TEMPERATURE MEASUREMENTS AT THE SURFACE AND IN SHALLOW DRILLHOLES

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Report 8, 1989

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ABSTRACT

In its first part, the present work compares the results of two different but complementary approaches in geothermal investigations i.e. structural geology and geothermal mapping. A conformity and a close correspondence are underlined by the shallow temperature measurements carried out at Reykholt-Reykjavellir area, South-Iceland.

Temperature logging and interpretation are the subjects of the second part of this report. Five wells were logged and the temperature gradients calculated from the logs are similar to the regional gradient.

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1. INTRODUCTION

1.1 Scope of the work

This report illustrates the concluding outcome of the author's training on the eleventh session of the UNU Geothermal Training Programme, in Reykjavík, Iceland, under a Fellowship award from the UNU and the Government of Iceland.

The training programme started with an extensive five-weeks introductory lectures course on relevant aspects of geothermal energy. This was ensued by a series of specialized seminars and field works embracing leading procedures employed in geothermal investigations.

In view of the present status of geothermal development in Algeria, the main emphasis in my training was set on temperature data acquisition and interpretation.

The figures and data used in this report were taken from actual measurements, made by the author, at Reykholt-Reykjavellir and at Kjalarnes areas, South-Iceland.

2. SURFACE TEMPERATURE SURVEY OF REYKHOLT, BRAUTARHÓLL AND REYKJAVELLIR IN SOUTH-ICELAND

2.1 Purpose, procedure and equipment

The purpose of the work was 1. to map in detail the occurrence of hot springs and hot ground in the Reykholt-Reykjavellir area, 2. to correlate the findings of the geothermal mapping to the geological structure of the area and 3. to acquire, in this way, a basic knowledge of the geothermal fields that might be useful for planning for more sophisticated and more expensive research methods.

For making a geothermal map based on shallow measurements, one must measure the temperature in the ground at a convenient depth and at regular intervals and plot the data on a map of sufficiently large scale for tracing isolines. The intervals between measuring points are not fixed in advance. When the values recorded are relatively high, one has to reduce these intervals in order to delimit and to follow more precisely their distribution. In the present work, the temperature measurements were taken at 0.5 m depth and the intervals were chosen either 10, or 5 m for values higher than 12°C.

Prior to the ground temperature measurements, one has to make an assessment of all the geothermal manifestations (springs, red clay, hard soil, vegetation, etc) occurring in the area; the information held by the land owners can also guide the survey. The measurements can be disturbed by sewage water; to take them into account is of importance for the interpretation. It is only then that the position of the measured profiles is decided with regard to the best way of covering the maximum surface of the area under study. The outer limits of the survey area are decided and the direction of the profiles to be followed is written down. A steel pointer sometimes had to be driven in with the help of a hammer; this affects the thermal equilibrium and therefore a few minutes (1 or 2 mn, depending on how hard the ground is) are needed for the hole to retrieve its initial thermal state. When the temperature had stabilized, a digital thermometer was used to measure it. The data was then plotted on a map.

When no map is available, one has to draw one by marking indicators such as house corners, roads, trenches, etc related to a base line. By following this method, Reykjavellir area, of which there was no map available in the necessary scale, was drawn and the scale adopted was 1:1.000.

The equipment that was used included:

-A measuring string, marked at regular intervals, depending on the scale of the survey. In the present work, the string was 300 m and it was marked at five, ten and hundred metres intervals.

-A right angle lens and a measuring tape were used to locate reference points on each side of the base line, or measured profiles.

-A digital thermometer, consisting of three parts: A stick with a sensor on the end (this is 1 m), an electric cable through which the signal is conducted and a box containing a circuit that transforms the current received from the sensor to a voltage, and a voltage-meter where the value is recorded.

-A T-shape steel rod with a pointed end. To drive into the ground one often has to use a heavy hammer.

-Maps. For the present work two maps in the scale 1:5.000 and 1:2.000 were used. They only covered the area around Reykholt including Brautarhóll. For Reykjavellir a map in the scale 1:20.000 was available.

-Other tools included range poles, compass, mercury thermometer, tape measure and other common instruments.

2.2 Geology of South-Iceland

2.2.1 Lithology-Stratigraphy

The basement rocks of the area investigated belong to the Plio-Pleistocene (Jóhannesson et al., 1982). The basement series rocks are locally covered by late Pleistocene to recent sediments. The Plio-Pleistocene series have been slightly titled towards NW and eroded. Rocks are composed of alternating layers of basalt lavas, hyaloclastite of subglacial origin and sedimentary beds, mainly reworked hyaloclastite but also tillite and glacial sediments.

Rocks are generally of low permeability due to alteration. At Reykholt, there is a 754 m deep borehole with little permeability except near the bottom where a fracture apparently was cut. Fracturing has produced secondary permeability.

For siting of production boreholes, it is thus of greatest importance to locate the youngest and most permeable fractures precisely.

2.2.2 Tectonics

*** Seismicity**

Most of the seismicity of Iceland is related to the Mid-Atlantic plate boundary that crosses the country. In Iceland the plate boundary is displaced to the east by two major fracture zones: The South Iceland Seismic Zone in the south and the Tjörnes Fracture Zone in the north. The largest earthquakes in Iceland occur within these zones and may exceed magnitude 7.

The research area lies in the northern part of the South-Iceland Seismic Zone. Many of the earthquakes have been associated with faulting and the faults generally seem to be oriented NS or NE-SW. The destruction zones are elongated in the N-S direction, but the South-Iceland Seismic Zone as a whole has an E-W orientation.

Most of the faults are arranged en echelon. This structure appears on many different scales, ranging from metres to kilometres, and suggests right lateral movement on N-S striking faults. The sense of motion implies a least compressive stress in a horizontal NW-SE direction and a maximum compressive stress in a NE-SW direction (Einarsson and Björnsson, 1979).

* Faults and Fractures

Tectonic maps of Reykholt and surroundings show prominent faults with a northeasterly trend between 8 and 70° (Franzson, 1977; Georgsson et al., 1988). A northeasterly (N30-45°E) trend is inherited with the growth of the lava pile. Younger faults related to the South-Iceland Seismic Zone would be expected to form a conjugate set, with north-south and WSW-ENE trends.

Exposures close to the geothermal anomalies are found only at Reykholt. There the main thermal anomaly is clearly related to a fracture trending N38-40°E. Several faults are seen on the existing tectonic maps trending towards Reykjavellir but in the field they can only be traced to within 1-1.5 km distance from the thermal area.

2.2.3 Regional geothermal gradient

There exists a geothermal gradient map of the whole of Iceland (Flóvenz and Sæmundsson, 1989). Regional geothermal gradients can only be determined outside geothermal areas where heat loss is by conduction. The temperature gradient generally decreases symmetrically away from the spreading volcanic zones.

In South-Iceland, there are numerous geothermal areas of low temperature type; one of them is Reykholt-Reykjavellir. From the geothermal gradient map it can be seen that the regional gradient there should be around 150°C/km.

2.3 Test area

* General description and earlier investigations

The region involved in the surface temperature measurement survey is located in South-Iceland at about 90 km east of Reykjavík, Fig. 1. The principal activity in the area is agriculture, especially greenhouse farming.

The geothermal investigations carried out in the area, other than occasional temperature measurements, date back to the nineteen forties. In 1944, the flow rate and the temperature of two hot springs occurring at Reykholt are recorded as 10 l/s at 100°C and 0 l/s at 97°C (Rannsóknarráð, 1944). At Reykjavellir, a hot spring gave 3 l/s at 79°C (same reference).

In 1967, Thorvaldur Ólafsson (1967) registered the flow rate and the temperature of a hot spring occurring at Reykholt. He recorded 10.6 l/s at 98°C and mentioned a yearly mean flow of this hot spring as 14 l/s. Three hot springs located at Reykjavellir gave 0.5 l/s at 100°C, > 1 l/s at 73°C and < 0.1 l/s at 53°C.

Another hot spring situated in the southernmost part of the Reykjavellir group yielded 7.5 l/s at 68-70°C.

In 1945-50, seven boreholes were drilled at Reykjavellir reaching a depth ranging between 30.5 and 112 m. The maximum temperature obtained is 114°C at 52 m.

A borehole was drilled at Reykholt, in 1974, attaining a depth of 754 m. The maximum temperature obtained is 129°C.

The borehole doubled the flow of water from the Reykholt field. Hjalti Franzson (1977) established a geological map of the region outlining faults and fractures.

Flóvenz et al. (1985) established a resistivity map of the southern lowlands in Iceland at 500 m depth below sea level based on Schlumberger soundings. It shows that the area covered by the study is of low resistivity at this depth. The lowest resistivity was found at Reykholt.

2.3.1 Reykholt

For convenience in the present work, Reykholt area has been divided into three parts regarding its extension and its topography.

Reykholt 1 lies up on a hill (altitude 110 m) and on its western slope. It constitutes the highest place of the areas involved in the ground temperature measurements. It surrounds, in its southwestern part, three school-buildings.

Reykholt 2, in the southernmost part of the area, is about 250 m distant from Reykholt 1. The area covered by the survey lies on a hillside, 70-80 m of altitude, facing a river around 600 metres distant.

Reykholt 3, in the western part at 350 m from Reykholt 1, lies on a gentle slope (altitude 75 m). The area covered by the surface temperature measurements is limited by trenches.

2.3.1.1 Geothermal manifestations

A. Reykholt 1

In the northern part, up on the hill, there is a hot spring. The water wells up through a fracture that is oriented NE-SW.

The hot spring is now contained within a concrete cistern elongated NE-SW and covering the fracture. The yield of the hot spring is 14 l/s.

Another hot spring is located 20 m SE of the cistern. There is no water flowing in it but boiling noise can distinctly be heard.

At 25 m east of the concrete cistern, there is a borehole. It was drilled in 1974 and reached a depth of 754 metres. The maximum temperature recorded was 129°C. The borehole yield is the same as that of the hot spring, 14 l/s.

At 30 m SSW of the concrete cistern, there is an area of red clay covering a surface of 50 m x 15 m in size. It is elongated in the NE-SW direction. The red clay is regarded as a geothermal manifestation, the red color being given by alteration of the soil and bedrock.

B. Reykholt 2

The land owner observed that in the snowy time, in some places the ground does not freeze due to the heat which emanates from the soil. Besides this, some white incrustations can be seen in a stream bed (dry at the time of surveying) occurring there. The area indicated by the land owner was surveyed and proved to be anomalously hot. Here it is referred to as Reykholt 2.

Eight springs have been located in the southernmost part of the area along the foot of the field. Their temperatures are 8.4, 9.5, 9.2, 9.3, 9.2, 8.7, 18.0 and 12.9°C. The two hottest ones are hotter than the summer average temperature; they occur downslope from the snow melt area. The others can be regarded as cold.

C. Reykholt 3

In the western extremity of a trench of 20 metres length and 1.5 m depth, occurs a warm spring. The temperature taken there is 16.5°C. The flow rate is very small and the water flows towards NW to another trench.

2.3.1.2 Geology

a. Lithology

The area covered by the geological mapping in the southeastern part of Reykholt shows two major lithologic rock types, basalt and hyaloclastite, Fig. 2. The basalt is mostly developed in the northern part where it constitutes the highest points. It has a columnar structure.

Below the basalt, there are two hyaloclastite units. Both have a brecciated form but from the grain size, two units are defined: An upper hyaloclastite of coarse grain and a lower hyaloclastite, fine grained. In its southern and northern parts, the upper hyaloclastite contains pillows or pods merging into sheets.

In the SE, there are steep cliffs formed by the hyaloclastite. There, the basalt intercalations of the upper hyaloclastite have pinched out and the two hyaloclastite units come together.

b. Structure

The Plio-Pleistocene rocks of South-Iceland have been tilted to the NW and dip about 5° in the Reykholt area.

At Reykholt two fractures trending N38-40°E are prominent. One of them cuts along the main thermal anomaly on top of Reykholt-hill (Reykholt 1).

In the southern part of Reykholt, faults trending WNW-ESE were observed. They have throws of several metres to the south.

A rose diagram of the trend of 41 fracture and fault is shown in Fig.3. The old SW-NE trend and young WSW-ENE trend seem to merge and are most strongly represented on the diagram. The NNE-SSW trend of the diagram probably represents the second fracture trend of the conjugate seismic zone fracture system.

2.3.1.3 Geothermal map

*** Reykholt 1**

The area covered by the survey is of 400 m x 300 m. The isoline 12°C deduced from the ground temperature measurements shows two large anomalies, Fig.4. They are en echelon; both of them following the same direction, NE-SW.

The northern anomaly covers a surface of 220 m x 60 m. The only large hot spring is close to its northern end. This anomaly contains three thermal maxima: A, B and C from the north to the south.

The highest temperatures and the hot springs occur in A. This maximum, covering a surface of 45 m x 15 m, has a N-S trend.

The maximum B, is located at 10 m from A. It follows a NNE-SSW direction. It covers an area of red clay and the highest shallow temperature recorded within it is 42.8°C. The surface covered by B is 50 m x 20 m. The maximum C, 36 m south of B, occupies a surface of 20 m x 10 m and presents a NNE-SSW direction.

The southern anomaly, surface: 190 m x 50 m, contains two small maxima: A and B from the north to the south. Both follow the same direction, NNE-SSW and are separated by a distance of 33 metres.

