FINAL REPORT

Part 1.3 of the project
DEEP ROOTS OF GEOTHERMAL SYSTEMS

Project ID: 13-05-003

Coordinator: Knútur Árnason

Start date: 1.7.3013

Duration: Three years

Partners: Uppsala University, Cornel University, Landsvirkjun, Orkustofnun, Orkuveita Reikjavíkur, HS Orka

1 Project summary

This project was a part of the main project on “Deep Roots of Geothermal systems” (DRG). The aim was to try innovative (unconventional) seismic methods to study seismic velocities in the geothermal system in the Krafla volcano, known to host magmatic heat sources at relatively shallow depth. ISOR operates an eleven station (five in boreholes and six on surface) permanent seismic network in the Krafla area for Landsvirkjun. The idea behind this project was to temporarily operate more dense network for better location of events and to look for seismic reflections and phase conversions of seismic waves from local earthquakes. It was furthermore planned to use distant earthquakes and explosions to record seismic waves arriving nearly vertically (under-shooting) up through the volcano. The idea was that this would give information about the seismic velocity structure in the volcano and revile presence of magma. The design of the seismic experiment was done in cooperation with prof. Ólafur Guðmundsson at Uppsala University (UU) in Sweden.

The plan was that ISOR would be responsible for the data collection, with funding from the GEORG programme, and that UU would provide PhD student to process the data. ISOR successfully recorded high quality data as planned. A comprehensive description of the data collection, basic processing and archiving was given in the annual report for the second year (2015, following this final report). It turned out, however, that UU did not have a PhD student available for the data processing and interpretation. This caused some delay of the project. Fortunately, the coordinator got in contact with a seismic group at Cornel University in USA, led by prof. Larry D. Brown, a renown seismologist. The seismic group at Cornel had been working on similar ideas as behind this project, i.e. to study reflections of seismic waves from local earthquakes and it turned out that the DRG seismic data set from Krafla was ideal to test their ideas and approaches. The data were consequently given to the Cornel group and a PhD student, Doyeon Kim from South Korea, has been working on them.

The group at Cornel has applied two types of data processing. The first approach is what they call “*Virtual Reflection Seismic Profiling“* where they use seismic interferometry to transform the recorded seismograms from local earthquakes into a virtual reflection seismic data and used „standard“ reflections seismic tools (normal move-out and stacking) to enhance signals of reflections in the data. In this approach, it is crucial that the seismic signals are recorded in a dense array, as was done in the DRG seismic experiment in Krafla. The stacked data showed clear sign of reflections and the dominant one seems to coincide with the magma body encountered at 2.1 km depth in IDDP-1. These results have been published in the “Journal of Geophysical Research” and the abstract of the paper is given below:

Paper 1, abstract:

“The details of magma plumbing beneath active volcanoes remain a major challenge in eochemistry, geophysics, and volcanic hazard evaluation. Here we apply a relatively novel variation of seismic interferometry, which we call Virtual Reflection Seismic Profiling, to produce a high-resolution image of a known crustal magma body. The technique takes advantage of recent advances in both seismic instrumentation (dense arrays) and seismic analysis (seismic interferometry). We have applied this technique to data recently acquired at an iconic volcanic system, Krafla, which lies on the mid-Atlantic ridge as exposed in northern Iceland. What make this particular site exceptional are encounters with rhyolitic magma in two drill holes, K-39 and Iceland Deep Drilling Project-1 (IDDP-1). These known magma bodies represent a unique calibration opportunity for surface geophysical measurements of magma distribution at depth. In this study, we produced a stacked, seismic reflection section by applying common depth point processing techniques to virtual shot gathers derived from interferometry of P waves from microearthquakes generated by tectonic, magmatic, and/or geothermal activity. We observe a strong, coherent reflection on the seismic section at a travel time corresponding to the depth at which magma was encountered in the IDDP-1 wellbore. We interpret this reflection to be from magma or magma-related fluids. Additional coherent reflections may correspond to other components of the magma plumbing beneath Krafla. These results represent a promising new technique for structural imaging with natural sources that can be applied to a wide array of geologic and energy problems that involve natural or induced seismic clusters.“

