GEORG

GEOTHERMAL RESEARCH GROUP

ANNEX I

Project Plan

RESISTIVITY SURVEY OF GRÍMSVÖTN

Project ID: **09-01-016**

Coordinator: **Knútur Árnason, ÍSOR**

Start date: **01.12.09**

Duration: **3 years**

Partners: **IES-UI, UBC-Canada, GEONICS Ltd.-Canada**

1 Project description

Studies of the crustal structure of volcanoes have always played an important role in geothermal exploration. Geological mapping of extinct, eroded volcanic centres offer first hand evidence on the architecture of the interior of volcanic roots with intrusions of various types and intensely altered rocks being prominent. For active volcanoes, geophysical methods such as seismics, gravimetry and resistivity methods have been applied. Each method has its strengths and weaknesses and the resolution varies. Resistivity methods have the advantage of being highly more sensitive to temperature in comparison with the other methods.

The target area of the survey is Grímsvötn in the glacier Vatnajökull. It is the most active volcano in Iceland in terms of eruption frequency, with over 60 known eruptions in the last 800 years. The volcano is mostly covered by 300-600 m thick ice but the bedrock topography has been mapped with radio-echo soundings. The ice cover allows for good estimates of natural heat loss of the volcano and have revealed that the Grímsvötn geothermal area is one of the most powerful in the world with thermal output of 2000-4000 MW. Seismic and GPS geodetic studies suggest that a magma chamber is located under the Grímsvötn caldera at 3-4 km depth, and a gravity survey suggests a much larger high-density, probably intrusive body in the upper crust under the volcano.

The combination of a highly active volcano, a large and powerful geothermal system and an overlying glacier leads to constant melting of ice, accumulation of melt water in a caldera lake, and periodic draining in large floods (jökulhlaups). The exceptionally high thermal output has apparently been ongoing for centuries, making Grímsvötn an enigmatic geothermal system. Yet, in terms of overall structure Grímsvötn seems no different from several other central volcanoes in Iceland. Standard geothermal prospecting (resistivity or electromagnetic) has until now not been used in Grimsvötn. The application of such methods would offer important new information on the behaviour of geothermal areas.

Extensive surveying by resistivity methods (mainly central-loop TEM) has shown that the high-temperature geothermal systems in the basaltic rocks of Iceland have a very distinctive and diagnostic resistivity structure in the upper most on km. The resistivity is mainly controlled by alteration mineralogy. Cold unaltered rocks outside the geothermal system have high resistivity. At about 50°C alteration set in and between 100°C and 230°C aggressive alteration is present with conductive alteration minerals (smectite and zeolites). At temperatures higher than 240°C the conductive alteration minerals are replaced by resistive minerals (chlorite and epidote) and the rocks become resistive again. The resistivity structure of the high-temperature systems is therefore characterised by a low resistivity cap and an underlying resistive core.

Recent deep resistivity surveys in Krafla and Hengill area, by joint application of TEM and MT, have shown deep conductors under the geothermal systems with the top at about 2.5-3km depth.. In Krafla the deep conductors coincide with the S-wave shadows observed during the Krafla fires and interpreted as magma chamber(s) (Einarsson, 1978). The nature of the deep conductors Under the Hengill area is not as clear as in Krafla. There are no signs of S-wave shadow under the Hengill area. The deep conductors are found under an are of intense seismicity from 1990 to 2000 and uplift and they are believed to reflect hot shallow intrusions and dykes.

Deep resistivity surveys have greatly improved the understanding of the inner and deep nature of volcanic high-temperature geothermal systems. The unique situation in Grímsvötn, being covered by glacier and hence having a colorimeter makes them very interesting to study further. By studying its resistivity structure and knowing its thermal output gives an opportunity to estimate the total thermal output of other high-temperature systems. In order to study the resistivity structure of the uppermost few kilometres of the crust under Grimsvötn, a resistivity survey will be carried out using the Long Offset Transient Electro-Magnetic (LOTEM) method. The reason why the LOTEM method will be used in stead of more conventional methods such as MT is that measuring the electric field in the surface, which is needed in MT, is very difficult in the extremely resistive snow and ice.

