



## **ANNUAL REPORT YEAR <2012-2013>**

**< CarbFix project >**

Project ID: 09-02-001

Coordinator: Sigurður Reynir Gíslason, University of Iceland

Start date: January, 2010

Duration: 4 years (due to delays), June 2010-June 2013

Partners: Orkuveita Reykjavíkur and University of Iceland

## 1 General status of the project

< The overall objective of the CarbFix project is to develop and optimize a practical and cost-effective technology for mineral storage of carbon dioxide in basaltic rock, and to train young scientist to carry this knowledge into the future. The project consist of a field injection of CO<sub>2</sub> charged water in the vicinity of Hellisheidi power plant, associated monitoring, laboratory experiments, computer modelling of fluid flow and gas-water-rock interactions, tracer tests, natural analogue studies and cost analysis.

Initially, the project faced delays in injection at the field site in Hellisheidi due to operational problems in a pilot gas separation station which has been built next to Hellisheidi power plant as detailed in the Annual report for the year 2011-2012.

In March 2011 a full scale injection test was carried out with 800 kg of commercially bought pure CO<sub>2</sub>. This was done to synchronize the injection system, evaluate the injection and sampling technology, identify and remedy any potential technical problems associated with operating the experiment, and finally to practice sampling of injection and monitoring fluids. The injection test was a success.

In a second test, 175 tons of commercial pure CO<sub>2</sub> were injected over a period of 6 weeks in January/February/March 2012.

Injection of gas mixtures (CO<sub>2</sub>-H<sub>2</sub>S-H<sub>2</sub>) from Hellisheidi power plant commenced on June 12<sup>th</sup> 2012 and continued until August 8<sup>th</sup>. Overall 65 tons of the gas mixture was injected.

The injection of the gas mixture continued in 2013 but was hampered by the decrease in the transmissivity of the injection well. A combined effect of bacteria response to the injection of the gas mixture and precipitation of iron-sulphides within the injection well was probably the cause. Because of this it was decided in the autumn of 2013 to stop injecting gas mixtures into the CarbFix injection well and join forces with the SulFix project and inject CO<sub>2</sub>-H<sub>2</sub>S-H<sub>2</sub> gas mixture into the deep and sterile part of the geothermal system at Hellisheidi (>205°C) in the spring of 2014.

Reservoir monitoring and characterization at the CarbFix site in Þrengsli continued throughout 2012 to the present (March 2014).

In short, injection of pure CO<sub>2</sub> was success. We mastered the injection technique, the CO<sub>2</sub> was fully dissolved in water in less than 5 minutes within the injection well, and about 85% of the injected CO<sub>2</sub> was mineralized within a year (Sigfusson et al. 2014; Alfredsson et al. 2004; Matter et al; 2013; Stute et al. 2013; Gislason and Oelkers 2014). These results are in concert with previous reactive transport modelling prediction of 100% mineral storage of 1,200 tonnes of pure CO<sub>2</sub> within 10 years (Aradottir et al. 2012).

Below we will report on the work package funded by George during the 3 year of the contract, WP-1: CO<sub>2</sub> charged seawater-basalt experiments >

## 1.1 Project progress/time schedule:

<

### WP-1: CO<sub>2</sub> charged seawater-basalt experiments (June 2012-June 2013)

Effect of ionic strength on the dissolution rates of basaltic glass and plagioclase (Labradorite) at pH 3.6 and temperature 25°C

Mineral storage of carbon involves dissolution of silicate minerals providing divalent cations that combine with dissolved carbon to form carbonate minerals. The dissolution rates of various silicate minerals suggest that the most efficient source of the divalent cations for the carbonisation process are basalts and ultramafic rocks. To limit the risk associated with buoyancy of injected CO<sub>2</sub> and to enhance CO<sub>2</sub> – rock interaction it is advantageous to dissolve the gas into an aqueous solution, prior to its injection. Carbon dioxide dissolution however, requires large water volumes that may not be available. In such cases seawater might be the only viable option. The objective of this study was to measure the effects of individual major cations in seawater on basaltic mineral and glass dissolution rates.

The first experiments were carried out on basaltic glass and plagioclase of intermediate composition (Labradorite) and a second set of experiments on pyroxene and the pure Na-end-member of plagioclase, albite. Plagioclase and pyroxene are the most abundant minerals in crystalline basaltic rocks.

