Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Geothermal Surface Exploration in Iceland

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Keywords: Geothermal exploration, reconnaissance, surface exploration, geological prospecting, geophysical prospecting, geochemical prospecting, exploration wells, drilling, environmental assessment, conceptual model

ABSTRACT

The paper describes in a general way what kind of surface studies are carried out in Iceland in exploration of our geothermal high temperature fields. It is outlined what is required to engage in a complete exploration work in a new greenfield geothermal resource area. At present, this is usually what is needed to fulfil the requirements to apply for, or receive, exploitation rights in a geothermal area.

The aim of the work is based on three main components.

- The recognition of possible geothermal resources to develop.
- The geo-scientific work needed to estimate its size and potential.
- The project development work needed to be able to carry out the exploration, plan for the exploitation and estimate it's feasibility.

The recognition of a geothermal resource starts with a reconnaissance study. This is a project area assessment and the purpose is to collect as much information and scientific data as possible that is already available, regarding the geothermal resource. Usually this will result in the ranking of the area compared to other areas and first estimation of which areas are more promising than others.

The objectives of the geo-scientific work mainly consists of identifying the main geothermal reservoir and roughly estimating the size, reservoir temperature, energy potential and accessibility and putting forward a preliminary conceptual model. The area(s) that are deemed interesting will get to the next stage where the "run of the mill" geo-scientific research will be carried out. This stage is done through a series of different research methods.

The project development work will address technical, physical, environmental and economical factors connected to the expected utilization of the resource. One of the main outcomes of this work is a road map for the development of geothermal power, which can be a platform to put forward a strategy in the development of geothermal energy.

1. INTRODUCTION

Iceland is rich in geothermal resources due to the volcanic activity (fig. 1), and the heat flow through the crust is several times higher than the world average. Traditionally the geothermal fields are divided into *high-temperature fields,* where temperatures above 200°C are found at 1 km depth and *low-temperature fields,* in which temperatures are lower than 150°C in the uppermost kilometre. Resources with temperatures between 150 and 200°C have sometimes

