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Mapping Geothermal Features and Usage of Thermal Camera in Monitoring Geothermal Fields. Case from Námafjall and Theistareykir High Temperature Fields in NA Iceland

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ABSTRACT

With advances in thermal imaging and thermal cameras becoming more like conventional cameras, imaging of geothermal features in the field is becoming an important alternative to conventional methods. In previous studies, infrared images used in geothermal fields have mainly been with air images and Landsat images. Handheld thermal cameras have been used in volcanology but not so much in geothermal mapping. In Iceland, previous studies have mainly been with air images (infrared) that have covered large areas. In our previous work we have used handheld infrared camera to map and monitor geothermal fields in addition to conversional methods. This paper outlines a study where ground based thermal images are compared with results from conventional geothermal and soil temperature mapping. With data obtained in Theistareykir and Námafjall NA-Iceland, thermal images taken from the ground are compared with geothermal mapping in-situ thermocouple measurements. Results show the same pattern although temperature from the thermal camera is lower than the in-situ temperature. The difference between the measurements is significant; the temperature measurements are done at 15 cm depth but the thermal camera from several hundred meters. So the temperature difference between the methods ranges from 30-75°C depending on circumstances.

1. INTRODUCTION

The Northern Volcanic Zone of Iceland extends from the centre of Iceland to the Öxarfjördur Bay in the north. It consists of five NNE striking left-stepping en echelon volcanic systems. The 70-80 km long Theistareykir fissure swarm is the westernmost, then Krafla (with Námafjall within) fissure swarm extending some 100 km. Theistareykir is characterized by large normal faults with maximum displacement of 200-300 meters and rift fissures. To the north, the fault and fissure systems meet the NW strike slip Húsavík-Flatey Fault System. The most recent volcanic activity in the area (Theistareykir lava) occurred some 2500 years ago. The geology of the Námafjall area is characterized by an active rifting zone, forming a graben zone through its center, where volcanic craters, volcanic pyroclastics and lava flows. The main fissure swarm is framed by Krummaskard at the western foothills of Námafjall to the east and the Grjótagjá fissure to the west. The most recent volcanic activity occurred during the Krafla Fires in 1975-1984. The high temperature geothermal activity in both areas is connected to recent magma intrusions. The rift zone hosts the plate boundary where the American- and Euro-Asian plates drift apart (Seamundsson, 1971 1978 and 1979).

Remote sensing is the science of obtaining information about sites without actually being there. Active and passive radiations are captured to make up images of the study area. In this paper we focus on data acquired by passive remote sensing using thermal infrared wavelengths. By such methods we can obtain thermal information over large areas, and sometimes see what otherwise may remain hidden or at least inconspicuous. In Figure 1, a visual light image and a thermal image from the same area are shown. The thermal image shows where the highest temperature is located and the flow directions of the geothermal fluid. This demonstrates how the thermal image can be used in an effective way.

This paper demonstrates how thermal images, together with conventional methods, can be used to map geothermal features together with conventional methods. The examples are from two areas in north Iceland, Theistareykir and Námafjall. In both areas we have several types of manifestations and hot grounds. Also, we have reviewed remote sensing literature in the thermal infrared section for earth science and especially geothermal research.

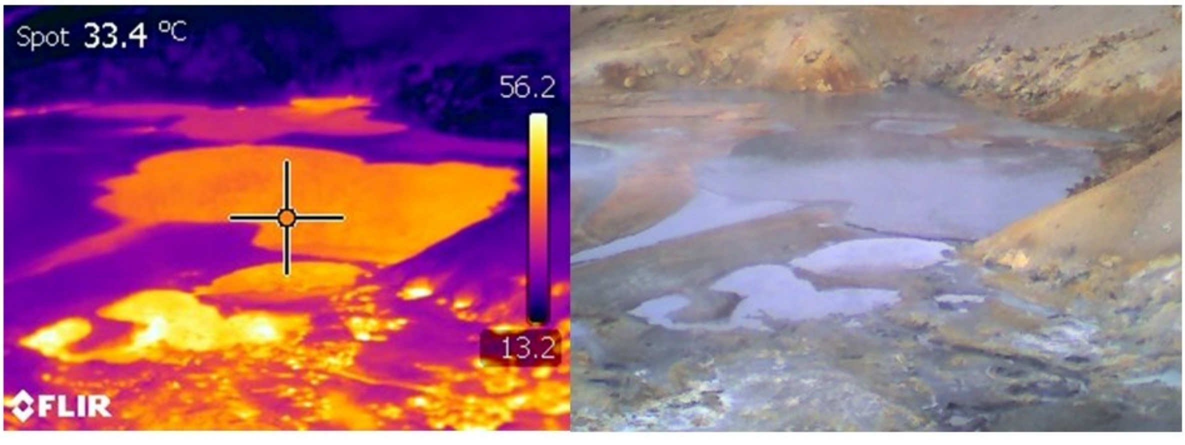

Figure 1: A visual image and a thermal image from the same area. The thermal image shows where the highest temperature is within the mud pods.

