NATIONAL ENERGY AUTHORITY
Department of Natural Heat

INTERPRETATION OF INFRARED IMAGERY OF MÝVATN AREA

by
Lokesh Chaturvedi and Guðmundur Pálmason

Reykjavík, Iceland, December 1967

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ABSTRACT

Although infrared remote sensing has been widely accepted as a valuable tool for research and exploration in Earth Sciences, much remains to be done to establish the methods and criteria for a proper interpretation of IR imagery. This work is an attempt to establish such criteria and a study of several variables which affect the tone pattern on the IR imagery of a typical thermal area in Iceland. A field trip in the area and a close examination of the IR imagery have provided the basis for this work. It is hoped that a systematic study of variables that affect the IR imagery, encountered in diverse geological environments, will result in establishing a firm basis for the interpretation. This in turn should result in reducing the need of extensive ground control.

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1. Introduction

Mývatn area is one of the several regions in Iceland where infrared imagery surveys have been conducted during the recent years. These surveys are part of a program to study the distribution, configuration and intensity of thermal anomalies related to structure and volcanism in the median volcanic zone of Iceland. This program is 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 area covered by this report lies in the northern part of the median volcanic zone of Iceland, which is considered to be a tectonic rift system continuing the Mid-Atlantic ridge structure across the aseismic Scotland-Greenland rise. Large-scale thermal activity in this zone is related to a long history of volcanism and crustal movements. Interpretation of infrared imagery of the area near Mývatn lake has been carried out for a limited purpose of identifying and understanding different geological and geographical factors present in this region which affect the IR imagery. Once these variables are clearly understood, it is then possible to isolate the regions of anomalous thermal radiation and to determine their relationship with the geologic structure and volcanism.

2. Technique of Infrared Imagery

The term "Infrared imagery" is used to describe the final result of airborne infrared scanning, obtained on a photographic film. The ordinary aerial photographs are taken in the "visible" range of the spectrum, i.e. between 0.3 to 0.72 microns. The "near" and "middle" infrared ranges from 0.7 to 5 microns, and if the "far" infrared is included the total infrared range would be from 0.7 to 1000 microns. As used in Iceland, the system is sensitive to radiation in the 1.0 to 5.5 microns wavelength region and could be filtered to the 4.5-5.5 microns band to take advantage of the atmospheric transmission window between 4.5 and 5.0 microns, while avoiding reflected solar radiation at shorter wavelengths.

To obtain the IR imagery of an area, the airborne IR scanning equipment is flown over the terrain in a straight line. The equipment used for IR surveys in Iceland was designed and constructed by the Infrared Physics Laboratory of the University of Michigan. It consisted of an Indium antimonide detector which transduces the infrared radiation emitted from the earth's surface into wideband electrical signals. These signals, together with stabilized synchronization pulses, provide the input to an image recorder. The video signals are displayed on an intensity-modulate cathode ray tube and recorded on film which passes in front of the tube at a rate proportional to the apparent ground speed of the aircraft. The scanner was mounted in an Air Force C-130 aircraft especially equipped for arctic conditions. It should be noted that since the scanning mirror sweeps an angle on either side of the vertical, the scale of the final image varies with distance from the points directly below the flight line (the nadir line).

3. Geological Setting of the Area

The area covered by this report lies east and north of lake Mývatn in the northern Iceland. The field check was conducted by one of us (L.C.) east of Mývatn up to Námafjall and to the north up to the southern edge of Gaesafjöll. The area covered is shown in fig. 1.

The area around Mývatn has been investigated by several geologists and a good summary is provided by S. Thorarinsson (1960). Van Bemmelen and Rutten (1955) have studied some of the prominent mountains in the area. Saemundsson (pers. comm.) has done a preliminary study of the geology of the southern part of this area and has prepared a geological map (unpubl.). Gudmundsson and Arnórsson (1965) have made a magnetic survey of the area and have prepared a detailed geological map of the Námafjall geothermal region. The area north of Mývatn lake has not yet been properly studied geologically, because of its difficult acessibility.

The area lies in the presently active, neo-volcanic zone of Iceland. It is covered by pleistocene basalts, rhyolite domes, hyaloclastite breccias, pillow lavas, historic lava flows, glacial moraines and outwash, and wind-blown sediments. Lake Mývatn occupies a shallow depression with maximum depth only about 5 meters. The level of the lake is 277 meters above sea level.

