

## GEOLOGY AND GRADIENT WELLS

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### ABSTRACT

Drilling of gradient wells is a method used in exploration of both high- and low-temperature geothermal fields. The applicability of the method depends on the permeability of the subsurface rock and the depth to groundwater. Low permeability is a prerequisite for the method to give reliable results because it is very important to avoid disturbance from internal flow of water inside wells. The drilling depth is accordingly anywhere from a few tens of metres to a few hundred metres. The latter may be necessary in areas of young or unaltered volcanics and low ground water level (such rocks are also as a rule costly to drill and secure from caving in). In fracture controlled low-temperature fields shallow boreholes come out best. This method has been applied also in high-temperature geothermal fields both as a regional survey and as testing the validity of indirect evidence (from geology or resistivity) of a potential. It is clear that knowledge of the hydrological conditions of the prospect area is needed, and also familiarity with the basic principles of hydrogeology.

### 1. THERMAL GROUND SURVEY

Drilling of gradient boreholes is in a way an extension of a ground temperature survey (temperature measured at 50-100 cm depth). In Iceland this method has been applied both in low- and high-temperature geothermal fields, partly with a different purpose in mind, however. In the low-temperature areas the method is used to outline the areal extent of an anomaly, its size and shape with the purpose of siting a hot water borehole. An example is shown from a left lateral fracture zone in South Iceland (Fig.1,2 and 3). Warm springs in a bog with draining ditches indicated a thermal upflow. The ground survey suggested two parallel NE-SW trending fissures. Well number 1 was shallow but used for two decades. Well 2 was

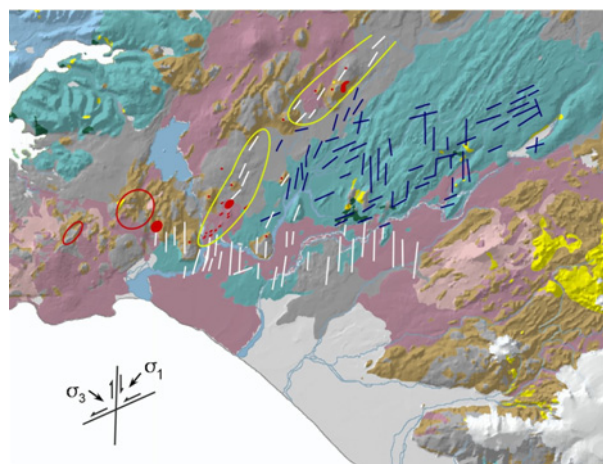


FIGURE 1: South Iceland Seismic Zone (a transform fracture zone) connects the two rift zones in South Iceland. It is characterized by a conjugate set of N-S and ENE-WSW faults. They are shown white where active and blue where extinct, indicating a former position north of the present location

unsuccessful. Well 3 struck a fissure and yielded plenty of 59°C water but the temperature was inverted at 115 m depth indicating lateral flow along the fissure system.

In high-temperature fields the method (ground temp. survey) has been applied only once in Iceland, in one of the smallest by area (Reykjanes) to estimate its thermal output. However, the main profit there was of a different kind, i.e. giving a basis to record changes, first decline of surface activity over a period of 40 years followed by a dramatic increase. This occurred after beginning of production on a large scale and thickening of a steam zone as a consequence of drawdown. A thermal ground survey of this kind was carried out in the Eburru and Olkaria geothermal fields at the early stage of prospection (Noble and Ojiambo 1975). It extended and outlined the shape of many fumarole fields in a clearer way than could be judged from the manifestations alone in a hot and dry climate at day time. No changes due to exploitation of the fields have been observed there.