The second approach was to use what they call „*reverse Vertical Seismic Profiling*“ (rVSP). This is a variant of standard VSP, where, in stead of having signal sources on the surface and recording in a borehole, having the source in the subsurface and record on the surface. This approach also reviled strong coherent reflections where IDDP-1 hit magma and, furthermore, showed deeper reflections which might be due to deeper magma sills than the one encountered in IDDP-1. A paper describing these results has been submitted for publication in "Geophysical Research Letters" and its abstract is given below:

Paper 2, abstract:

"The geometry and distribution of magma in the crust remains a controversial topic with recent studies questioning the classic model of large magma chambers. In this investigation, high-resolution 3D 28 reflection images of crustal discontinuities beneath the Krafla geothermal field in northern Iceland were generated by applying oil industry Vertical Seismic Profiling (VSP) techniques to microearthquake sources. Exceptionally large amplitude reflections (bright spots) at a depth of 2.1 km correlate with rhyolitic magma encountered in the IDDP-1 borehole. Although similarly bright reflectors at about 4 km correspond in depth to the top of an inferred magma chamber from previous seismic studies, the scattered reflectivity that persist beneath this deeper reflector argues for a distributed magma system rather than a classic large feeder chamber."

The results of this limited seismic experiment in Krafla are very (even surprisingly) promising. They show that recording with dense seismic networks in areas with micro-seismicity like in Krafla and applying innovative data processing can give relatively detailed information on the subsurface structure . Methods for detecting magma (heat sources) at shallow crustal depth by geophysical methods on the surface have long been sought. MagnetoTellurics (MT) has been thought to be the best candidate and has sometimes successfully detected deep large magma bodies but results from Krafla show that MT cannot detect small distributed magma pockets as are believed to be present in Krafla. Recently ideas about magma storage in volcanos have increasingly been developing from the concept of large "magma chambers" towards more complex magma plumbing systems with distributed storage in localised sills. Surface geophysical methods for detecting magma are not only relevant for geothermal development. They are also of great importance in volcanology and monitoring of volcanic hazards. As an example, the city of Naples in Italy is near to, and partly within, the Campi Flegrei caldera, which has recently shown volcanic unrest.

Encouraged by the results of the DRG seismic experiment, prof. Larry Brown and the seismic group at Cornel University is, in cooperation with ÍSOR, preparing an application for funds from the "National Science Foundation" in USA to carry out large scale survey in Krafla. The survey would involve deploying about 600 state of the art, continuous recording, seismic sensors in a dense 2D areal array in a 2km x 3km grid at a spacing of 50m, covering the eastern part of Vítismór and the southern slopes of Krafla, i.e. the area around the wells IDDP-1 and K-39, which hit magma. This survey is also meant as an important input into the "Krafla Magma Testbed" project.

2 Project Management

The project management has been by the coordinator (Knútur Árnason, ISOR). Before and during the installation of the network, frequent telecommunication took place between the coordinator, prof. Ólafur Guðmundsson at UU and the staff installing the seismograms.

The preliminary data processing and archiving of the data in the seismic database at ISOR was managed by Knútur Árnason and Karl Gunnarsson. The final processing and interpretation of the data was managed and done by the PhD student Doyeon Kim and prof. Larry Brown at Cornel University.

3 Student involvement

The actual installation of the seismic stations was led by MsC Pálmar Sigurðsson, a summer student at ISOR, and Karin Berglund, an MsC student at Uppsala University, with the help of technicians from ISOR. Karin's and Pálmar's efforts and dedication are highly appreciated.

The final data processing and interpretation was done by Doyeon Kim, a PhD student at Cornel University.

4 Publications and disseminations

Paper publishes in Journal of Geophysical Research: Solid Eart (following the report):

Magma reflection imaging in Krafla, Iceland, using microearthquake sources

Doyeon Kim[1] , Larry D. Brown[1], Knútur Árnason[2], Kristján Águstsson[2], and Hanna Blanck[2]
[1]Earth and Atmospheric Sciences, Cornell University, Ithaca, New York, USA, [2]Iceland Geosurvey (ISOR), Reykjavik, Iceland

Paper submitted for publication in Geophysical Research Letters (following the report):

Magma "bright spots" mapped beneath Krafla, Iceland, using reflected waves from local crustal microearthquakes

Doyeon Kim[1], Larry D. Brown[1], Knútur Árnason[2], Ólafur Gudmundsson[3], Gylfi Páll Hersir[2],

5 Cost statement

Cost statement is given in a separate Excel document.