Fissure eruption has been the predominant form of postglacial volcanic activity in the area with roughly N-S tectonic alignment. There are numerous N-S trending fissures, crater rows and faults present in the area. Some of these faults run parallel to each other for tens of kilometers and are clearly visible as zones of gaping fissures.

North of Mývatn, Gaesafjöll is a large table mountain with a central crater, most probably formed subglacially during the last glacial period. The top of this mountain is covered by postglacial lavas. According to Van Bemmelen and Rutten (1955), the postglacial top eruption gave rise to at least two different flows of lava in the surrounding plains. Northeast of lake Mývatn is the rhyolitic dome known as Hlidarfjall which appears to have been formed due to a subglacial rhyolitic eruption. Hlidarfjall is a steep elongated ridge rising to 771 meter height with extensive scree on the lower slopes. All along the crest, however, laminated acidic rocks crop out.

Námafjall, east of lake Mývatn, is the main geothermal area with many hot springs and solfataras. It forms the southern part of the Dalfjall-Námafjall ridge which is considered to be the result of a subglacial fissure eruption. It is entirely built up of fine hyaloclastite breccia, except near the summit where irregular layers of lava are found intercalated with the hyaloclastites.

A prominent feature east of Mývatn lake is Hverfjall. According to Thorarinsson (1960), this explosion crater was formed at the beginning of a new eruption cycle that started about 2500 years ago. It must have built up by a single phreatic explosive eruption, producing about 0.5 cu. km. of tephra. The crater walls are covered by coarse residual material left there as the finer fractions were carried away by wind. Between Hverfjall and lake Mývatn as well as north of the lake, the area is covered by several lava flows of a more recent age, only occasionally covered by some vegetation.

Besides these prominent features described above, the Reykjahlid moraines area covers a fairly large region west of Hlidarfjall and north of Mývatn. These glacio-fluvial deposits are supposed to be the end-moraine and outwash deposits left by a substage of the last glaciation. At present, these deposits make up hills north of Mývatn sloping gently down to the south. According to Van Bemmelen and Rutten (1955), these deposits are only a thin veneer over a substratum of basalts, but Thorarinsson (1960) estimates them upto 100 meters thick,overlying basalt.

4. Apparent Controlling Factors Producing Tonal Contrast

The photographic tone of an object sensed by IR equipment is primarily a function of the intensity of the object's infrared radiation emission which in turn depends upon the object's emissivity and temperature. The emissivity is the ratio of radiation emitted by a body possessing a certain temperature to the blackbody radiation at the same temperature. Hence, ideally, for the same object or material, the tone seen on the final photographic image of IR is a function primarily of the object's temperature. However, since the geological materials are not homogeneous enough to have the same emissivity for any appreciable geographical extent, various other factors besides the temperature of the material play a role in determining the grey tones produced on IR imagery. These factors must first be taken into account and their effect nullified by an analysis procedure, if the net result due to the differential thermal radiation only is to be determined.

In addition, thermal radiation itself does not seem to depend upon the temperature of the ground only. Following is an attempt to group these diverse factors in the most concise terms possible.

Factors affecting thermal radiation:

1. Dependent upon the physical properties of materials
   a. Heat capacity
   b. Thermal conductivity
2. Dependent upon the environment
   a. Topography
   b. Moisture content and the evaporation process
   c. Wind
   d. Sky cover and its effect on radiation exchange
   e. Vegetation - amount and variety

Many of the above mentioned criteria also control the emissivity characteristics. In addition, slight variations in the properties of the materials, i.e. differences in texture, age, soil cover etc. changes the emissivity characteristics. However, since the imagery used here was taken at night, all the visual radiation was cut out.

For the sake of establishing a consistent criterion for interpretation, the grey tones of the IR imagery of Mývatn have been grouped into five categories (fig. 2), numbered I to V, with no. I being the lightest tone and V being the darkest. Of course, these categories do not represent any clear cut boundaries geologically or with regard to the degree of thermal radiation. Table I illustates the most commonly seen grey tones on the IR imagery of Mývatn, characteristic of one or a combination of more than one factors. This table is based on the examination of the photographic record of IR scanner and the ground check of this area and is not necessarily applicable to any other area or any other set of imagery taken in the same area. This table should therefore be used only in conjunction with the categories established and shown on fig. 2.

Once the above mentioned standards are established, the areas with anomalous light tones are interpreted as areas with potentially high thermal radiation. These areas are marked X on fig. 2.

