FINAL REPORT

Project Deep Roots of Geothermal Systems, Part 1.1.
Crustal deformation and gas measurements of Krýsuvík geothermal system

Project ID: Part 1.1

Coordinator: Sigrún Hreinsdóttir

Start date: January 2013

Duration: Three years

Partners: Evgenia Ilyinskaya, Freysteinn Sigmundsson

1 Project summary

The project has broadly followed the work planned. The details of inflation/deflation episodes at a natural geothermal system not influenced by geothermal production (Krísuvík), have been captured by detailed geodetic measurements utilizing Global Positioning System (GPS) geodesy, both campaign measurements and continuous measurements, and interferometric analysis of synthetic aperture radar images (InSAR). Gas emenating from the geothermal area has been measured and its variations with time. The observed crustal deformation has been modelled in terms of processes in the deep roots of the geothermal system, and changes in geochemistry interpreted.

Measurements

A GPS geodetic network was measured at Krísuvík both in 2013 and 2014 as a part of the DRG project (over 30 stations centred on Krísuvík). In 2013 the network was also measured using a gravity meter. Continuous measurements were carried out to sites (KRIV in Krísuvík and MOHA in Móhálsadalur), and semi continuous measurements at three additional sites. SAR images during snow free months were acquired and collected over the study area by the TerraSAR-X satellite. The geodetic network was measured again in November 2015 using both GPS and gravity meter with additional support from HS Orka.

A Multicomponent Gas Analyzer System station (MultiGAS) was installed at Hveradalir in Krýsuvík (63° 53.449' N, 22° 4.190' W) on 26 April 2013, next to a fumarole in an area of high and persistent surface geothermal activity. Data collection was discontinued over a short period from 27 June – 5 July 2013 but then continued until November 2013.

Samples of dry gas and condensate were collected from fumaroles in areas of intense and continuous surface geothermal activity within the three sub-areas of this study (four samples in Hveradalir, two in Seltún and two in Austurengjar). The steam samples were analysed for gas composition.

CO_2 flux was measured using the accumulation chamber method. Soil CO_2 flux and soil temperature were carried out on approximately 25×25 meter grid, where possible. The total number of measurement points was 435; 217 of which were in Hveradalir, 136 were in Seltún and the remaining 82 were in Austurengjar. Most of the measurement points were taken in late summer or autumn of 2013, during dry and calm weather conditions.

Results

Deformation:

In early 2009 the Krýsuvík region on the Reykjanes Peninsula started inflating accompanied by high seismic activity. From late 2009 to May 2010 the region deflated again to its pre inflation level. From May 2010 until the end of 2011 the region inflated again (Figure 1), this time at a more rapid rate with uplift of over 7 cm measured. GPS and gravity measurements were conducted as well as analysis of InSAR images to try to better understand the underlying source/s. The geodetic data suggest inflation of a 4-5 km deep source beneath Sveifluháls, triggering intense seismic activity in the overlying crust due to the interaction between the plate boundary that crosses the region and the inflation source.

Since 2012 the region has been subsiding with deflation source estimated at 3 km depth beneath Móhálsadalur. The location of the deflation source coincides with a previously mapped low resistivity zone from MT measurements suggesting the presence of water, magma or conductive minerals.

