ANNEX I
Project Plan

The Hengill geothermal reservoir. Evaluation of subsurface geological data

Project ID: **09-02-005**

Coordinator: Hjalti Franzson / Iceland GeoSurvey

Start date: 1.1.2010

Duration: 12 months

Partners: Iceland GeoSurvey
Reykjavik Energy,
University of Iceland

1 Project description

1.1 General description

The Hengill area is one of the largest geothermal systems in Iceland, covering about 110 km^2. It has been explored and exploited for over 60 years by Reykjavík Energy (OR) and according to an energy resource assessment it can yield 5500GWh/y or 700 MWe.

The main aims of this project are to develop a comprehensive model of the reservoir system and to train students in geothermal research.

Several scientific methods have been used to map the Hengill reservoir, including geological and geothermal mapping, geochemistry of surface rocks and thermal fluids, volcanology, seismicity, extensive TEM and MT resistivity soundings and gravity surveys.

Hengill is considered to be one geothermal system but segmented into several sub-systems. Detailed relations between these subsystems are inconclusive. Initially the Nesjavellir system - located at the north side of the Hengill system - was explored and exploited, but intense drilling has taken place in the southern part of Hengill since 2001. To date over 100 production and reinjection wells have been completed, and 50 shallower monitoring and cold groundwater wells.

Once the drilling stage is reached the information used in analyzing the reservoir include drilling logs, geological and geophysical properties of the reservoir formations and temperature and pressure distribution within the reservoir. Flow testing of wells gives information on productivity, discharge enthalpy and the geochemical character of the reservoir fluid. Flow tests also reveal well interference and the first response of the reservoir to production. These data are incorporated into models to predict the behaviour of the system with utilization.

Reservoir rocks respond to temperature by changes in mineralogy – some minerals dissolve while other form. The mineral assemblages reflect the local temperature conditions resulting in broadly depth dependent zoning. In a geothermal system that has been stable for a long time there should be a correlation of the reservoir temperature and mineral assemblages with depth.

The large data base from Hengill, both temperature measurements and mineral studies, make it possible to test this expected correlation. However, results vary; in some cases the correlation is present but in many cases the correlation is poor. Electrical conductivity in geothermal reservoirs is, at least partly, controlled by mineralogy rather than temperature of the reservoir rocks. Consequently, it is crucial to understand the connection between the actual temperature, mineralogy and the electrical structure.

The main aim of the project proposed here is to use the large data base available to build a 3D model of the whole geothermal reservoir. Data have been gathered by several geological, geophysical and geochemical methods. ISOR has recently acquired a powerful, state-of-the-art computer program which can integrate the different data sources for the Hengill 3D reservoir model.

For the modelling we need to map the interior of the geothermal system accurately. This mapping includes:

- the history and structure of the volcanic system,
- the permeable structures and aquicludes that control the flow of geothermal fluids in the reservoir,
- the shape of the geothermal system based on mineral alteration and temperatures,
- the evolution of the geothermal system derived from the integration of hydrothermal alteration studies, fluid inclusions and formation temperatures.

Drill cuttings have been collected and analyzed (binocular) during drilling but further mineralogical studies are necessary for additional information on the properties of the reservoir rocks. Some of the sub-projects include:

1. comparison of TEM-MT surveys, borehole resistivity logging and detailed analysis of resistivity in different clays which are the main conductors for sub-surface electric currents,
2. study of the alteration of olivines and pyroxenes at variable alteration stages,
3. comparison of sulfide minerals and temperatures in order to establish possible temperature zonation,
4. chemical analyses (microprobe) of alteration minerals and comparison within the geothermal reservoir to assess heterogeneity and possible up-flow zones of geothermal fluids,
5. study of the origin and evolution of geothermal waters and alteration minerals by strontium, oxygen and deuterium isotope analysis.

Presently, the sustainability of the geothermal resources that are being explored or exploited is highly debated in Iceland. A sound evaluation of the sustainability must rely on available evidence from the geothermal system in question and how the reservoir responds to production. OR, ISOR and University of Iceland (UI) are fully aware that such an evaluation must be based on a solid scientific foundation. The proposed research project will contribute significantly to such a foundation. The project involves six MSc students that already have considerable experience in borehole logging and the project will reinforce their understanding of geothermal processes.

1.2 Scientific objectives

The main scientific results of this project are twofold.

- Comprehensive overlook and model of the Hengill geothermal reservoir incorporating all available data collected from surface mapping and drillhole data.
- New data and detailed information of the mineralogical changes taking place in the reservoir and how they relate to present day thermal structures of the reservoir.

A fundamental feature of geothermal activity is the extraction of heat from hot reservoir rocks by circulating groundwater. This heat extraction is accompanied by chemical exchange between the reservoir rocks and the groundwater – mainly transfer of chemicals from the rocks to the fluid but to a lesser extent from original meteoric or seawater to reservoir rocks. The main thrust of our proposal is to further our understanding of these transfer processes on the micro-scale.