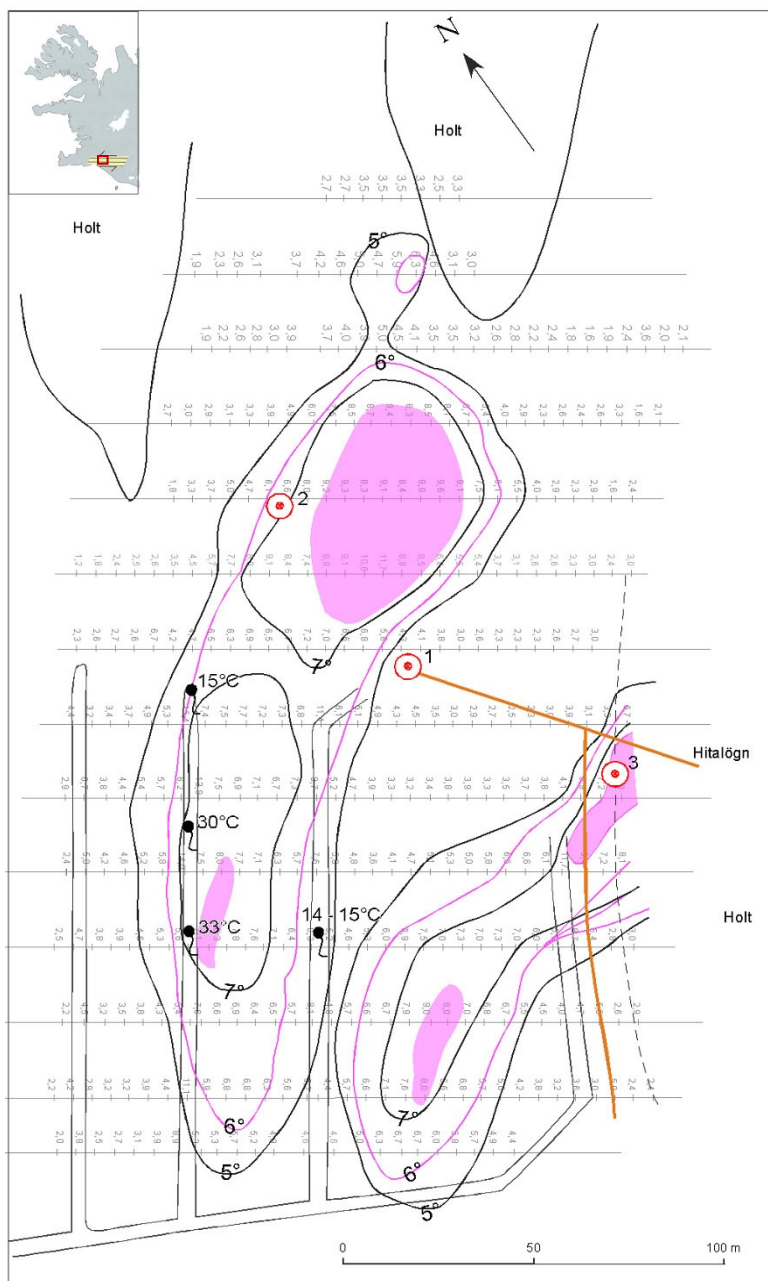


FIGURE 2: Example of a soil temperature survey. The locality is in the western part of the South Iceland Seismic Zone (SISZ).

Warm springs are found in drainage ditches dug in a wet bog. Soil temperatures of over 10°C at 60 cm depth are shown in pink. Holt to the northeast and east are hills where Pliocene bedrock (basalt) is exposed. The survey was made in December. The trend of the thermal anomalies follows the trend of earthquake fissures which are the main targets for hot water drilling in the SISZ. Two en-echelon segments of a N-S main right lateral strike-slip fault were found

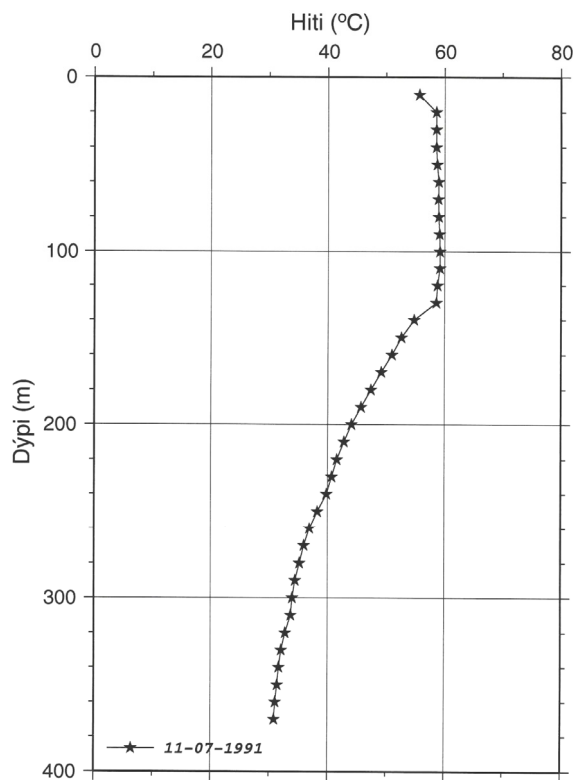


FIGURE 3: Temperature profile of SH-3 (of Figure 2). Plenty of 59°C hot water was found in a fissure from 70-120 m depth. The fissure was permeable down to ~250 m but the temperature inverted below 120 m, indicating lateral flow from higher ground to the North

## 2. LOW-TEMPERATURE GEOTHERMAL FIELDS

In low-temperature areas gradient boreholes need to be no deeper than 30-60 m if the permeability is low. The regional geothermal gradient must be known also as a basis for recognizing thermal anomalies. The greater the difference, the better are the prospects for success. The method has proved most useful in areas where the geothermal system is confined to a fracture of local extent. In Iceland many exploitable geothermal systems have been discovered by this method where there were no surface manifestations. Figures 4 and 5 from West Iceland are an example. The very high near surface gradients stem from a convective geothermal system. In this case it proved to be 85°C extending with constant temperature from 400 m down to at least 800 m (depth of production borehole). Fracture controlled