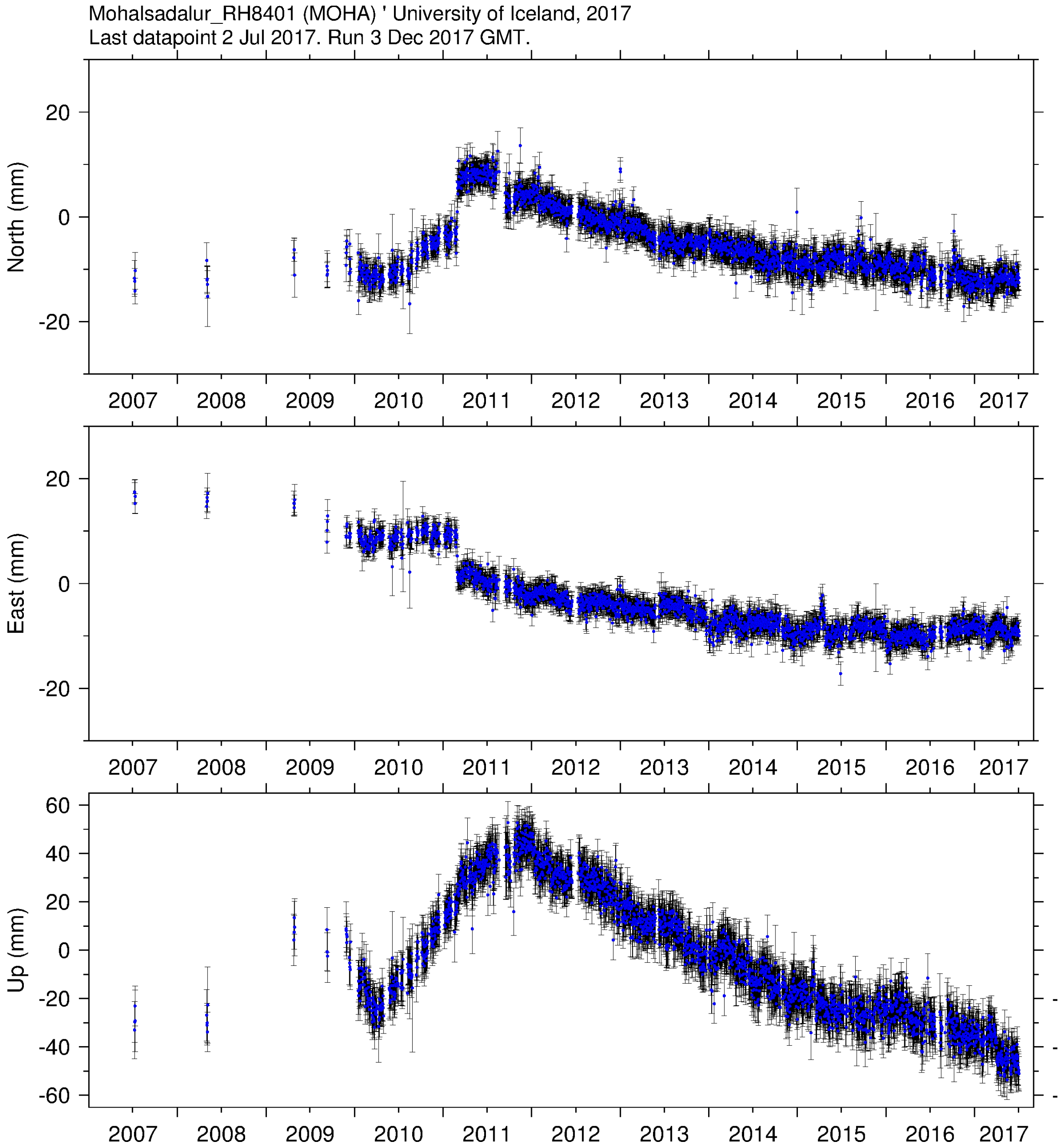

Figure 1. Detrended GPS times series from stations MOHA (Móhálsadalur) analyzed using the GAMIT/GLOBK software, using over 200 global reference stations in the analysis to estimate site positions in the ITRF14 reference. The inflation period from May 2010 until the end of 2011 was captured in detail by this time series, as well as the following deflation period. Figure from: https://strokkur.raunvis.hi.is/~sigrun/MOHA_08.png

The ground deformation is well mapped by continuous GPS time series (Figure 1) as well as InSAR time series analysis (Figure 2). The InSAR technique maps the change in range from ground to satellite and can be displayed as a time series using satellite images acquired at different times. Figure 2 shows outcome of such analysis over the Krísuvík area (white are on map is Lake Kleifarvatn). Area of decrasing line-of-sight (red color increasing with time) documents inflation of the area reaching a maximum near end of 2011, later images show less signal (as the area has deflated again).