The maximum A covers a surface of 17 m x 12 m and has 15.5°C as the highest temperature while B covers a surface of 17 m x 14 m and presents 16.6°C as the highest temperature.

This anomaly is open towards NW. The sewage water occurring there, in the northwestern fronts of the school and the headmaster's house, disturbed the shallow temperature measurements in that part.

The southern anomaly occurs on a hill side and might suggest a lateral off-flow. However, being for the greater part offset south relative to the main northern anomaly, it is considered more likely that it represents an upflow related to a parallel fracture.

* Reykholt 2

The surface (500 m x 170 m) covered by the survey is located between 70 and 80 m altitude. The geothermal map shows two anomalies, Fig. 5. The western one covers a surface of 280 m x 80 m. It is elongated in an E-W direction. The highest surface temperature recorded there is 15.4°C. The eastern anomaly occupies a surface of 135 m x 100 m and has 17.5°C as the highest temperature. Its direction is N-S. The anomaly is broader in its southernmost part. The 12°C isotherm seems to indicate a flow towards the south where two tepid springs (18.0 and 12.9°C) are located. The fact that the two anomalies are located along the same altitude range along the foot of the hill (70-80 m) indicates no effect of the tectonic. The anomalies are likely related to an outflow coming from the main hot spring area up on the hill, at 100-110 m altitude (Reykholt 1).

* Reykholt 3

The surface covered by the survey is of 230 m x 70 m, Fig. 6. The hot spring located there shows a temperature of 16.5°C. The measurement was taken at 60 cm below the water level, of a trench, in other words at 2.10 m depth below the ground.

At 0.5 m depth, the temperature measurements recorded in the surrounding of the hot spring are rather low, ranging from 8.7 to 10.8°C.

2.3.2 BRAUTARHÓLL

Located at about 650 m, west of Reykholt-School, the area surveyed by the ground temperature measurements covers a surface of 244 m x 100 m.

The only geothermal manifestation found is a barren area of red clay. This was opened recently by a trench burrowed there. Orkustofnun files report a highest temperature of 30°C (Georgsson et al., 1988).

The geothermal map shows three anomalies occurring on a gentle hillside sloping of towards west, Fig. 7. The two easternmost anomalies with 10 m between them follow the same direction NE-SW. Both have a thermal maxima of 14.1°C . The third, in the southwestern part constitutes the biggest anomaly. It is separated from the eastern ones by the trench. The two thermal maxima within it follow an ENE-WSW direction. The highest value found in the present temperature survey (23.6°C) is located 10 m west of the trench and the red clay.

The broadness of the biggest anomaly and the tongue extending down to the plain indicate some subsurface flow of warm water from an upflow on the upper hillside.

2.3.3 REYKJAVELLIR

2.3.3.1 Surface conditions

Reykjavellir area is located 1 km WSW of Brautarhóll. It lies on a flat ground, half of it wet and half of it dry. An old farm with greenhouses (abandoned now) testifies a geothermal utilization in the past. At the far south of the area studied, a hot spring was dug out some 8 years ago and a pumping station installed, supplying five farms with hot water.

From the greenhouses to the north, the area is elevated by about 4-5 m. Most of it is dry and its ground is hard. A stream eroded bench marks the boundary between the high and the low ground.

2.3.3.2 Geothermal manifestations

Six hot springs are located in the Reykjavellir area. Their temperatures are respectively, from the north to the south: 44, 39, 65, 68, 75 and 76.5°C. They are aligned on a NE-SW direction.

At 45 m, south of the greenhouses, the hot springs engender a small shallow brook of maximum width of 5 m, flowing towards the south. The water flow from the hot springs is small. Georgsson et al. (1988) reported 1.1 l/s. The hot springs with the main flow is farther south, at 330 m from the greenhouses. Flowing to the south, the outflow is, in places, up to 12 m wide. The flow rate is 3.8 l/s (Georgsson et al., 1988). Both sides of the small streams are grassy, the eastern sides are marshy.

2.3.3.3 Boreholes

In 1945-50, seven boreholes were drilled at Reykjavellir. The depths reached were from 31 m to 112 m and the maximum temperature recorded is 114°C at 52 m depth. The boreholes are all collapsed now except two and some of the locations shown on the map (Fig. 8) are uncertain. The depth of the bedrock is around 34 m. The bedrock is overlain mostly by clay according to the drilling reports.

The water table in the boreholes is at surface level in the low ground but at 3-4 m in those at higher ground indicating that the geothermal system is at low pressure.

2.3.3.4 Geothermal map

At Reykjavellir a surface of 620 m x 250 m was covered by the ground temperature measurements (Fig. 8). The geothermal map, deduced from the surface temperature distribution, shows three anomalous places: A, B, and C.

The anomaly A, in the northernmost part of the area, presents a hardened soil certainly due to the heat that has baked the soil. The temperatures there, are high, ranging from 18 to 30.5°C at 0.5 m depth. The anomaly is elongated, following a NE-SW direction. To the east of A another anomaly, much smaller, presents an ESE-WNW direction. It occurs where anomaly A broadens to the south. The highest temperature values occur there, near the eastern edge of anomaly A. It is unclear what causes the ESE-WNW trend. Possibly it is due to lateral subsurface flow.

B is the biggest anomaly by its temperature and extension. It contains most of the hot springs. At least four of the boreholes were drilled in this part; the temperature taken, at surface, in two of them, at the extreme north of B, are 95 and 64°C. This anomaly presents an offset structure with three segments. The offset is induced either by real fractures underneath or by the bench. The three offset segments of anomaly B show a NE-SW direction.

The anomaly C is located in the southern part of the area under study around the largest hot spring. Its orientation is NE-SW. It is offset to the east relative to the big anomaly (B).

A, B and C, following individually the same direction (NE-SW) present an offset alignment; this structure is likely related to young fractures. The general pattern conforms well with the fracture pattern of the South-Iceland Seismic Zone.

The computer map (Fig. 8a), although basically identical to the hand-drawn one, shows even better the offset segments of the main thermal maxima of the field. (Fig. 8b exhibits a three-dimensional representation).

This structure (offset) and the direction followed by the anomalies suggest that a deep fracture is controlling the system. This explanation is supported by the fact that test pumping, amounting to around 30-40 l/s, of the southernmost hot spring at anomaly C, caused drying up of hot springs within anomaly B (information given by local people).

As shown in Fig.9, the alignment of the anomalies follows the same trend as a fault outlined by Hjalti Franzson (1977) near Brautarhóll (1.2 km NE of Reykjavellir) and east of Hrosshagi (1.5 km west of Reykjavellir).

2.4 Conclusions

The individual anomalies outlined by the shallow temperature measurements, the 12°C isotherm, have a general direction NE-SW.

The structural survey carried out at Reykholt, where the exposures are close to the geothermal anomalies shows that the main thermal anomaly is clearly related to a fracture trending N38-40°E.

Small thermal maxima follow NNE-SSW and mainly ENE-WSW directions. They are arranged en echelon and are likely related to fractures underneath.

In the Reykholt-Reykjavellir area, we are in presence of two kinds of fractures: Old fractures whose direction is NE-SW.

They are indicated in the geological maps and they are strongly represented in the rose diagram; and young fractures, arranged in offset structure, outlined by the thermal maxima.

These directions conform well with the fracture pattern of the South-Iceland Seismic Zone.

2.5 Recommendations

The conducted geothermal mapping represents the first step in the geothermal investigations. It has the merit to advice and to guide further studies.

Other methods must be used to locate the upflow of hot water i.e. the youngest and the most permeable fractures more precisely.

For this purpose, the resistivity sounding is the recommended method for the extensive and flat Reykjavellir area.

At Reykholt, resistivity measurements are not applicable because of buildings, pipelines, fences, etc. There, shallow boreholes for gradient measurement might be useful as a next step.

At Brautarhóll, both methods are applicable. The choice of method would eventually depend on cost.

3. TEMPERATURE LOGGING OF BOREHOLES AT KJALARNES-STEYPUSTÖÐ AND AT KORPÚLFSSTAÐIR, SW-ICELAND

As specified by Webster, a log is "a record of sequential data". This record or log shows the fluctuations of the physical parameters related to the depth.

The information we obtain (i.e. reservoir temperature, location of the aquifers, temperature gradient, heat flow), temperature emerges as the key parameter in geothermal investigations.

3.1 Equipment

Several models of logging tools are utilized in geothermal logging (Stefánsson and Steingrímsson, 1981). They differ by their design, size, shape, etc. All electric logging equipments comprise three constituents: The downhole sonde from where the signal departs, a cable through which the signal is fed and the registration line where it is registered. Closely depending on the logging speed, it is requisite to have the cable drum motorized in order to get continuous measurements.

3.1.1 Description

Because of their small size and the efficiency of transmission, the resistivity thermometers are currently the most frequently employed in well logging. The transmission is generally effected through an electric cable, and the measuring value is recorded by an elementary resistivity meter.

The opportunity was bestowed to me to take part in the fabrication of one kind of resistivity thermometer for logging operations. A negative temperature coefficient thermistor sensor was welded on a two conductor cable. For insulation, the thermistor was put into a plastic tube filled with silastic and epoxy ribbon at the top. Several hours later, the tube was fixed into a brass pipe, to prevent the sensor from being broken. At the end of the pipe, there are some holes for the sensor to get freely in thermal contact with the water in the well.

3.1.2 Calibration

Thermistors have negative temperature characteristics i.e. the resistivity decreases as the temperature increases. Before use, the thermistor must be calibrated. For this purpose, a simple calibration method has been utilized. The thermistor, coupled to an ohm-meter, is plunged in a heat basin. Heating the water, we note down the temperature values from a mercury thermometer and the resistance values from the ohm-meter. Higher accuracy is obtained by heating the water slowly while stirring continuously. Due to the drift of the thermistors, periodical recalibration is required.

Table 1 shows the calibration results for the thermistor together with the differences between calculated and measured temperature values (R 00I).

The temperature-resistance equation deduced from the values given in table 1 is:

$$R = \exp(A+B*T_0/T+C*(T_0/T)**2).$$

Where:

$A = -3.69314595$

$B = 18.23458369$

$C = -1.82833745$

$T_0 = 273.15$

T = Temperature in degrees Kelvin

The curves (linear and logarithmic) deduced from these data are shown in Figures 10 and 11.

Table 1. Calibration of thermistor.

Temperature (°C)	Resistance (Ohm)	R00I (°C)
0.02	332300	-0.03
10.20	195900	0.01
20.02	120700	0.17
30.62	75500	-0.15
40.65	48900	-0.09
50.54	32600	0.01
60.51	22200	0.04
70.28	15500	0.13
80.41	10950	0.06
90.61	7920	-0.27
100.41	5760	0.13

3.2 Temperature profile

Disturbances occur during drilling. The direct disturbance effect on the temperature measurements is the cooling of the rocks surrounding the well by the drilling fluid. It is appropriate to log the well during drilling or soon after in order to locate aquifers in the well. It is also valuable to log the well several times during the warming up period after drilling, at increasing time intervals, to get complete and comprehensive idea of the properties of the aquifers.

Temperature changes in the reservoir during production can be monitored by logging one or several wells in the geothermal production area at certain time intervals.

The time for the wells to warm up from cooling during drilling is variable depending on the geological and geothermal conditions of the wells. The high permeability of the rocks and the large number of the aquifers in thermal areas engender short recovery time (a few months) for warming up.

3.2.1 Temperature gradient

The temperature log displays the temperature inside and around the well. The temperature usually increases with depth but quite different profiles can occur.

Constant temperature gradient log is probably the most usual temperature profile surveyed. Such temperature profiles are deciphered as being the consequence of heat conduction in the crust and that the heat flow is governed by heat conduction alone.

The heat flow follows the equation:

$$Q = K * \Delta T / \Delta z$$

As the thermal conductivity K of rock is fairly constant, the temperature will be a linear function of depth:

$$T = T_0 + a * z$$

Where,

Q : Heat flow
T : The temperature
T_0 : Annual mean temperature at surface
z : Depth
a : The temperature gradient $\Delta T/\Delta z$
K : The thermal conductivity

3.3 Test area

** Kjalarnes

Kjalarnes area is situated some 20 km outside Reykjavík. A few shallow wells have been drilled in the area. The location of the wells is shown in Fig. 12.

3.3.1 Data acquisition and interpretation

Temperature logging of five wells was carried out. The wells 2, 3, 4 and 9 are located in Kjalarnes-Steypustöð while the well HS-18 is at Korpúlfsstaðir just outside Reykjavík. The wells at Kjalarnes were drilled a few weeks before the logging was executed while well HS-18 was drilled a few years ago. The temperature profiles are shown in Figures 13-17.

A temperature cross section through wells 2, 4, and 9 was made (Fig. 18), and a map showing the temperature distribution at 30 m above sea level at the Kjalarnes-Steypistöð area was drawn (Fig. 19). The values for the shallow well 3 were extrapolated.

At shallow depth, the wells are disturbed by air temperatures (above water level), annual temperature variations and ground water flow below 10-14 m. All the wells show a linear (gradient) increasing temperatures with depth.

The temperature gradient and the annual mean temperature were calculated from the temperature logs. The results are shown on Figures 13-17 and summarized in Table 2.

Table 2. Temperature gradient and annual mean temperature determined from temperature logs in wells at Kjalarnes and at Korpúlfsstaðir.