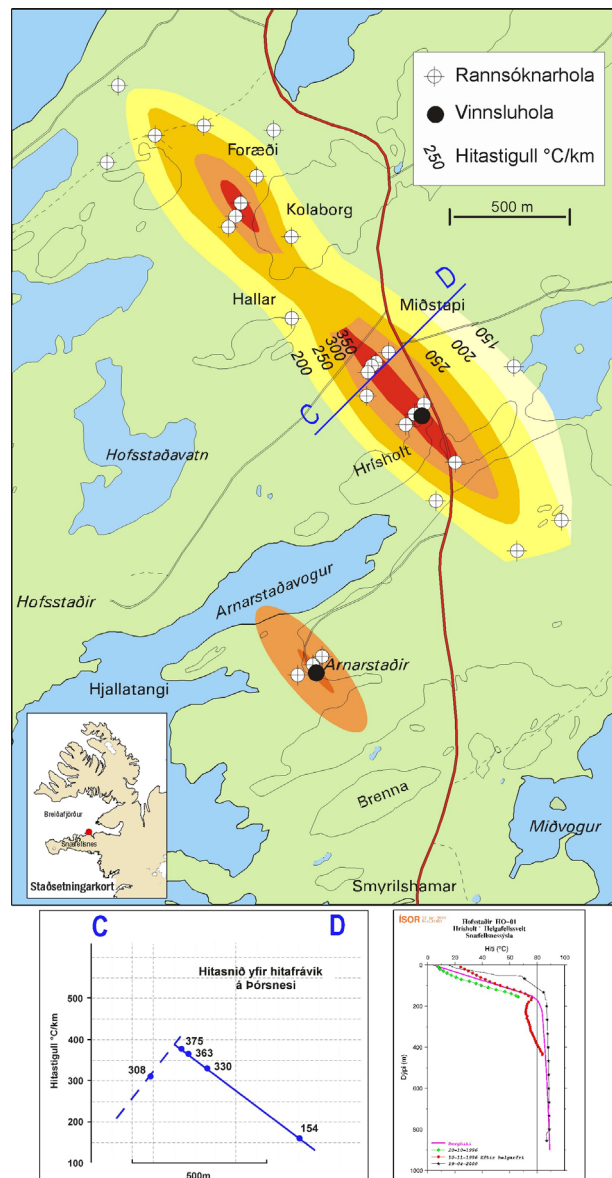


FIGURE 4: A regional thermal gradient survey was made of the Snaefellsnes Peninsula. An indication was found here in the first shallow borehole. This was followed up by further drilling of shallow wells (60 m deep, on average 2 were drilled per day). The outcome is shown on the map. A production borehole was drilled vertically into the peak of the larger anomaly. It produced about 20 l/s of 85°C hot water from a single fissure which was cut at 810 m depth. A second reinjection borehole was drilled 1500 m to the NW with the purpose of intersecting the same fissure. It was struck at 400 m depth with a similar yield and water temperature. Interference from a pressurization test occurred within less than 5 minutes.

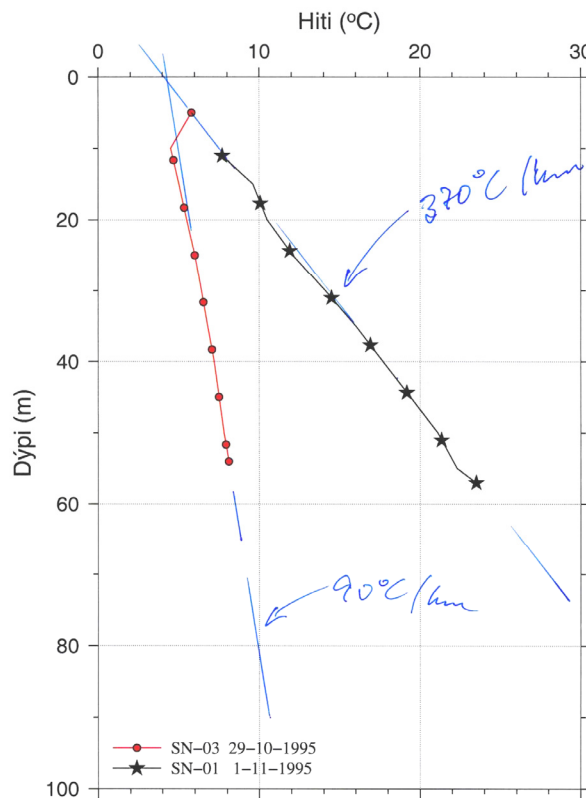


FIGURE 5: Thermal gradient in area of Figure 4. The bedrock there is zeolitized Miocene basalt lavas of very low permeability. Two shallow boreholes, 1500 m apart, show near surface regional gradient, versus local anomalously high gradient. Such high values as found in SN-1 can only be explained by an underlying geothermal system. There are no surface indications of a geothermal system in this area