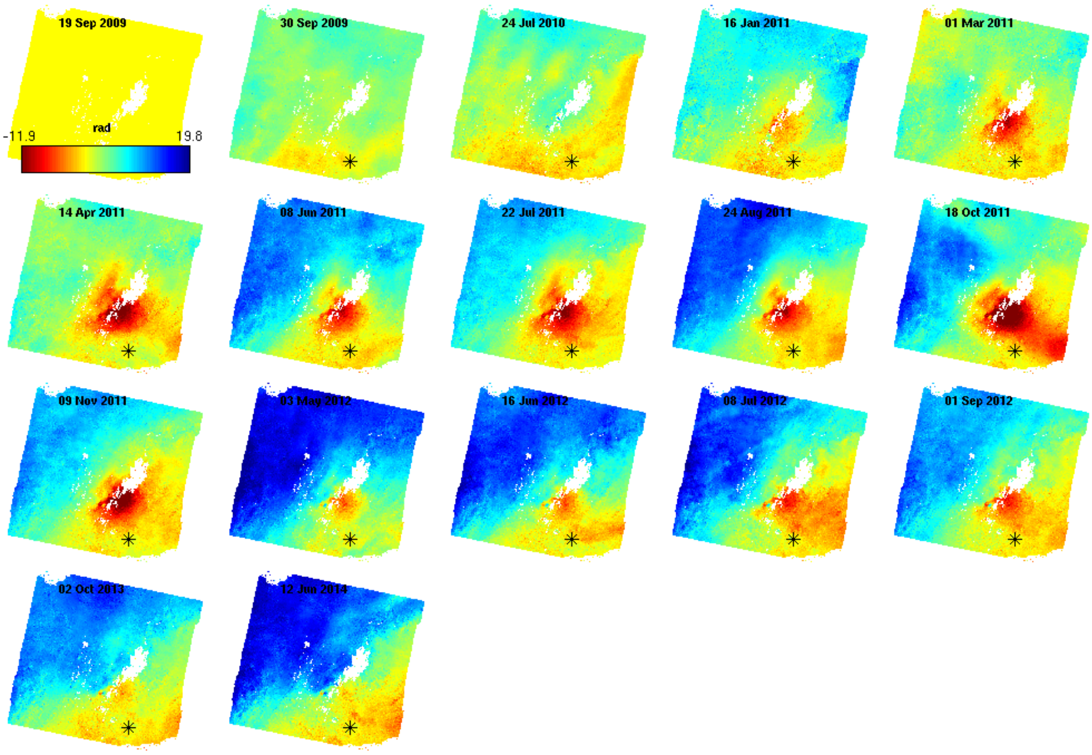

Figure 2. Unwrapped interferograms formed by images from the TerraSAR-X satellite for the descending track (34) using Persistent Scatterer processing. The figure shows inflation from 2009 until the end of the 2011 and then deflation as well as plate spreading across the region. The scale is in radians, where 2π radians correspond to a change of 15.5 mm (equal to half the wavelength of the satellite used). The scale is relative, but the total change of about 30 radians corresponds to a relative change of 74 mm.

In addition to GPS-time series from continuous measurements, and InSAR observations, campaign GPS measurments provide important additional constraints. Results are shown in Figures 3-6, both observations and a model to explain the observations.

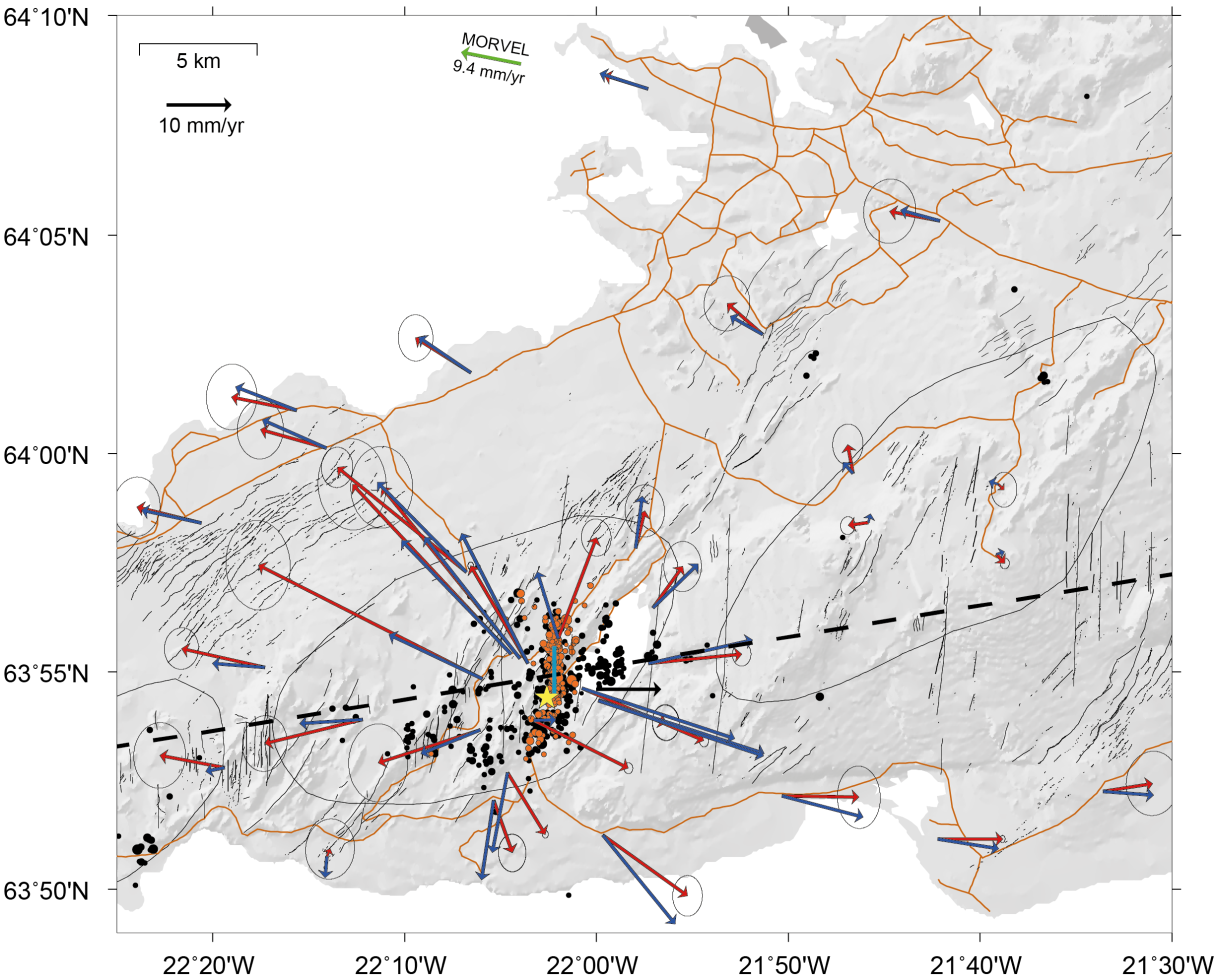

Figure 3. Inflation (red vectors) and seismic activity (black dots) from April 2010 to the end of 2011 (red vectors). The GPS data are modeled assuming the same background plate boundary motion as in 2001-2008 in addition to the coseismic offset for the 27 February 2011 earthquake sequence (orange dots). The best fit mogi suggests inflation at 4-5 km depth (yellow star). The misfit to the data is greatest closest to the source suggesting that a more complicated source is needed to explain the near field data.