Well n.	Temperature gradient (°C/100 m)	Annual mean temperature (°C)
2	10	4.6
3	10	4.2
4	11	4.8
9	9	4.6
HS-18	11	4.1

3.4 Conclusions

The calculated geothermal gradient is 9 to 11°C which is similar to the regional gradient. The annual mean temperature in the Reykjavík area is about 4.5°C.

The curves show that in the upper part of the wells studied there is a flow of cold ground water. This part is probably more porous and permeable than the lower part which is dense, with low permeability and where no aquifer has been identified.

The temperature at 30 m a.s.l. shows that well 3 is closest to the heat source.

ACKNOWLEDGEMENTS

I express my profound gratitude to my advisor, Dr Kristján Sæmundsson, Head of the Geology Section of the Geothermal Department at the National Energy Authority, for his support of this work, his prolific discussions and his patient guidance of the first part of this report.

My deep consideration goes also to Miss Helga Tulinius for her worthwhile instruction of the second part of the present work.

Many thanks are also due to the staff of the UNU Geothermal Training Programme, especially to Dr Ingvar Birgir Friðleifsson and to Gylfi Páll Hersir for their valuable assistance and for the perfect organization of the training.

My sincere recognition to the staff of the Drawing Office for having helped me with my drawings.

I would like to acknowledge the CDER/HCR for providing opportunity my further study in Iceland.

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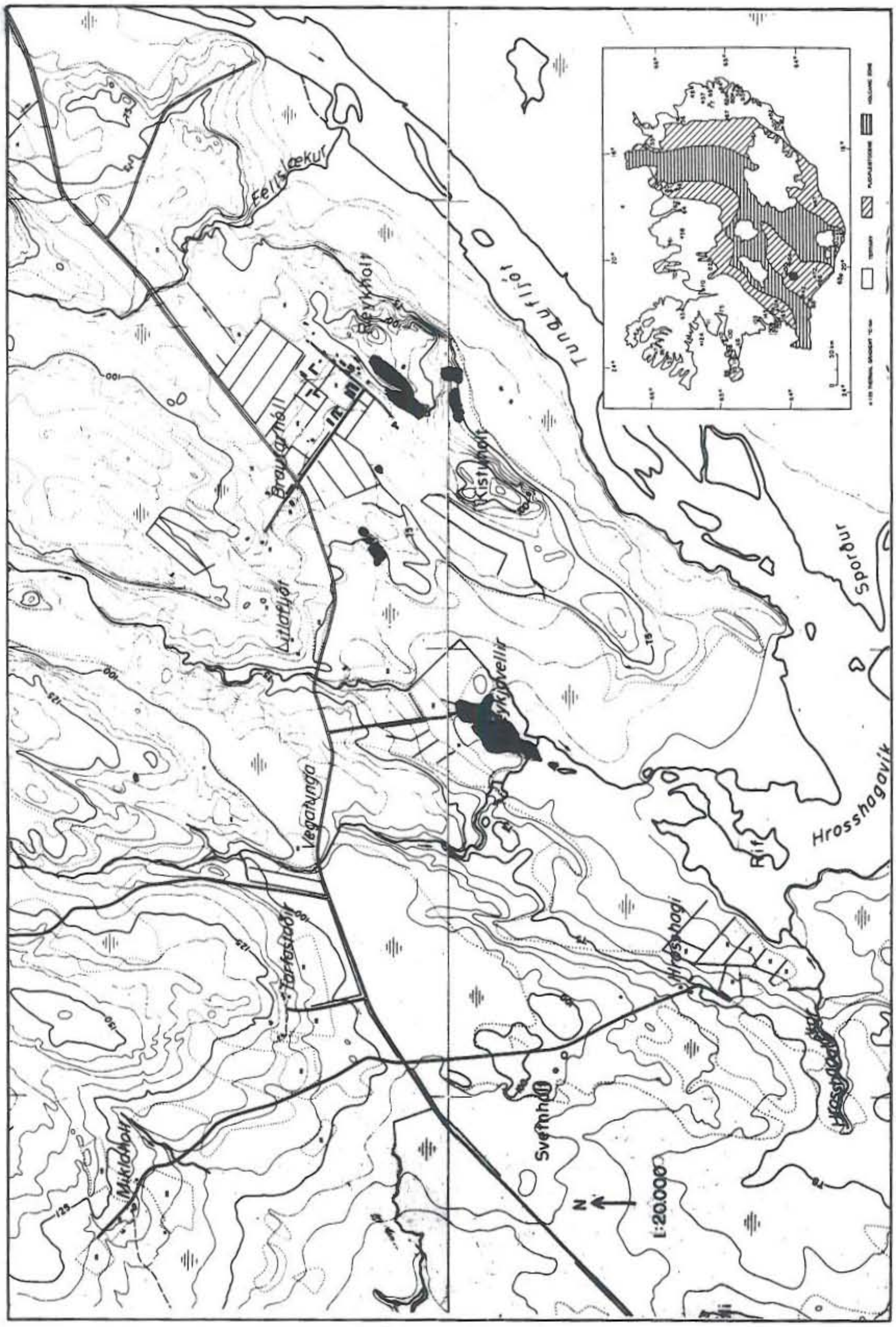

Fig. 1: Location of the areas under study.

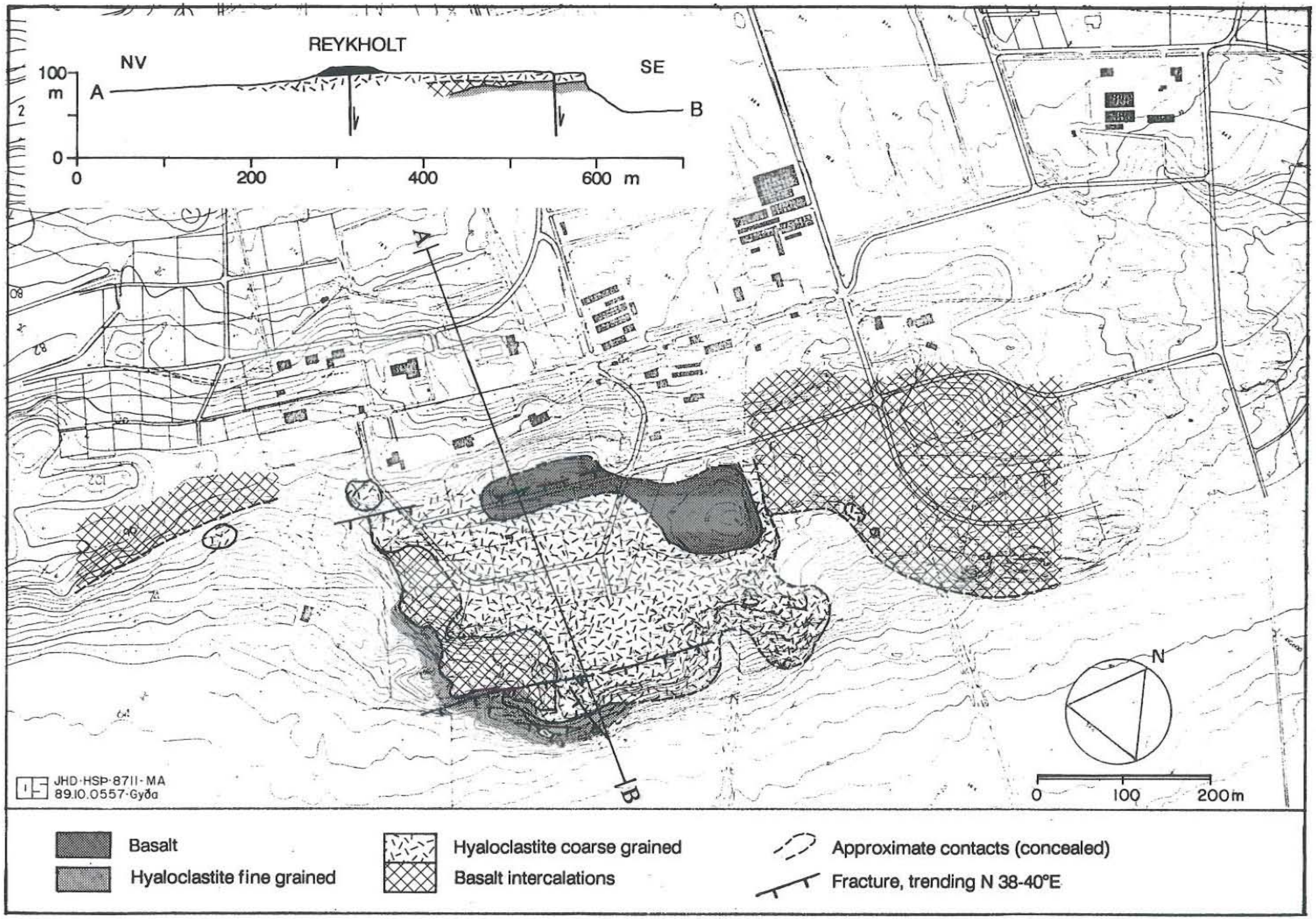

Fig. 2: Geological map of Reykholt area

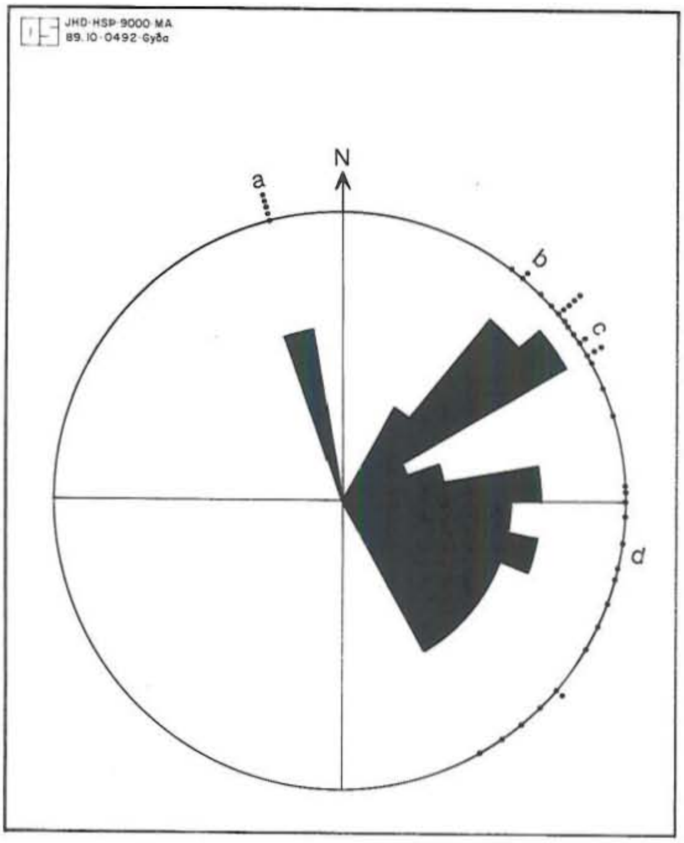

Fig. 3: Structural survey carried out in August 1989, outlining,

- a: fractures dipping steeply (>80°) towards west. No offset.
- b: prominent fractures in Reykholt. Some that did not cross the measured lines have throws of several meters.
- c: fractures of small throw dipping steeply, some to NW some to SE.
- d: faults with throw of several meters to south mostly.

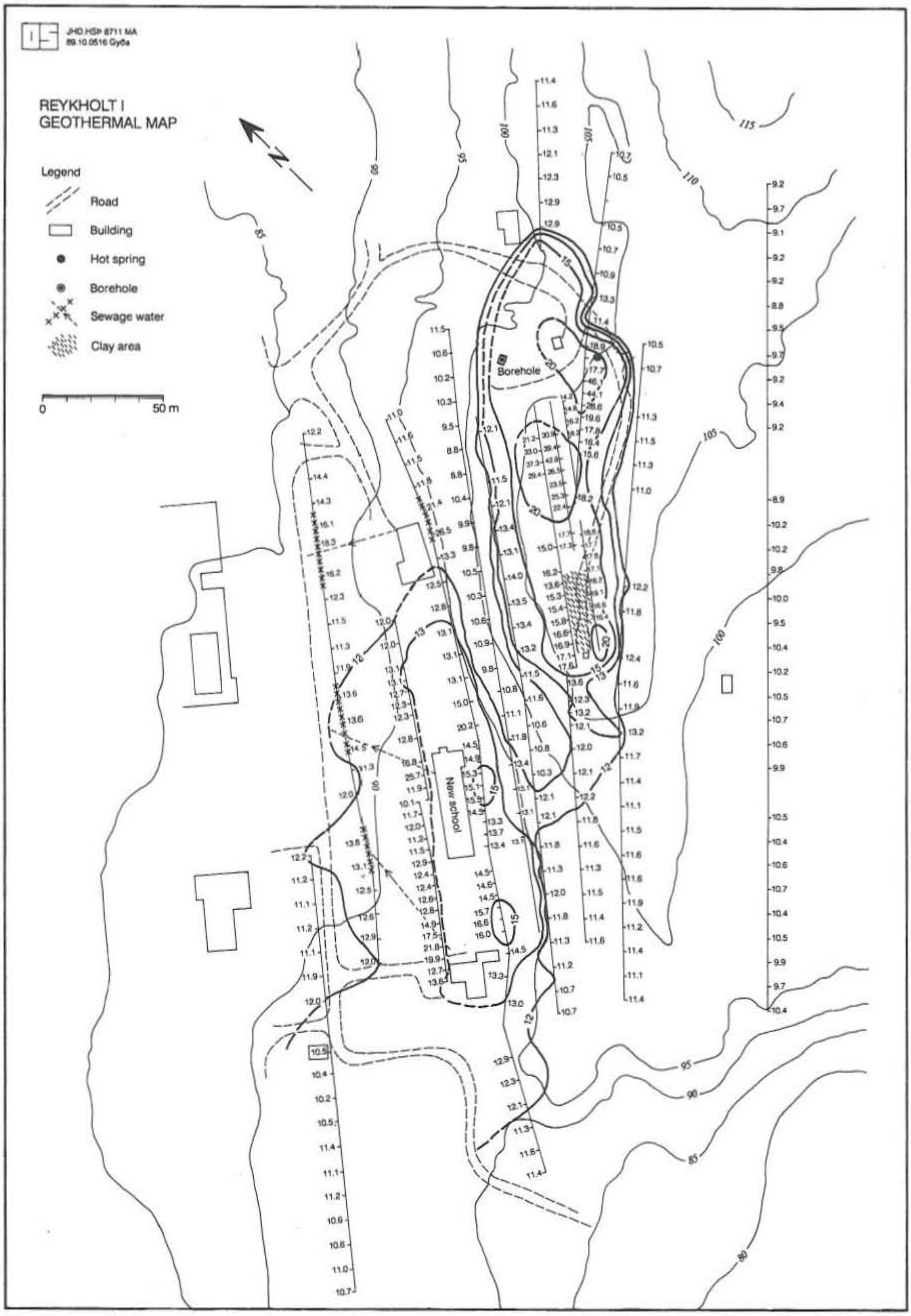

Fig. 4: Reykholt 1. Geothermal map based on measurements at 50 cm depth. The measurements were taken in August 1989.