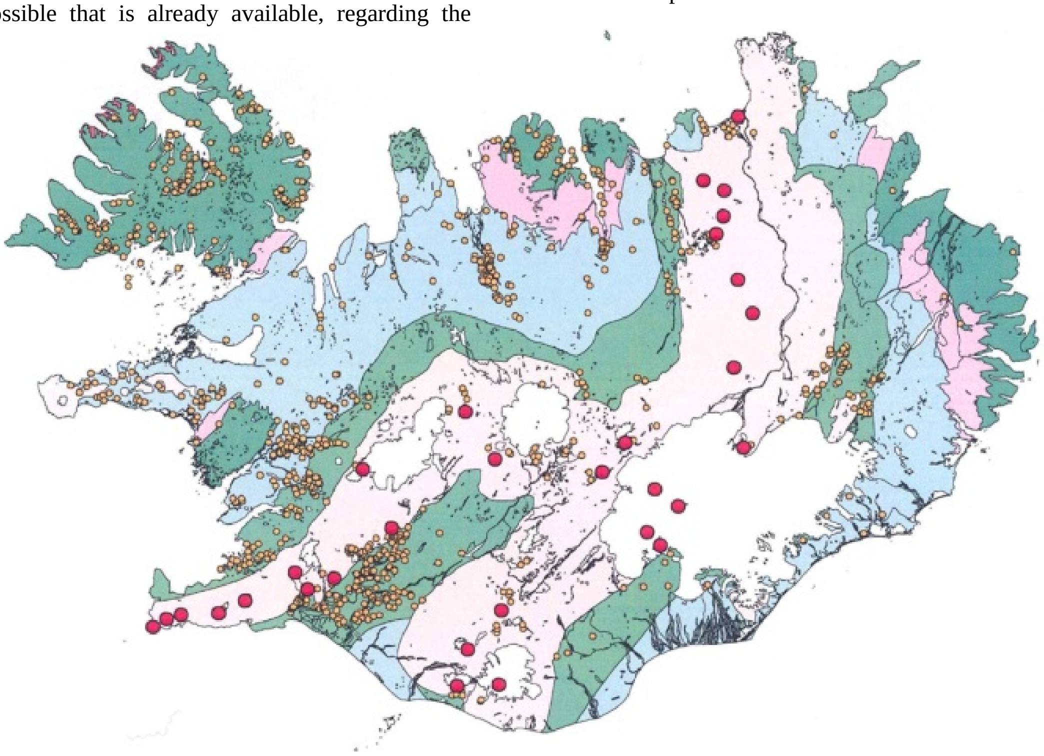

Figure 1. Geothermal map of Iceland. High-temperature fields inside the active volcanic zones are shown as red circles, and hot and warm springs as yellow circles (unpublished data from Iceland GeoSurvey's geothermal database).

been referred to as *intermediate*. Some 30 high temperature fields have been identified in Iceland, all within the active volcanic zones that cross the country from southwest/south to northeast/north, as shown in Figure 1. The low temperature activity is highest on the flanks of the volcanic zones but some low temperature resources are found in most parts of the country.

Exploration, drilling and utilization of the low temperature fields for space heating started during the first half of the last century but during the last decades the development of the high temperature fields for power generation has been the main issue in geothermal development in Iceland.

The methodology and the strategy of the exploration and development of the Icelandic geothermal high temperature fields have been under critical discussion and review ever since their utilization started a few decades ago (Björnsson 1970, Stefánsson et.al. 1982).

The strategy adopted for early development was to estimate the power capacity of each field through exploration and drilling, and subsequently design and construct a power plant with a view to fully utilize the estimated field capacity in a single power development. Later this strategy has been changed to stepwise development where the capacity of the field is tested with a relatively small power unit and later expanded in steps until the full potential of the field is developed (Stefánsson, 2002).

The objective of this paper is to give a general overview of surface exploration methods applied in Iceland with the main focus on the volcanic high temperature fields.

2. GEOCHEMICAL EXPLORATION.

The exploration and development of a geothermal field leads us through several steps. In the geothermal literature various approaches in defining the steps can be found. The first step in geothermal investigations is usually studies of the geothermal activity found on surface in the area under investigation. These manifestations are the first indication or evidence for the existence of a potentially exploitable geothermal resource. The manifestations can be of various types, ranging from active hot springs and fumaroles to hot and steaming grounds to cold but altered grounds, indicating diminishing or extinct geothermal activity on the surface.

The surface activity offers us a window to the underlying geothermal system. The main objective of geochemical exploration as a part of a geothermal exploration programme is to obtain information on the subsurface chemical composition of the fluid in the geothermal system and to use this information to estimate the temperature of the reservoir as well as the source of the fluid and to locate active upflow zones. Speciation programs are used to obtain equilibrium speciation of the fluid, to simulate processes such as boiling and cooling, and to predict potential corrosion and scaling. Potential environmental effects can be predicted and the geochemical information is used together with other data to model the geothermal system.

The geochemical studies of thermal fluids are performed in three steps: Sampling of water and gas; analysis of the fluid and interpretation of the data. For the most part sampling and analysis are routine work whereas the interpretation is not and a number of methods have been proposed. Subsurface reservoir temperatures are estimated with the help of geothermometers that are based on the composition or isotopic ratios of thermal waters and gasses. Geothermometers are often divided into three groups: Water geothermometers, gas geothermometers and isotope geothermometers. The water and gas geothermometers are often referred to as chemical geothermometers (fig. 2 and 3); They can be described as either univariant, e.g. SiO_2, CO_2, H_2S and H_2 or based on ratios of elements such as Na/K, CO_2/H_2, CO_2/N_2 and CO_2/Ar. The univariant geothermometers are simple to use but have the disadvantage that they are sensitive to secondary changes such as dilution, condensation and steam loss (fig. 3). On the other hand geothermometers based on elemental ratios are not as susceptible to the secondary changes but rate and equilibrium conditions may limit their usability. It has proven useful to use as many geothermometers as possible, as the discrepancies between different geothermometers may provide important information about the nature of the geothermal system.

