GPS-mapping of geothermal areas in West Iceland and tectonic interpretation

Phase 2: Klettur-Runnar

– An overview –

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1. INTRODUCTION

In 2005, we selected Klettur-Runnar in Reykholtsdalur as subject for our second phase of geothermal mapping of West Iceland (Fig. 1). Though these manifestations belong to the geothermal system of Reykholtsdalur, they are not in continuation of those mapped in Kleppjárnsreykir, Deildartunga, and Hurðarbak South during the 2004 field campaign (Khodayar et al., 2004a).

The present mapping is a part of the "*Bergsprungur í skjálfabeltum og gosbeltum*" project, which aims at better understanding of the tectonics of unstable plate boundaries. The main purpose of our geothermal study is firstly to relate the surface manifestations to local structural features such as faults and fractures, and secondly to document the present state of the geothermal activity to provide a base of knowledge against which later changes can be determined. As a wider coverage is obtained during our geothermal mapping, we hope to correlate the results with our data on regional fracture distribution, geological mapping, and earthquake activity in South and West Iceland. The outcome of this research will shed light on the geometric relationship of the geothermal activity to past and present plate boundaries, intra-plate volcanic systems and earthquakes, as well as major structural discontinuities in context of rift-jumps and unstable transform zones.

Earlier extensive works in this region include the location, geochemistry and discharge of the hot springs studied over all Iceland (National Research Council, 1944). A similar study was carried out later on by Ólafsson (1967). The first detailed field mapping of the manifestations and geophysical measurements in Reykholtsdalur were done by Georgsson et al. (1978). Torfasson (2003) described the general location of the springs in Iceland and made synthesis of data available to date.

We used the same methodology for our mapping as in 2004 in West Iceland, and in 2005 in South Iceland. First, we identified the location of geothermal manifestations mainly on the ground of descriptions from literature, as well as our own field observations. Then we mapped the structures with the help of a GPS hand-held device, which has a resolution of 1-2 m on the ground. The temperatures of the manifestations were measured with a thermometer. The discharge and water chemistry were not studied during the 2005 field campaign. Below is an overview of the geothermal features mapped in the three sub-areas of Klettur-Runnar (Fig. 1).

2. GENERAL DESCRIPTION OF GEOTHERMAL MANIFESTATIONS

The selected areas were mapped mainly in October and November 2005 when the ground was frozen and covered by snow, and the air temperatures was -0.5°C to -11.7°C. These were ideal conditions for finding the hot spring, but also for identification of the cold springs.

A total of 207 geothermal features were mapped in Klettur-Runnar (Fig. 2). They consist of 31 cold springs (1°C-9.9°C), 123 warm and hot springs (10°C-49.9°C), 47 hot springs (50°C-83.1°C), and one borehole (64.3°C). Another 5 structures were mapped that did not present surface temperatures but were free of snow and ice in a frozen surrounding, indicating a possible geothermal source near the surface (Figs. 2 and 3). The mapped features are natural springs, eyes by the edge of man-made channels or in the pools, and a few fractures. Water fills most of the manifestations, and green vegetation, occasional steam, swamp and algae are associated with most of them. Manifestations are all in the 10.000 yr. old silt and clay sediments filling the Reykholtsdalur valley.

We divided the 207 mapped features into three areas: Area 1 to the west, Area 2 to the east, and Area 3 to the south (Fig. 1). In this report, we concentrate on a general description of the three sub-areas, on a preliminary interpretation of their surface temperatures, on their overall tectonic organisation, and on a comparison with the mapping of Georgsson et al. (1978) as a point of reference. The detailed investigation of Area 1 will be presented in a BS report by S. H. Markússon at the University of Iceland, Faculty of Natural Sciences.

The temperatures presented below are the maximum measured. The names of the springs are those used by Georgsson et al. (1978) during their mapping of Klettur-Runnar.

- Area 1 has 99 hot and cold springs including 4 small zones free of ice and snow (Figs. 1 and 2). For comparison, Georgsson et al., (1978) mapped 10 features with single springs, one feature with three springs and another with six springs in this area. The 99 mapped features are not on a continuous line but concentrated in three separate sub-areas to the north, middle and south of Area 1 (Fig. 2). North of Area 1, a group of warm and hot springs lie in an irregular pool filled with water, swamp and occasional algae. The hotter features (47.2°C-54.1°C) are in the southern part of this pool, adjacent to the hottest manifestations (61.2°C - 64.5°C) that include the "Laug" spring used for heating Klettur summer houses. Manifestations become gradually cooler north and southwards. In the pool, the temperature drops first to 39°C-10°, mostly along a NNE line, then to 7.2°C-8.6° in a diffused zone by the northern edge of the pool. Between the south of these manifestations and Reykjadalsá river, the last two manifestations are 41.2°C and 47.1°C, and are aligned N-S.