5. Explanation of Some Interpreted Features

Following is an explanation of some of the geological and geomorphological features with regard to their corresponding signatures on the IR imagery. These remarks are based on the field study.

5.1. Water filled depressions:

All the lakes and small ponds in the area present the grey tone I on the IR imagery. The largest of these is, of course, Mývatn, whose boundaries present a very clear contrast with the surrounding lava flows and sandur plains. Although parts of Mývatn lake are heated by hot spring waters (discussed in sec. 5.9), most of the water-filled basins in the area are at ordinary temperatures. The explanation for the water basins showing lightest tones on IR imagery (see fig. 2) is then provided by the following considerations:

TABLE I

	WET (Running or still water)		DRY
	Hot ←	Cold →	
TOPOGRAPHY		Depressions full of water (I)	Dry depressions (V) Steep slopes (II to III)
LITHOLOGY		Unconsolidated-sediments (IV to V)	Bare recent lava flow (III) Unconsolidated sediments (III to IV) Old lavas (III) Palagonite breccia (III to IV)
STURCTURE	Fissures (I to II)	Fissures (IV to V)	Fissures (IV to V)
TEXTURE	Rough textured lava with hot water circulation at depth (II to III)		Rough textured lava (III) Fine textured, less porous lava (IV-V)
VEGETATION		V	IV to V
VISIBLE THERMAL ACTIVITY	I		

Interpretation Key for the Infrared Imagery of Mývatn Area

(I to V refer to the grey tone classification on IR imagery as shown on fig. 2)

a. The emissivity of water (see table II) is very high as compared with the other geological substances. This accounts for the higher radiation in IR spectrum range.

b. Water being a transparent substance, the volume of the body taking part in radiation, per unit surface area, is larger for water than the opaque hard surfaces.

c. A body of water takes longer time to cool at night as compared with rock and soil materials. Therefore these are at higher temperatures during the night when the IR imagery was taken.

The anomalous white tones associated with heated bodies of water are discussed in a later section.

5.2. Dry depressions:

Those depressions in the area (in moraine material, lavas or the centers of explosion craters) which are not filled with water indicate very little radiation. These are generally the darkest spots (IV to V intensity). Most of these depressions have moisture in the soil although no standing water remains because of high porosity. This moisture and the shade from the sun keeps these depressions at a lower temperature than the areas at a higher elevation (see area B in fig. 2).

5.3. Vegetation:

Most of the area around Mývatn is completely barren of vegetation, except for some sparse and scattered growth of lyng (berry) plants. The area between Hverfjall and lake Mývatn, however, has enough growth of kjarr (small birch trees) which seem to affect the IR imagery. Plants with the associated moisture and shades reduce the thermal radiation from the area of their growth and make it appear darker on the IR imagery. These areas are indicated by the letter C on fig. 2.

TABLE II

MATERIAL	EMISSIVITY
Quartz, polished	0.712
Granite, polished	0.815
Feldspar, polished	0.870
Obsidian, polished	0.862
Basalt, polished	0.904
Dunite, polished	0.856
Dolomite, polished	0.929
Granite, rough	0.898
Dunite, rough	0.892
Basalt, rough	0.947
Sand, large grains	0.914
Sand, large grains, wetted	0.936
Sand, small grains	0.928
Water, pure	0.993
Water, plus thin film of petroleum	0.972
Water, plus thin film of corn oil	0.966

Emissivity values for various earth materials

(Taken from Buettner, 1965)

5.4. Scree covered slopes:

The scree covered slopes of table-mountains (e.g. Gaesafjöll), ridges (e.g. Hlidarfjall) and explosion craters (e.g. Hverfjall) invariably show lighter tones i.e. higher radiation. This may be because of their receiving more solar radiation - a possibility that seems all the more plausible because the southern slopes show lighter tones. This effect must be accentuated by the circulation of hot air through the scree slopes during the daytime which remains trapped in the pores and escapes when the air gets considerably cooler outside at night. This phenomenon has been widely observed in the porous lava flows in Iceland. Some of the slopes, like on the southwestern side of Gaesafjöll may be due to hot springs or hot water flowing down them below the scree cover, but this has not been checked in the field.