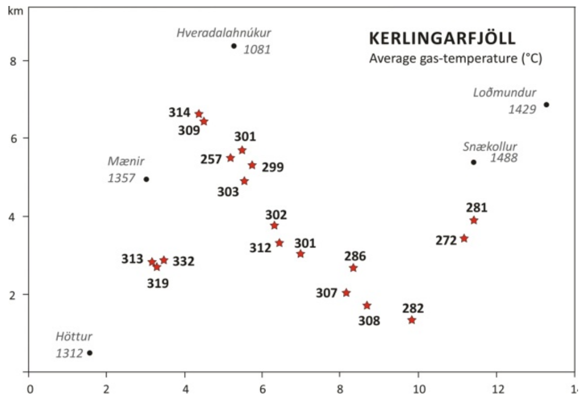

Figure 2. The calculated average reservoir temperatures (in °C), based on several gas geothermometers, from fumaroles in the Kerlingarfjöll high temperature area, central Iceland. Black dots and names represent mountain peaks with elevation in meters. The scale on both axes is in kilometers (Hjartarson and Ólafsson, 2005a).

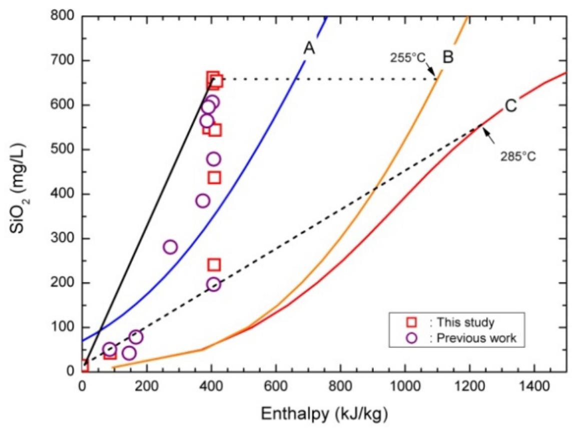

Figure 3. Silica-enthalpy mixing model for waters from the Hveravellir high temperature area, central Iceland. Curve A=solubility of amorphous silica; curve B=quartz solubility corrected for steam loss by adiabatic boiling to 100°C; curve C=solubility of quartz (Hjartarson and Ólafsson, 2005b).

To trace the origin of fluids in geothermal systems the most powerful tracers are stable isotopes and conservative elements and their ratios to chloride. Ternary diagrams such as Cl-Li-B and Cl-SO_4-HCO_3 have also proven useful to distinguish waters of different origin.

Soil temperature and diffuse degassing measurements are used to locate up flow zones and active faults and are helpful methods to assess the size of a geothermal system and to better site exploration wells (fig. 4 and 5). The soil degassing measurements also allow the evaluation of natural heat loss from the geothermal system.

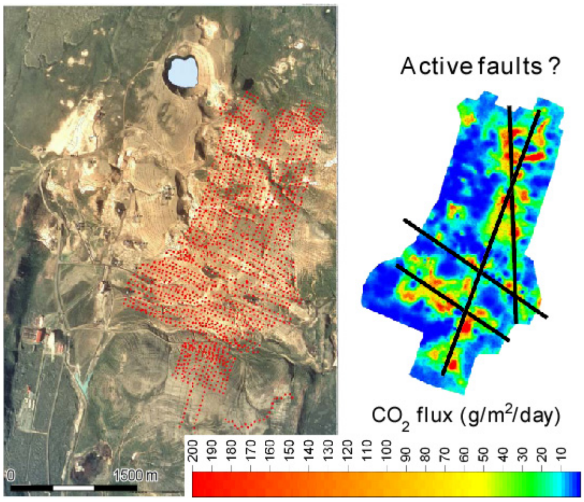

Figure 4. Soil diffuse degassing at the Krafla high temperature area, north Iceland. To the left, red dots show the locations of soil flux measurements, and the map to the right shows the magnitude of the diffuse CO_2 flux through soil (Ármannsson et al. 2007)

Figure 5. Mapping soil diffusion in the field in Iceland.

