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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 (LBNL), USA Massachusetts Institute of Technology (MIT), USA/ Reykjavik University (RU) Landsvirkjun Power Reykjavík Energy HS Orka

1 General status of the project

The 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 participating partners are Lawerence Berkeley National Laboratory (LBNL) and Massachusetts Institute of Technology (MIT) in the USA and Iceland Geosurvey (ISOR) and Reykjavik University in Iceland. In the middle of 2012 Uppsala University (UU) joined the project with funding from Sweden research funds.

The focus of the project is the development of joint geophysical imaging methodologies for geothermal site characterization and the demonstration of their potential in three areas: Krafla and Hengill area in Iceland, and the Coso area in California, USA. The main emphasis is on joint inversion of passive seismic (micro-earthquake) and ElectroMagnetic (EM) data. The project focuses largely on already existing data but had two components of collection of new data. The project was broken down in five basic tasks as follows:

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

(1) Analysis of seismic, 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.

Collection of new data:

Setting up the seismic in **Task Dc1** was completed in during the first year (2010) and the seismic network recorded according to schedule. The project and its connected projects operated 38 seismographs on the Reykjanes Peninsula, between Grafningur in the east to Reykjanes in the west, throughout 2010 until the summer of 2013. Of these, 16 were provided by Uppsala University (UU), 14 by MIT, and 8 by the Icelandic seismograph resource, Loki. The Uppsala and MIT seismographs are broad band, recoding data in the frequency range between 0.01 to 40 Hz. The Loki seismographs are intermediate band and record data between 0.2 and 40 Hz. The recording devices record data on disk at the site and data were collected 2 to 4 times during the year from each site. Overall data recovery was approximately 77%, which is satisfactory, while the Icelandic Loki instruments returned about 99% data, which is excellent. The seismic data are reformatted and archived in Uppsala and at MIT and then distributed to the project partners. Analysis of data from the Krýsuvík have been under way since 2011 at MIT, with new data added to complement the previously processed data.

The seismic instruments were removed in the summer of 2013. The network produced large amount of quality data during the deployment, recorded swarms of seismic activity in Krýsuvík and in Hengill geothermal fields. Analysis of the new data are now being carried out at UU and MIT.

The data collected in **Task Dc**1 has been completed and all seismic instruments have been removed. Data collected in previous years have been analysed and processed by RU, UU and MIT and seem to be of good quality. The new data are being analysed and processed but due to high volume of data work on that task continues. Seismic data from the permanent SIL seismic network are likewise being analysed by MIT to complement the recorded data.

After analysis of the exciting EM data in Krafla, the collection of Control Source MT data in **Task Dc2** was cancelled. The addition of this CSMT data was not necessary for the scope of this project.

Data analysis and interpretation:

Work with in **Task 1** is close to completion. Analyses and 3D inversion of EM (MT) data from Krafla and Hengill are in final stages. Inversions done with 3 different inversions codes (from LBNL, University of British Columbia and Prof. Siripunvaraporn from Mahidol University in Thailand) have been performed. Results show that consistent resistivity structures are recovered, even though different approaches are used for each of the codes. In spite of some differences in the models, the common resistivity structures seen in the 3 independent inversions results show that there is robustness to the 3D inversion of MT data. The work in this part of the project has been carried out mainly by Guðni Karl Rosenkjær at ISOR, a PhD student at the University of British Columbia, and Erika Gasperikova at LBNL. Papers reporting on the findings are in the final stages and will be submitted to pier reveiwed journals in the summer of 2014.

In addition work on inversion of MT data from Krýsuvík and Coso geothermal area's have also been done, to support the efforts of the joint inversion of the seismic and MT data.

The independent analysis of seismic data are progressing well. In Krafla, tomographic inversion have been done, revealing interesting velocity structures that make the base for comparison with the MT data. This work has been many cared out at UU and with new data being process in Hengill area similar baseline tomographic inversion are being done. Inversion data from Krýsuvík are further along, using a subset of the recorded seismic data in the area. Work on adding the newer data to the inversion are underway.