1.1 Geothermal systems

Geothermal systems are areas of anomalously abnormal crustal heat flow. These systems are located in specific sites around the world and are classified in various ways based on heat source, heat transfer, reservoir temperature and geological settings among other parameters. Geothermal systems are commonly classified in major groups, such as volcanic systems, convective systems, and conductive sedimentary systems. These geothermal systems are suitable for various applications, depending on the reservoir temperatures and fluid chemistries. The high-temperature volcanic systems are utilized primarily for electric power generation, and the low~~er~~ to medium- temperature systems for space heating and other direct uses. In Iceland, geothermal systems are divided into high- and low-temperature hydrothermal fields or areas. This division is based on infrared temperature at 1 km depth; high temperature fields are greater than 200°C, while low temperature fields are less than or equal to 150°C in the uppermost km (Böðvarsson 1964). The high temperature fields are all related to volcanism, whereas the low temperature fields draw heat from the normal heat flow of the crust. Other temperature subdivisions have been proposed, by adding intermediate or medium temperature systems in between the two main categories. The study areas in this paper are both high temperature fields and found within a volcanic zone with historically active volcanism.

Within high temperature fields, there are several types of surface geothermal features that can be observed. Depending upon the temperature and outflow rate of geothermal fluids, discrete surface features can include hot springs, fumaroles, geysers, mud-pots, and steam-heated pools. More widespread areas of heated or steaming ground occur due to conductive heat loss above the outflow zones.

1.2 Lithology mapping and volcano monitoring

Thermal Infrared remote sensing data is not only acquired from aircraft. Some instruments that are thermal infrared sensitive have been put into satellites. For example, Band 6 in the Landsat series of satellites collects data on TIR wavelengths. Also the Advanced Space born Thermal Emission and Reflection Radiometer (ASTER) include a thermal infrared sensor.

Rowan and Mars (2003) describe the efforts to use TIR remote sensing to map the lithology or bedrock composition from ASTER data. Because of the different emission characteristics of different rock types, they can map the lithological and formation differences where there is no vegetation, such as in the Nevada desert in USA. They show that using the TIR bands in combination with other bands it is possible to map rock types on a regional scale. Their study shows that Thermal Infrared data can distinguish between igneous rocks and hydrothermally altered rocks using different combinations of wavelength bands of the same area.

Satellite remote sensing of geothermal areas has not been useful for detailed mapping. This is due to resolution limitations, with pixel size being 90 by 90 m. Whilst this can be enough for regional studies, this resolution is inadequate in detailed geothermal applications.

Thermal Infrared instruments have been flown over erupting volcanoes to monitor the flow of lavas. These studies have been carried out in Hawaii and on Mt. Etna in Italy. In addition, Higgins and Harris (1997) describe a computer algorithm to detect thermal anomalies from AVHRR (Advanced Very High Resolution Radiometer) images, in an attempt to create a remote system to monitor volcanoes in near real-time. A 3 by 3 kernel is run over the image, and pixels with a higher value over known volcanic areas are interpreted as evidence of activity.

1.3 Remote sensing of geothermal areas

The literature details geothermal exploration and research as far back as the 1960's with the use of remote sensing. These studies describe new developments and technology, which produced useful results. These early studies show that geothermal activity can be seen on TIR data, but no detailed processing was carried out on the data. They experienced various problems, such as spatial resolution and methods of analysis.

The first geothermal area studied with TIR technology was the Wairakei geothermal area on North Island, New Zealand. Dawson and Dickinson (1970) study heat flow from the thermal area. TIR data was used to map the extent of thermal features, and field measurements were used to obtain temperature data. They note differences in heat discharge from the same place (hot ground) depending on the water content of the soil. The wetter the soil, the more heat is discharged. Vegetation in soil affected by geothermal heat was represented differently in TIR data and was used to map the extent of hotter ground.

Thermal infrared images were also tested for geothermal exploration in other countries. Pálmarsson et al. (1970) and Friedman et al. (1972) report on thermal infrared flights over Icelandic geothermal areas flown in 1966 and 1968. Pálmarsson et al. (1970) discuss TIR images taken over the Reykjanes and Torfajökull geothermal areas. These images collected data on the 4.0 – 5.5 µm wavelength bands. The images were all collected on film, and they were quantified with field temperature measurements. That was completed for the Reykjanes geothermal area at the same time these TIR studies were being conducted. The area was being explored and developed for the building of a sea salt factory, which used geothermal energy to boil sea water and deposit salt. The study uses the same technique as described by Dawson and Dickinson (1970) to quantify heat flow from the area (Pálmarsson et al., 1970). They also state that these anomalies are much better distinguished in the TIR imagery than on other aerial photography. For the Torfajökull area, this study does not have complete direct heat measurements in comparison to the Reykjanes geothermal area.

Reykjanes and Torfajökull were not the only geothermal areas in Iceland that were photographed using TIR imagery instrument. Among the other fields photographed was the Kverkfjöll area in the Northern Vatnajökull glacier. This area is located at the margin of the glacier and interacts with it. Freidman et al. (1972) report on that study. The images, taken on a film sensitive to IR wavelengths, were manipulated as regular stereo images and used to map thermal features and the movement of the glacier margin. The images were also used to estimate thermal discharges from the area.

