ANNEX I
Project Plan

Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization

Project ID: **09-02-003**

Coordinator: Knútur Árnason, ISOR

Start date: February 1st 2010

Duration: 36 mounts

Partners: Lawrence Berkeley National Laboratory (LBL), USA
Massachusetts Institute of Technology (MIT), USA/
Reykjavik University (RU)
Landsvirkjun Power
Reykjavík Energy
HS Orka

1 Project description

1.1 General description

This project concerns and is the basis for the Icelandic part of a comprehensive Icelandic/USA cooperative project under the International Partnership for Geothermal Technology (IPGT) agreement. The Icelandic partners are Iceland GeoSurvey (ÍSOR) and Reykjavík University (RU). The USA partners are Lawrence Berkeley National Laboratory (LBL) and Massachusetts Institute of Technology (MIT). This document is accompanied by and largely based on a more comprehensive document submitted to the Department of Energy (DOE) in applying for funding of the USA part of the cooperative project.

The focus of the cooperative project is the development of joint geophysical imaging methodologies for geothermal site characterization and the demonstration of their potential in three areas: Krafla volcano and associated geothermal fields in Northeastern Iceland, the Reykjanes-Hengill area (RHA) in SW Iceland that includes a number of producing geothermal facilities, and the Coso area in California, USA. The Coso field is a high-temperature reservoir similar to Krafla in Iceland. Each area is a locus of significant geothermal energy production. While the activities in each area will be different, all will be focused on the use of combined geophysical imaging methods for site characterization to enhance image resolution to better identify zones of geothermal fluids. The complex geology of these sites also makes them excellent targets for developing and testing of new imaging techniques and new strategies for joint imaging, with the explicit goal of transferring the proven technology to other high temperature geothermal systems.

In Krafla, extensive electromagnetic (EM), gravity and seismic data sets already exist, with additional seismic data acquisition ongoing from micro earthquake (MEQ) sensing arrays. It is also proposed to augment the MEQ data with new controlled source electromagnetic (CSEM) measurements, an emerging technology for imaging fluids. Acquiring time lapse CSEM data offers much potential to image changes in subsurface fluid concentrations in the Krafla field, especially when these data are coupled with MEQ data arising from fluid injection activities in the field as well as time-lapse seismic imaging (from MEQ data or ambient seismic noise tomography). Evaluation of the technology's success at Krafla will be based upon the value of new knowledge gained on the reservoir properties, including fracture orientation and density, and fluid concentrations.

In the Reykjanes-Hengill area, we will conduct a field campaign to collect new teleseismic, regional, and MEQ seismic data and seismic noise to improve the resolution of imaging the regional geological/tectonic setting over what can be done with existing data and established imaging practices. The new data will also enhance the monitoring of seismicity arising from accompanying operations at producing geothermal fields and will be used in conjunction with existing EM and gravity data that has been collected in the area.

At Coso Hot Springs, existing MagnetoTelluric (MT) data and induced MEQ data will be used to test joint imaging methodologies. These results will be correlated with production data to provide an integrated model of the producing reservoir. A successful outcome will depend on whether previously known correlations between the electrical resistivity, density and velocity anomalies, including MEQ focal events, can be more clearly linked to fluid bearing fractures from known well producing intervals.

Determination of reservoir parameters (temperature, fluid saturation, permeability and rock fracture density and porosity) is of more interest than the geophysical attributes (electrical conductivity, seismic velocity and mass density). Rock physics models can sometimes provide the linkage between attributes and reservoir parameters, but in many cases no clear relationship can be defined. Most insight from the joint analysis of different geophysical attributes can be gained in complex geothermal systems where rock physics models break down. In such cases the alternative approach is to seek common structural relationships in the attributes, which can provide indirect information on the underlying geological processes. It forces structural conformance between the different geophysical attributes, where earthquake attributes (locations, magnitude, source dimensions and failure mechanisms) with 3D tomographic images of P-and S-wave attributes (velocity fields, reflectivity, anisotropy and amplitude) constrain and complement electrical imaging. Electrical data can also be used in a reciprocal way to constrain the tomographic imaging of the seismic attributes or vice versa. To force structural similarity a cross gradient constraint can be employed during the imaging process (see accompanying DOE proposal for details). This constraint has the desirable characteristic that it can map common geological structure that is not dependent upon changes in magnitude of the various geophysical attributes, and can also admit structure that is only constrained by one data type and not others.