## 2. HIGH-TEMPERATURE GEOTHERMAL FIELDS – FROM GRADIENT WELLS TO EXPLORATORY DRILLING

For interpretation it is important to know the basic character of a high-temperature geothermal system. Typically there is boiling groundwater at some depth from which steam and gas are boiled off to escape at the surface (fumaroles, solfataras, mud pots, hot ground). Sometimes the steam and gas get drowned in a (perched) near surface aquifer (in areas of sedimentary cover, Kaldakvísl). At low altitude the reservoir water may flow out forming flats of silica sinter deposited from boiling springs, often with geyser-activity (spout intermittently).

Drilling of gradient wells is sometimes applied in high-temperature areas. Gradient boreholes may be shallow or deep depending on the nature of the near surface rock. Preferably they should reach well down into near impermeable rock (due to alteration). Shallow boreholes (<100 m) in permeable rocks are not likely to yield temperatures much higher than 100°C, but they may show meaningful areal temperature variations and thus extend surface indications downwards (example from Djibouti, Stieltjes, 1976). In Iceland 40-60 years ago shallow wells were drilled in the midst of fumarole fields

geothermal systems can develop anywhere, also in areas of low geothermal gradients including the continental average of  $\sim 30^{\circ}\text{C}/\text{km}$ .

Sedimentary basins are probably the most extensive hot water reservoirs. As regards those it would be sufficient to compile data on the sedimentary fill, permeability of the different sedimentary units and their facies changes. Many basins have been targets in oil prospection in particular molasse basins, but also sediment filled continental rifts.

The second main issue here is the geothermal gradient. The Hungarian basin e.g. gives high but variable values ( $50\text{-}70^{\circ}\text{C}/\text{km}$ ) (Rybach and Muffler, 1981). Basic information on such parameters often exists but may not be open as it is owned by private companies. Faults may add significantly to permeability and dilute a brine fluid (commonly found in basin fills) by recharge from precipitation.

in Námafjall, Hengill, Krýsuvík and Reykjanes, (Figure 6) using inappropriate equipment, and insufficient casing.