In the sixties and seventies, the first remote sensing satellites were launched in orbit. In a report by Williams et al. (1974) there is an attempt to look at the extent of a geothermal area by looking at the snowmelt pattern using ERTS-1 MSS system. The report indicates that it is possible to map the extent of geothermal areas using data collected during the winter.

Mongillo (1988) used a thermal infrared imagery video recording device mounted on a helicopter in his study in New Zealand. The system was set up incorrectly, so the images had more noise than expected and the system could not record vertical images due to leaking of fluid from the system. As a result, most of the images are oblique (taken at an angle). All the interpretation in this study was done visually, and therefore it is hard to quantify the result. After extensive preparation of the data, they conclude and show that different geothermal features can be identified from this imagery.

LandSat images have also been applied to geothermal areas (Alcantara ,1988; Mongillo et al.,1995; Ramasamy et al.,1994; Ruiz-Armenta and Ledesma, 1995). They mostly use stressed vegetation and linear alignment of features, as well as mineral reflectance from altered and fresh bedrocks to determine the extent of geothermal areas. These studies use images that have spatial resolution of around 30 – 100 m pixel size. That resolution can give an idea of the extent of area, but in order to use them to monitor changes in geothermal areas the resolution must be increased.

In the early 1990's, the Department of Physics and Engineering in University of Iceland experimented with an airborne TIR sensor. Árnasson et al. (1994) reported on the development of the instrument and its application over populated areas, open ocean and geothermal areas. Experimental flights were flown over several geothermal areas including the Hengill area. Since this project was more about designing a sensing system than the application of technology to a specific task, the images from this time consist of only one flight line over each area of geothermal manifestations. However, for three years in a row, thermal infrared missions were flown over geothermal fields as reported by Árnasson (1994, 1995). These images do not cover the whole area, as they are single flight lines. The study shows the images and compares them in printed format on paper, as they were not presented in a GIS format. These studies show again that the TIR imagery can be used to map and monitor geothermal manifestations.

The most recent research that applies remote sensing techniques to geothermal exploration is reported from Nevada USA (Calvin et al. 2002, 2006). Their research applies satellite imagery with a pixel resolution of 90 m in the deserts of Southwestern USA, where vegetation is not an issue. Remote Sensing imagery, both from airborne and satellite sources, has been used to look at mineral alterations at the Steamboat Springs and Bradys Hot Springs in Nevada. These studies use both night and daytime imageries. This research is mostly concerned with mineral composition.

It has been shown that infrared imaging gives strong results as a normal thermocouple, when the distance from the object is within one meter (Lynne and Yague 2012). As the distance increases from the object, so does the radiation between the object and the camera. Therefore, the closer you are the more accurate the temperature measurement. There are several things that can affect the quality of image: poor focus, cloud cover, steam from fumaroles, view angle and the distance (Stevenson and Varley, 2008; Oppenheimer et al., 2006). From our previous work we can see the same temperature patterns, although temperature from the thermal camera is lower than in-situ temperature (temperature difference between thermal camera and in-situ measurements depends on several parameters, such as distance from the object 70-100 m where the image is taken, in case of Hveragerði the maximum difference it was round 65°C) (Einarsson and Kristinsson 2010).

2. GEOTHERMAL MAPPING AND THERMAL IMAGING FROM THE GROUND

In the above sections, the focus has been on previous studies where thermal images obtained from airborne and spaceborne platforms have been discussed and briefly reviewed geothermal systems and their divisions in Iceland. In the following section, we outline studies carried out in the high temperature fields in NE-Iceland using traditional methods with thermocouples in measuring temperature of geothermal features. Also, we present how handheld FLIR T360 thermal cameras can been used to see the distribution of thermal activity in the same area.

The traditional method to estimate temperature distribution in soils is to use thermocouples to measure temperature at 10 cm. These soil temperature measurements are important when identifying aquifers in places where geologic structures many be intersected (Flóvens, 1985). They can also be used to map linear structures were soil and vegetation covers the area. With data obtained in Theistareykir and Námafjall we try to compare temperature measurements with thermal imaging to see the outline and the structure of the geothermal features and their distribution.

2.1 Monitoring thermal manifestations in high temperature fields at Theistareykir and Námafjall.

In 2012 and 2013, monitoring of the geothermal fields in NA-Iceland have been reported (Kristinsson et al. 2013a and Kristinsson et al., 2013b). This has been divided in several categories, describing thermal manifestations of the respective high-temperature fields, the chemical composition of steam from the fumarole and in the case of Theistareykir, the results of the gas flux measurements as well. Here we will focus on the geothermal mapping of manifestations and thermal imaging.