The cooperative Icelandic/USA project is supported by the power companies developing the geothermal areas considered in the project by providing both geo-scientific data and data pertaining to power production and field management (see letters of support accompanying this proposal). They are: Landsvirkjun Power (Krafla), Reykjavík Energy and HS Orka (HRA) and Geothermal Program Office, Naval Air Weapons Station (Coso).

ISOR and the respective power companies will provide existing data from the Krafla and RHA sites and LBL the Coso data. The technological baseline for the project (see work plan above) will also involve separate earthquake and EM imaging experiments in the RHA and Krafla. LBL & ISOR will analyze MT/CSEM/TEM data and MIT, ISOR & RU the earthquake data. The results from these experiments will be shared amongst all institutions. All institutions will participate in the joint imaging data analysis, coordinated through LBL.

1.2 Objectives and GEORG WP relevance

This project has relevance to WP2, mainly Task 2.2. The PhD student will get contacts to many research institutions and universities. The main relevance is to all tasks of WP4. It aims at improving exploration technologies, both applied methods and interpretation. It aims at better understanding the geological/physical processes at work in geothermal systems, both natural (volcanic) and enhanced. It aims at better resolution to decrease drilling risk and help in sustainable resource development. A strong relevance to all the tasks of WP8. The results will be published in scientific journals and presented at scientific meetings and conferences.

2 Work plan and time schedule:

As explained before this document is accompanied by and based on a more comprehensive document submitted to the Department of Energy (DOE) applying for funding for the USA part of the cooperative Iceland/USA project. For technical details mentioned here, reference is made to this document. The project will, to a large extend, deal with already existing data, but to complement the datasets, passive seismic data will be gathered in the Hengill-Reykjanes peninsula areas (RHA) and a Controlled Source Electro-Magnetic (CSEM) survey will be conducted in Krafla. The journey to a fully joint inversion of complimentary geophysical data will be in four increasingly ambiguous steps. The main subtasks are as follows:

(Dc1) Set up seismic network on the Reykjanes peninsula, record seismicity, seismic noise and process.
(Dc2) Perform CSEM survey in Krafla and process data.

(1) Analysis of seismic, ElectroMagnetic (EM) and gravity data independently using existing techniques to form a base line for comparison to improved techniques.
(2) Joint inversion of EM and MEQ data using existing techniques that are coupled in a leap-frog fashion in a manner where first one and then the other technique is applied in succession and the output of the inversion from one technique is used as input to the other technique.
(3) Fully-coupled inversion of seismic and EM data using an acoustic formulation for seismic data in the Laplace Transform domain.
(4) Fully-coupled inversion of seismic and EM data using an elastic formulation for seismic data in the Laplace Transform domain.

The project is scheduled for three years. The time schedule in terms of ongoing activities each year is as follows:
Year 1
Gather existing data at the three proposed test sites. Begin acquiring seismic data on the Reykjavik Peninsula. Carry out imaging of each data type in isolation to provide technological baseline. Analyze independent imaging results for correlations. Implement and start testing joint imaging methodologies (steps 2 and 3). Document all findings (conference proceedings and publications).
Year 2
Analyze geophysical data using joint imaging methodologies (steps 2 and 3). Acquire first CSEM data set at Krafla. Complete seismic acquisition and begin data analysis. Evaluate results with images obtained from each data type in isolation (technological baseline). Document initial findings (conference proceedings and publications)
Year 3
Make improvements to joint imaging methodology based upon the prior year's results. Acquire second CSEM data set at Krafla to map saturation changes. If results in step 3 warrant, implement methodology described in step 4 of the proposal. Continue and complete analysis of data using improved joint imaging methodology. Access joint imaging technology to improve geothermal resource characterization practices. Document all findings (conference proceedings and publications). Prepare final report.