The inflation was accompanied by high seismic activity most notably a seismic swarm that started on the 27 February 2011, with five earthquakes exceeding M3 (Figures 4 and 5). The largest earthquake was an M3.7 event west of lake Kleifarvatn.

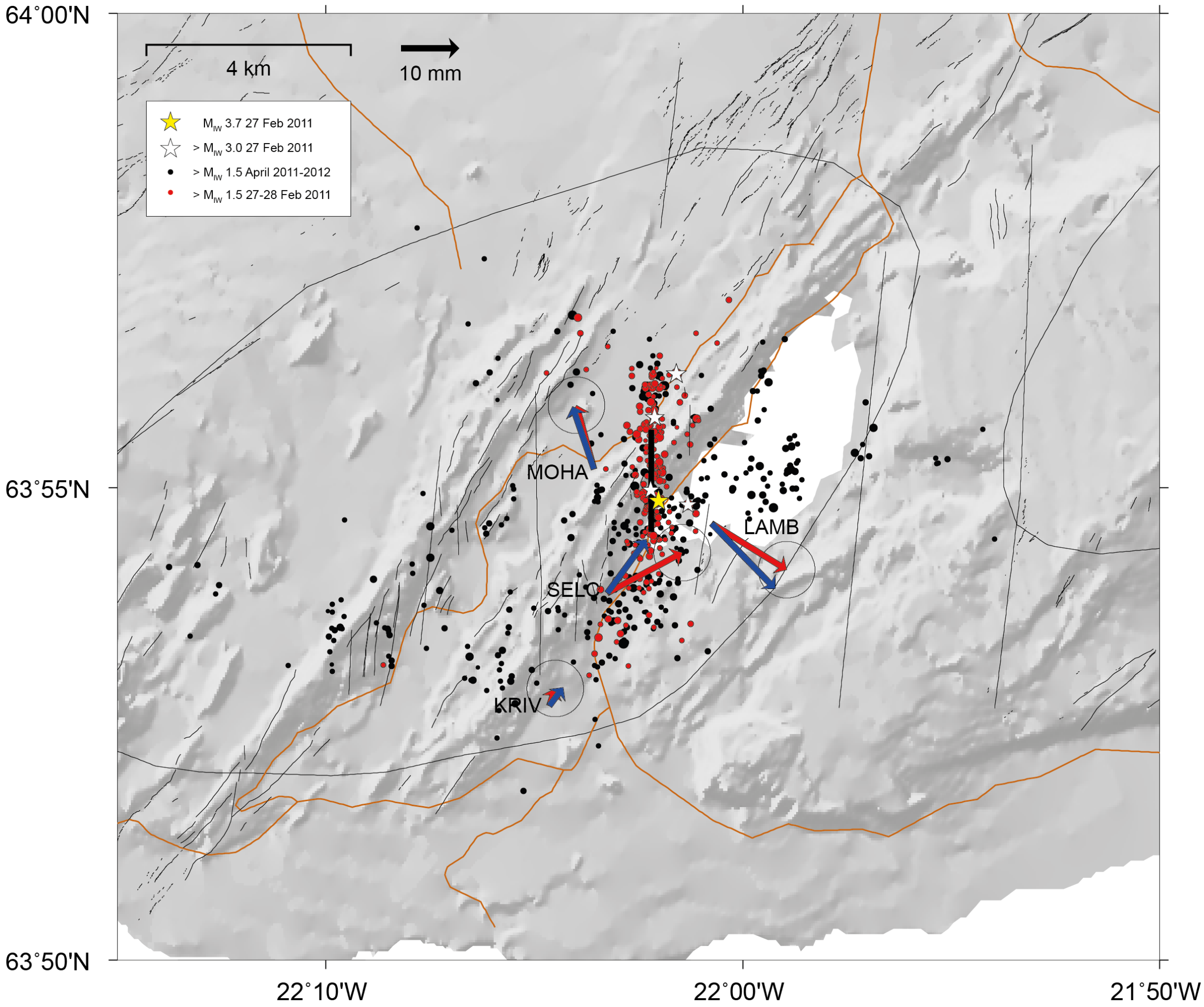

Figure 4. Coseismic offsets (red vectors) due to the 27 February 2011 M3.7 earthquake (yellow star). The best fit model (blue arrows) has a right lateral, north trending, strike-slip fault giving MW4.7 with a 0.2 m slip on a shallow, 0.4 to 2 km deep and 2 km long rupture. The figure shows also relocated earthquake recorded by the SIL network.