The base in this work is in geothermal maps of Theistareykir and Námafjall from Saemundsson (2007, 2010). In our work we measured and described all visible geothermal features and their distribution compared with the maps and previous descriptions from the areas. In Figures 2 and 5, our data are shown on the maps from Saemundsson (2007, 2010). We divided the geothermal features in similar ways as Saemundsson did in his maps. The extent and activity of thermal manifestations observed in the summer of 2012 at Theistareykir was in general similar to what was described by Sæmundsson (2007). The main discrepancies are that the fumaroles at the northern edge of Bæjarfjall Mountain are no longer active and that the activity in a patch of thermal manifestations approximately 2 km north of Hitur had diminished. The thermal activities at the southern end of Randir and at the fault south of Hitur may have increased slightly. There are also some indications of increased thermal activity around the well pad of wells ThG-3, ThG-6 and ThG-7. In Námafjall little or no changes were observed in the activity of thermal manifestations compared to the map of Kristján Sæmundsson (2010) and older descriptions. In Figures 3 and 4, we see examples from thermal imaging from Theistareykir and in Figures 6 and 7, examples from Námafjall. The distance from the camera and the thermal activity is approximately 400 m, so the accuracy in temperature is rather low. In this thermal imaging we have a fixed scale from 0-30°C. The thermal imaging was taken in August, late in the evening after sunset, outside temperature was between 5-8°C. From the direct measurements (temperature taken at 15 cm depth) we can see temperature in the thermal image representing heat around 30°C, fumaroles with temperatures higher than 90°C with the lowest being soil temperature around 10°C. From our mapping in both areas we can note that the thermal imaging reveals the distribution of the thermal activity and linear structures very well, but the distance from where the image was taken is too long to get accurate temperature values. Another method to see how geothermal activity distributes through soil is to map snow melt when the first snowing begins. In the beginning of November, snow melt was tracked in the Námafjall area and the results are shown on Figure 8. The results were similar to what was mapped during the summer, although the melted area was slightly bigger.

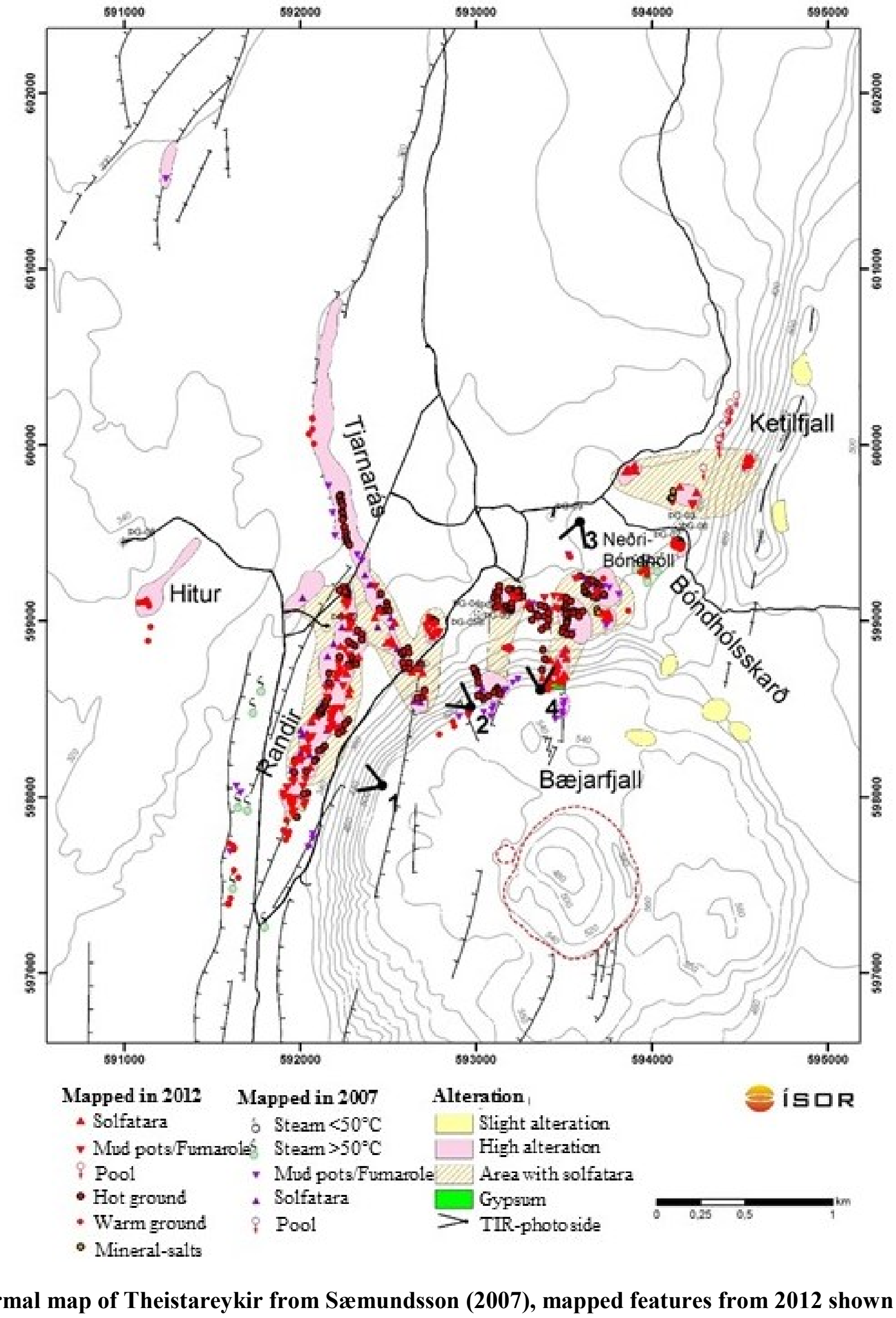

Figure 2: Geothermal map of Theistareykir from Sæmundsson (2007), mapped features from 2012 shown separately.