Commonly the extent of alteration of reservoir rocks varies extensively which reflects the permeability of the rocks, the thermal history (sub-fields can be in the process of heating or cooling) and the nature and age of the host rock. The reservoir rocks have two fundamentally different origins:

- Some are originally deposited at the surface – mainly as lava flows or hyaloclastites. These start at ambient surface temperatures and are subsequently buried by younger formations and gradually transported downwards with accompanying temperature increase.
- Intrusives are reservoir rocks emplaced at magmatic temperatures and cool progressively down to reservoir temperatures, meanwhile acting as the main heat source of the geothermal system – with some heat lost to endothermic alteration processes.

The igneous reservoir rocks - as observed in drill cuttings - are very different in their degree of alteration ranging from totally fresh rocks to totally altered. The details of this alteration process are important for the heat extraction process and provide useful estimates of water-rock ratios in different parts of the reservoir. Some water has short residence time through the most open channels while some water is stored for the long-term in the reservoir rocks. This resident water comes especially important in systems where exploitation converts water-dominated systems into steam-dominated ones.

A new approach proposed here is to analyze Sr isotopes in water and alteration minerals. This yields estimates of the movement of Sr between meteoric water, primary minerals, alteration minerals and the resulting geothermal fluids. This approach will add to the information obtained from oxygen and hydrogen studies.

1.3 Education/Infrastructure quality

The project involves seven MSc students who will work as a group but on different aspects of the reservoir model. This will provide excellent training while making a significant scientific contribution. The students have already been introduced to sub-surface exploration by experienced scientists. As a research group they will take further steps by processing geological data and integrating with data from other sources and developing a reservoir model.

Five of the students belong to ISOR´s borehole section and have been deeply involved in geothermal drilling in the Hellisheiði geothermal field. In addition to drill site logging, each student will focus on two to three wells performing detailed mineral analysis and streamlining other information for incorporation into a comprehensive model of the reservoir similar to models for other geothermal reservoirs in SW-Iceland.

These initial steps are largely based on known and accepted methods used in assessing and modelling the Icelandic high-temperature areas. A sound comprehensive geothermal model is subsequently a necessary base to build more detailed and focused research projects, which may then lead to the adoption of new applied research in geothermal exploration. There is no doubt that this will enhance the competence of the research group, both students and their advisors.

The initial focus of the research project involves training the MSc students in combining the various data sources from the boreholes and surface data and the construction of a comprehensive model of the reservoir, emphasizing the mapping of permeable structures and the evolution of the hydrothermal system.

In the second phase of the project, each student will focus on specialized subjects by selecting suitable samples for the questions being tackled. These specialized projects will mostly be supervised by UI staff and the students will be trained in using highly sophisticated UI analytical equipment. This part of the project will expand the students experience and may well result in new analytical methods that could be adopted in the future as standard research techniques of geothermal systems, not only in Iceland but also abroad.

Geothermal research is truly multi-disciplinary science. This research project combines all the classical methods of subsurface modelling of geothermal systems, provides a strong forum for students and specialists to learn from each other, strengthens bonds between applied geothermal research and academic research, and adds new research methods to further the understanding of geothermal processes, the renewability of geothermal resources and how they can be utilized in a sustainable manner.

1.4 Objectives and GEORG WP relevance

WP-2. Six BSc students will receive a MSc in the field of geothermal sciences by the end of proposed project.

WP-3. Project promotes basic research and helps to realize concepts from basic research.

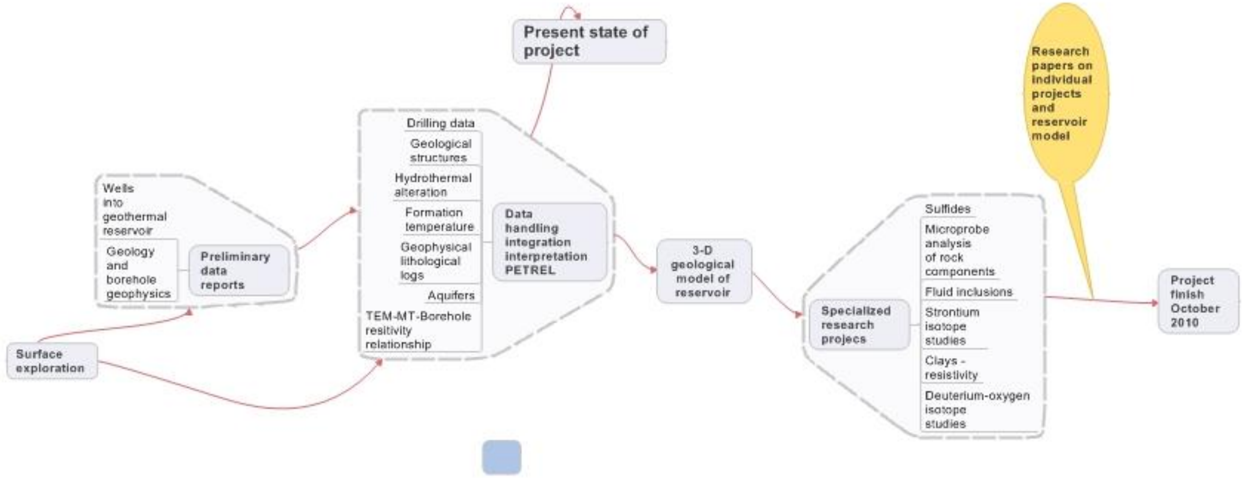
WP-4. Results will have significant implications for research and technological development of geothermal systems.