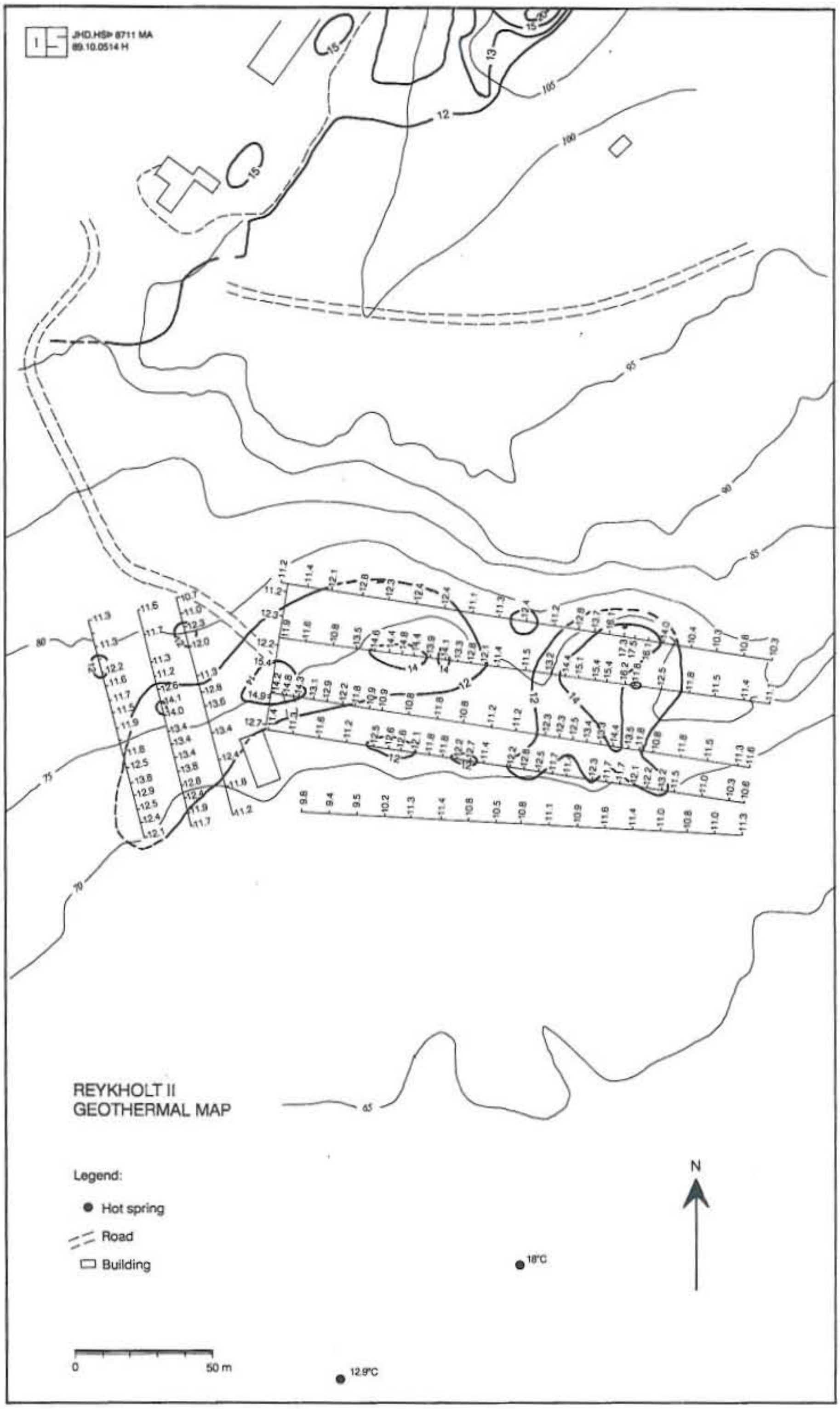

Fig. 5: Reykholt 2. Geothermal map based on measurements at 50 cm depth. The measurements were taken in August 1989.

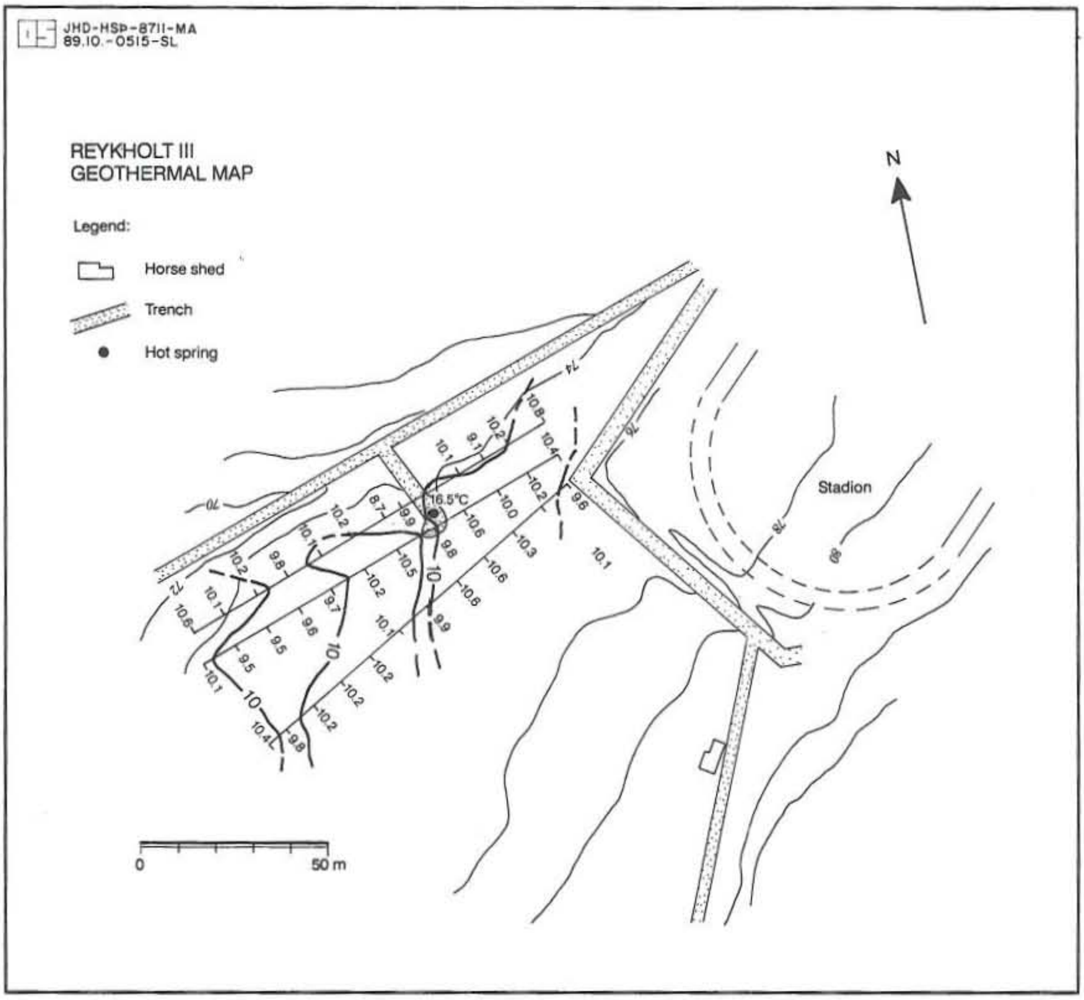

Fig. 6: Reykholt 3. Geothermal map based on measurements at 50 m depth. The measurements were take in August 1989.

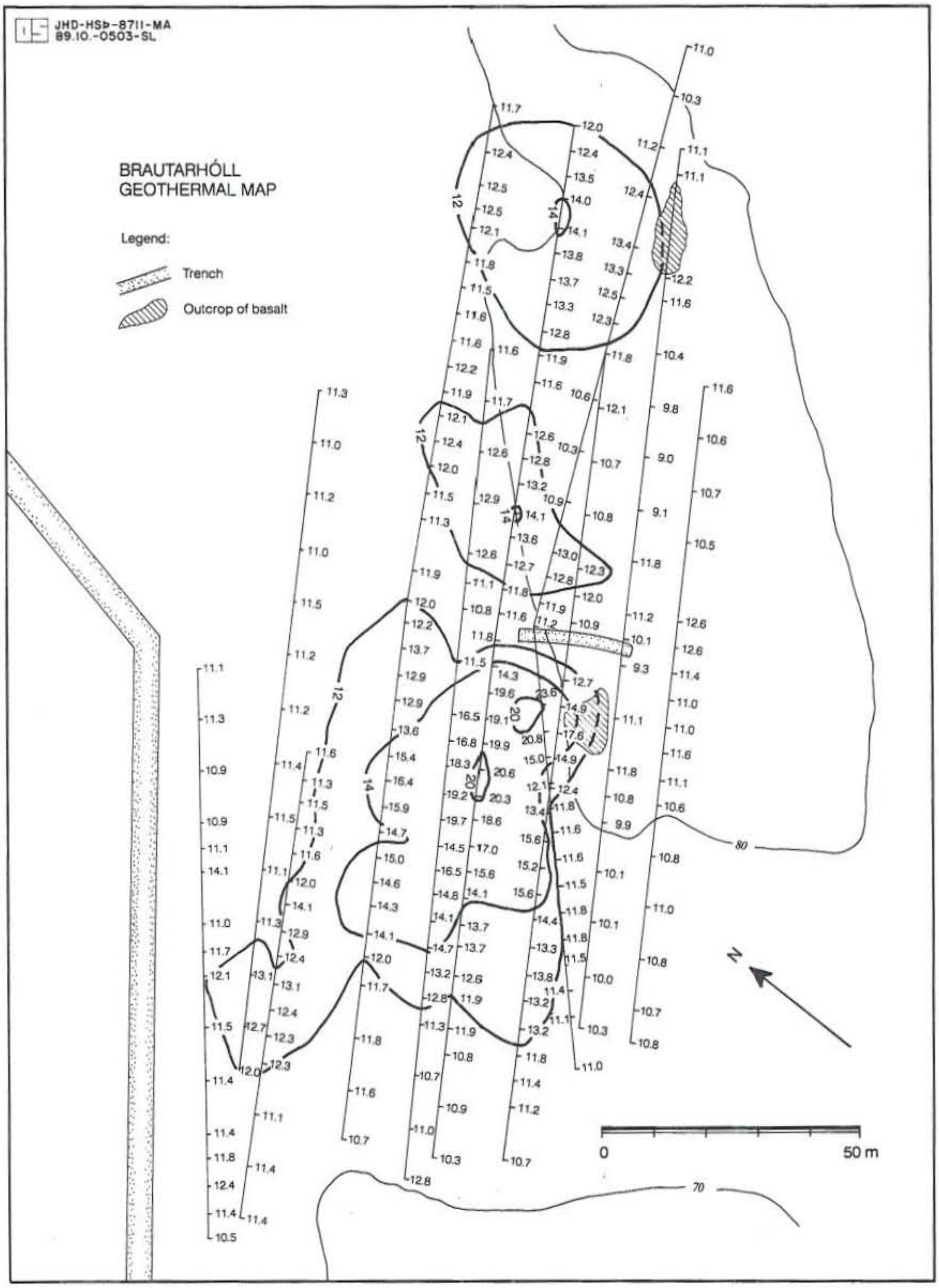

Fig. 7: Brautarhóll. Geothermal map based on measurements at 50 m depth. The measurements were taken in August 1989.