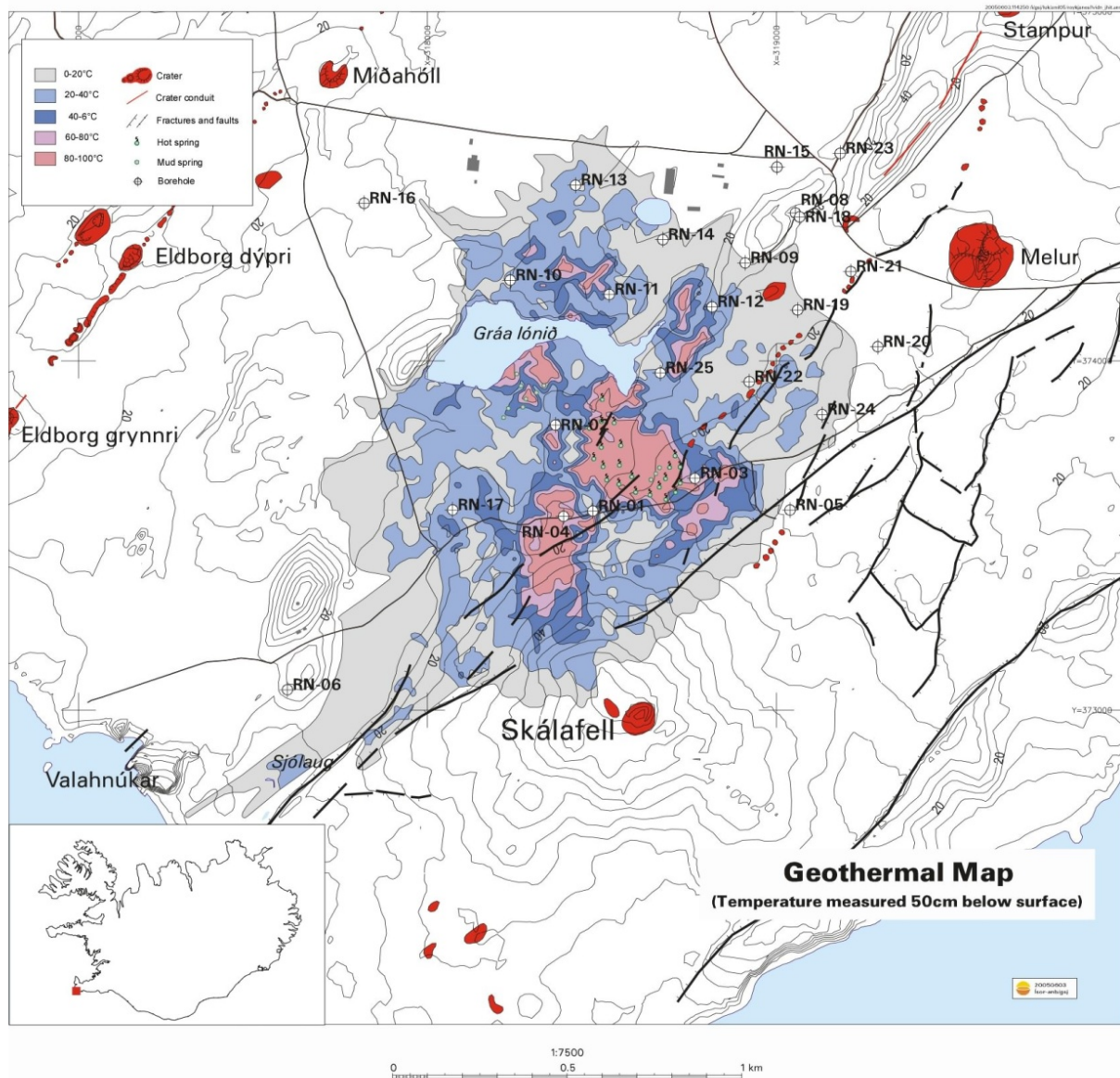


FIGURE 6: Ground temperature survey of Reykjanes, a high-temperature geothermal field at the tip of the Reykjanes Peninsula, SW-Iceland. The bedrock is Holocene basalt lavas. The first boreholes (RN-1-4) were drilled in the hottest part of the field. They all failed due to overpressure and insufficient casing (collapse). Borehole 5 was drilled to the east of the thermal anomaly. It failed also because of caving in of unaltered and unstable rock. It was drilled close to a fault and ended at 100 m. The first successful borehole (RN-8) was drilled into altered hyaloclastite 100 m northeast of the hottest area.

The hyaloclastite is part of a NE-SW ridge system (constructional features show up in height contours). It proved later to be the main upflow zone of the field

The main purpose was to produce steam and locate a good production zone. Most of the boreholes ended in blow-up and/or collapse. Their depth varied from less than 100 m to over 300 m. Temperature logs were obtained only from the last ones drilled. Some of those boreholes have been blowing to this day. At Námafjall they emit dry steam and attract tourists not knowing how they came about. At that time a few boreholes, interestingly some of the first ones, were also drilled on more stable ground well away from the fumaroles (Krýsuvík). Those could be kept under control and they yielded valid information about subsurface temperature, in fact were useful gradient boreholes as

planned. Those early attempts failed because knowhow was insufficient to complete a shallow borehole into a steam zone underlying a highly active fumarole field. The subsurface extent and trend of such a field, however, could have been judged from the thermal gradient in boreholes drilled into altered rock some distance away.

Shallow gradient boreholes may give a misleading result. An example from Krýsuvík, Iceland (35 years back) is shown (Figures 7 and 8). Down to 300 m depth the results look promising, and no indication is seen of the temperature inversion, which occurs at greater depth. A recent example from Krafla is of interest. There a resistivity survey (Figure 9) was followed up by two shallow step-out boreholes (well away from the production area) and a third full-scale production hole where the prospects looked best - but proved the worst. One of the shallow boreholes showed the prospective resistivity anomaly to be cold the other to be hot as was inferred from surface geology. The latter was followed up by a production borehole, which was a success.