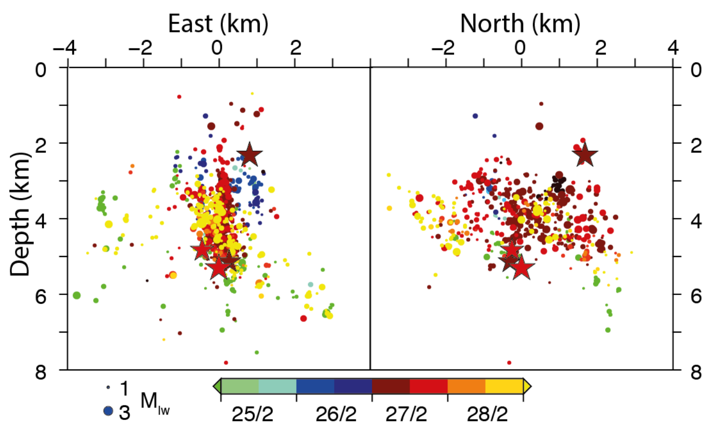

Figure 5. Cross section of relocated earthquakes 25-28 February 2011 (Sigurlaug Hjaltadóttir, Icelandic Met Office)

Since 2012 the Krísuvík area has been subsiding (Figure 6).

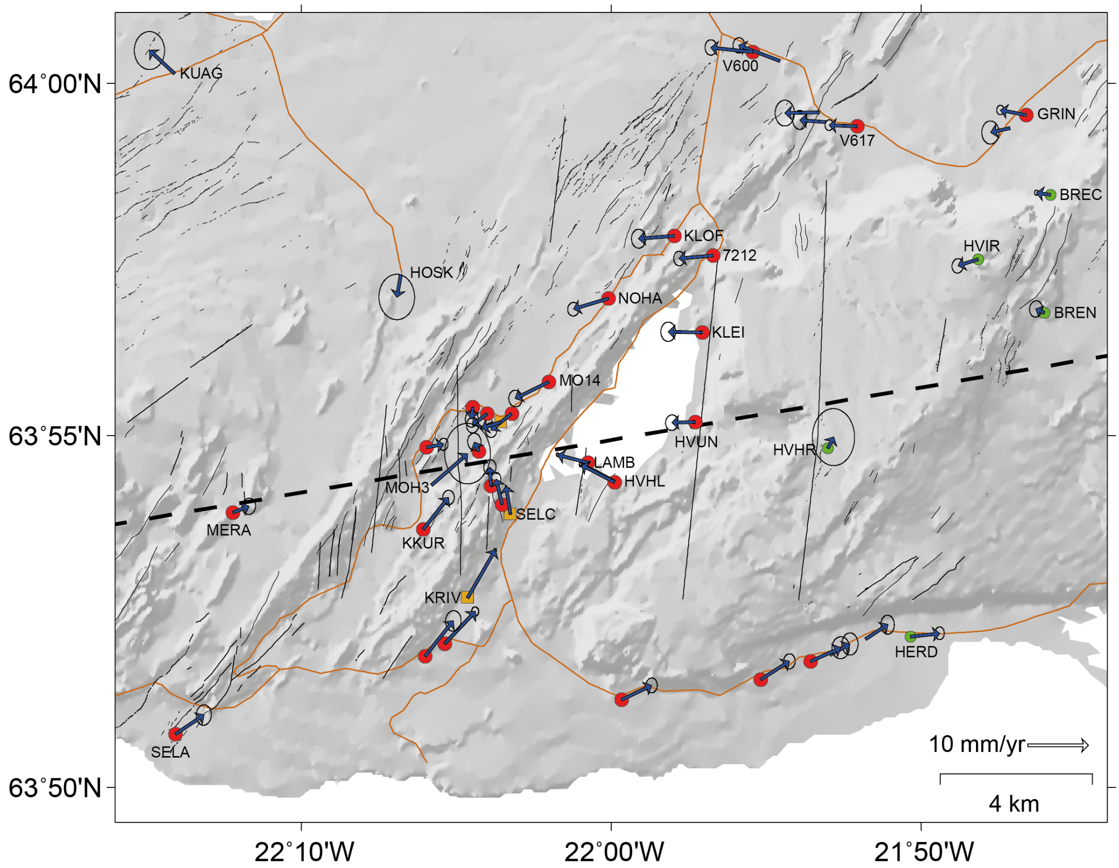

Figure 6. GPS measurements from 2012 to 2015 from the Krísuvík region, with 95% uncertainty ellipses relative to the plate boundary (dashed line). Red and green dots show sites measured in 2015. The deformation shows both deformation due to the plate boundary (left lateral shear and extension) and subsidence due to a source at about 3 km depth in Móhálsadalur (star). Orange squares show continuous GPS stations during the project. Green and red circles show sites measured with GPS in the spring and fall of 2015, respectively. Others were measured in 2013. The data are best fit by 19 mm/yr left lateral motion and 6.5 mm/yr extension below locking depth of 6 km along the plate boundary (dashed line) as well as contracting source at 3 km depth in Móhálsadalur (star). Green squares show continuous and semi continuous GPS stations.