3. CONCLUSIONS

Temperature infrared from ground-based thermal images shows the same thermal trends as conventional methods using thermocouples. That can be explained with the underlying difference between the two datasets. Soil temperature measurements are taken at 15 cm depth and in-situ, whereas the thermal image is taken some distance from the site; it captures the radiant temperature and then atmospheric variables become a factor in the temperature measured. As the distance increases from the object, so does the radiation between the object and the camera. The temperature difference between the methods ranges from 30-75°C depending on circumstances. Remote sensing cannot replace geological mapping of geothermal manifestations, but it can beneficially complement and change the approach of new geothermal prospects exploration. As demonstrated in the paper, TIR images can be used to detect geothermal features, which emit radiation anomalies from the earth's surface. Results show that Thermal Infrared data can map locations of geothermal manifestations and can be most useful in arbitrarily delineating the extent of geothermal prospects, especially where manifestations are virtually absent. By using these methods together, it can improve geothermal mapping especially for monitoring geothermal fields.

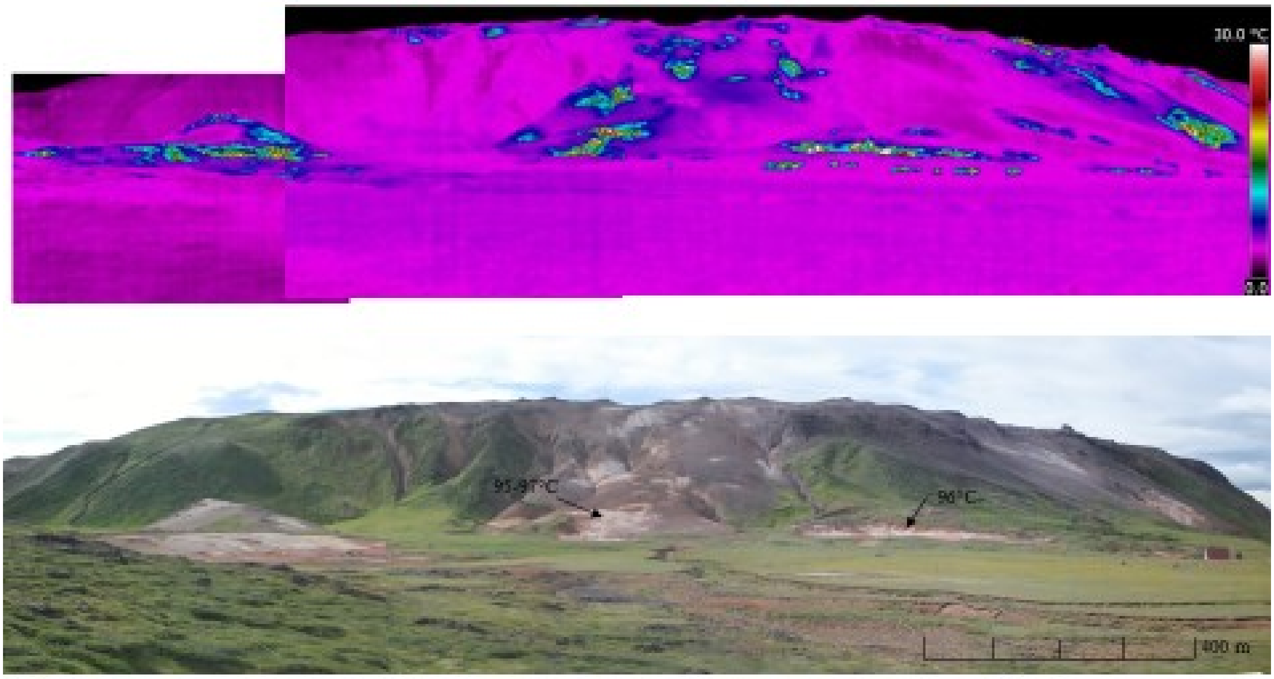

Figure 3: Thermal image and the visual one of Bæjarfjall in Thestareykir, the images are taken from the same location shown one figure 2 (TIR photo side 3). Manifestations are mainly mud pots and fumaroles with some solfatara.