The survey will be carried out by laying a large loop (1km x 1km) of wire on the glacier. A big current (~10 A) square wave will be transmitted into the loop. Switching the current in the loop will change its magnetic field which in turn induces currents in the ground. The three components of the transient secondary magnetic from these currents will be measured by standard MT recording systems. The loop will be placed about 10-15 km away from Grimsvötn and the transient magnetic field recorded on perpendicular profiles crossing Grímsvötn and, if time allows, in a dens net in the central area. In order to illuminate the subsurface resistivity structure from different directions, at least two different source locations will be used. It is estimated that the transient magnetic field at each measuring site will be recorded for about three hours or about 1000 transients.

The recorded time series with the transient magnetic field will be split into individual transients that go into advanced signal processing (de-convolution, filtering and stacking). The data will be interpreted in terms of the subsurface resistivity structure by highly advanced three dimensional (3D) inversion, inverting simultaneously for all the recorded data for all sources. This is a very computationally intensive process and hence the inversion software uses parallel computing on computer clusters.

The resulting 3D resistivity model will be interpreted jointly with other existing geophysical data from Grímsvötn, such as gravity and seismic (active and passive) to make a conceptual model of the Grímsvötn volcano and its high-temperature geothermal system and their inner structure.

The main objectives of a LOTEM survey of Grímsvötn are:

- To map the spatial extent and depth span of resistivity anomalies in the upper crust under Grímvötn, allowing comparison with other high-temperature geothermal areas.
- Map the location and extent of magma bodies in the uppermost 3-5 km of the crust under the volcano.
- Use the data and comparisons with other geothermal systems to assess the reasons why a pristine geothermal system has heat release similar to that of a large thermal area under full exploitation (e.g. Nesjavellir, Hengill, Krafla).

In the proposal submitted to GEORG it was planned to have the University of Cologne (UC) as a partner. They have long experience with LOTEM and possess a powerful transmitter. In the mean time UC had to change their plans and could not provide the transmitter for the planned field in June 2010. New partners have been found. They are the University of British Columbia (UBC) and GEONICS Ltd. in Canada. UBC is one of the world leading institutions in advanced 3D inversion of geophysical data. The PhD student attached to the project will spend considerable time there both taking courses and working on the inversion of the data. GEONICS Ltd. is also a world leading company in building equipment for electro-magnetic prospecting. They are interested in developing equipment suitable for surveys similar to the on planned in Grímsvötn. GEONICS will provide the necessary transmitters and technical support during field work. They are furthermore developing a new type of receiver which they plan to test in the survey.

2 Objectives and GEORG WP relevance

The main scientific objective of the project is to add significantly to the understanding of the nature of high-temperature geothermal resources and their connection volcanic activity. By performing geothermal exploration of Grímsvötn and comparing to other geothermal systems the thermal budget of such can be better assed. This is highly relevant for WP4, Tasks 1-5. Another objective is to establish the know-how of using LOTEM method which might be relevant in geothermal exploration because, like the TEM method, it can be applied on snow in the winter. Then many places that are poorly accessible in the summer become easily accessible. Yet another objective is to develop, through the cooperation with GEONICS Ltd., improved instrumentation for electromagnetic imaging which has worldwide relevance and the cooperation with the UBC, which is one of the world leading institute in 3D imaging, is of high relevance to Task 4 of WP4. A PhD student has been attached to the project which makes it relevant to WP2. Education and training of young scientist is of great importance because many of the leading "geothermists" in Iceland are aging and soon will have to pass the baton to younger people. The results will be presented in scientific meetings and publications giving relevance to WP8. Meeting these objectives should aid in achieving GEORG’s main goals of increasing geothermal utilization and making Iceland an energy independent case study and carbon neutral society because of the increased understanding of geothermal systems the project should enable. The project should also aid in the development of a more creative research and education environment in Iceland, strengthen the ties between industry and research organizations as well as increasing beneficial international cooperation.

3 Work plan and time schedule:

The main phases of the proposed work are the following:.

(1) Collection of available data from Grímsvötn.
(2) Model calculations to optimize field setup .
(3) Field campaign and data collection.
(4) Processing of data and 3D inversion.
(5) Second field campaign.
(6) Processing of data and 3D inversion.
(7) Final publication of results.

The results of these phases will be published in interim reports and research articles. It is assumed that the thesis of the PhD student involved in the project will be composed of three research articles.