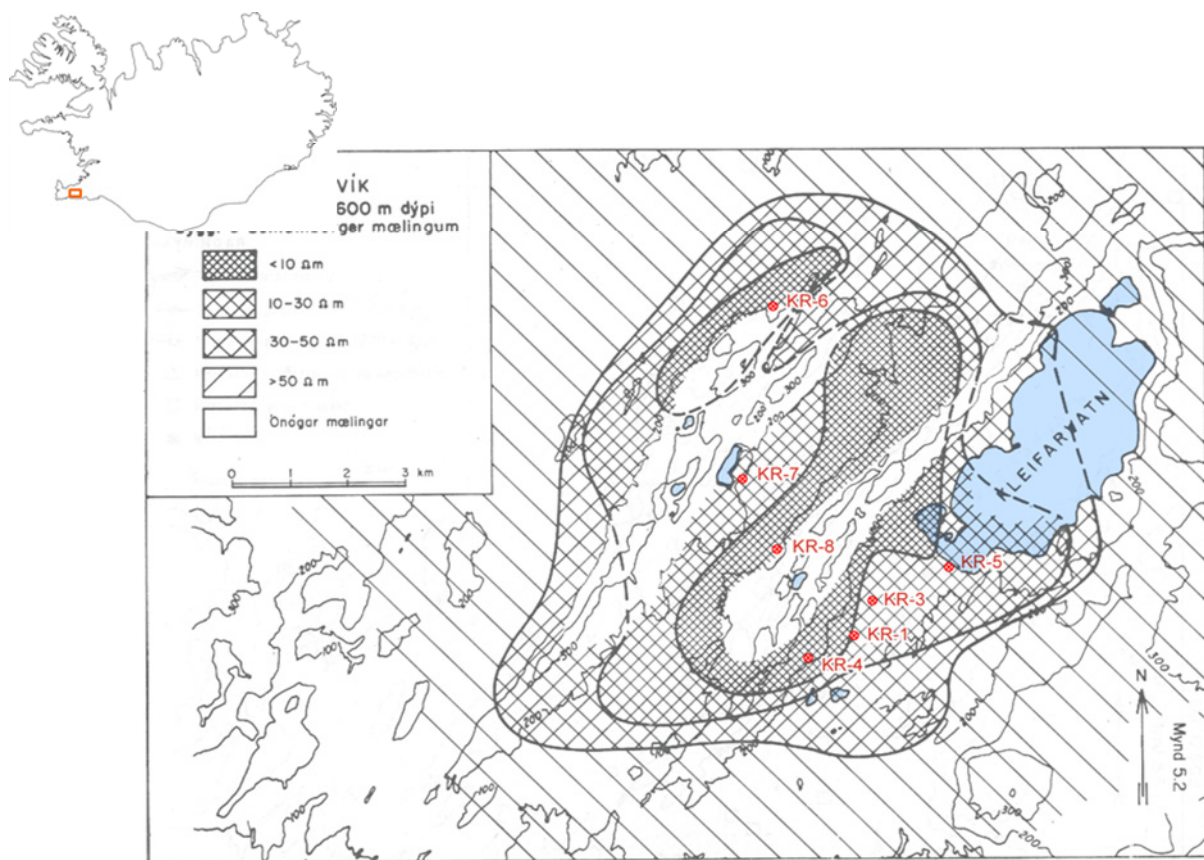


FIGURE 7: Krýsuvík. Resistivity at 600 m depth. Krýsuvík is the largest geothermal field by area on the Reykjanes peninsula, SW-Iceland. Geological structure, thermal manifestations and resistivity surveys indicate NE-SW trending prospective zones superimposed on a circular area, possibly a caldera. The markings show the location of moderately deep exploratory wells that were drilled 35 years ago. None of them found an upflow zone. Exploration by deep drilling is being taken up again these years concentrating this time about zones where eruptive fissure cluster

In Iceland the method (drilling of shallow gradient wells or medium depth exploratory wells) is not used as an early step in subsurface exploration, except where resistivity alone indicates a resource. Gradient boreholes or more often deep exploratory boreholes are drilled to follow up surface exploration if the results of the various methods correlate tolerably well.

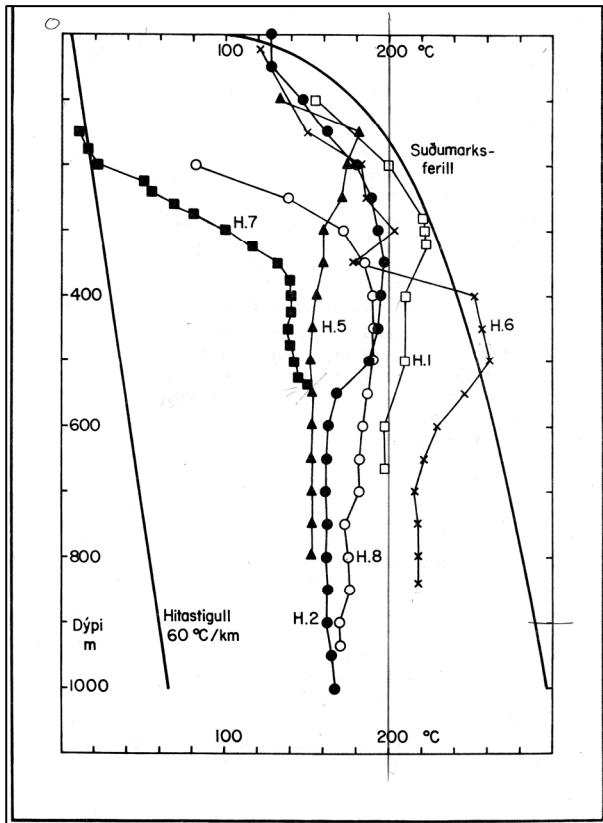


FIGURE 8: Temperature logs of exploration wells at Krýsuvík, shown in Figure 7. Down to 300 m depth none of the wells indicated the temperature inversion which occurred at greater depth. Gradient wells of 300 and in some cases 500 m depth would in this case have been misleading

(due to old age and exhaustion of the heat source) or a drop in water level (hydrostatic pressure) which might have occurred in the course of geological time. Think of pluvial periods (high lake stands) in low latitudes equivalent to glacial periods at high latitudes.