5.5. Moraine and outwash plain:

Point E in fig. 2 indicates the area of glacial moraine and outwash deposits. Here the margin of ice-sheet from the last glaciation period remained stagnant for several hundred years. When the water from this stagnant lake flowed down south, it left behind channelways which still mark the topography. On IR imagery, the long N-S depressions show tonal intensity of IV or V and the higher areas between II and III. Some of the lighter tones in this region may be due to higher thermal radiation along the fault lines which also extend N-S and which must have played a role in determining the N-S alignment of topographic features.

5.6. Lava flows:

There are a number of pre-historic and historic lava flows in the vicinity of Mývatn. Each of these different lava flows has a unique characteristic, thereby producing distinctive signatures on the IR imagery. Thus, the lava flow at the northern edge of lake Mývatn, which flowed down from a row of craters NE of Hlidarfjall in 1729, can be clearly traced (fig. 2, F). The Dimmuborgir area (fig. 2 F), SW of Hverfjall, is significant in this respect. This area (Dimmuborgir = The Black Castles, in english) represents the site of an ancient lava-lake which must once have been filled with the same lava that gave birth to the craters in and around Mývatn (Barth, 1942). This lava in Dimmuborgir subsequently flowed out towards lake Mývatn leaving behind a very rugged, scoriaceous lava floor with lava tunnels and passages coated with glazy lava. The rough texture of Dimmuborgir area is in clear contrast with more smooth lava flows to the south and towards east, although the tonal intensity is not much different.

5.7. Faults and fissures:

There are a large number of faults and open fissures running approximately in a N-S direction in the Mývatn area. Some of the larger fissures extend through miles and are several meters wide. Through many of these fissures, hot water circulates at depth and occasionally comes up to the surface formin hot springs. Some of these fissures are clearly seen as thin white streaks on the IR imagery (Fig. 2, G). These fissures look like other ordinary fissures on ground or on conventional photographs. Thus, with the help of IR scanning, the fissures with anomalous thermal circulation can be delineated.

5.8. Visible hot ground:

Námafjall is the largest region with visible thermal activity, in this area. It is a ridge composed of fine hyaloclastite breccia (commonly called "móberg" in Iceland) longitudinally dissected by numerous faults and gaping fissures. The area of this surface thermal activity is clearly seen on the IR imagery (fig. 2, H). Fig. 1 shows a more correct geographical location of these interpreted areas.

5.9. Moderately hot ground due to hot water circulation

Northwest of Hverfjall, on the eastern bank of lake Mývatn (at point K in fig. 2), there is a distinct grey tone anomaly in the lava field showing a region of intensity III in an area of intensity IV and V. As Barth (1942) pointed out, on the basis of a shallow thermal survey conducted in the area in 1937, this is one of the regions where the lake receives water through underground channels which carry somewhat heated ground water. Fig. 3, which shows the result of the thermal survey conducted by Barth in 1937, indicates the close correspondence of the region of slightly heated ground water (max. $21^{o}C$) with the zone of anomalous thermal radiation (fig. 2, K) recorded by IR scanner in 1966 - 29 years later.

6. Interpreted Areas of Anomalous Thermal Radiation:

The entire area of Mývatn has an abnormally high heat flow and heated water circulates along porous lavas, fissures and interconnected fracture zones at fairly shallow depths. This is apparent from observing the IR imagery which shows many areas of apparently abnormal thermal radiation. However, after taking into account all the factors discussed above, there remain certain regions which seem to indicate a high value of thermal radiation. These areas, discussed below, do not explicitly show any thermal activity or high temperatures on the surface, but a more thorough examination in the field may reveal the causes for this apparently higher thermal radiation. These areas are marked X in fig. 2.

6.1. Hlidarhaedhir - between Reykjahlidh and Námafjall

About 1 1/2 km east of Reykjahlidh on the old road going to Námafjall, on the north side of the road, there is an escarpment. It is situated at the end of a long fissure which extends all the way upto Hlidarfjall. This escarpment is seen on the IR imagery as an area of high thermal radiation. On the ground it is bounded by two N-S extending faults about 1/2 km apart and consists of 1729 and earlier lava flows. The heat rising along these faults and radiating from the porous lava escarpment seems to be the only plausible explanation until it is explored further.

6.2. Lava flow north of Mývatn

The lava flow of 1729 accumulated north of lake Mývatn (discussed in sect. 5.5.; fig. 2, E) shows grey tone intensity lighter than normal. This may be due to the circulation of hot water at depth in this porous lava flow which radiates heat to the surface without any explicit thermal activity.