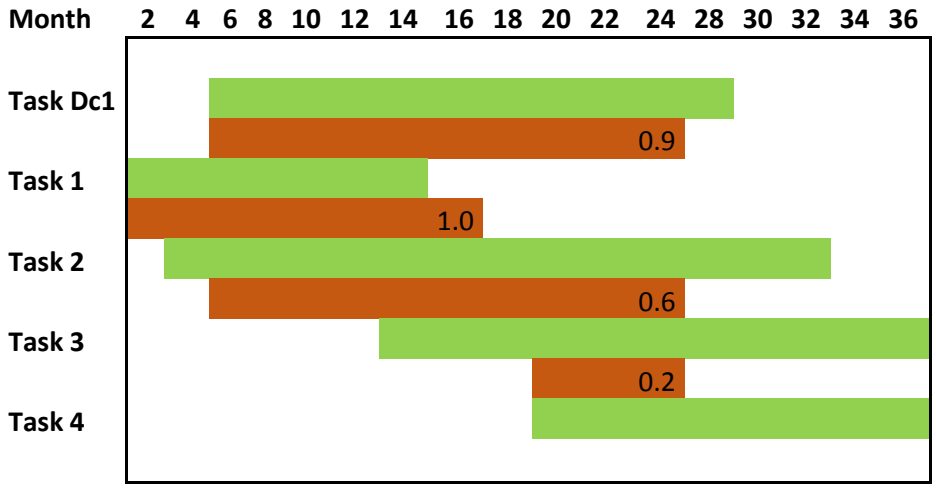
Work under **Tasks 2** has been done in Krafla and Coso, with interesting results. The work has been carried out by LBNL, UU and MIT. Results show that using “leap frog”, where resulting velocity model from an inversion of seismic data is used to impose structural constraints to an inversion of MT data and vice versa, reveal consistent results to stand alone inversion of the MT and seismic data. The joint models are in more agreement with each other, where structures are shared in the velocity and resistivity models. Work on performing these kind of inversions for Hengill and Krýsuvík are underway.

Task 3 and **Task 4** have progressed slowly. The authors of the 3D EM inversion code (LBNL) and the double-difference seismic tomography inversion codes (MIT and UU) have continued their work on

linking the codes together, but technical difficulties have proven difficult to resolve. At this stage it is unclear weather this part of the project will completed.

1.1 Project progress/time schedule:

The following chart shows the schedule for different tasks (green bars), work performed (brown bars) and fraction of work anticipated outcome accomplished (numbers in brown bars).



2 Project Management

The overall project leader is Dr. Gregory A. Newman at LBNL. The project leader of the GEORG funded Icelandic part is Knútur Árnason at ÍSOR. A total of eight project meetings have been held.

A kick-off project meeting was held at MIT soon after the project started. A second project meeting was held at LBNL July 2010; third project meeting was held in Reykjavík October 5.-8., 2010, he fourth project meeting took place in Reykjavík October 10.-14. 2011. These meetings were discussed in previous report, for year 2012.

Fifth project meeting was held in October 2012 at MIT. At this meeting general project issues and plans for interpreting the results of this project with geology in the area's were discussed.

Sixth project meeting was held in Iceland in March 2013, were all the participatants in the project presented results in a 1-day, pubulicly open workshop. The results of the comparisons of the MT invesion using the 3 different inversion codes was presented, as well as preliminary results from joint seismic and MT inversion

Seventh project meeting was held at Uppsala in October 2013, were participants discussed the progress of their work components and general project issuses.

Eight project meeting was held in Berkeley in June 2014. A similar format was at this meeting, were project matters were discussed as well as progress on joint inversion of Krafla and Coso where precented. In addition discussion on results of Krýsuvík independent seismic and MT inversion were discussed, and plans for joint inversion of these data were layed out.

On top of the regular meetings, Guðni Karl Rosenkjær visisted LBNL for a week in February 2013, to work with Erika Gasperikova on the EM part of the project. In addtion, Erika Gasperikova made a week long visit to ISOR in June 2013 to continue this work.

3 Student involvement

Under the project, Guðni Karl Rosenkjær is working on his PhD studies at the University of British Columbia. His work focuses on methodology and best practice in 3D inversion of MT data in cooperation with LBNL (Erika Gasperikova). The results, based on data from Hengill, Krafla and Coso, will be submitted for publication in a scientific journal in 2014.

4 Publications and disseminations

Erika Gasperikova, Gregory Newman, Danny Feucht, and Knutur Árnason*: 3D MT Characterization of Two Geothermal Fields in Iceland*, GRC *Transactions*, Vol. 35, 2011

Gudni Karl Rosenkjaer and Douglas Oldenburg: *3D Inversion of MT data in Geothermal exploration: A workflow and application to Hengill, Iceland*. Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30 - February 1, 2012

Haijiang Zhang, Erika Gasperikova, Beatrice Parker, Ari Tryggvason, Olafur Gudmundsson, Tim Seher, Gregory A. Newman, Michael Fehler, and Knutur Arnason: *Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization.* 2012 Geothermal Resources Council, Reno, October 1, 2012

5 Cost statement

The actual project cost for the first two years (1.2.2010 to 31.1.2012) is detailed in a separate excel document following this report. The main costs are for the PhD student (Guðni Karl Rosenkjær), 9.1

KIkr, specialists at ISOR and RU, 6.1 KIkr, operational cost of the seismic network, 1.8 KIkr and travel cost, 3.6 KIkr. The PhD student expenses are according to budget, but the cost of ISOR experts is below the budgeted amount. There are two main reasons for this. Firstly the project has been in the phase of merging together software, which is the main responsibility of LBNL, MIT and UU, with little participation from ISOR. The work load on ISOR specialists will increase as the project progresses. Secondly ISOR specialists were heavily loaded with commercial services during this period, mainly 3D inversion of MT data. Operational cost is somewhat below the budget, but there are some further costs in the pipe line. Travel cost has exceeded the budget. This is mainly because the cooperation