3. GEOLOGICAL EXPLORATION.

After the reconnaissance study and in conjunction with detailed studies of the geothermal surface manifestations, geological mapping is carried out in the geothermal area under exploration. These tasks usually involve geological and structural mapping as well as mapping of the thermal manifestations (fig. 6). Samples are collected of the thermal alteration minerals and sampling of rocks for dating and chemical analyses is also a key factor. Mineralogical studies of volcanic rocks and their thermal alteration, including chemical analysis, x-ray diffraction, etc., which are used for creating a detailed map of the area will be necessary for the conceptual model for the area. Relative ages of structures and volcanic activity in the area may enhance the understanding of the geothermal activity and help in predicting what the controlling structures of the geothermal resource are. It is our experience that the volcanic fissures are often highly permeable and a good target for drilling wells (Franzson et.al. 2010). The chronological order of the various volcanic events is dated based on historical accounts and on C^{14} and tephra chronological data. For this work, the interpretation of aerial photographs, satellite images and other remote sensing techniques to delineate faults, lineaments, terrain etc. may prove vital. This may also include infrared photography to outline possible surface heat flow anomalies.

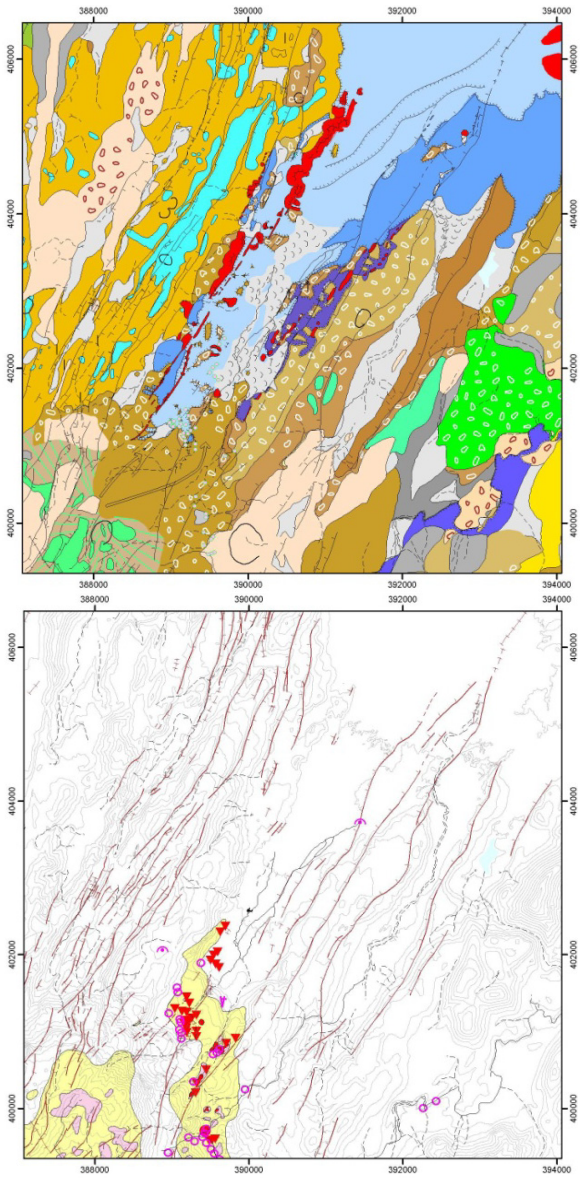

Figure 6. A typical geological map (top) from the Nesjavellir geothermal field, Iceland. Red color are volcanic fissures. Structural- and geothermal information from the same field are shown on the lower map. Yellow and pink areas are geothermal alteration and triangles and circles are fumaroles and springs (Sæmundsson 1995a and 1995b).