6.3. Hlidarfjall

Hlidarfjall, situated northeast of lake Mývatn, is a rhyolitic dome thought to have been formed as the result of a subglacial rhyolitic eruption. The alignment of this ridge is roughly NW-SE (fig. 1), but on IR imagery the tonal anomaly extends in a N-S direction - very nearly paralled to the fracture system. Several faults cut across Hlidarfjall and the anomalous tonal area seems to be directed and bounded by two of the major ones. This anomaly is very similar in nature to the one reported by McLerran and Morgan (1965) for the Gibbon Hill in the Yellowstone National Park area. This hill is also a rhyolite dome, nearly a mile in diameter and rising about 800 feet above the surrounding countryside. McLerran and Morgan (1965) have explained the Gibbon Hill radiation anomaly to have been caused as a result of "heat retained by the rhyolitic mass from the time of its formation and transferred to the surface by conduction". Commenting further, they report: "More likely however, the heat is being conveyed to the surface by water from the unknown heat reservoir at depth. This latter interpretation is supported by the observation that the elongation of the thermal anomaly is in the direction of the greatest topographic slope and that several warm springs can be seen issuing from the ground near the base of the hill".

In the case of Hlidarfjall, the faults cutting across it and continuing for several kilometers in either direction provide a clear mechanism for transmission of heat energy both by radiation and through the circulation of hot water. However it seems doubtful that it is still transmitting heat to the atmosphere by conduction.

6.4. Moraines and Sandur plains west of Hlidarfjall

Some of the higher grounds and slopes in the moraine area shows tonal anomalies which cannot be explained by any known facts. The only explanation that can be given for these is that through the faults that traverse this area, the thermal radiation from the depth escapes and produces anomalous tonal patterns on the IR imagery.

6.5. Slopes of Gaesafjöll

Tonal intensity II is shown by the slopes of Gaesafjöll almost all around it. This is partly responsible for considering "slope" as one of the controlling factors in producing tonal patterns on IR imagery. However, some areas on these slopes (marked X, fig. 2) show particularly light tones. The area on the western slope in the southern portion of Gaesafjöll shows higher radiation coupled with stream-like features and an area of lower ground showing lesser radiation immediately below. Since no hot springs are seen in this area on the surface, there may be a flow of heated water just below the scree which runs to the lower ground (also marked X) thereby causing the anomalous signatures on the IR scanner. This, of course, need to be investigated further in the field.

7. Summary

The area studied has a very high heat flow. Heated water circulates underground through fissures and porous lava flows, keeping much of the region at a higher than normal atmosperic temperatures. This is only natural to expect in volcanically such an active area.

The tonal pattern on IR imagery are produced by a combination of several geologic and topographic factors. After these are taken into account, there still remain certain regions which show abnormally high IR radiation which can only be interpreted as caused by higher thermal radiation. Many of these areas are not known to exhibit any surface thermal activity. The explanations given for these anomalies need to be further checked in detail in the field.

8. Acknowledgements:

The infrared imagery used for this work was obtained in 1966 under a program jointly sponsored and organized by the U.S.Geological Survey, The Air Force Cambridge Research Laboratories, The University of Michigan and The National Energy Authority of Iceland. Mainly responsible for this effort were Dr. J.D.Friedman (USGS) and Dr. R.W.Williams (AFCRL) to whom we are thankful. We also wish to express our thanks to our colleagues in The National Energy Authority and particularly to Dr. K. Saemundsson, for their invaluable help in various phases of the work.

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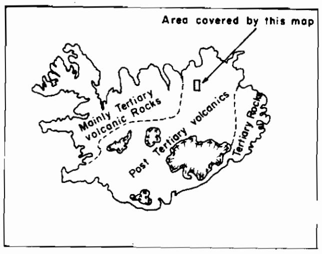
Preliminary Geologic Map of Mývatn Area