  Most of the mapped features of Area 1 are in its middle part (Fig. 2), where measured temperatures range from 10.3°C to 66.3°C. The hottest measurements were found in the "Stapalaug" spring (66.3°C), as well as along a WNW fracture (62.5°C) in the NE striking channel at the intersection with the longer NW man-made channel (Fig. 2). To the north of Stapalaug spring, many small eyes in a swampy pool are aligned NNE. The Stapalaug itself has 3 m length, 2 m width, and 2 m depth, with swamp, little steam and occasional bubbles. It has an overall N-S direction. Elsewhere, temperatures are generally lower in the eyes within the man-made channels, except one feature in the longest NE man-made channel, which is 40.5°C. The eyes in the channels form either a NW line, or a NE line, similar to the strikes of the channels themselves. Sometimes swamp and algae are associated with the eyes in the channels and occasionally they have little discharge. The few hotter manifestations to the west of the NW striking channel are also aligned NE. Two of the zones free of ice and snow present geothermal alteration and possible silica at the surface but no surface heat. One of these zones is located west of the NW channel (and the WNW fracture). It is circular, has considerable oxidation, and is 17.5°C at 10 cm depth. The other one is an isolated feature located south of the above springs and strikes N-S (Fig. 2).

  In the southern part of Area 1 (Fig. 2), older geothermal alteration, with oxidation and possible silica crop out in two small zones free of snow and ice forming a N-S line. Further south, hot water was found in two E-W striking man-made channels surrounded by ice and snow. Water in the northernmost channel is hotter (23°-29°C) and comes out of four places through the channel wall. Occasionally, gentle steam and slight discharge are associated with these points. The southern channel is the coldest, with five manifestations of 3.5°C, forming an E-W line in the channel. A pool with several eyes, swamp, algae and bubbles, exists between these two channels and strikes NNE (Fig. 2). Temperatures are higher in this pool, up to 45.5°C, but the eyes within the pool are aligned WNW-NW dominantly. No other manifestation was observed between the southernmost E-W channel and the Aviation Hangar (Flugskýli).

- In Area 2, we measured 82 features including one borehole (Fig. 2). Georgsson et al. (1978) mapped 20 features in this area, of which most are with single spring but five have two, three, four, six and thirteen springs. The mapped manifestations are aligned on two distinct parallel lines, one longer (the eastern line), stretching from the spring “Kletturlaug” to the north to the edge of Geirsá to the south. The other (the western line) is shorter and its manifestations are on both sides of Geirsá river (Fig. 2).

  In the eastern line, springs lie in an overall NNW-SSE zone (Fig. 2). Generally, temperatures are higher in the northern half of this zone (25.5°C-83.1°C) than in its southern half (8°C-60.1°C). The northernmost spring, “Klettslaug”, is 74°C and is used for heating the Klettur farm. Seven smaller springs between 29.7°C and 70.5°C are associated with Klettslaug and appear through the green vegetation in the Holocene soil. Steam escapes from these manifestations, and some have small discharge. These springs are aligned on two N-S lines and one E-W line. Two cold springs (5.3°C-7.3°C) separate the Klettlaug springs from the “Smáragrundalaug” located further southeast. “Smáragrundalaug” springs are 66.1°C to 83.1°C, and the highest temperature in the entire mapped areas was found on a NW fracture at the intersection of two NE fractures in this group of springs. Considerable steam and discharge accompany these manifestations. Further to the southeast, several colder springs (26.4°C and 50°C) appear on the southern slope of a small stream west of Geirsá river. Still further to the southeast, the “Sundlaugarpyttur” spring appears as an isolated pool with 76.3°C, swamp, algae and occasional steam. The last manifestations to the west of Geirsá river are located by the tip of an ENE man-made channel very near the river (Fig. 2). They consist of two small eyes with 56°C to 62.5°C that have noticeable discharge, silica layer and considerable oxidation in the mud. East of Geirsá river, a group of springs lie over tens of metres in a grassy flat area near the river. They have a general NW orientation, their temperature ranges between 25°C and 77°C, steam and swamp is associated with some of them, and a few have a slight discharge. The water from the river mixes with the springs or the eyes nearest to the river, and small fishes were observed in the springs of lower temperatures. Further southeast, geothermal manifestations were found mainly inside a long NW man-made channel, but also outside of it where the springs are aligned N-S and NNE (Fig. 2). The springs inside the man-made channel are 38°C to 60.1°C. The most prominent of them is to the north of the channel where water, occasional steam, green vegetation, thick swamp, and algae were observed mainly in the channel, surrounded by ice, or in the slope above the channel. The springs and eyes outside of this channel are aligned N-S and NNE and are 18.8°C to 57.1°C, mostly above 33°C. The eyes are inside two swampy pools with occasional steam, surrounded by green vegetation. Generally, these groups of springs present a shift to the southwest compared to the other springs of the eastern line. The last spring of the eastern line is an isolated feature by the northern shore of Geirsá river. It has an E-W direction and is 28°C.