A digital elevation model is constructed based on existing data, e.g. topographic maps, aerial photographs, satellite data, and control data points obtained during other fieldwork. This will be a basemap for the the collection of maps produced during the exploration phase and for later development of the field. These maps are stored and maintained in a GIS system.

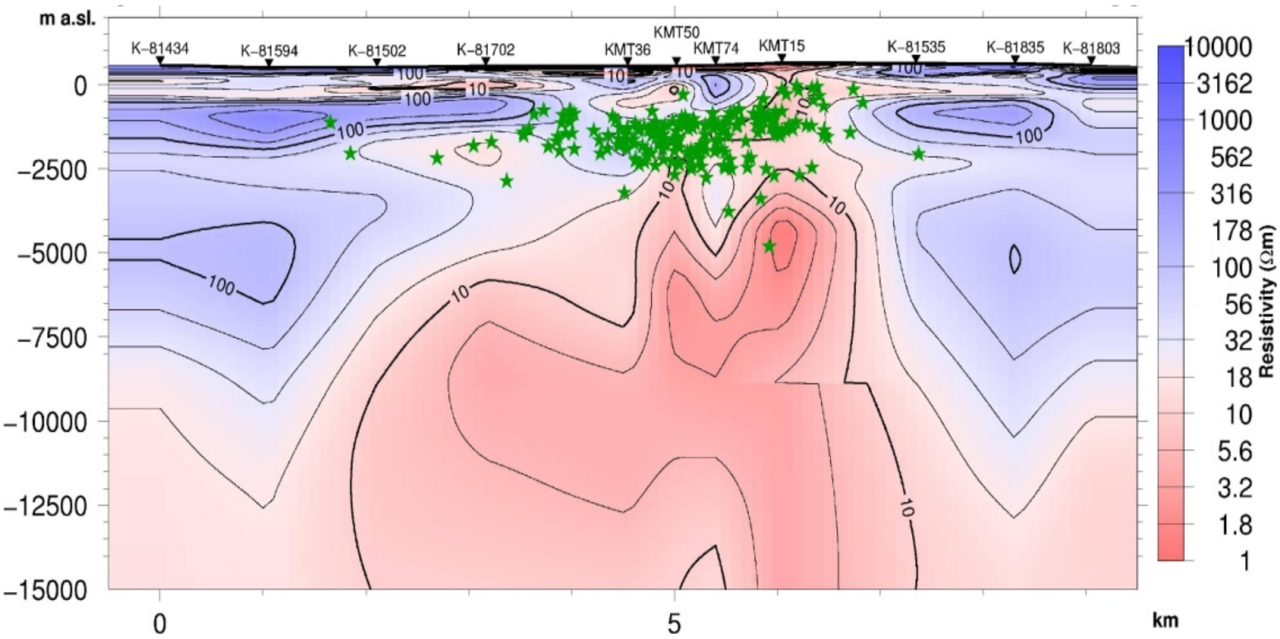

Figure 7. Resistivity section in Krafla high temperature area combined from TEM and MT measurements. The low resistivity at surface dipping down to 1-2 km depth is the so called low resistivity cap. The low resistivity layer at 10 - 12 km depth doming up under the geothermal field to about 2 km depth shows the heat source, possibly the magma chamber under the volcano. Green stars are the epicenters of earthquakes. (Arnason et.al., paper in progress).

Historical evidence for the volcanic history of the field is studied. This is used for the evaluation of geological hazard in the area of geothermal exploitation and to plan for mitigating measures. This is partially included in the geological mapping. Information on the seismic activity in the area is also collected. The volcanic and seismic history data forms the basis for risk assessment of developing the field.