The main results of crustal deformation studies are presented above, but the results are also in preparation for a manuscript to be submitted to an international journal (Sigrún Hreinsdóttir et al., in preparation).

Gas emissions:

Gas emissions from Krýsuvík geothermal system have been examined and correlated with crustal deformation and seismicity. The results are reported in a manuscript that has been submitted for publication (Guðjónsdóttir et al., Gas emissions and crustal deformation from the Krýsuvík high temperature geothermal system, J. Volc. Geotherm. Res, submitted 2017). The manuscript is submitted together with this report, main results are listed here below.

The results from the MultiGAS dataset as well as the fumarole samples indicate that the gas emissions from the Krýsuvík system are H_2O dominated with CO_2 as the most abundant dry gas species, followed by lesser amounts of H_2S. The subsurface equlibrium temperature was calculated as 278 °C.

The diffuse CO_2 soil flux is variable ranging from 10.9-70.9 T/day from the three observation areas with the highest flux in Hveradalir, the location of the MultiGAS station. The total flux was calculated as 101.4 T/day.

Correlation of the MultiGAS data with the geophysical data shows that peaks of H_2O-rich emissions follow events of crustal movements. Coinciding with the H_2O-rich peaks, SO_2 is detected in minor amounts (~0.6 ppmv) but this is the first time it has been detected in the Krýsuvík area. The high variations in H_2O/CO_2 and H_2O/H_2S ratios measured by MultiGAS are considered to be related to the intensity of degassing activity in the fumarole. The activity of the fumarole appears to be lower during intervals of low or no recorded seismic events. H_2O/CO_2 and H_2O/H_2S ratios are believed to be lower due to condensation processes affecting the H_2O concentration before the steam reaches the inlet tube.

Additional gas measurements were deemed necessary bringing Þráinn Friðriksson from ÍSOR into the project. He guided the MS student SRG with sampling of dry gas and condensate and CO_2 flux measurements as well as analysis and interpretation. The results were presented in SRG MS thesis and paper has been submitted to JVGR. The additional fieldwork and analysis was supported by FUTUREVOLC.

Interpretation:

Combination of GPS and InSAR is well suited to detect deformation in geothermal areas.

Krísuvík geothermal area is located at the central axis of the Reykjanes Peninsula plate boundary deformation axis, affected by shearing and extension. No significant deformation in deep roots of its system detected 2001-2008.

Two periods of inflation followed be deflation detected, due to pressure changes at 3-5 km depth under the geothermal area. The larger one has 8 cm of uplift, and same amount of subsidence

Pressure change in the roots of the geothermal system can explain observed deformation. Build-up of pressure in a sealed part of the geothermal system followed by relaxation to pre-unrest conditions, can reproduce the observed behavior. The location of the deflation source coincides with a previously mapped low resistivity zone from MT measurements suggesting the presence of water, magma or conductive minerals. This zone is interpreted as the roots of the geothermal system at Krísuvík.

The observed deformation pattern deviates from that of a magmatic intrusion in a shallow crust in the sense that injection of magma is not expected to show decay to previous levels as observed. Therefore interpretation of the data in terms of magma movements is not straight forward. We suggest that temporal variation in upflow through the deep roots of the system or sealing in the lower part of system may have built up the pressure enough to cause the deoformation, eventually without with little or minor involvement of magma. Pressure variations due to arrival of volcanic gas into the roots of the geothermal systems needs also investigation, although no major changes in gas have been observed at the surface.

In addition to the planned core work within the DRG1.1 project, there have been significant complementary studies of ground deformation due to temperature variations (cooling of lava flow, Wittman et al., 2017), as well as ground deformation due to utilization at both Krafla (Drouin et al., 2017) and Reykjanes geothermal areas (Parks et al, submitted). This allows comparison of deformation processes in different geothermal areas, as reported in a presentation at the final conference of the IMAGE project. (Sigmundsson et al., 2017).

An additional involvement has been the participation of FS in work for the Krafla Magma Testbed (kmt.is) initiative and the earlier Krafla Magma Drilling Project. This relates to DRG, as it has similar aims of understanding the deep roots of geothermal systems.

2 Project Management

Sigrún Hreinsdóttir (SH) was the PI of the project. Sigrún has led the project and decisions on the work plan, together with key collaborative scientists. Evgenia Ilyinskaya (EI) was responsible for the continuous gas measurements in Krýsuvík, and Þráinn Friðriksson (ÞF) provided guidance for gas flux measurements. During the project period Sigrún Hreinsdóttir changed her position from University of Iceland to GNS Science, New Zealand. Freysteinn Sigmundsson at University of Iceland has assisted Sigrún with coordination in the later phase of the project.