  The western line has lower temperatures and fewer geothermal manifestations (Fig. 2). The four features east of Geirsá river are pools and springs with 12.8°C and 46.7°, including an area without ice and snow that could be covered by the river during summer. Slight silica deposition was found in the gravel in these areas. West of the river, three cold springs burst out of the 10.000 yr old sediments on the slope of a hill to the northwest. They are 8.2°C and 8°C, have a slight discharge, and are aligned on a N-S line. Thick mud-swamp and oxidation are associated with these springs. The last three manifestations of the western line are southeast of these cold springs in a grassy area west of Geirsá river (Fig. 2). They are 36°C, 42.5°C and 50.7°C, and the discharge of one of them flows down the slope toward the river. Except the cold springs that appear on a separate tectonic line, the warmer springs of the western line are aligned NW, NNE and possibly ENE.

- A total of 30 features were mapped in Area 3, south of the road 516. They are 15 cold springs (<9.9°C), 14 warm springs (10°-50°C), and the borehole (64.3°C) in Runnar (Fig. 2).

Georgsson et al. (1978) mapped 5 features in Area 3, with thirteen springs in Runnar. Our mapped cold springs are mostly south of the Hangar (Flugskýli), and a few ("Skörð") in a small valley northwest of Runnar (Fig. 2). Oxidation is associated with most of these cold springs. South of the Hangar, some of the springs have discharge, forming a small stream. The most obvious strike observed among these cold springs is NE. Further south, other cold springs appear west of Geirsá river. They strike mostly NW, accompanied by deep swamp. The cold and warm springs of "Skjálftagrund" and "Vilmundaeyri" are located by the second bend of Geirsá river south of Runnar (Fig. 2). The "Skjálftagrund" springs strike NNE and are up to 19.5°C, most of the heat being in the river near the shore. Steam escapes from these springs and occasionally white deposition (silica?) appears in the gravel of the river bank. The "Vilmundaeyri" springs are partly on the southern river bank in the swampy Holocene soil, and partly in the river. Their highest temperatures are between 9.5°C and 18.8°C, and the hottest manifestations are aligned WNW. The group of Skörð cold and warm springs are on a WNW line. The warmer springs are 10.2°C and 25.6°C, in a swamp in the entrance of the small valley and in the 10.000 yr old sediments on the slope above the valley.

Due to the implementation of the borehole in Runnar the temperature and the distribution of the springs has changed since the time Georgsson et al. mapped this area in 1978. Presently, manifestations are mostly between the summer house and the river. The borehole, used for heating the summer house at Runnar, and the main spring in a small river bay are the two prominent features (Fig. 2). Direct access to the borehole was not possible, and a 64.3°C temperature was measured in the water flowing from the pipe of the borehole. The main spring was reshaped by the owner as a natural pool. It is 48.5°C but water from Geirsá mixes flows in the pool. Swamp, abundant bubbles, and small fishes lie in the bottom of the pool. The pool and the borehole seem aligned NE. Other features in Runnar are to the southwest of this spring near Geirsá river. They are in a swampy area free of ice where manifestations are 18.6°C to 47.3°C. These manifestations are either aligned WNW or NNE. A pipe from the borehole stretches beneath the gravel and flows into the river, giving rise to the steam in the river. But natural geothermal manifestations are only on-shore. The last two springs are northeast of the Runnnar summer house. One of them is 31.3°C, with occasional bubble, surrounded by a concrete construction and is in use for the heating of the older house in Runnar. Just next to it a cold spring appears through the soil with 6.6°C, swamp, algae, oxidation and little discharge. These last two springs could be aligned NE.

3. TEMPERATURE ZONES

Interesting results appear after plotting the average surface temperatures of individual zones on the map, using a selected colour gradient (Fig. 3). The average values were obtained based on maximum temperatures. For practicability, the zones are numbered from 1 to 10 (Fig. 3). Zones 1 to 3 in Area 1 have an average temperature of 34.6°C, 34.2°C, and 21°C, respectively. In Area 2, zone 4 (or the eastern line) has an average temperature of 49.2°C, while zones 5 and 6 on the western line are 37.1°C, and 8.1°C, respectively. Area 3 contains four distinct zones, of which zone 7 is the coldest (5.1°C), followed by zone 10 (9.2°C), and sub-area 8 (14.7°C). Zone 9 is the hottest with 32.6°C (Fig. 3).

Above observations indicate inhomogeneous average temperature within the three mapped areas. Generally, the eastern line of Area 2 is the hottest zone in the entire mapped field, while Area 3 is overall colder, except around Runnar.

4. TECTONIC ORGANISATION

Geothermal activity in Reykholtsdalur is fracture-related and the basement rocks in this valley are heavily fractured. These rocks are a part of the Borgarfjörður Block that is bounded to the east by the active Reykjanes-Langjökull Rift Zone (RLRZ), and in the far west by the extinct Snæfellsnes Rift Zone-SRZ (Jóhannesson, 1980). The Borgarfjörður Block was formed over 15

Ma of tectonic history that includes rifting, shift of rifting activity from SRZ to RLRZ about 7 Ma (Kristjánsson and Jónsson, 1998), and possible oblique rifting or transform faulting (Khodayar and Einarsson, 2002). The recent intra-plate Snæfellsnes Volcanic Zone stretches perpendicular to the rift zones. The 1974 Borgarfjörður intra-plate earthquakes occurred near the eastern tip of this volcanic zone (Einarsson et al., 1977), just one valley farther north from Reykholtsdalur.