2.1 *Time schedule:*

Subtask	Start	Finish	Deliverable/Milestone
Data collection task Dc1	01.05.2010	30.12.2012	Interim reports/Publication(s)
Data collection task Dc2	01.05.2011	30.08.2012	Interim reports/Publication(s)
Imaging task 1	01.02.2010	30.12.2010	Interim reports/Publication(s)
Imaging task 2	01.04.2010	30.12.2011	Interim reports/Publication(s)
Imaging task 3	01.01.2011	30.12.2012	Interim reports/Publication(s)
Imaging task 4	01.10.2011	30.02.2013	Final report/Publication(s)

3 Project Management

Gregory A. Newman at LBL will be the lead PI for the overall cooperative project. Michael Fehler will coordinate and direct the MIT team. LBL and MIT will be responsible for development of the joint imaging technology. LBL will provide the EM codes and MIT the MEQ software.

Knútur Árnason will be the PI on behalf of ISOR and Ólafur Guðmundsson on behalf of RU. The project will be managed by a consortium of the PIs of the participating institutions.

An Icelandic PhD student will be attached to the project. He will be a student at Reykjavík University or the University of Iceland. Specialists from ÍSOR, RU, LBL and MIT working on the project will supervise the PhD student. The PhD project will be concentrated on processing and interpretation of passive seismic and EM data and joint inversion of complementary data sets. The project aims at building a bridge between key research institutions in Iceland and the USA and complies well with the priorities defined by the International Partnership of Geothermal Technology (IPGT) and by the Department of Energy in the USA, where funds are being sought by the US partners.

The daily activities will be coordinated by electronic communication and telephone meetings. The project will start with a kick-off meeting, once approved, and annual meetings (or as deemed necessary) are expected. It will furthermore be necessary that ISOR and RU PI's and the PhD student will visit LBL and MIT over extended periods to insure smooth progress and that project deliverables and milestones are met. Reciprocal visits to the participating Iceland institutions will be required as well.

The progress and findings of the project will be reported in interim reports, published in peer revived scientific magazines and presented at scientific meetings and conferences.

4 Budget overview

Cost item		Requested funding		Other financing		Total
2010/2011	Salaries					24.000
	Operational expenses					96.278
	Travel expenses					1.200
	Total 2010/2011:	10.000	8%	111.478	92%	121.478
2011/2012	Salaries					24.000
	Operational expenses					143.234
	Travel expenses					1.200
	Total 2011/2012:	10.000	6%	158.434	94%	168.434
2012/2013	Salaries					24.000
	Operational expenses					145.932
	Travel expenses					1.200
	Total 2012/2013:	10.000	6%	161.132	94%	171.132

Grand Total	**30.000**	**7%**	**431.044**	**93%**	**461.044**

4.1 *Explanation of cost:*

The budgeted cost of the proposal to DOE is listed here under operational expenses.

Cost of the RHA seismic network consists of consumables for deployment of 10 seismographs and travel to recording sites for instrument service. Instruments are provided by MIT at no extra cost. Consumables include batteries (50 kISK/instr.), building materials for instrument vaults, masts for mounting wind generators e.t.c., insulation, cables and waterproof boxes. RU provides wind generators at a capital cost of 80.000 ISK/instr., which we depreciate by 1/3. Estimated total material cost is 1.500 kISK. Three visits are required/year/instr. to retrieve data. Travel costs are estimated as 333 kISK per full round of visits to all 10 instruments.

The financing of the CSEM experiment in Krafla comes mainly through the DOE grant, except that ISOR will provide summer students and LVP food and accommodation in Krafla during field work.

Other costs are for travelling and office work of ÍSOR and RU specialists and a PhD student.

The matching contribution of the institutions involved brakes down as follows:

a) ÍSOR's matching contribution covers overhead, facilities and partly salaries associated with the work of the PhD-student, who will be located at ÍSOR, and associated with work of ÍSOR specialists.
b) The RU's matching contribution covers most of the salaries and overhead for permanent staff involved in the project.