4. GEOPHYSICAL EXPLORATION.

The first step in geophysical exploration of a geothermal field is a resistivity survey of the area. Resistivity methods have been used extensively in geothermal exploration in Iceland for decades. At first DC methods were used in the eighties but were succeeded by the TEM (transient electro-magnetic) method.

Transient Electro Magnetic (TEM) and Magneto Telluric (MT) measurements involve measurements of stations strategically located, covering the geothermal area. The parameters controlling the resistivity of rocks are temperature, fluid content of the rock, salinity of the fluid and the type and concentration of the geothermal alteration minerals.

In high temperature fields the rock minerals undergo alteration depending on the in situ temperature. From temperatures of 100°C up to 220°C, zeolites and smectite are dominant minerals. Smectite is a highly conductive clay mineral. At temperatures of 220-240ºC zeolites disappear and the smectite is gradually replaced by more resistive chlorite. At temperatures exceeding 250ºC the resistive chlorite and epidote are the dominant minerals. This results in a characteristic resistivity structure of a high temperature field with an up-doming low resistivity cap underlain by a high resistivity core. The interface of the two marks the 240°C isotherm in the geothermal field provided there is an equilibrium between the temperature and the alteration at present (Arnason et.al., 2000).

The TEM resistivity method is used to delineate the geothermal system within the uppermost 1000 meters below surface. To explore further depths the MT (magneto-telluric) method is applied. MT measurements can detect resistivity structures some tens of kilometers below ground surface (fig. 7) and may detect the heat source and up flow zones of the geothermal field. They have been used for the last few years in geothermal exploration in Iceland and are considered to be a standard exploration tool in the future along with the TEM method. Interpretation is usually 1D but when it comes to more complicated areas, 2D or even 3D interpretation is necessary to explain the resistivity structures.

During the exploration phase and prior to utilization of the field it may be feasible to carry out a gravity survey with GPS elevation and location coordinates. This is done to map out gravity anomalies that might be linked to the geothermal resource. The gravimetric surveys, together with the GPS data, are also used as base information for later monitoring of land elevation and gravity changes that are caused by seismicity, volcanism and last but not least by the proposed utilization of the geothermal field (fig. 8).

Aeromagnetic measurements are sometimes used at the start of an exploration phase in a high temperature area for the purpose of roughly outlining the areas which have been demagnetized due to increased temperatures. Magnetic measurements are also sometimes used in exploration of low temperature fields, since the water bearing fractures are often connected with dykes and faults that may be easily detected with magnetic measurements.

Available data on seismic activity in the area is usually studied and active zones of seismicity are mapped out and correlated with known fractures in the area, as the earthquake activity will reveal active fractures that may act as flow channels for the geothermal fluid within the reservoir. It will show areas of heat extraction (cooling cracks) where fluid might be cooling hot intrusives. In some cases in Iceland, several seismometers have been installed to monitor the area in question for a few months or even years to collect micro-seismic data. This has proved to produce valuable data for the purpose of recognizing the controlling structures of the reservoir and to map out the most likely structures to be permeable (Julian and Foulger 2009).

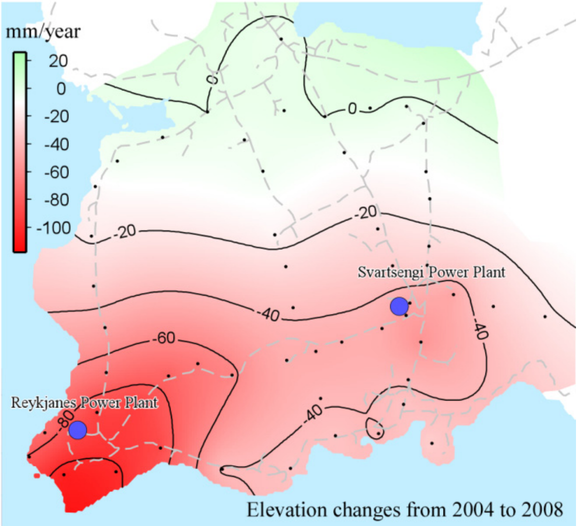

Figure 8. Elevation changes during exploitation in the years of 2004-2008 in Svartsengi and Reykjanes geothermal areas, Reykjanes peninsula, Iceland (Magnússon 2009)