Though the manifestations mapped in Kleppjárnsreykir, Deiltartunga and Hurðarbak (Khodayar et al., 2004a) belong to the Reykholtsdalur geothermal field, they are not on the same fracture systems as those mapped in Klettur-Runnar (Figs. 1, 4 and 5). Before a general understanding can be gained on why low temperature geothermal activity is concentrated in Reykholtsdalur east of Þverá unconformity, and what is the relation of this activity to the past plate boundaries and Quaternary deformation, a detailed mapping and an accurate estimation of the tectonic directions within each geothermal site is needed.

Georgsson et al. (1978), attribute the geothermal activity of Klettur-Runnar to one WNW striking fracture stretching from northwest of Klettur to the middle of Area 2, and three other NW striking fractures stretching from the middle of the Area 2 and from west of Klettur toward Kroppsmúli mountain to the southeast. Based on geophysical measurements within these areas, they suggest the existence of an E-W dyke at the latitude of Smáragrundalaug, and a NNE dykes connecting the cold and warm springs of Area 3 south of Runnar. They also suggest that the manifestations at Runnar are on a NNE normal fault with downthrown toward the northwest.

Generally, our temperature measurements are in the same range as those found by Georgsson et al. (1978), and our tectonic conclusion is in good agreement with theirs. In detail, however, we observe more complex tectonics around Klettur-Runnar (Fig. 4). Our conclusions profited from the advantage of mapping more features than Georgsson et al., including colder springs, and with more accuracy due to the use of a GPS device.

We suggest that geothermal manifestations in Klettur-Runnar are aligned on several major and local fracture sets. The regional fractures strike dominantly N-S at both ends of Area 1, and NW in its middle part (Fig. 4). In Area 2, by contrast, the two dominant fractures are parallel and strike NW, favouring the hottest springs on the eastern and western lines. N-S alignment is found only among the colder springs of the western line. A different tectonic setting is present in Area 3, dominated by the NE and WNW structures. The main structure of Area 3 is a long NE striking fracture, which stretches from northeast of Runnar to the southwest of Flugskýli (Fig. 4). This fracture is longer than on Georgsson et al. (1978) map, strikes more easterly, and is used by both the hot and the cold springs. Cold springs are at the southwestern tip of the fracture, while hot springs of Runnar are on the northeast portion of the same fracture (Fig. 4). The Skjálftagrund warm springs are on another NE striking fracture, parallel to the fracture of Runnar-Flugskýli. The warm and cold springs of Vilmundaeyri, Skörð, and those southeast of Flugskýli are on WNW regional fractures. Similar to the NE striking Runna-Flugskýli fracture, The Skörð fracture also is used by both the cold and the hot springs (Fig. 4). It is likely that the borehole at Runnar is located at the intersection of the WNW and NE fractures.

Though 10.000 yr old sediments filling Reykholtsdalur valley are not heavily fractured as their basement rock, tectonic lineation can be observed occasionally either in the sediments or in the remnant of Tertiary lavas cropping out locally within the sediments. The strikes of the regional fractures that we deduced from the organisation of the springs of Klettur-Runnar are well visible also on aerial photographs (Fig. 5a and 5b).

The local fractures responsible for surface geothermal manifestations generally strike similar to the regional structures. In Area 3, both the local and the regional structures strike NNE and WNW. In Areas 1 and 2 some of the springs are aligned along N-S, NW, and WNW directions, parallel to their regional host fractures. Others, however, line up along single fracture, or are at the intersection of several fractures, striking differently from their regional host fractures (Fig. 4).

The local directions of the springs include the E-W trend, which is rare among regional fractures, although it was observed in surface ruptures of the Borgarfjörður earthquakes of 1974 (Einarsson et al., 1977). No differences appear between the tectonic settings of the cold springs and those of the hot springs.