Nóv.67LNC/GP/G	Tnr. 23 J-Mývatn	Fnr. 8204

Fig. I



LEGEND

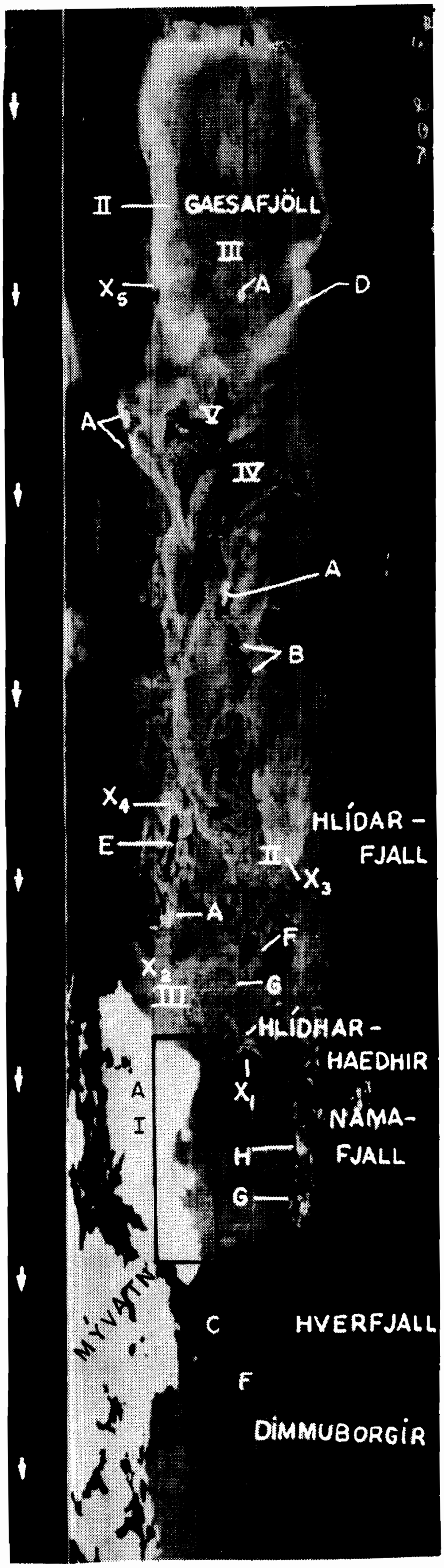
▨	Most recent Lava flow	1728 A.D.
⁚	Hverfjall tuff	2500 B.P.?
d c b a	Lava flows of one series	Postglacial
4 3 2 1	Lava flows of another series	Postglacial
+ +	Lava flow of unknown relative age	Postglacial
° °	Glacio fluvial sediments	Last glaciation
▩	Fine hyaloclastite breccia (Palagonite formation). Showing much hydrothermal alteration	Subglacial
▧	Rhyolite	Subglacial
	Centers of volcanic eruption	
	Faults	
	Dry depression	
	Depression filled with water	
	Námafjall thermal area Specific hot areas interpreted from IR imagery	

Note: Relative age and location of lava flows east of Mývatn adopted from K. Sæmundsson's unpublished geologic map of this area.
This map is meant mainly for use with IR imagery and should not be regarded as an authoritative geologic map.

0 1 2 3 Km

0 1 2 Miles

Fig. 2	INFRARED IMAGERY OF MÝVATN AREA SHOWING INTERPRETATIONS.	NOV. 67 LNC/GP/P TNR. 24 J — Mývatn FNR. 8205



EXPLANATION.

I, II, III, IV, V	Tonal Intensities. I lightest, V darkest. (see sec. 3 and table I).
A	Water filled depressions.
B	Dry depressions.
C	Vegetation cover.
D	Scree covered slopes.
E	Glacial moraine.
F	Lava flows.
G	Faults and fissures showing higher thermal radiation.
H	Visible hot ground.
K	Moderately hot ground.
X	Areas of anomalous thermal radiation. X_1 – Hlídarhaedhir X_2 – Lava flow north of Mývatn. X_3 – Hlídarfjall. X_4 – Moraines west of Hlídarfjall. X_5 – Slopes of Gaesafjöll.
Gaesafjöll	Table Mountain.
Hlidarfjall	Rhyolitic dome.
Námafjall	Hyaloclastite ridge.
Hverfjall	Crater formed due to phreatic eruption.
Dímmuborgir	Rough textured lava.
Mývatn	Lake.
▯	Area covered by Fig. 3.
Note:	Scale of this imagery shrunk in E-W direction. For proper scale, see fig. 1.
Scale:	↔ 1 cm = 1.62 km. ↕ 1 cm = 1.12 km.

Fig. 3.