THE EXPLORATION RESULTS

The general surface exploration phase for Icelandic geothermal fields concludes with exploration reports where the results of the various disciplines are described and discussed. A conceptual model derived from all the data collected is presented for the field, the drilling target is defined and 1-3 sites for exploration drilling are suggested. At this stage a rough volumetric resource assessment is carried, often using the Monte Carlo approach.

The geothermal surface exploration in Iceland has mainly been financed by the Government and Icelandic energy companies. The conclusion of the exploration phase defines a milestone in the development. The Government itself will not continue to develop the fields but the question is if the exploration results do or do not encourage a developer (in our case the Icelandic energy companies) to take the exploration to the next level, which is proving the resource at depth with exploration drilling.

Under normal circumstances, the exploration phase of developing a high temperature geothermal resource includes the drilling of two to five exploration wells. In Iceland the normal procedure for these exploration wells is to drill a full size well in commercial diameter. This way shallow geothermal gradient wells and the deeper slimwells are bypassed. In high temperature areas the gradient wells have to be several hundreds of meters deep to give the appropriate gradient information. Drilling the full sized wells is more expensive than the slimwells and geothermal gradient wells, but for the purpose of flow testing and sampling the resource at depth, the larger wells are more efficient and it is our experience that such wells give much more valuable and reliable information than gradient wells or slimwells can offer us. If the full sized wells are successful, they may later be used as producers or injectors when utilization commences.

A preliminary reservoir model is based on available information on parameters such as reservoir thickness and aerial extent, reservoir temperature and pressure, formation porosity and permeability, flow characteristics of wells, the fluid chemistry and other results from the surface exploration and from the exploration wells.

The first approach to evaluate the resource upon completing the exploration is to carry out a volumetric assessment of the resource. This assessment is later revised when information is obtained from the exploration drilling, often by applying Monte Carlo statistics to the volumetric assessment. Long term testing of productive exploration wells will define the expected productivity of future wells as well as yield information on the pressure response (drawdown) of the reservoir to fluid production. This is necessary to be able to plan for the next steps of developing the geothermal resource, getting the first estimate on potential and where to start focusing the work within the exploitation license area.

5. CONCLUSIONS

The Icelandic experience through decades of exploration of high- and low temperature areas is that the investment in a proper and thorough exploration program before the drilling of exploration wells is money well spent. This is the basis for the decision of developing the geothermal area further or not, and if the results are encouraging, the multidisciplinary approach of collecting data will in most cases be a sound foundation of placing and designing exploration wells.

One failed well, which can be linked to lapses in the exploration work, whether it is omission of doing the exploration, collection of poor data or misinterpretation, can cost up to five times more than the full spectrum of a solid multidisciplinary surface exploration program.

It is therefore, in our view, extremely important to put great emphasis on the exploration phase before deciding to drill an exploration well, so that that the siting of the well can be made with the good confidence. It will not, however, remove the risk from the drilling but will certainly lower it. Saving a few tens of thousands of dollars on exploration might cost a few million dollars in the end.

ACKNOWLEDGEMENT

Geothermal exploration work is a multi disciplinary work carried out by a team of geothermal experts. We thank our colleagues and co-workers that have participated in geothermal exploration in Iceland during the last decades. Thanks are also due to the government of Iceland and the Icelandic energy companies that have led and promoted the geothermal developments. We would also like to thank Ólafur G Flóvenz for his review and comments on the manuscript.

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