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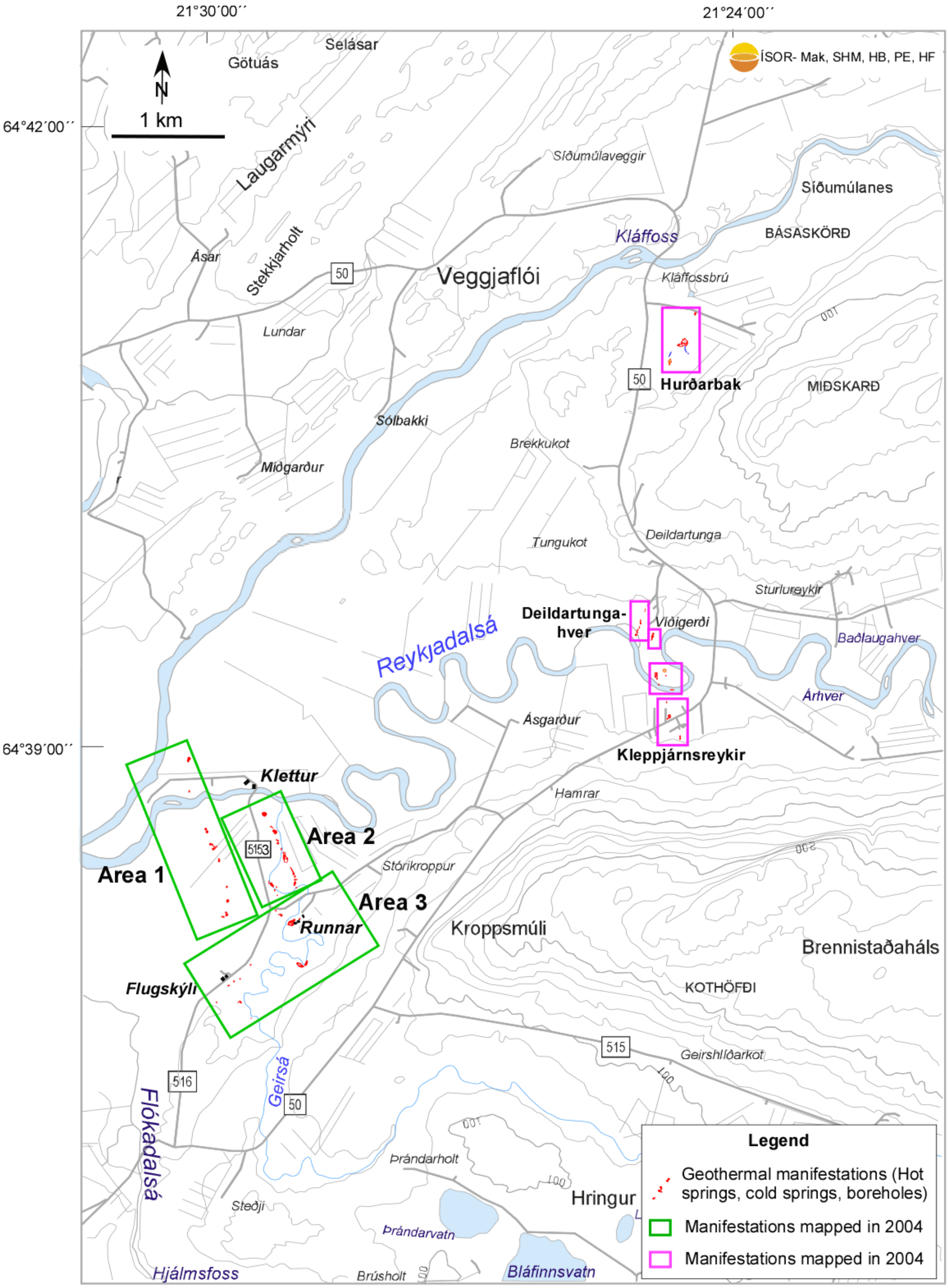

Fig. 1. Location of geothermal manifestations mapped with the GPS during the 2005 field campaign in Klettur-Runnar. Geothermal features mapped in 2004 (Khodayar et al., 2004a) are also reported on the map (Coordinate system ISNET 93). The size of manifestations is exaggerated.