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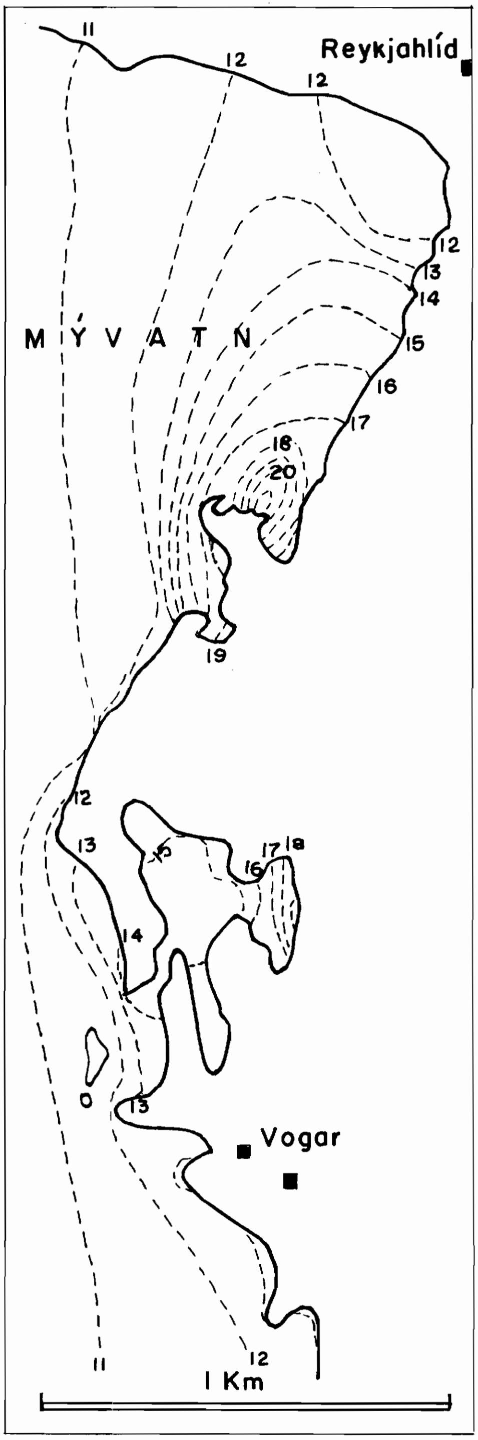
Jarðhitadeild.

NORTHEASTERN PART OF MÝVATN SHOWING THE TEMPERATURE DISTRIBUTION (°C) AT A DEPTH OF 0.5 METERS.

NOV. 67/LNC/GP/P
TNR. 25
J – Mývatn.
FNR. 8206



Air temperature at the time was 10 °C. Measured on August 12, 1937. (T.F.W. Barth, 1942 b.).

Fig. 4

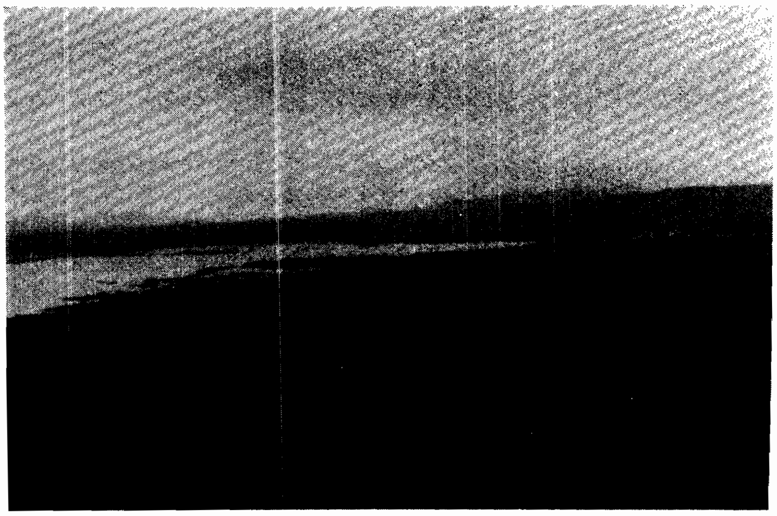
Jarðhitadeild.

PHOTOGRAPHS OF MÝVATN AREA.

