



FINAL REPORT

H₂S sequestration into geothermal systems

Project ID: 11-04-003

Coordinator: University of Iceland, Andri Stefánsson

Start date: 01.04.2012

Duration: 3 years

Partners: **Ingvi Gunnarsson (Reykjavik Energy), Sigurður H. Markússon (Landsvirkjun),
Shuhei Ono, MIT, USA.**

1 Project summary

Hydrogen sulphide (H₂S) is commonly emitted into the atmosphere from geothermal power plants, causing potential environmental problems. Possible H₂S disposal method is injection back into the geothermal systems whereas H₂S mineralizes into sulphides. The project “H₂S sequestration into geothermal systems” was aimed at defining the geochemistry of geothermal H₂S sequestration and its geochemical feasibility.

The major project parts included:

- Geochemical reactions and sulphide formation under geothermal conditions
- Multiple sulphur isotopes as tracers of H₂S sequestration processes
- Geochemical feasibility of H₂S sequestration into geothermal systems

The results of the project have been published in the following reports and scientific papers:

- Guðbrandsson S., Stefánsson, A. (2014) Experimental study of H₂S sequestration in geothermal systems. Science Institute UI Report, RH-14-2014. (App.1)
- Stefánsson A., Keller N.S., Gunnarsson-Robin J., Ono S. (2015) Multiple sulfur isotope systematics of Icelandic geothermal fluids and the source and reactions of sulfur in volcanic geothermal systems at divergent plate boundaries. *Geochim. Cosmochim. Acta* 165, 307-323. (App.2)
- Marieni C., Přikryl J., Aradóttir E.S., Gunnarsson I., Stefánsson A. (2017) Towards green energy: Co-mineralization of carbon and sulfur in geothermal reservoirs. *International Journal of Greenhouse Gas Control* [submitted]. (App.3)
- Gunnarsson-Robin J., Stefánsson A., Ono S., Torssander P. (2017) Sulfur isotopes in Icelandic thermal fluids. *J. Volcanol. Geotherm. Res.* [in press]. (App.4)
- Přikryl J., Marieni C., Gudbrandsson S., Aradóttir E.S., Gunnarsson I., Stefánsson A. (2018) H₂S sequestration process and sustainability in geothermal systems. *Geothermics* 71, 156-166. (App.5)

2 Project Management

The participating group of institutions comprises University of Iceland (UI), MIT, USA (MIT), Reykjavik Energy (OR), and Landsvirkjun (LV). The Science Institute, University of Iceland (UI) head office was responsible for the financial management of the project.

The main leaders of the research project are: from UI: Andri Stefansson, professor in geothermal geochemistry; from MIT: Shuhei Ono, professor of isotope and sulphur geochemistry; from OR: Ingvi Gunnarsson, scientist; from LV: Sigurdur H. Markússon, project manager. Several graduate students and postdoctoral scientists were involved in the project and included: Jóhann Gunnarsson-Robin, MSc student at University of Iceland 2013-15; Snorri Gudbrandsson, postdoctoral researcher at University of Iceland 2014-15; Jan Přikryl, PhD student at University of Iceland 2013-

present; Chiara Marieni, postdoctoral researcher at University of Iceland 2015-16; Nicole S. Keller, postdoctoral researcher at University of Iceland 2012-16.

Majority of the project work was conducted at UI. This included: experiments, chemical analysis, sample preparation and treatment. The main PI, students and postdoctoral researchers were all at UI. Sample and material access of geothermal fluids and rocks was made available through the collaborators at OR and LV and sulphur isotope analyses were done at MIT.

The project was funded from various sources. During the years 2012-2014 the project was funded by: Georg, Reykjavík Energy (OR), Orkurannsóknarsjóður LV.

3 Student involvement

A large part of the project: “H₂S sequestration into geothermal systems” was carried out by graduate students and postdoctoral researchers. Students and postdoctoral researchers involved in the project included:

- *Jóhann Gunnarsson-Robin* – MSc and PhD student at University of Iceland 2013-15 and 2015-present. Thesis: Multiple Sulfur Isotope Systematics of Geothermal Fluids at Krafla, NE Iceland, and the Source and Reactions of Sulfur in Volcanic Geothermal Systems.
- *Snorri Guðbrandsson* – Postdoctoral researcher at University of Iceland 2014-15. Project: Experimental study of H₂S sequestration in geothermal systems.
- *Jan Přikryl* – PhD student at University of Iceland 2013-present. Thesis: Water-rock interaction in porous media: an experimental and modelling study.
- *Chiara Marieni* – Postdoctoral researcher at University of Iceland 2015-16. Project: Experimental study of H₂S and CO₂ sequestration in geothermal systems.
- *Nicole S. Keller* – Postdoctoral researcher at University of Iceland 2012-16. Project: H₂S geochemistry in geothermal systems.