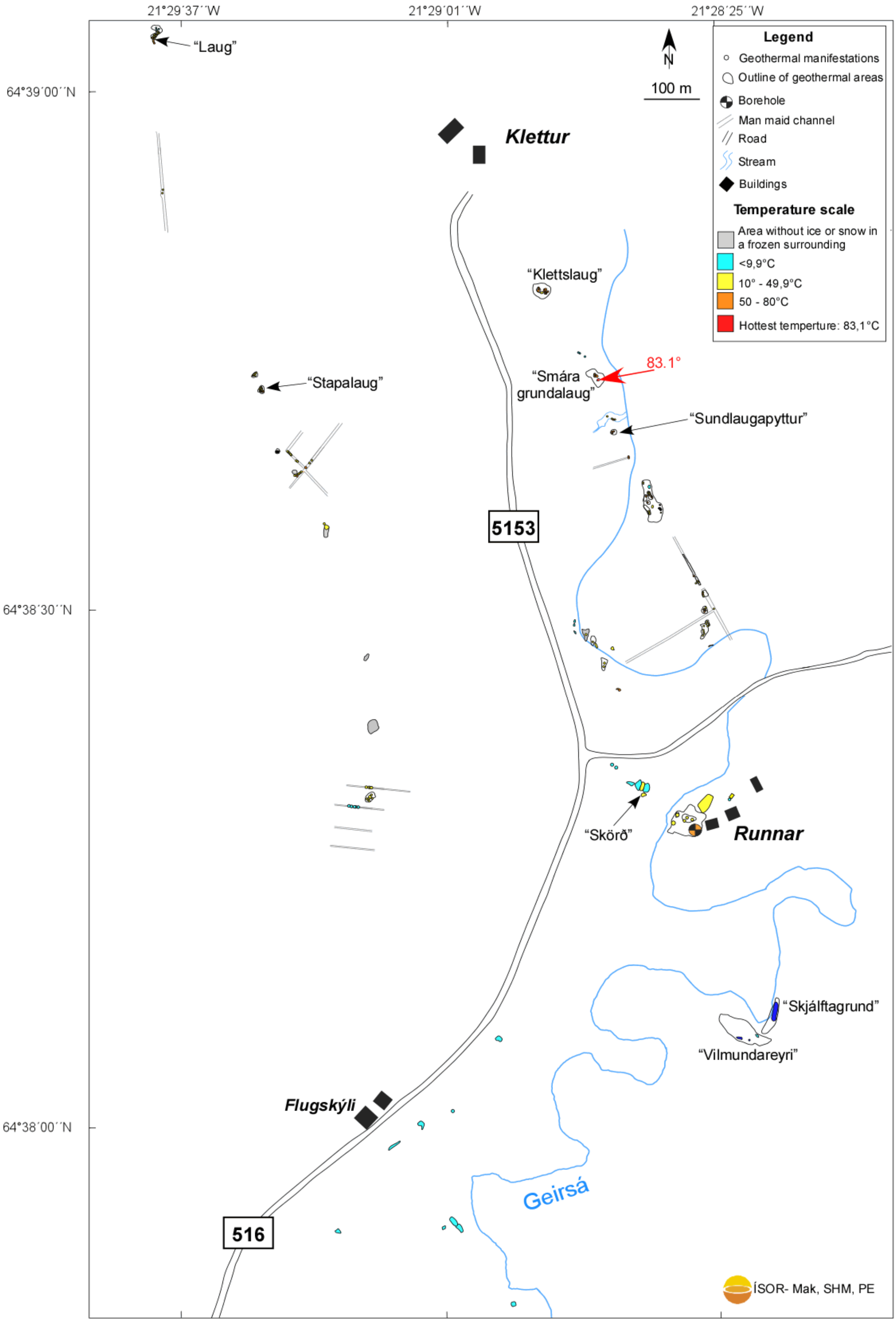

Fig. 2. Detail of the mapped geothermal manifestations in Klettur-Runnar. The size of the manifestations is exaggerated. The coordinate system is WG84, and the names of the springs are taken from Georgsson et al. (1978).