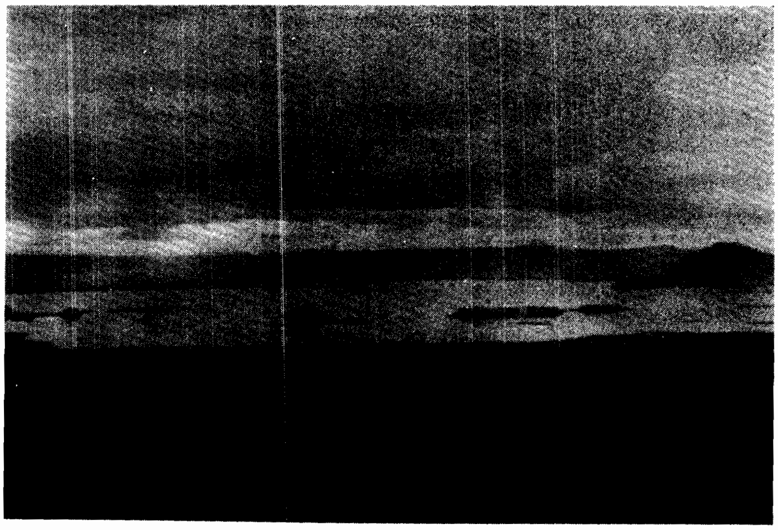
TNR. 26

J – Mývatn.

FNR. 8219.



a. From Hverfjall looking northwest towards Reykjahlídh. Lake Mývatn is to the left, rim of Hverfjall in the foreground. Pre-historic lava-flows in the center, partly covered with vegetation.



b. From Hverfjall looking towards lake Mývatn. Pre-historic lava flows in the foreground.

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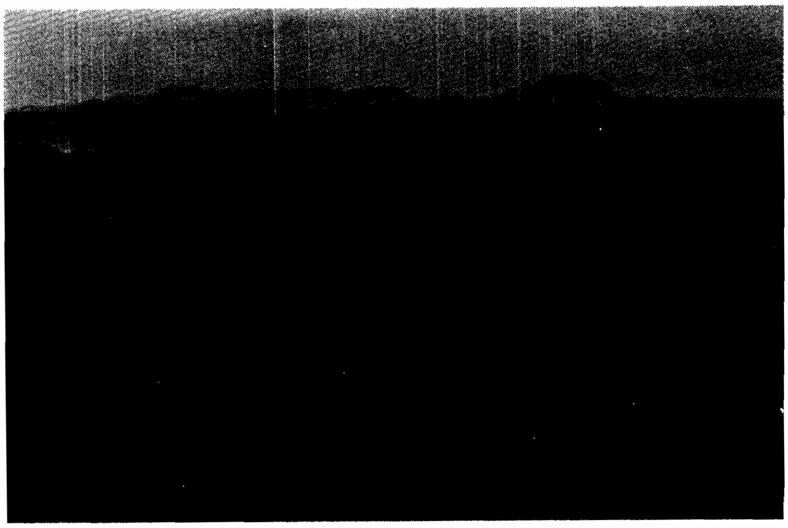
Jarðhitadeild.

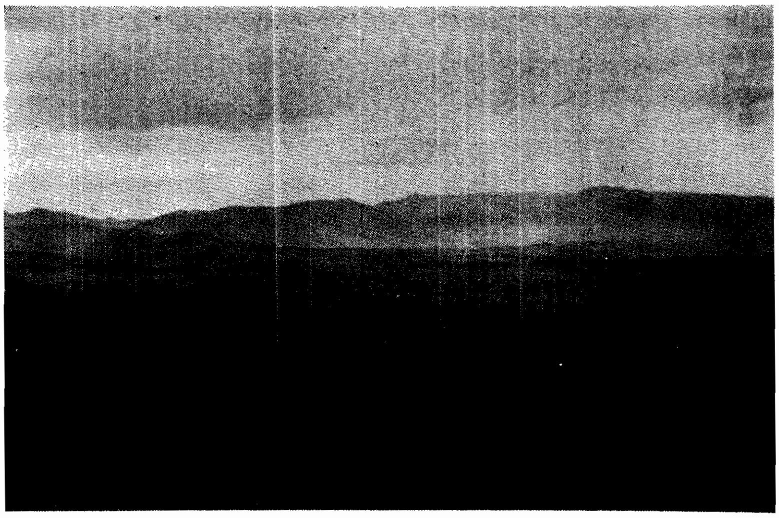
Fig 4 (cont.)

PHOTOGRAPHS OF MÝVATN AREA.

NOV. 67. LNC/GP/P
TNR. 26
J – Mývatn.
FNR. 8219.



c. Interior of the crater Hverfjall.
Námafjall thermal area can be seen towards left at distance.



d. Looking southwest from Hverfjall. Lava flow at right foreground. A crater – row can be seen at distance.