Three students at the University of Iceland were involved in the project (see Chapter 3), but an unexpected complication with respect to project management was that two of the students did not complete their planned degree. This influenced the project, but not its main findings. Key results for ground deformation are presented in this report. These results are also in preparation for submission to an international scientific journal.

SH was the main advisor of Ph.D. student Karolina Michalczweska (KM). SH was also the advisor of MSc student Sylvía Rakel Guðjónsdóttir (SRG), along with Evgenia Ilyinskaya and Þráinn Friðriksson, and co advisor of Werner Wittman. SH coordinated the geodetic fieldwork and was responsible for the GPS, InSAR and gravity data collection..

Freysteinn Sigmundsson (FS) was the main advisor of student Werner Wittman on the modeling of heat transfer (mostly funded by external project funding, by the NEMOH initial training network in volcanology, but with few additioanl months from DRG). FS also provided InSAR data to the project and guided KM with the InSAR analysis. FS provided additional funding for gas flux and dry gas and condensates gas sampling through the FUTUREVOLC project.

Evgenia Ilyinskaya (EI) was responsible for the continuous gas measurements in Krýsuvík and main advisor of SRG. EI guided SRG with the gas measurements and interpretation.

Þráinn Friðriksson (ÞF) guided MS student SRG with gas flux measurements and dry gas and condensates gas sampling as well as interpretation.

Stephanie Dumont (University of Iceland) helped with InSAR analysis.

Auður Agla Óladóttir (ÍSOR) helped with gas analysis and measurements.

In 2015 we requested additional funding from HS orka for repeat GPS and gravity measurements of the network to improve the velocity field. The fieldwork was carried out and data analyzed in November and December 2015.

3 Student involvement

Three students at the University of Iceland are involved in the project:

Ph.D. candidates Karolina Michalczewska, Werner Wittman, and MS student Sylvía Rakel Guðjónsdóttir.

Sylvía Rakel Guðjónsdóttir worked on gas measurements and interpretation in year 1 and 2. She finished her MS thesis in October 2014.

Guðjónsdóttir, S. R., Gas emissions from the Krýsuvík high-temperature geothermal system, Iceland, M.Sc. thesis Geology, University of Iceland, Faculty of Earth Sciences, 72 pp, October 2014. http://hdl.handle.net/1946/19901

Karolina Michalczweska has worked on the gravity, InSAR and GPS measurments in Krýsuvík Her work forms the basis fo rthe results on crustal deformation reported here.

Werner Wittmann worked on heat transfer and cooling models of lavaflows, sills and dykes, mostly from funding from the NEMOH project, but also from DRG support. His additional work was to provide further insights into the role of temperature variations as a source of deformation. Werner was advised by FS on the modeling but he also spent six weeks in New Zealand working with the PI in 2015 (at no cost to DRG).

4 Publications and disseminations

Guðjónsdóttir, S. R., Ilyinskaya, E., Hreinsdóttir, S., Bergsson, B., Pfeffer, M.A., Michakczewska, K., Aiuppa, A., Óladóttir, A.A., Gas emissions and crustal deformation from the Krýsuvík high temperature geothermal system, J. Volc. Geotherm. Res, submitted (2017).

Guðjónsdóttir, S. R., Ilyinskaya, E., Hreinsdóttir, S., Michakczewska, K., Bergsson, B., , Aiuppa, A., Óladóttir, A.A., Hjartardottir, A.R., Crustal deformation and gas emission from the Krýsuvík high temperature geothermal system, Iceland, EGU General Assembly Conference Abstracts, vol. 18, p 9253, 2016.

Guðjónsdóttir, S. R., Ilyinskaya, E., Hreinsdóttir, S., Friðriksson Th., Auippa, A., Bergsson, B., Gas emissions from the Krýsuvík high temperature geothermal system, poster at the MeMoVolc summer school 1-4 July, 2014 Stóru Tjarnir, Iceland

Guðjónsdóttir, S. R., Ilyinskaya, E., Hreinsdóttir, S., Friðriksson Th., Auippa, A., Bergsson, B., Gas emissions from the Krýsuvík high temperature geothermal system, presentation at DRG GEORG Annual meeting 2014.

Guðjónsdóttir, S. R., Gas emissions from the Krýsuvík high-temperature geothermal system, Iceland, M.Sc. thesis Geology, University of Iceland, Faculty of Earth Sciences, 72 pp, October 2014. http://hdl.handle.net/1946/19901

Michalczewska, K., Hreinsdóttir, S., Árnadóttir, T., Hjaltadóttir, S., Ágústsdóttir, T., Gudmundsson, M.T., Geirsson, H., Sigmundsson, F., Gudmundsson, G., Inflation and deflation episodes in the Krisuvik volcanic system, Am. Geophys. Un. Fall Meeting Abstracts. 2012 (presentation V33A-2843), http://abstractsearch.agu.org/meetings/2012/FM/V33A-2843.html

Michalczweska, K., L., Crustal deformation in the Krýsuvík area, presentation at the open workshop on processes in high-enthalpy geothermal systems, GEORG, Reykjavík, Iceland, 10 September 2013.