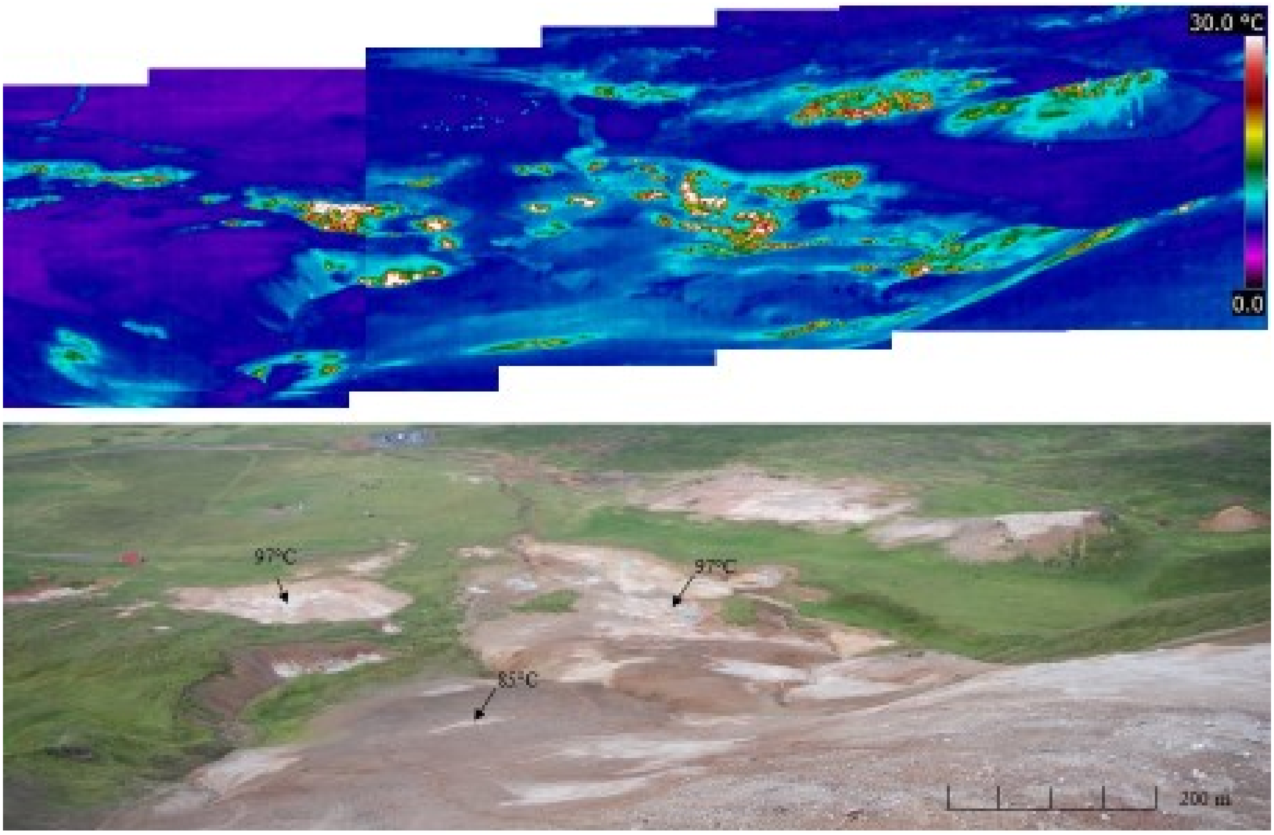

Figure 4: Thermal and visual images are taken from the top of Bæjarfjall in Thestareykir shown on figure 2 (TIR photo side 4) and shows the geothermal activity on the foot of the mountain. Manifestations are mainly mud pots and fumaroles in the center and some solfatara on the right side.

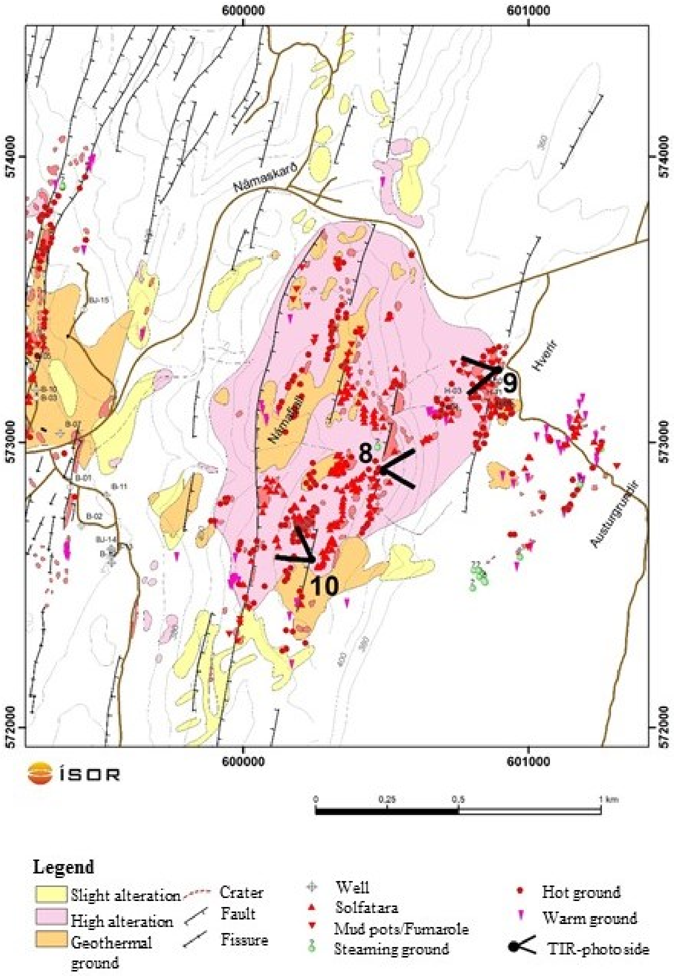

Figure 5: Geothermal map of eastern part of Námafjall, map is modified from Sæmundsson (2010).