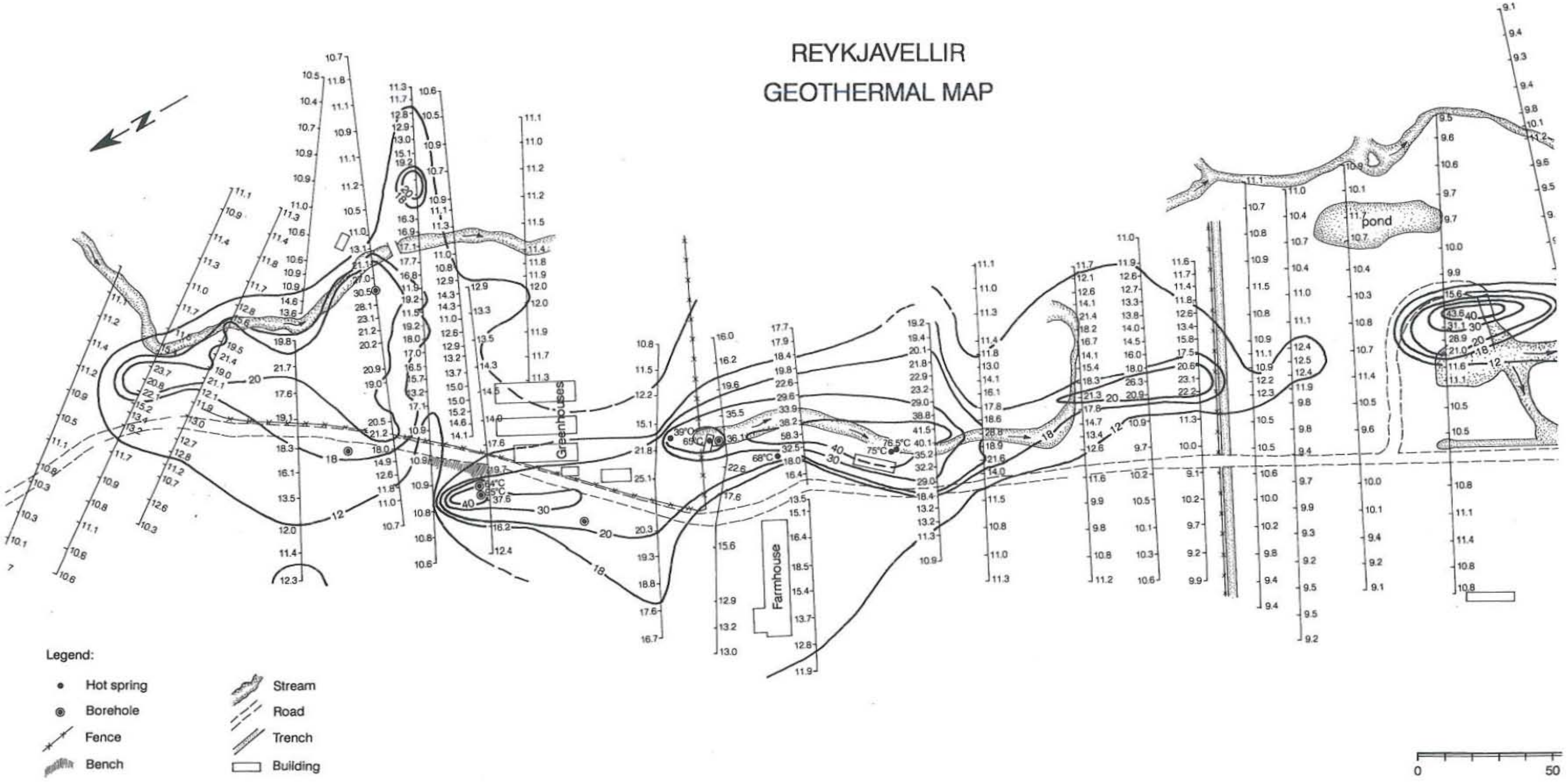

Fig. 8: Reykjavellir. Geothermal map based on measurements at 50 m depth. The measurements were taken in August 1989.

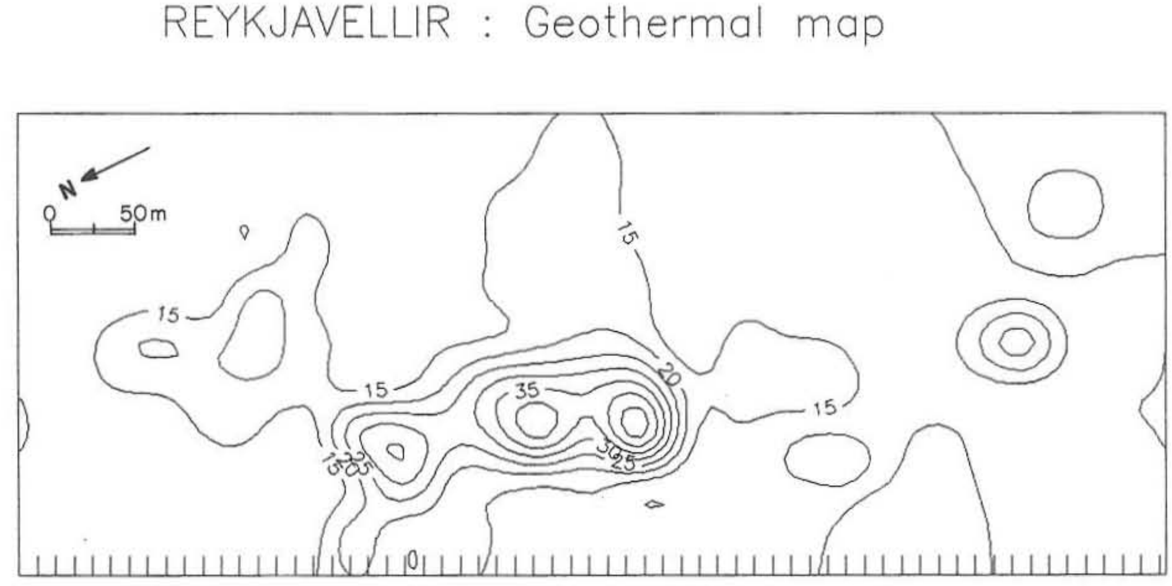

Fig. 8a: Geothermal map of Reykjavellir, made by computer.

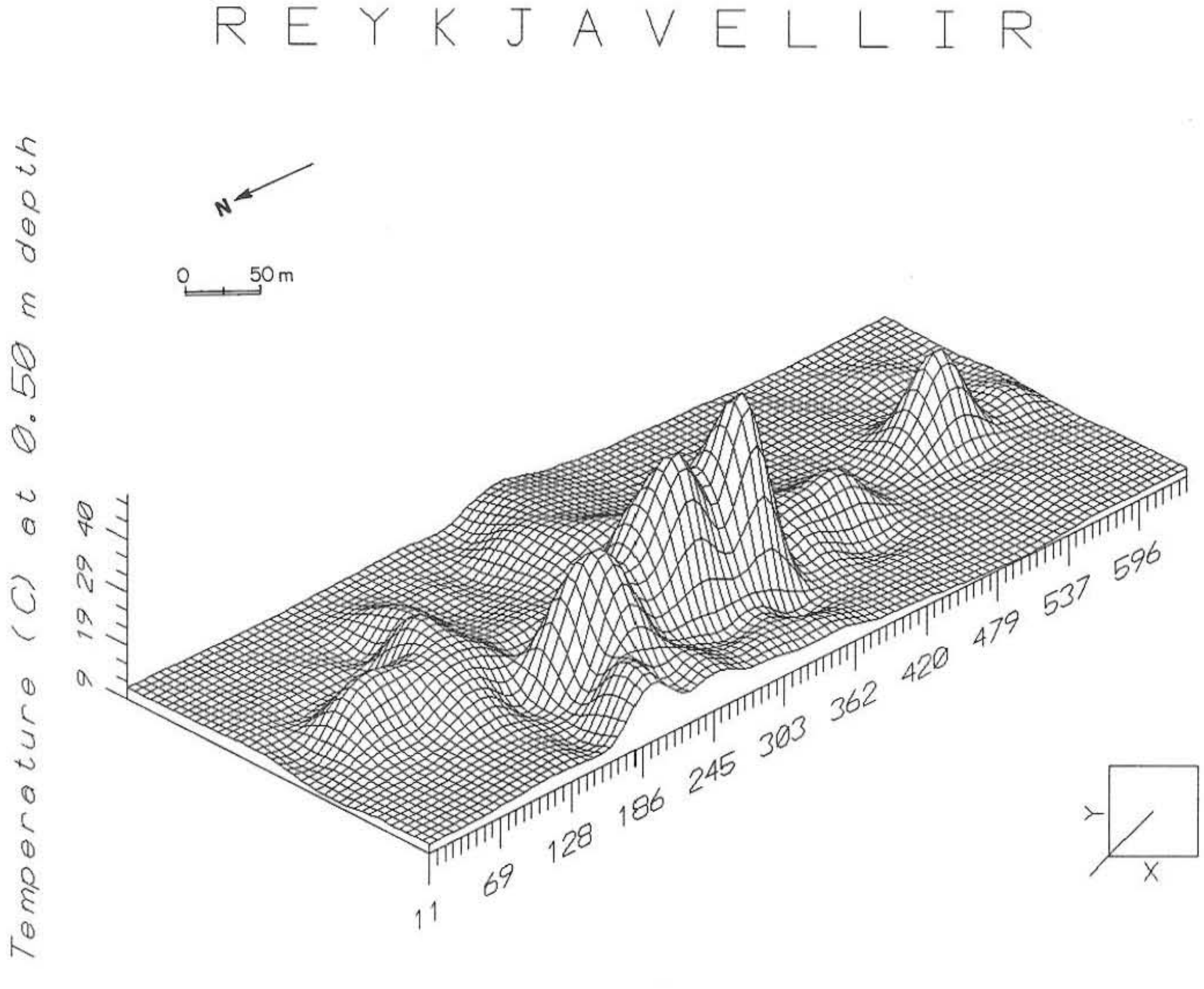

Fig. 8b: Geothermal map of Reykjavellir. Three-dimensional representation, made by computer.

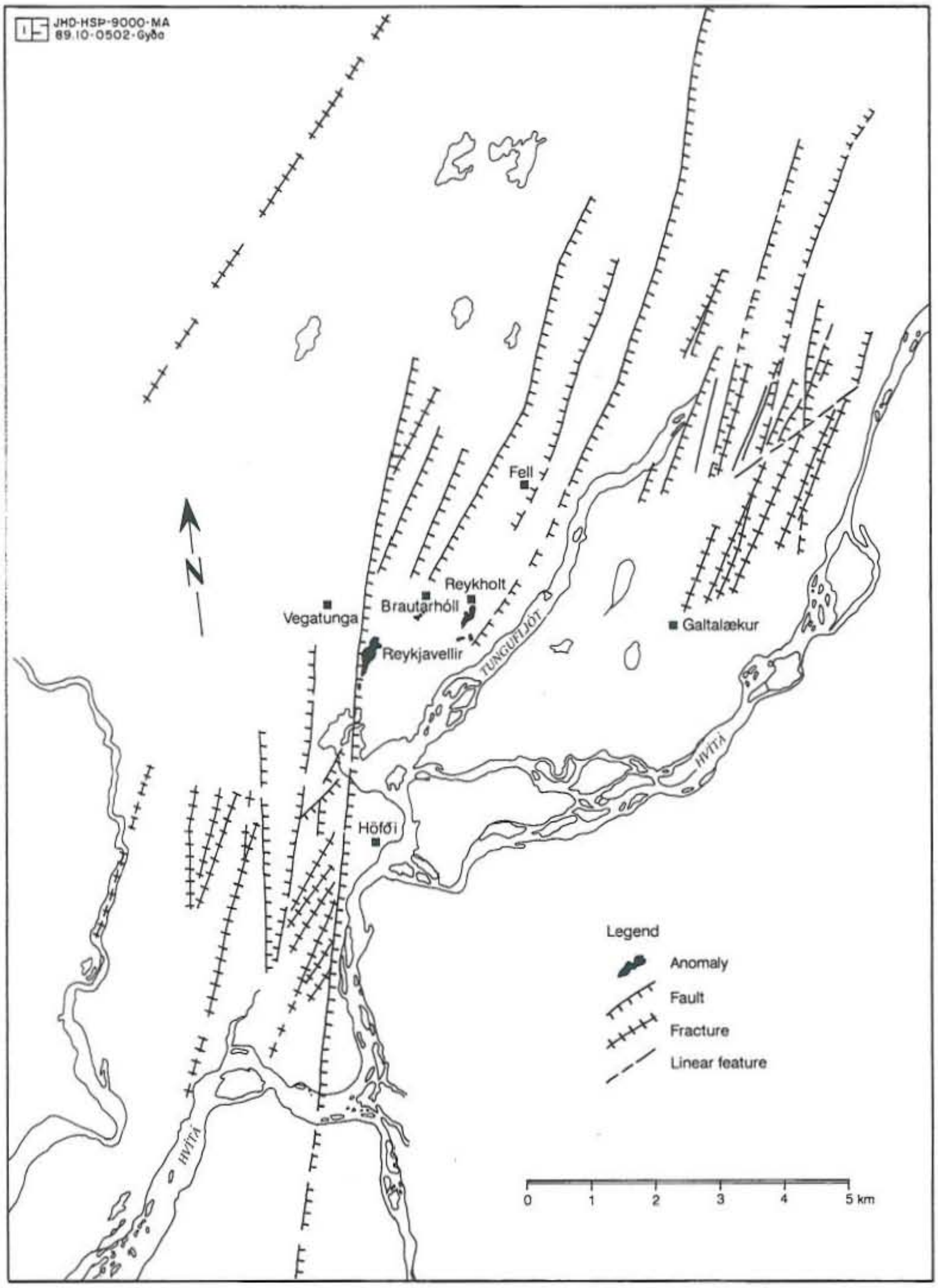

Fig. 9: Hot springs in the Reykholt-Reykjavellir areas in relation to the tectonics.
Hot springs areas of Reykholt-Reykjavellir are shown in outline according to the present survey.
The tectonic map is by H. Franzson (1977).
One linear feature (fracture or fault), prominent on air photographs, trending NE-SW has been added to the NE of Reykholt.