WP-6. Results of project will have implications for long-term utilization of geothermal resources.

WP-8. Results will be published in main-stream journals and introduced at domestic and international conferences.

2 Work plan and time schedule:

Work plan:



The above flow diagram shows the main ingredients of the research project with the deliverable milestones and dates.

2.1 Time schedule:

Subtask	Start	Finish	Deliverable/Milestone
Geological/thermal model	1/1/10	1/5/10	Fieldwork completed with report (paper)
Specialized research projects	1/5/10	31/12/10	Project and MSc-completion

3 Project Management

The participating group of institutions comprises OR, ISOR and UI. OR will allow unlimited access to all relevant data and samples, on which the project is based, and provides the main funding. The key research group consists of highly experienced scientists from ISOR who run the basic data collection and interpretation. The specialized projects will be supervised by senior academics at the UI and full access will be provided to their equipment (e.g. SEM-electron microprobe, MC-ICP-MS, gas mass spectrometer and other analytical instruments).

The main leaders of the research project are: Dr. Einar Gunnlaugsson, chief of OR research department. From ISOR: Dr. Hjalti Franzson, Chief geologist; Dr. Björn Harðarson, Senior geologist; and Dr. Svanbjörg Haraldsdóttir, geophysicist. From the Institute of Earth Sciences, UI: Dr. Karl Grönvold, research scientist; Dr. Árný Sveinbjörnsdóttir, research professor; Dr. Níels Óskarsson, research scientist; and Dr. Sigurður Steinþórsson, professor of petrology. The group will have full access to scientists of other geothermal disciplines within ISOR and OR. The MSc students at ISOR are Steinþór Níelsson, Theodóra Matthíasdóttir, Sveinborg H. Gunnarsdóttir, Sandra Ó. Snæbjörnsdóttir, and Helga M. Helgadóttir, and the UI students are Gísli Ö. Bragason and Kiflom Gebrehiwot from

Eritrea (UI/UNU-GTP-student). ISOR´s Petrel software specialist Gunnlaugur M. Einarsson will also be involved.

We firmly believe that now there is an exceptional opportunity to construct a comprehensive and detailed conceptual model of the Hengill field built on the extensive dillhole data available. We are confident that the research methods described here may lead to the adoption of new applied research methods in geothermal exploration in general. Presently the project is confined to Icelandic collaborative work but will lead to publications in mainstream journals and presentations at conferences both nationally and internationally. No less important the proposed research project will result in the emergence of several highly skilled and motivated new generation scientists in the field of geothermal research. This is particularly important today as most nations are increasingly focusing on renewable energy resources.

4 Budget overview

	Cost item	Requested funding		Other financing		Total
2010/2011	Salaries					28.750
	Operational expenses					9.100
	Travel expenses					0
	Total 2010/2011:	4.500	12%	33.350	88%	37.850
2011/2012	Salaries					0
	Operational expenses					0
	Travel expenses					0
	Total 2011/2012:	0	N/A	0	N/A	0
2012/2013	Salaries					0
	Operational expenses					0
	Travel expenses					0
	Total 2012/2013:	0	N/A	0	N/A	0

Grand Total	**4.500**	**10%**	**33.350**	**88%**	**37.850**

4.1 Explanation of cost:

Iceland GeoSurvey provides 3.75 mkr to the project or 20% of the total salary of the ISOR staff.

Reykjavík Energy is the main sponsor of the project with about 70% of the total cost of the project. The UI sponsors the project with the staff salary or about 3% along with analytical expenses.

It is proposed here that GEORG provides the wages of five MSc students in 2010 for 3 months according to the rules published by GEORG.

In its conclusion the GEORG Board of Directors suggested that if possible the project „Chemistry of fluid inclusions from high-temperature geothermal systems in SW-Iceland determined by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) " could also be included in the Grant (the grant application is available within GEORG). In this case one of the MSc-students left the Hengill project, which leaves out equivalent to 3 months wages, or 0,75 m kr. It is proposed here that this amount would go into that fluid inclusion project, which would suffice to test the validity of the method in Icelandic geothermal systems, and thus enhancing the probability of it becoming a valuable tool in future geothermal exploration and science. It is proposed that the project will come to an end in March 2010.