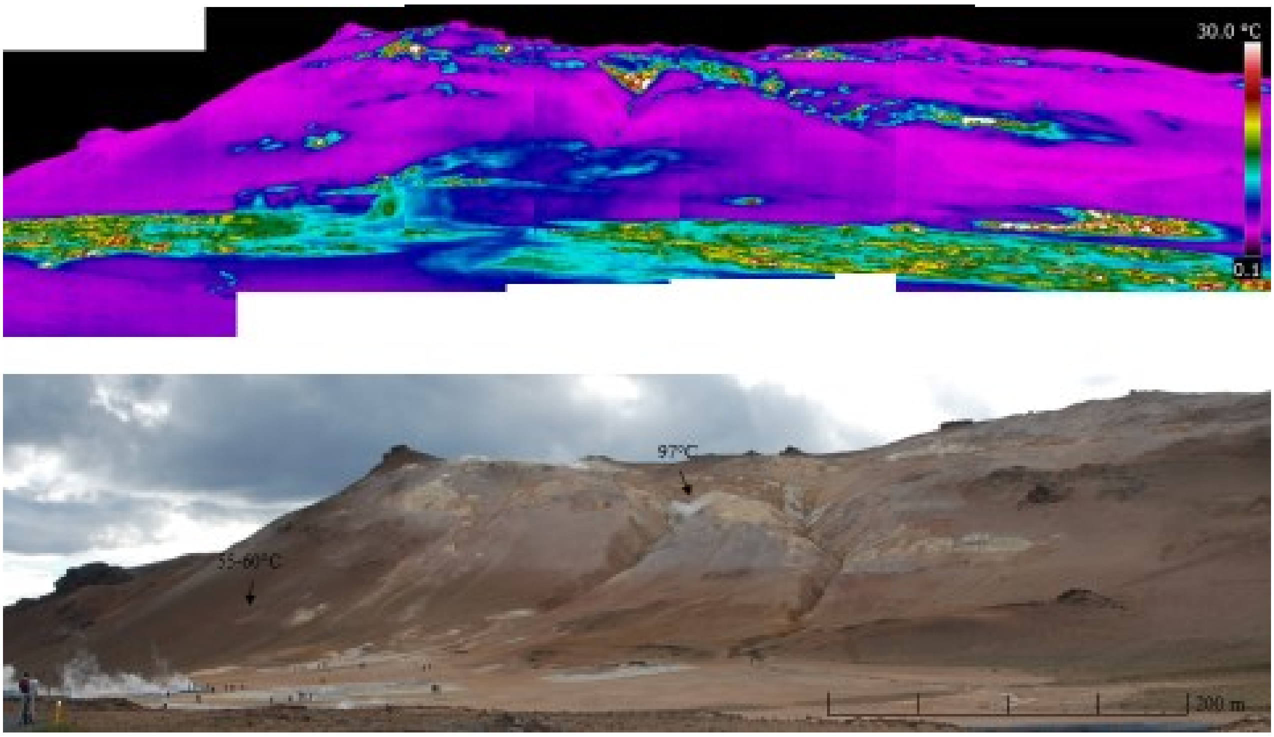

Figure 6: Eastern part of Námafjall, the visual image is taken slightly more to the north but they are showing the same area. Geothermal activity and alteration is high in this location. Location shown on figure 5 (TIR photo side 9. Manifestations on the hillside are solfatara but mud pots in the low land.