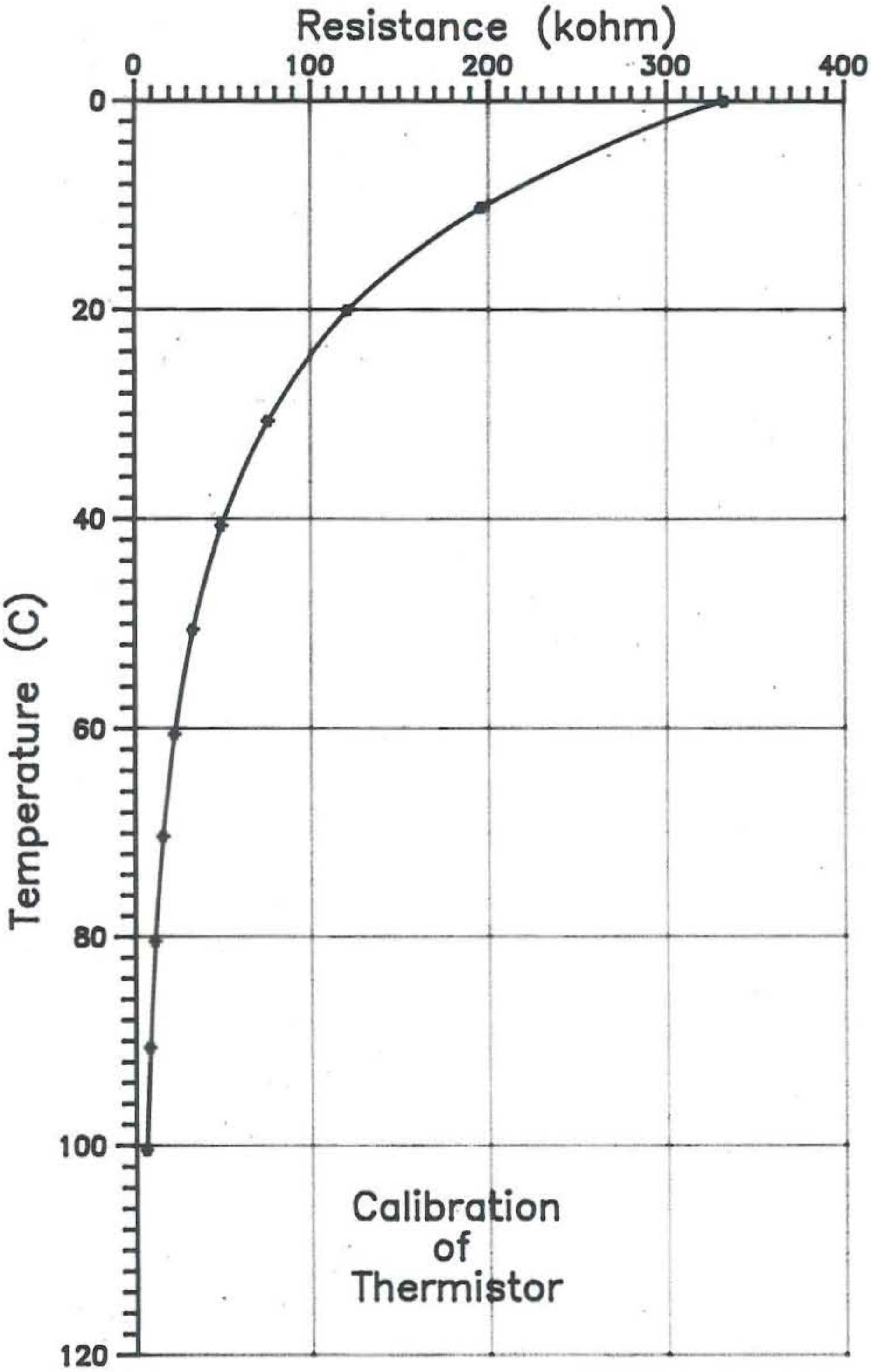

Fig. 10: Calibration curve (linear)

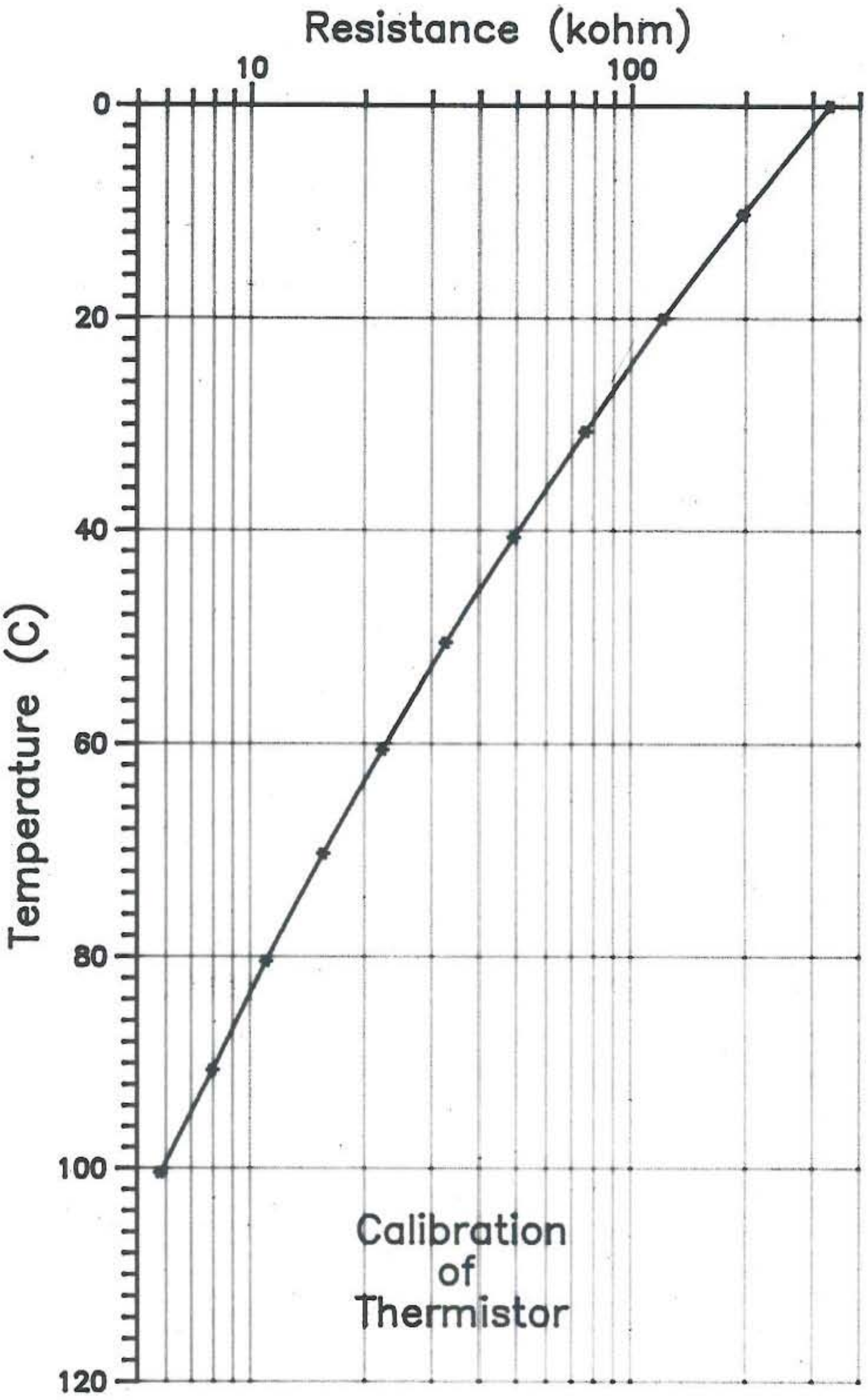

Fig. 11: Calibration curve (logarithmic)

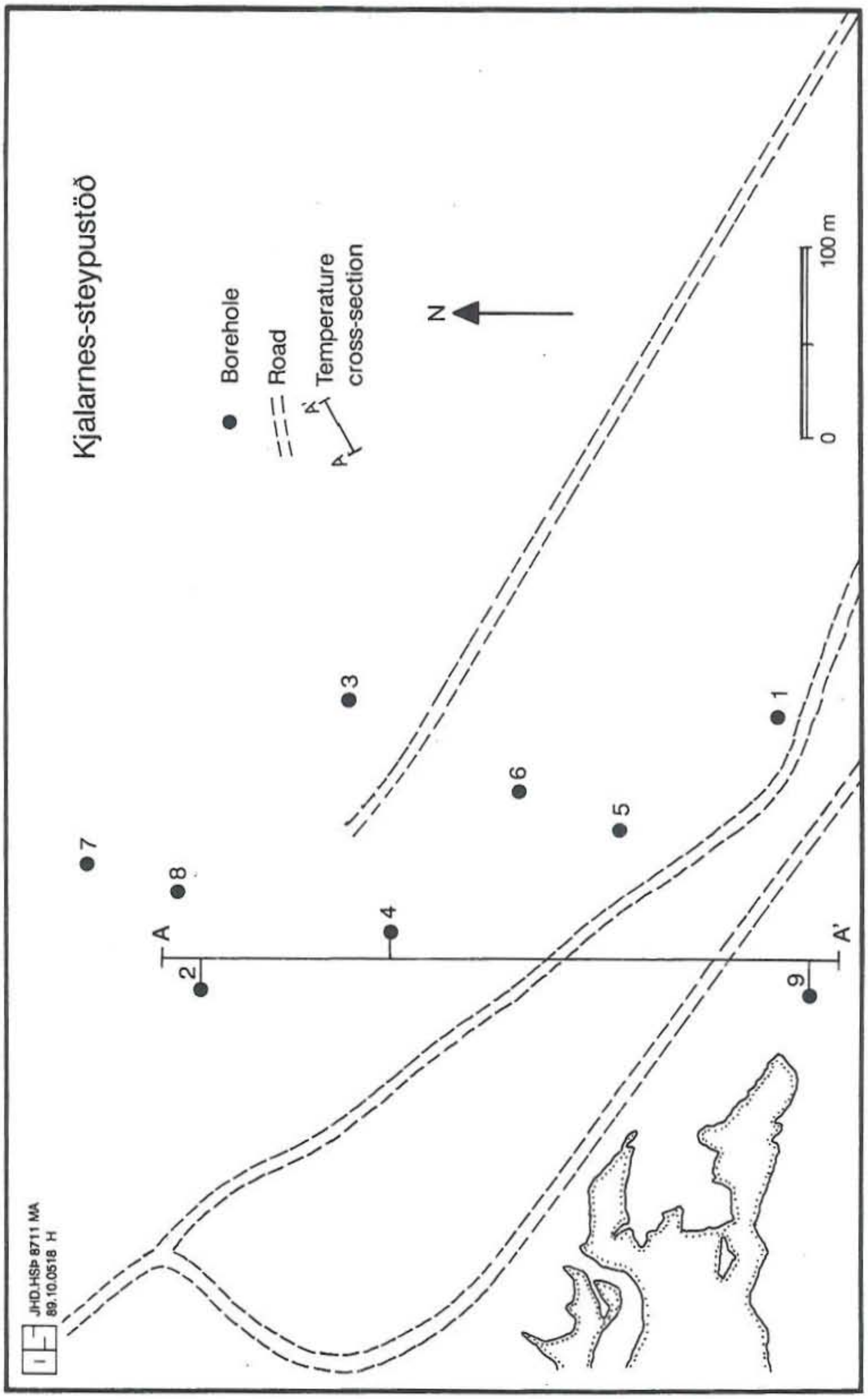

Fig. 12: Location of the wells (at Kjalarnes-Steypustöð)