Hreinsdóttir, S., et al., The inflation and deflation episodes of the Krýsuvík volcanic system. Manuscript in preparation.

Related publications (improving understanding of ground deformation in geothermal areas):

Wittmann, W., F. Sigmundsson, S. Dumont, and Y. Lavallée (2017), Post-emplacement cooling and contraction of lava flows: InSAR obser- vations and a thermal model for lava fields at Hekla volcano, Iceland, *J. Geophys. Res. Solid Earth*, *122*, 946–965, doi:10.1002/2016JB013444.

Drouin, V., Sigmundsson, F., Verhagen, S., Ófeigsson, B. G., Spaans, K., Hreinsdóttir, S., Deformation at Krafla and Bjarnarflag geothermal areas, Northern Volcanic Zone of Iceland, 1993–2015, Journal of Volcanology and Geothermal Research 344 (2017) 92–105.

Parks, M., Sigmundsson, F., Sigurðsson, Ó., Hooper, A., Deformation due to geothermal exploitation at Reykjanes, Iceland, 2003 to 2016: InSAR time series analysis, J. Volc. Geotherm. Res, submitted (2017).

Sigmundsson, F., Drouin, V., Parks, M., Li, S., Hreinsdóttir, S., Geirsson, H., Árnadóttir, Þ., Juncu, D., Hooper, A., Ófeigsson, B.G., and Magnússon, I.Þ. Geodetic imaging of changes in geothermal reservoirs and magma transfer: Towards improved modeling of volcanic and geothermal processes, IMAGE final conference IMAGE Final Conference, Novel Approaches for Geothermal Exploration 4-6 Oct. 2017 ÍSOR, Akureyri, Iceland (presentation and abstract)

5 Cost statement

The funding provided by the project was used to map ground deformation and gas release in the Kríusvík area, and work on understanding of geodetic and gas signals originating the deep roots of geothermal systems. Costs were mainly salary costs for additional staff hired to the project (Ph.D. and MS students).

In Year 1 there were 19 days of field GPS and gravity measurements. Additional 14 days of fieldwork were used for gas flux measurements and dry gas and condensates sampling to better understand the region. In Year 2 there were 14 days of field GPS measurements. In Years 3 and 4 there were additional measurements

We ran MultiGAS station and four semi continuous GPS stations during the project in addition to the IMO station KRIV. The cost of equipment and data transfer at site MOHA was contributed to the project. Installation of MultiGAS meter was funded by IMO and collaborators. Ten days of trips into the area by technicians to download data, change batteries, maintain equipment and help with fieldwork were covered by the project.

The project covered the cost of one international conference.

Overview of items in cost statement

Year 1, 2013:

Salary costs charged to the project include Ph.D. student Karolina Michalczewska (KM), 3 months, and Sylvía Rakel Guðjónsdóttir (SRG), 3 months, and some costs for technicians. Total of 2.431 þkr.

Contributed salary costs include 9 months salaries for KM, 12 months for Ph.D. student Werner Wittman (WW), 2 months for SRG, 4 months for SH, and 1 months for few others. Total of 14.350 þ.kr.

Other costs charged to the project include GAS measurements and analysis (1.200 þkr) and travel costs (500 þkr). Contributed costs include equal amount of cost for gas analysis (1.200 þkr), and contribution towards operational expenses from separately funded FUTUREVOLC project (1.000 þkr).

Year 2, 2014:

Salary costs charged to the project include 12 months for KM, 3 months for SRG, and some additional costs for technicians. Total of 5.130 þkr.

Contributed salary costs include 9 months salaries for WW, 2 months for SRG, 4 months for SH, 1 month for Evegenia Ilyinskaya (EI), and 3 months for Freysteinn Sigmundsson (FS). Total of 7.650 þ.kr.

Contributed other costs include running costs towards operational expenses from separately funded FUTUREVOLC project (1.100 þkr).

Year 3 and 4, 2015 and 2016:

Salary costs charged to the project include 5.5 months for KM, 9 months for WW, and some additional costs for technicians. Total of 5.411 þkr.

Contributed salary costs include 1.5 months salaries for WW, 4 months for SH, and 4 months for Freysteinn Sigmundsson (FS). Total of 5.733 þ.kr.

Costs charged to the project include travel costs for SRG to attend an international conference (458 þkr).

Contributed other costs include running costs towards operational expenses from separately funded FUTUREVOLC project (1.200 þkr).

Funded by other sources, not included in cost statement

InSAR images were provided by Freysteinn Sigmundsson at no cost to the project

Computer cluster to analyse and model the geodetic data were provided to the project by the University of Iceland at no cost to the project.

MultiGAS sensor was on loan from INGV during the project.

The continuous GPS station KRIV is operated by IMO, MOHA operated by IMO and University of Iceland.

SCINTREX gravity meter and Trimble geodetic GPS units were provided to the project by the University of Iceland.