Time schedule:

Subtask	Start	Finish	Deliverable/Milestone
(1) Collection of data	01.12.2009	01.03.2010	Interim report
(2) Model calculations	01.03.2010	01.05.2012	Interim report / Research article
(3) Data collection	01.06.2010	01.07.2011	Interim report
(4) Processing and inversion	01.07.2010	01.05.2011	Interim report / Research article
(5) Second data collection	01.06.2011	01.07.2011	Interim report
(6) Processing and inversion	01.07.2011	01.06.2012	Interim report
(6) Publication	01.06.2012	01.12.2012	Research articles

4 Project Management

The proposed project will be managed by the following team of experts having long-standing and comprehensive experience in geothermal and volcanological research and geophysical 3D imaging:

Mr. Knútur Árnason, ÍSOR
Prof. Magnús Tumi Guðmundsson, IES-UI
Prof. Doug Oldenburgh, UBC

Rob Harris, GEONICS Ltd.

ÍSOR is the main geothermal research institute in Iceland with about 90 staff members. The institute and its predecessors have been involved in geothermal research for more than half a century. In this project ÍSOR provides expertise on geophysical methods and equipment for the field work. Several other ÍSOR experts will be involved in the project including H. Eysteinsson, I. Þ. Magnússon and G.P. Hersir . The PhD student, Arnar Már Vilhjálmsson, is an employee of ÍSOR.

The University of Iceland has long-standing experience in application of geophysical and geodetical methods, in particular for volcanological research. Other IES-UI staff members to be involved in the project.

The University of British Columbia is one of the leading institutions in 3D geophysical imaging using electro-magnetic, gravitetric and other geophysical methods. UBC has developed a unique software for 3D inversion of electro-magnetic data and joint inversion with other data set. UBC will lead the inversion of the data of the project.

GEONICS Ltd. Is one of the leading manufacturers of equipment for time domain electro-magnetic prospecting. Geonics will provide transmitter and technical support during the fieldwork.

5 Budget overview

Consortium: **ÍSOR, UBC - University of Brittish Columbia, UI - University of Iceland and GEONICS**

Name of Project: **Resistivity survey of Grímsvötn**

ISK '000	Year		Year 1 2009/2010			Year 2 2010/2011			Year 3 2011/2012			**Grand Total**	
Salaries including overhead		**Unit cost**	Man-months	Total		Man-months	Total		Man-months	Total			
PhD student	ISOR	600	12	7.200		12	7.200		12	7.200		21.600	
Senior experts	ISOR	1.250	2	2.500		2	2.500		3	3.750		8.750	
Senior experts	UBC	1.250	3	3.750		3	3.750		3	3.750		11.250	
Senior experts	UI	1.250	1	1.250		1	1.250		1	1.250		3.750	
LOTEM operator	GEONICS	1.250	1	1.250		1	1.250			0		2.500	
Junior MT scientist	ISOR	600	1	600		1	600			0		1.200	
3 drivers (on glacier)		800	3	2.400		3	2.400			0		4.800	
Total			23	18.950		23	18.950		19	15.950		53.850	
Operational exp.													
LOTEM equipment				1.750			1.750					3.500	
MT equipment				1.600			1.600					3.200	
Cars and snow-scouters				500			500					1.000	
Sustenance				650			650					1.300	
Total				4.500			4.500			0		9.000	
Travel expenses													
Trvel costs				500			500			500		1.500	
Total				500			500			500		1.500	
Total cost				23.950			23.950			16.450		64.350	
Financing													
ÍSOR				5.900			5.900			5.000		16.800	
UBC				3.850			3.850			3.750		11.450	
GEONICS				3.000			3.000					6.000	
UI-IES				1.300			1.300			1.250		3.850	
Total other financing				14.050	59%		14.050	59%		10.000	61%	38.100	59%
Requested funding from GEORG				9.900	41%		9.900	41%		6.450	39%	26.250	41%
Total financing				23.950			23.950			16.450		64.350	100%

Explanation of cost:

The following aspects of the project budget should be considered:

(a) The third year budget has been revised such that the funding requested from GEORG has been reduced from that originally requested. Other financing has been increased correspondingly (ÍSOR). This will be revised as the project progresses.

(b) ÍSOR's matching contribution covers overhead associated with the work of the PhD-student, who will be located at ÍSOR. Thus GEORG's contribution towards the student's salary will not exceed the 9.5 MISK limit. It also covers about half of the instrument- and salary cost associated with the fieldwork as well as a part of the salaries and overhead for ÍSOR scientists involved in the project.

(c) The University of Iceland's matching contribution covers most of the salaries and overhead for permanent staff involved in the project.

(d) UBC matching contribution covers salaries and overhead of GNS scientific staff involved in the project.
(e) GEONICS matching contribution covers instrument cost associated with fieldwork and salaries of technician