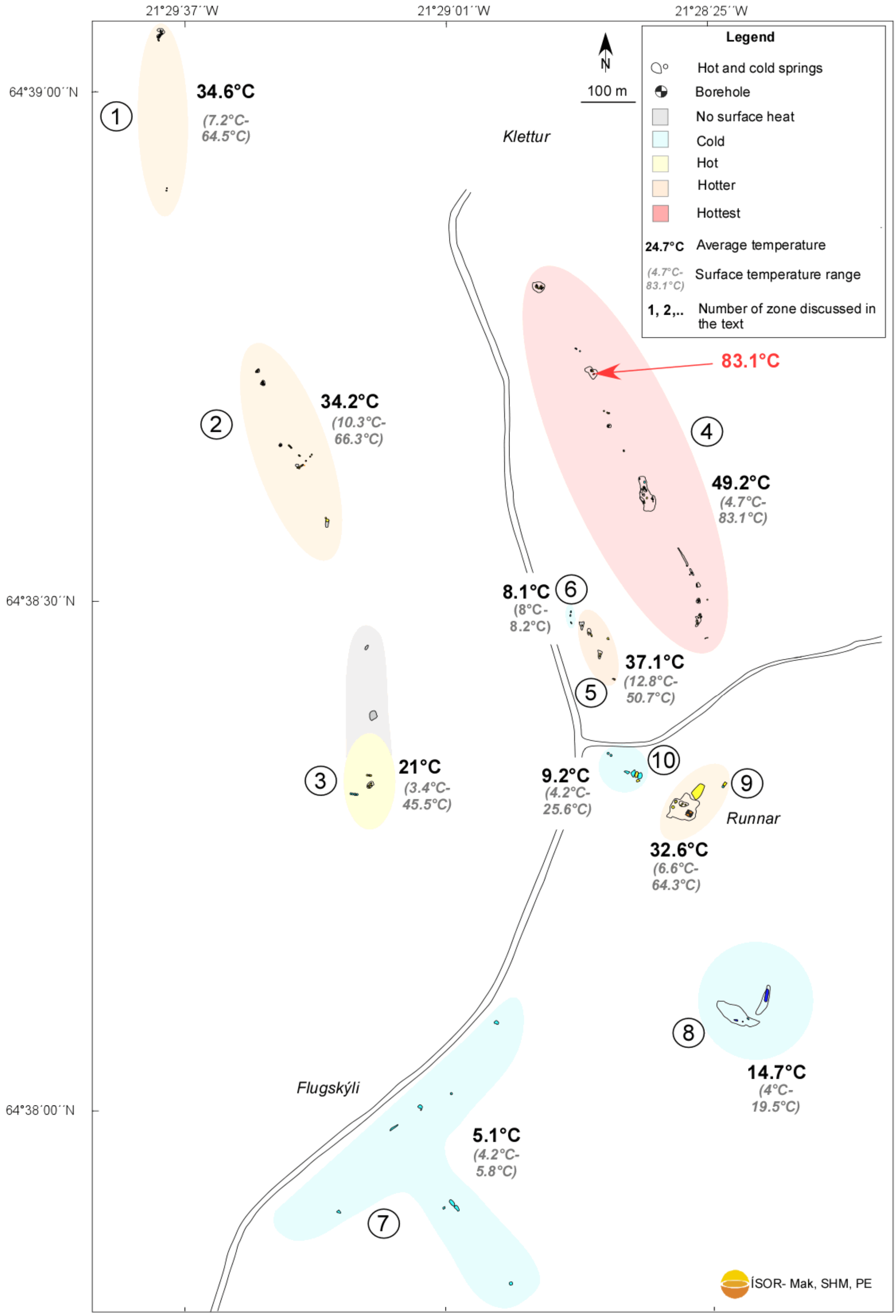

Fig. 3. The temperature zones in Klettur-Runnar (Coordinate system WG84). The size of the manifestations is exaggerated. The temerature zones were established based on average maximum temperature within each zone. The numbers of zones are only for description purpose (see text for explanation).

