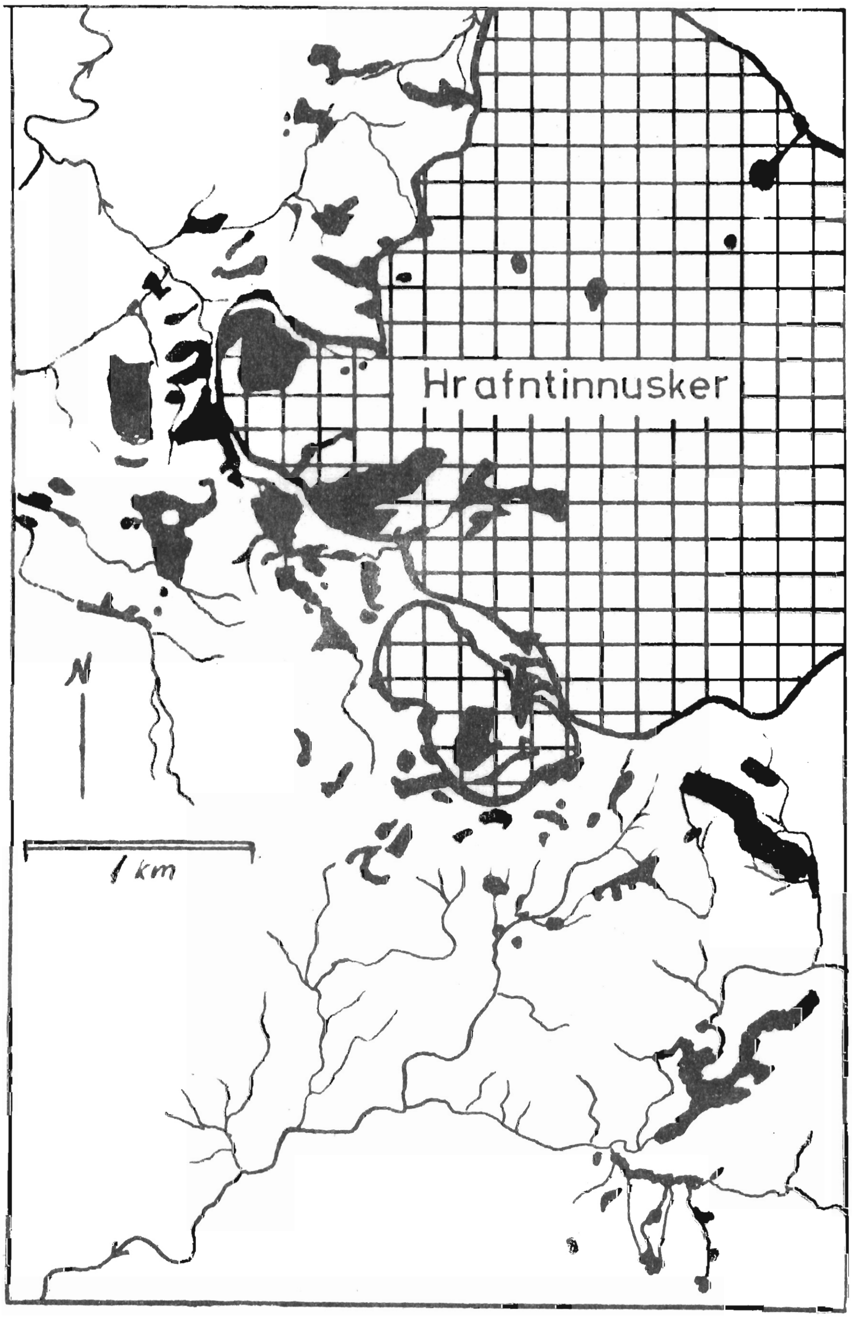



Fig. 7.
Pattern of hydrothermal features southwest of Hrafntinnusker as revealed by IR-imagery

Hydrothermal feature

Hrafntinnusker rhyolitic lava flow.