A geothermal gradient map was compiled of the Campi Flegrei geothermal field, within a caldera west of Napoli, Italy, from 30 to 140 m deep water wells (Corrado et al. 1998) (Figure 10). High but variable gradients were found within the caldera. Correlation of the local anomalies with small magma bodies as suggested by the authors seems rather doubtful. Viewed against other information such as structural features, hydrology, and the occurrence of geothermal surface manifestations the map seems to add little to the deep structure of the field. On the other hand it is a good basis for monitoring changes both associated with natural unrest and exploitation if such come about (deep drilling has revealed temperatures of 300-400°C below 1500 m depth).

The lessons to be learned are that gradient or exploratory wells should be drilled down to at least 500-1000 m. Such wells are usually drilled vertically. Inclined wells in the deeper range would be appropriate in rift zones, especially for the purpose of testing the permeability of vertical (or near vertical) fissures and dykes. Such may act as high-permeability anomalies and optimal feed zones (Hengill, Eldvörp). The most important information to be gained would be a temperature profile of the prospect area as compared with the alteration state of the rock. A misfit (high alteration state but low rock temperature) may indicate cooling of the system

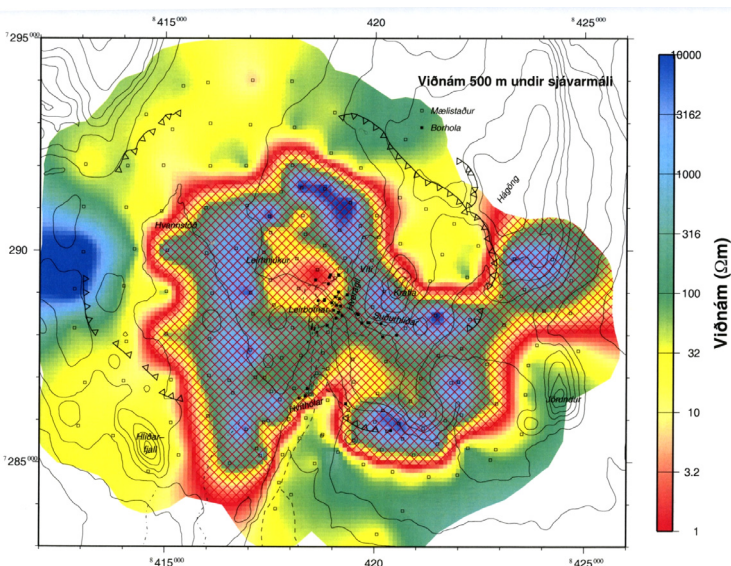


FIGURE 9: Resistivity map of Krafla at 900 m depth. The outline of the Krafla caldera is shown. Drilling of a gradient well into the anomaly east of the caldera proved it to be cold, probably an extinct part of the geothermal system from the time of its „youth“. A deep well drilled into the large anomaly which extends furthest south showed it to be a hot outflow zone. A sharp temperature inversion occurred below it, contrasting with high temperature alteration of the rock mass, but in accord with the high resistivity. The outflow is restricted to the uppermost permeable 500-800 m metres showing up as a low resistivity zone

It is important at an early stage of geothermal prospection to investigate the hydrology of the surrounding region such as precipitation, catchment area (for likely recharge), and depth to groundwater level, general flow direction and content of dissolved solids (get access to data from appropriate authorities). The last is an important issue to avoid locating deep wells in outflow areas too far off from upwelling geothermal plumes. The ground water level may be low (at several hundred metres depth) under large volcanic edifices which host a geothermal system. One way to get at them is by directional drilling.

Fumaroles are an indication of a boiling reservoir. Intensive fumarole activity and widespread hot ground (several hectares in extent) point to a steam zone at shallow depth (Figure 11, Námafjall). Such conditions call for precautions and an appropriate casing program when drilled into. In Iceland blowouts occurred under such conditions from time to time and are always time consuming and costly.

Temperature profiles are different in vapour dominated systems (nearly constant temperature and pressure with depth) versus water dominated systems where temperature increase is likely to more or less follow the boiling point curve at shallow depth. Temperature inversion commonly occurs, always indicating a marginal location or a mushroom character spread or outflow (Figure 11).