4 Publications and disseminations

The results of the project: “H₂S sequestration into geothermal systems” have been reported in 5 scientific papers and reports. These are attached in appendices

- Guðbrandsson S., Stefánsson, A. (2014) Experimental study of H₂S sequestration in geothermal systems. Science Institute UI Report, RH-14-2014. (App.1)
- Stefánsson A., Keller N.S., Gunnarsson-Robin J., Ono S. (2015) Multiple sulfur isotope systematics of Icelandic geothermal fluids and the source and reactions of sulfur in volcanic geothermal systems at divergent plate boundaries. *Geochim. Cosmochim. Acta* 165, 307-323. (App.2)
- Marieni C., Přikryl J., Aradóttir E.S., Gunnarsson I., Stefánsson A. (2017) Towards green energy: Co-mineralization of carbon and sulfur in geothermal reservoirs. *International Journal of Greenhouse Gas Control* [submitted]. (App.3)
- Gunnarsson-Robin J., Stefánsson A., Ono S., Torssander P. (2017) Sulfur isotopes in Icelandic thermal fluids. *J. Volcanol. Geotherm. Res.* [in press]. (App.4)

- Prikryl J., Marieni C., Gudbrandsson S., Aradóttir E.S., Gunnarsson I., Stefánsson A. (2018) H₂S sequestration process and sustainability in geothermal systems. *Geothermics* 71, 156-166. (App.5)

The results of the project: “H₂S sequestration into geothermal systems” have been introduced at local and international conferences in posters (7x) and talks (2x):

- Gunnarsson-Robin J., Stefánsson A., Keller N.K., Ono S. (2015) Multiple Sulfur Isotope Systematics of Geothermal Fluids in Iceland. *Goldschmidt Conference 2015* [poster]
- Gudbrandsson S., Moola P., Stefánsson A. (2014) H₂S Injection and Sequestration into Basalt - The SulFix Project. *AGU fall meeting 2014, GC43A-0675* [poster]
- Gudbrandsson S., Moola P., Stefánsson A. (2014) H₂S Injection and Sequestration into Basalt, SulFix. *ICC 2014, 30* [poster]
- Gunnarsson-Robin J., Keller N.K., Stefánsson A., Ono O. (2014) Boiling processes in geothermal systems: Effect on modelled reservoir compositions and sulfur isotope ratios. *ICC 2014, 31* [poster]
- Keller N.S., Stefánsson A., Ono S., Gunnarsson-Robin J. (2014) Geochemistry of sulfur in Krafla: using sulfur isotopes to unravel processes affecting sulfur compounds. *ICC 2014, 42* [poster]
- Keller N., Stefánsson A., Ono S., Gunnarsson-Robin J. (2013) Sulfur Isotope Systematics of Geothermal Fluids, Krafla, Iceland. *Min. Mag.* , 1445 [poster]
- Stefánsson A. (2015) H₂S sequestration into geothermal systems. *Georg open day* [talk]
- Stefánsson A. (2013) H₂S sequestration into geothermal systems. *Georg open day* [talk]
- Stefánsson A. (2012) H₂S sequestration into geothermal systems. *Georg open day* [poster]

5 Cost statement

The project: “H₂S sequestration into geothermal systems” supported by Georg span 3 years of work, from mid 2012 until mid 2015. During this time the total cost of the project was: 19175 ths IKR. Majority of the cost was related to salary and salary related cost (14452 ths IKR), operational cost related to instrumental cost and chemical analysis (1697 ths IKR) and travel cost related to conferences and analysis of S-isotopes at MIT, USA (2561 ths IKR). Overhead of research grants at Science Institute UI is 2.5%. The project was financed by grants from Gerog (9680 ths IKR), Orkurannsóknarsjóð LV (4899 ths IKR), Reykjavík Energy (4200 ths IKR) and various other minor sources (300 ths IKR).

A summary of the project finances and cost are given in Table 1 and 2. The final payment from Georg, 3275 ths IKR is still outstanding.

Table 1
Overview of project finances for 2012-2014. All numbers are in 1000 IKR

	2012-13 (yr 1)	2013-14 (yr 2)	2014-15 (yr 3)	Total
Gerog	3125	3280	3275 c	9680
Landsvirkjun (LV) ^a	1974	2925		4899
Reykjavík Energy (OR) ^b		4200		4200
Other and various sources			399	399
Total	5099	10405	0	19178

^a Support form LV through Orkurannsóknarsjóður LV

^b Support from OR related to experimental work and apparatus

^c The final payment is still outstanding

Table 2
Overview of project cost 2012-2014. All numbers are in 1000 IKR

	2012-13 (yr 1)	2013-14 (yr 2)	2014-15 (yr 3)	Total
Salary and related expences	4959	3894	5599	14452
Operational expences ^a	1319	83	295	1697
Travel expences ^b	870	555	1136 ^d	2561
Overhead ^c	179	113	176	468
Total	7327	4645	7206	19178

^a Operational expences include instrumental and laboraotry cost and chemical analysis

^b Travel expences include conference fees and travel cost related to conferences and analysis of S-isotopes

^c Overhead is 2.5%

^d Some of the travel expences for 2014 were cost related to the final S-isotope analysis carried out early 2015

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Andri Stefánsson