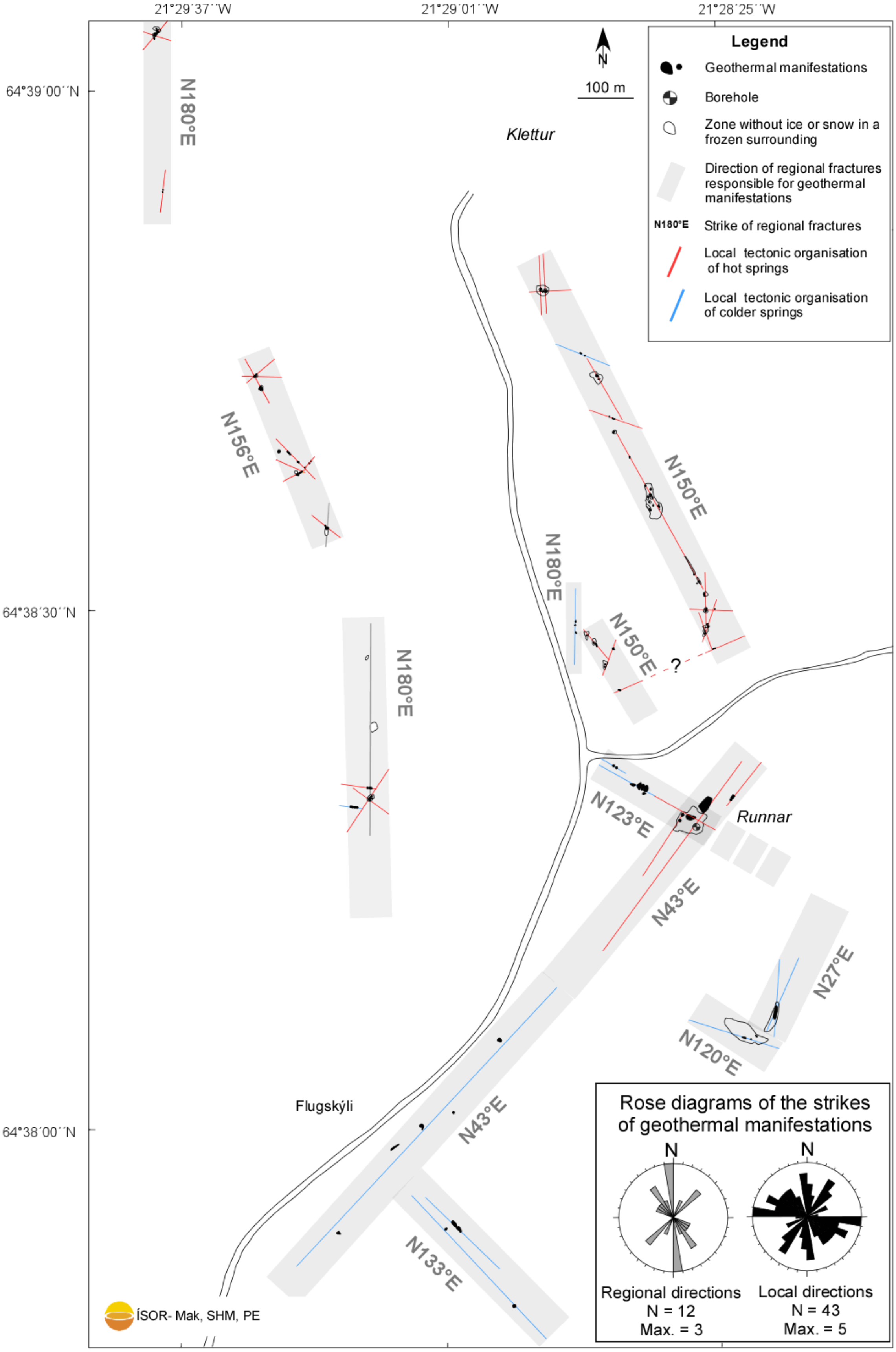

Fig. 4. Regional and local tectonic fractures responsible for geothermal activity in Klettur-Runnar, deduced from the alignments of geothermal manifestations.The coordinate system is WG84, and the size of the manifestations is exaggerated. Rose diagrams are with intervall of 10°.

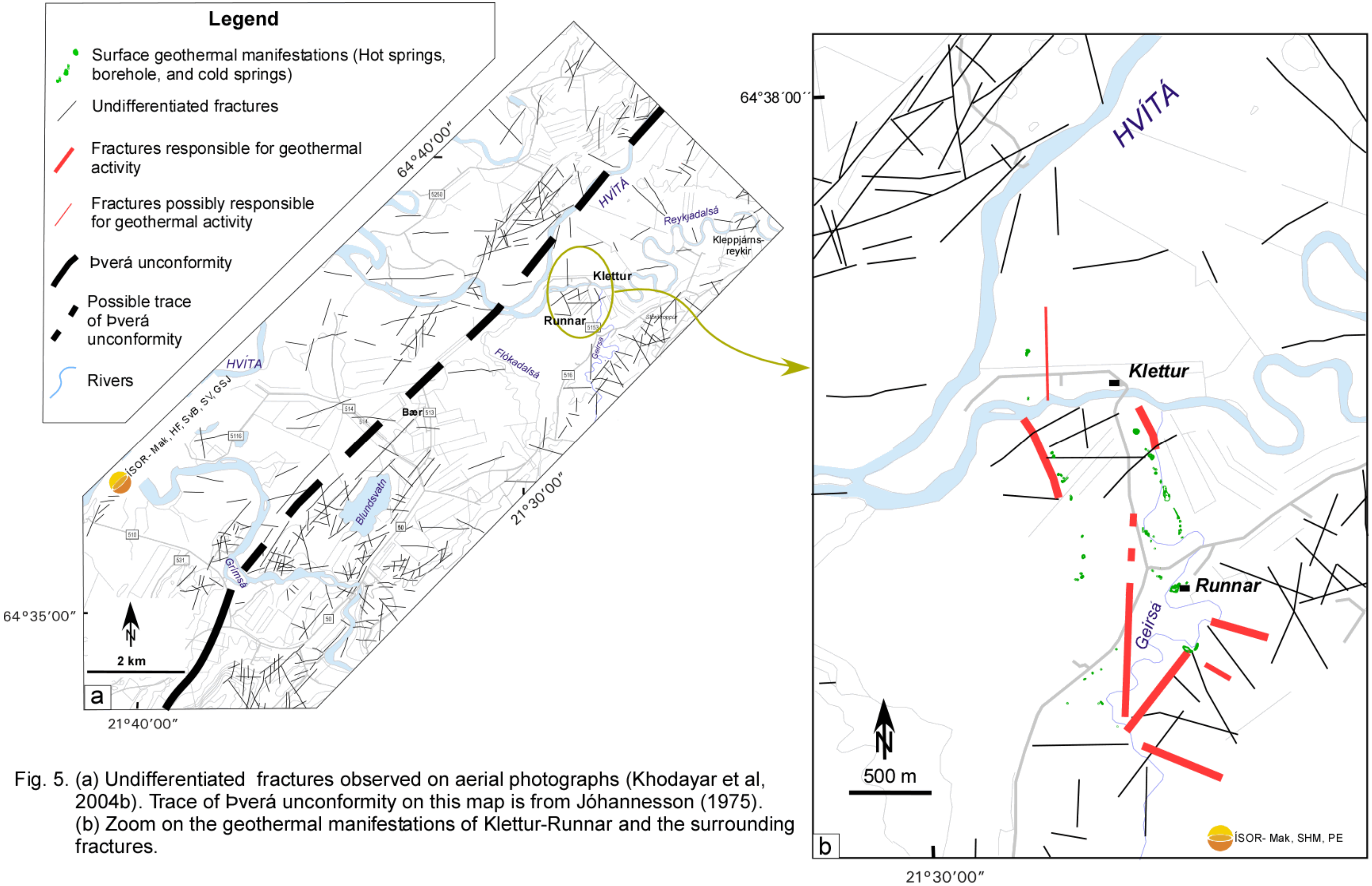

Fig. 5. (a) Undifferentiated fractures observed on aerial photographs (Khodayar et al, 2004b). Trace of Þverá unconformity on this map is from Jóhannesson (1975). (b) Zoom on the geothermal manifestations of Klettur-Runnar and the surrounding fractures.