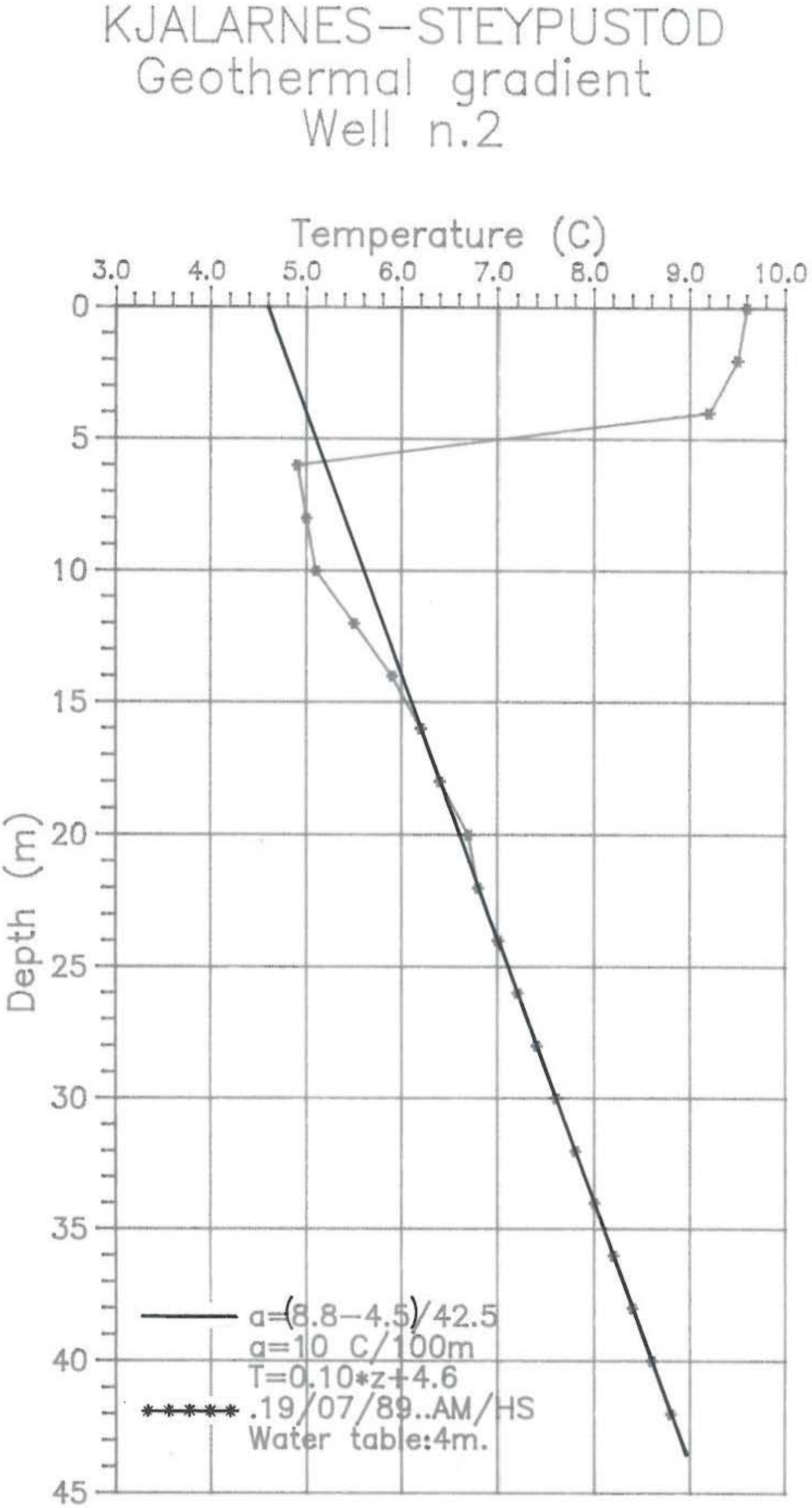

Fig. 13: Temperature profile, well 2

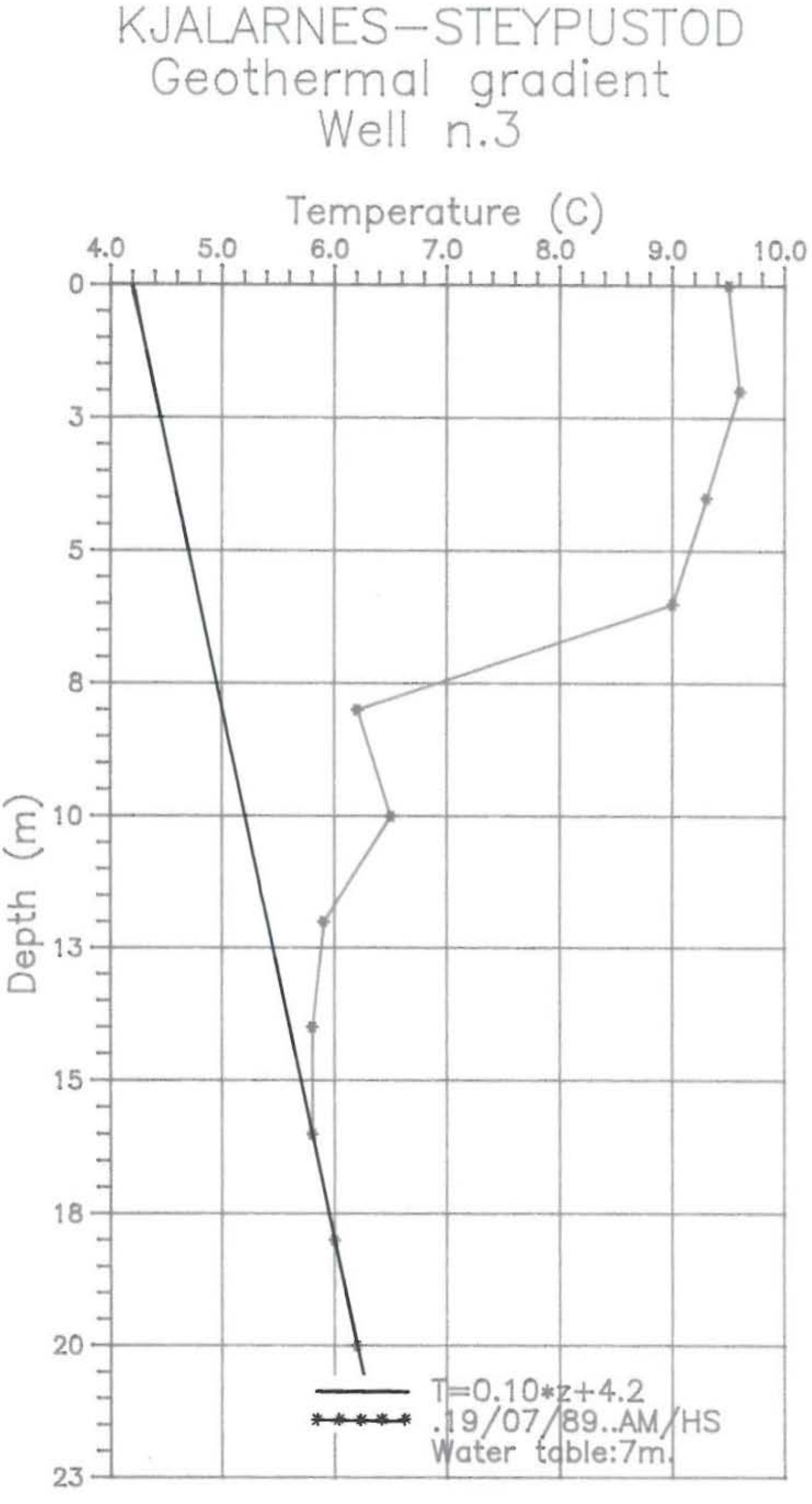

Fig. 14: Temperature profile, well 3

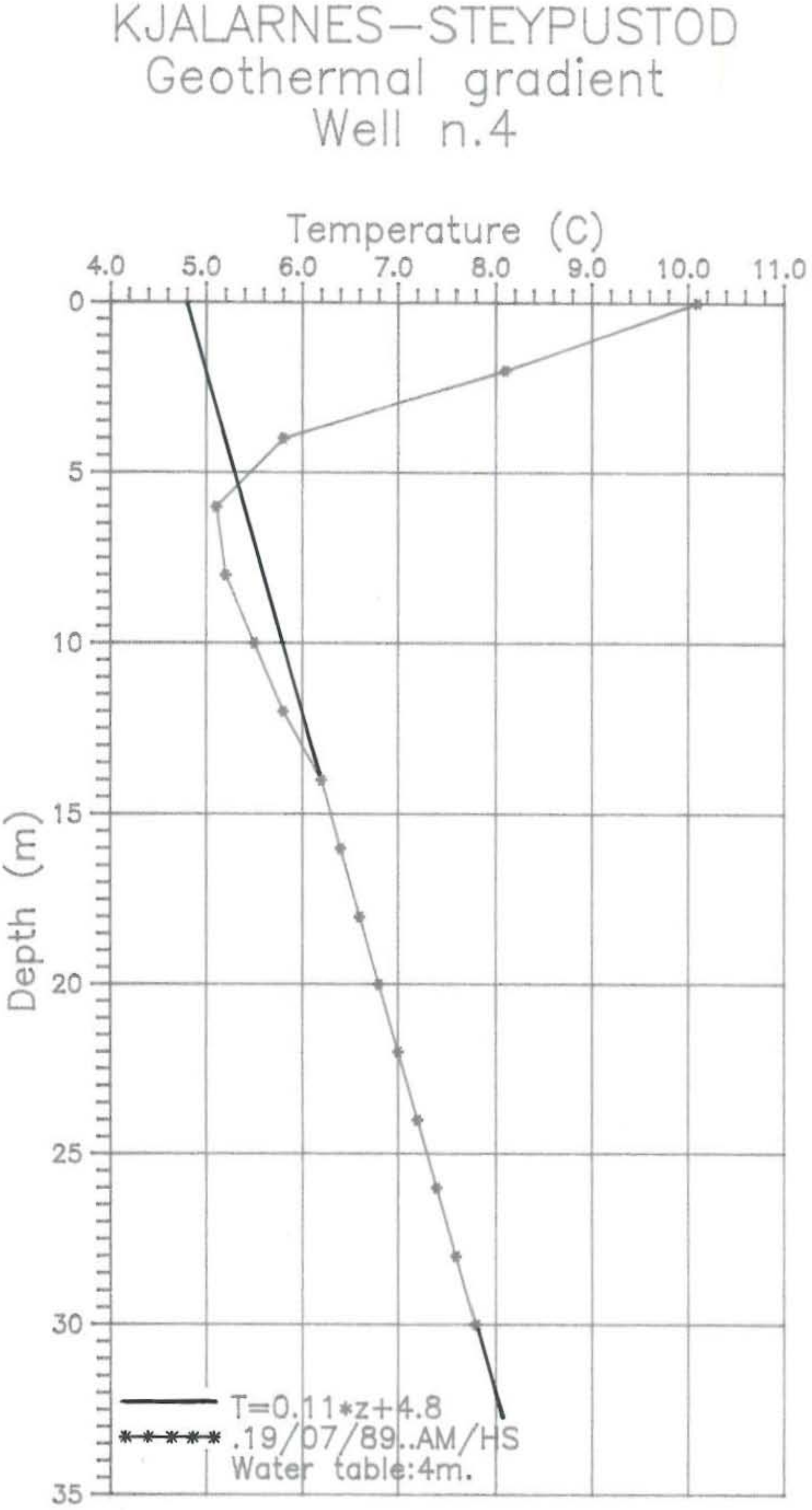

Fig. 15: Temperature profile, well 4

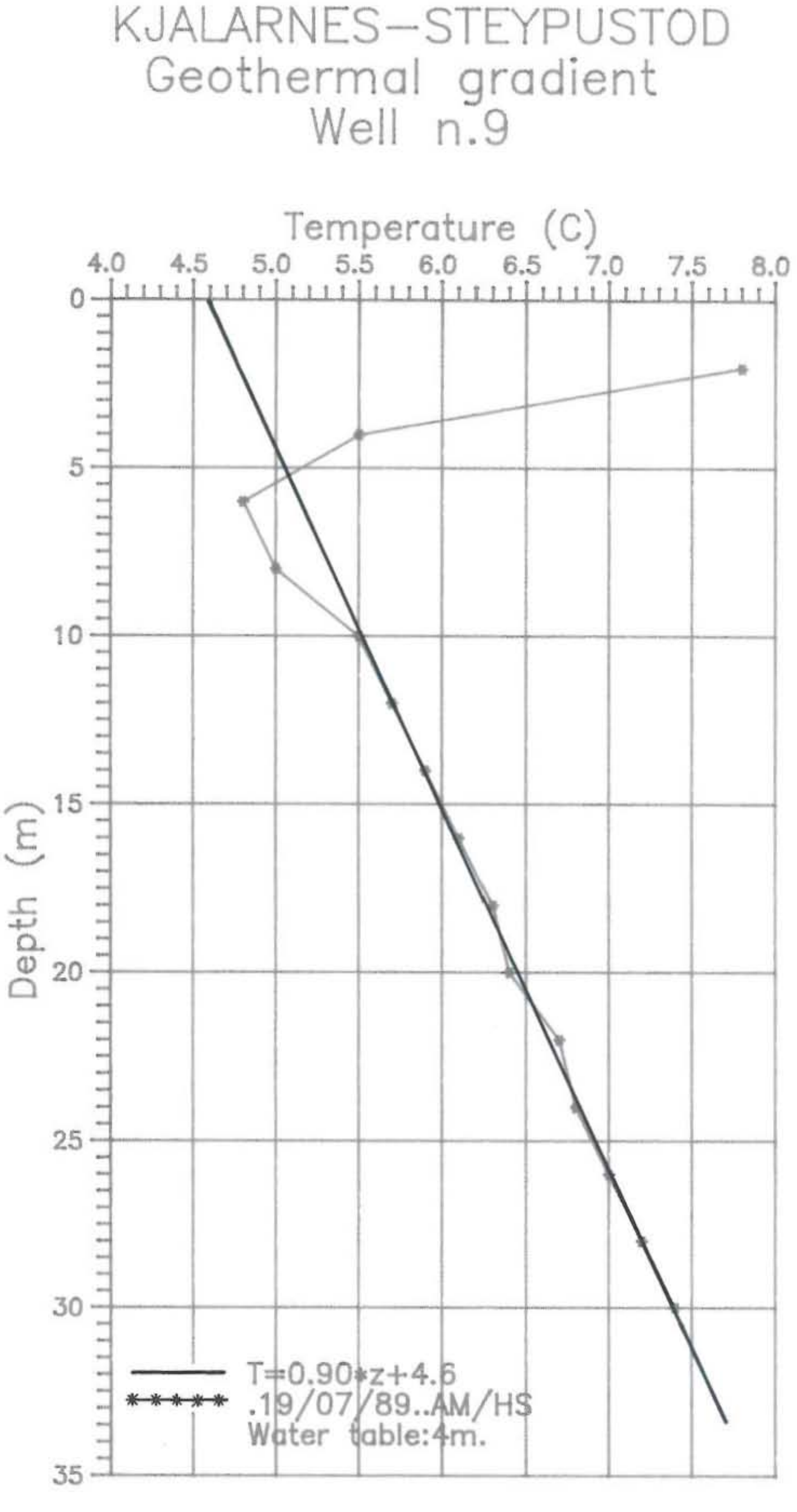