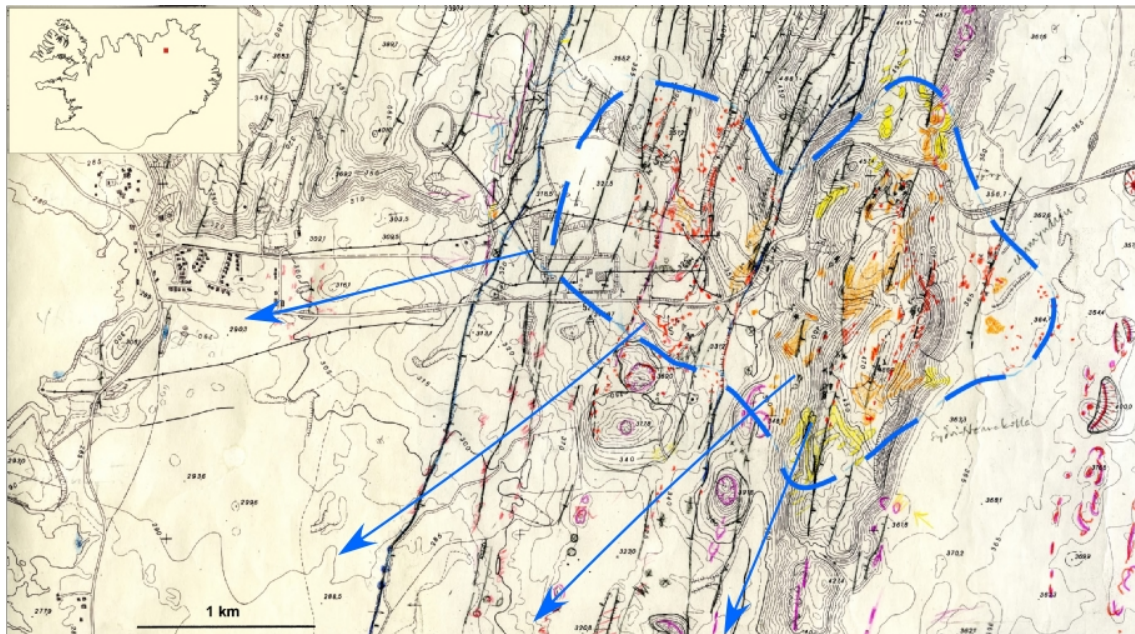


FIGURE 11: Geothermal map of Námafjall high temperature field in NE-Iceland

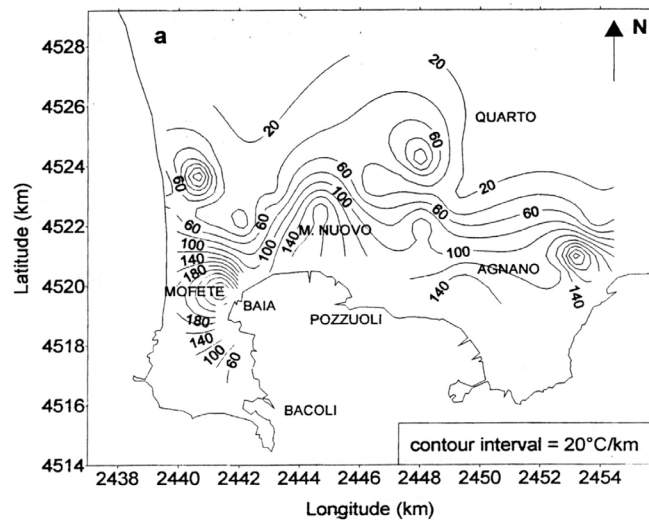


FIGURE 10: Geothermal gradient map of the Campi Flegrei high temperature geothermal field, Italy. The field is located in the northern half of a caldera. The map seems to be rather a blunt tool for concluding about deeper structure of the field, but may prove significant in volcano surveillance. Deep drilling (2000-2500 m wells have been drilled) revealed temperatures of between 300 and 400°C. (From : Corrado et al. 1998)



Námafjall high temperature field is 7 km south of Krafla on the same fissure swarm in NE-Iceland. As Figure 11 shows, Námafjall is traversed by a number of NNE-SSW faults and a few volcanic fissures. Hot ground and fumaroles depositing sulphur extend over large coherent tracts which follow the general fissure trend of the area. The first boreholes were drilled in the eastern part of the area 50 years ago. They struck into a steam zone and were difficult to keep under control. In the nineteen sixties 6 successful production boreholes were drilled in the western part of the field. They got plugged up by basaltic melt in 1977 (known because one of them erupted lava) when a dyke injection from Krafla intruded along the fissure swarm. The blue arrows (Figure 11) mark the outflow, which is 20-50°C hot at a distance of 1-2 km from the field.

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