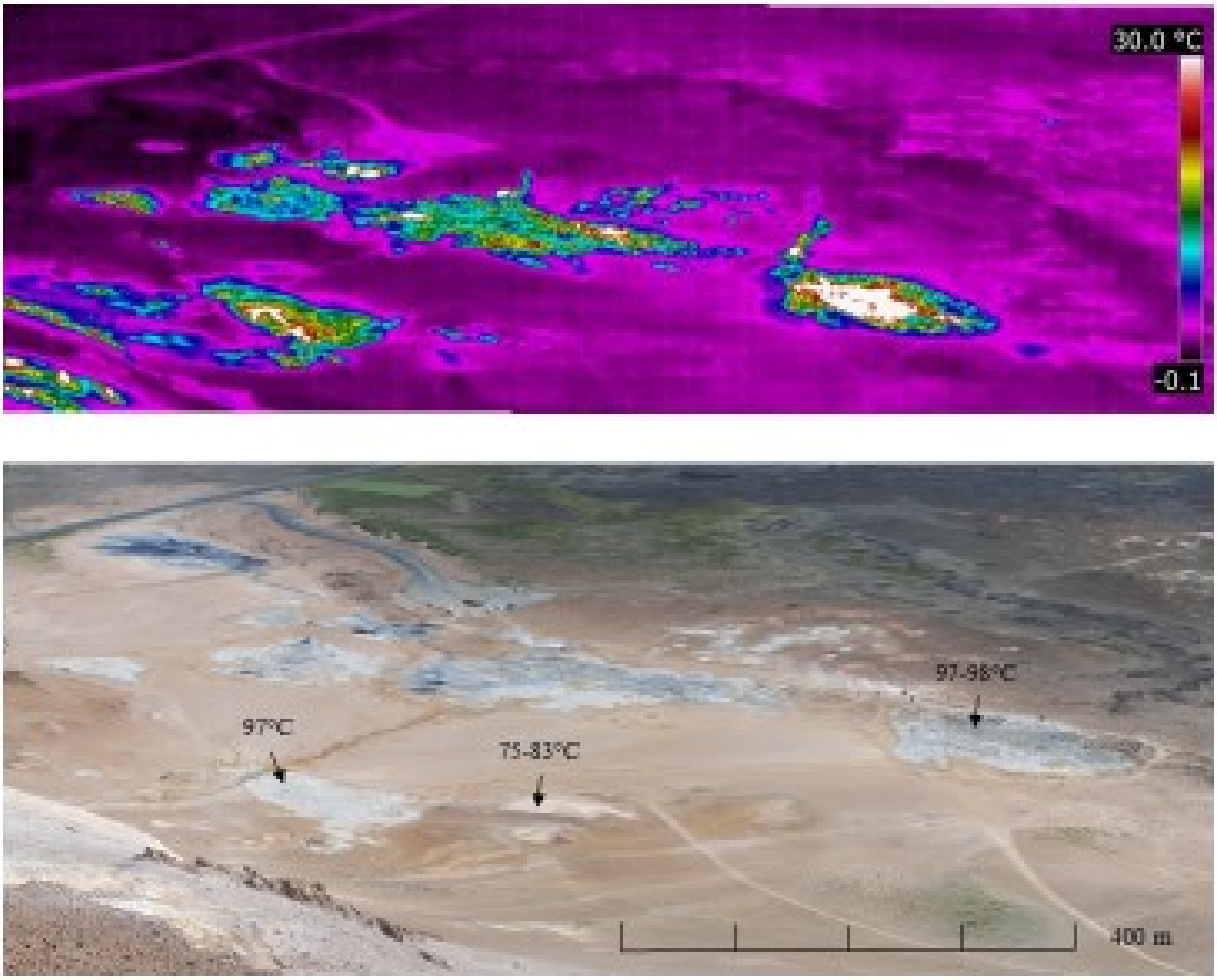

Figure 7: The same side from above shown on figure 5 (TIR photo side 8), thermal image shows ~~well~~ the most active areas. Manifestations mainly mud pots and fumaroles.

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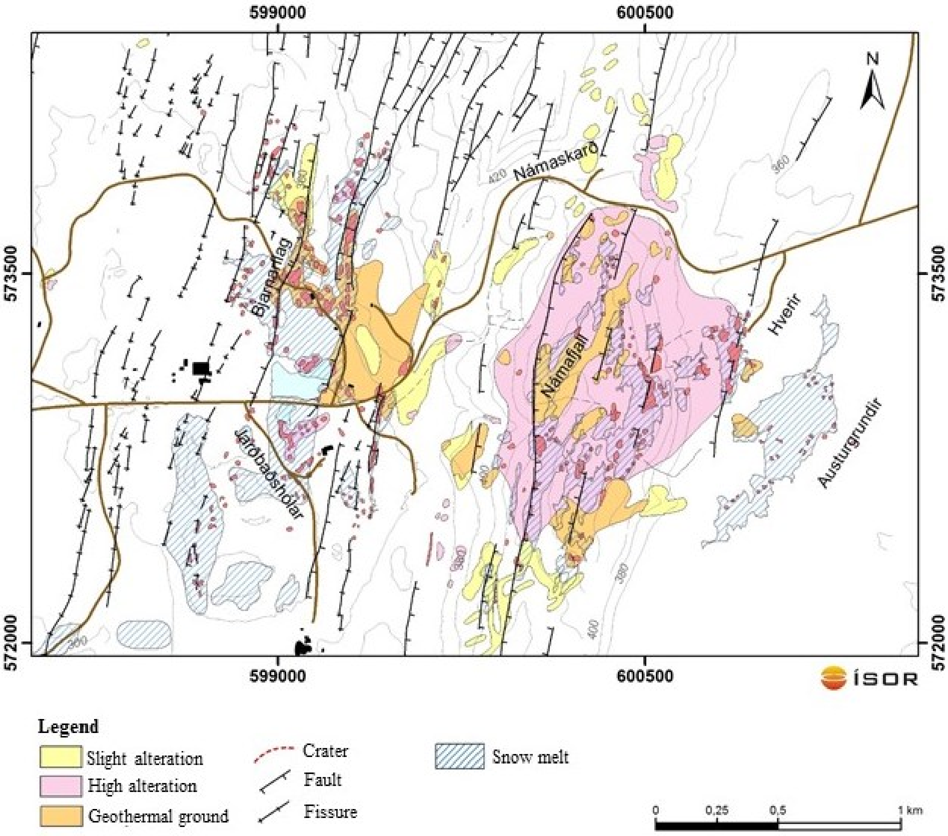

Figure 8: The geothermal map of Námfjall shows-where the geothermal activity has melted the snow. This was done in the beginning of November 2013. The snow melt is presented as polygons with blue strikes. The melted area is quite similar as the mapped area where geothermal activity was present during the summer time. The geothermal active areas line up as the major faults.

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