Fig. 16: Temperature profile, well 9

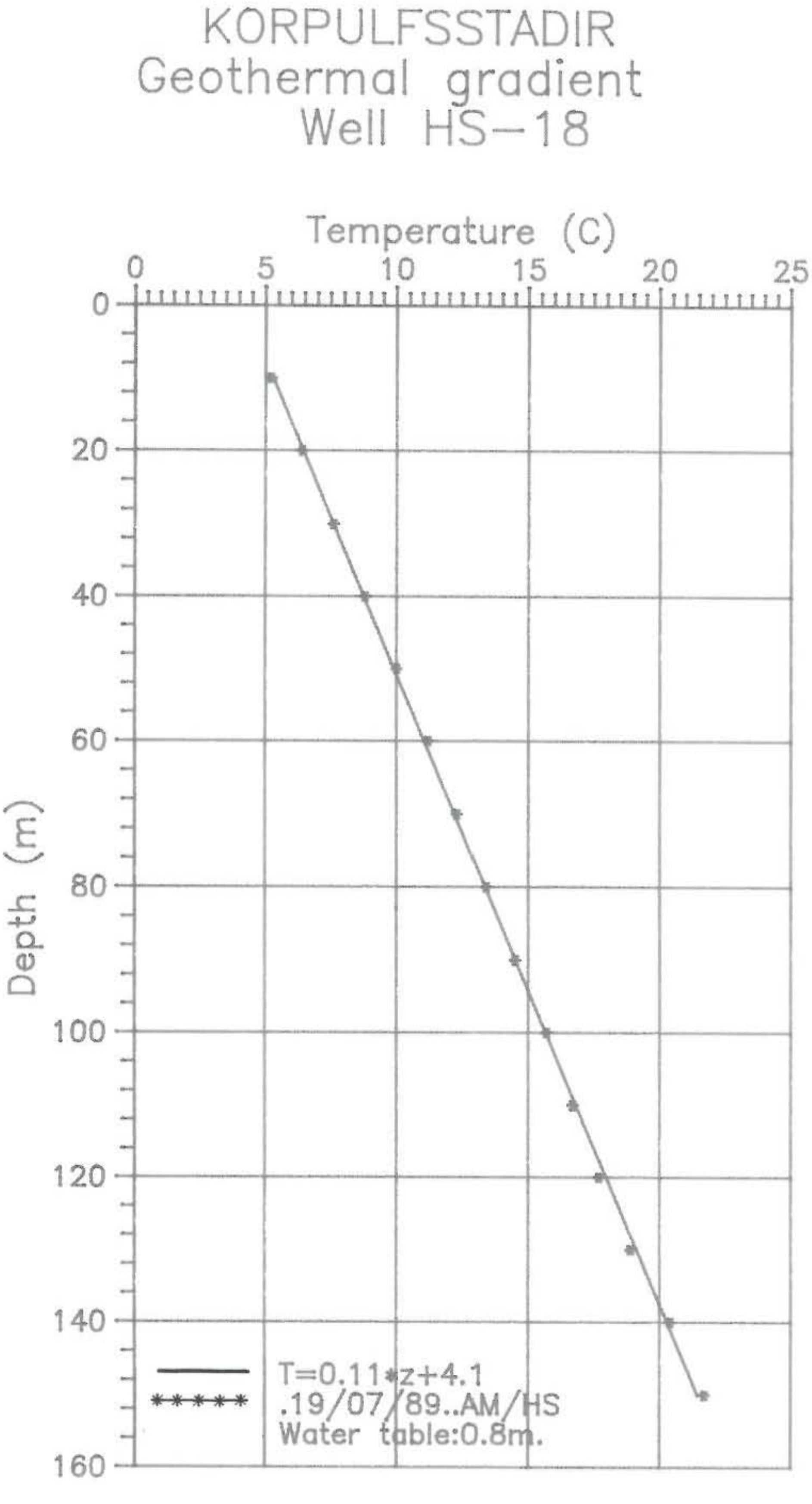

Fig. 17: Temperature profile, well HS-18

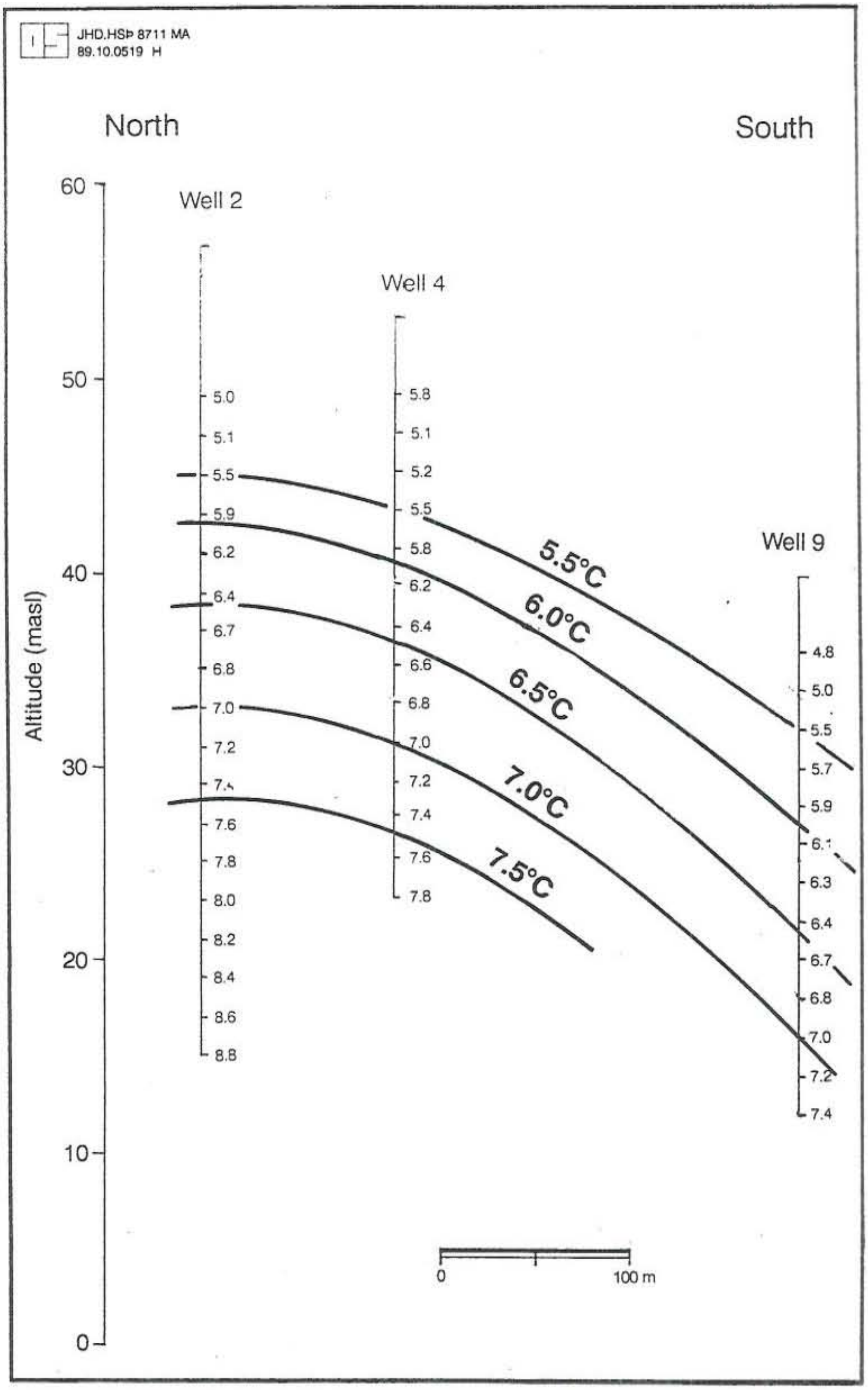

Fig. 18: Cross section through well 2, 4 and 9

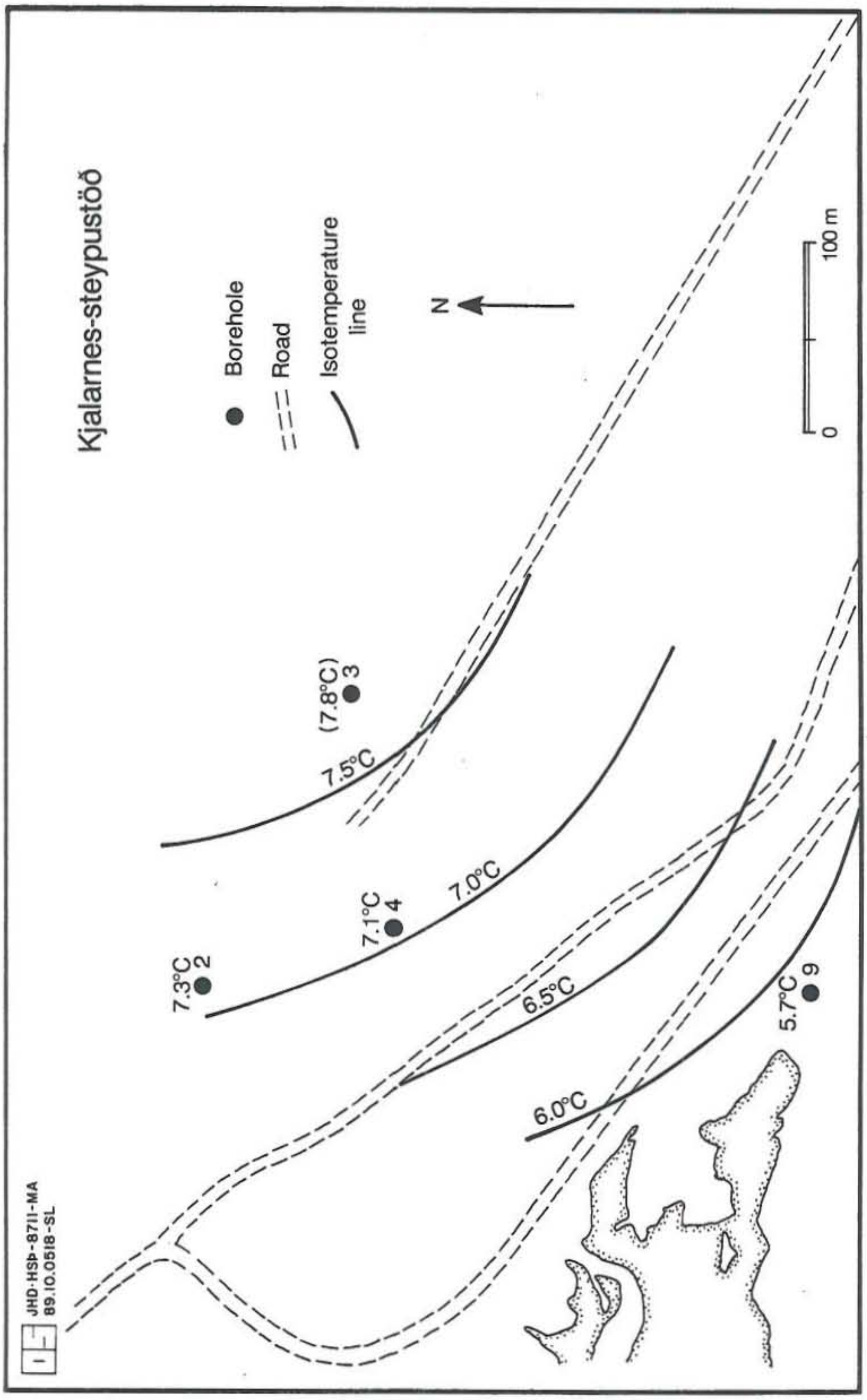

Fig. 19: Temperature distribution at 30 m a.s.l