The dissolution of basaltic glass and Labradorite was measured under steady state, far from equilibrium conditions in a flow through experimental reactors with inlet pH of 3.6 at 25°C. Inlet solutions with varying ionic strength of different cation concentration (Na, K, Ca and Mg) have been used to define the effect of ionic strength on dissolution. This experiment used an inlet fluid with different ionic strength of an electrolyte that was simultaneously pumped through three different reactors. This setup made it possible to measure the dissolution rates of the glass and Labradorite concurrently at the same conditions and at different electrolyte ionic strength. The reactor system was composed of acid washed PE™ 300 mL reactors maintained at constant temperature in a thermostat controlled water bath. These reactors were stirred using Teflon™ coated floating stir bars from Nalgene™ placed on the bottom of the reactors and propelled by a multi-position magnetic stirrer located underneath the water bath. Pumping rates from 0.85–1.0 mL/min were maintained using a Masterflex™ cartridge pump. All the reactor components were made of Teflon to avoid corrosion. At the beginning of the experiment the reactors were thoroughly cleaned, assembled, and run for 24 h with a cleaning solution to rinse the tubing and clean the reactor. The reactor was then flushed with deionized water. About 4 g of dry powder were put in the reactor. The reactor was then filled with the inlet solution, closed tightly, and placed in the water bath. Flow, temperature, and stirring rates were adjusted to desired settings. The outlet flow was sampled, filtered through a 0.2 µm cellulose acetate filter, acidified with concentrated supra-pure HNO<sub>3</sub>, and analysed for the silica content.

Steady-state silica release rates ( $r_{Si}$ ) determined for basaltic glass has shown that rates did not change with varying ionic strength for Na, K and Ca electrolytes while Mg is observed to inhibit dissolution rates with an increase in ionic strength. The Labradorite rates generally increase with

increasing cation concentration (ionic strength) for K and Ca electrolytes. While a general increase is noticed for Mg and Na electrolytes, rates are observed to be inhibited at very high concentration (500mmolal). The Na concentration of seawater is 468 mmolal, the Mg concentration is 53 mmolal and Ca and K about 10 mmolal (Bruland 1983)<sup>1</sup>. Also at very high concentration the divalent cations lead to lower rates compared to the monovalent ones. These results were described in 3 conference abstracts and posters in 2012 (Kiflom et al. 2012a, b and c) and in a manuscript in preparation for Chemical Geology.

A second set of experiments on pyroxene (augite) and the pure Na-end-member of plagioclase albite, were carried out in 2013. The dissolution rates were measured at far from equilibrium conditions in a flow through experimental reactors with inlet pH of 3.6 at 25°C. Inlet solutions with varying ionic strength of different cation concentration (Na, K, Ca and Mg) were used to define the effect of ionic strength on dissolution similar to the previous set of experiments on basaltic glass and Labradorite. The minerals were bought from the Ward-mineral supply company. In total we conducted 32 experimental series. We had problems reaching steady state during many of these dissolution rates experiments. Most likely explanation for it is that the minerals were not what we expected. In fact after thorough characterization of the minerals they turned out to be a mixture of minerals, the pure albite is a mixture of albite and nepheline, and the augite is most likely a mixture of fluoro-edenite (amphibole) and enstatite (orthopyroxene). We are in the process of assessing the data. The experiments are good, but the minerals are not what we wanted. This poses problems, but likewise some opportunities. We have explored the dissolution rate of two minerals simultaneously that dissolve at different rates. This will most likely lead to an interesting finding and a scientific paper.

## 2 Project Management

The CarbFix project was formally launched on September 29<sup>th</sup> 2007. It is a consortium of four partners, Orkuveita Reykjavíkur, the University of Iceland, Columbia University and CNRS in Toulouse, who signed a partnership agreement for the purpose of setting forth objectives, plans and undertakings with respect to the CarbFix project.

The project's management structure is the following:

### The Scientific Steering Committee:

- Sigurður Reynir Gíslason (Chairman). Research Professor at the Institute of Earth Sciences, University of Iceland. [sigr@raunvis.is](mailto:sigr@raunvis.is)
- Wallace S. Broecker. Newberry Professor of Earth & Environmental Sciences, Lamont-Doherty Earth Observatory of Columbia University, USA. [broecker@ldeo.columbia.edu](mailto:broecker@ldeo.columbia.edu)
- Eric H. Oelkers. Research Director - Chemistry and Earth Science, CNRS UMR 5563/Université Paul Sabatier, France. [oelkers@lmtg.obs-mip.fr](mailto:oelkers@lmtg.obs-mip.fr)
- Einar Gunnlaugsson. Head of Natural Resources Research, Division of Research and Development, Orkuveita Reykjavíkur, Iceland. [einar.gunnlaugsson@or.is](mailto:einar.gunnlaugsson@or.is)

The Management Team:

- Hólmfríður Sigurðardóttir (Chairman). Head of Environmental Affairs. Orkuveita Reykjavíkur, Iceland. [holmfridur.sigurdardottir@or.is](mailto:holmfridur.sigurdardottir@or.is)
- Juerg M. Matter. Lamont Associate Research Professor. Lamont-Doherty Earth Observatory of Columbia University, USA. [jmatter@ldeo.columbia.edu](mailto:jmatter@ldeo.columbia.edu)
- Andri Stefánsson. Professor at the Institute of Earth Sciences, University of Iceland. [as@hi.is](mailto:as@hi.is)

Project Manager:

- Edda S.P. Aradóttir, chemist at Natural Resources and Research, Division of Research and Development, Orkuveita Reykjavíkur, Iceland. [edda.sif.aradottir@or.is](mailto:edda.sif.aradottir@or.is)

Other parties involved in the project's decision-making:

- Martin Stute, Professor and Co-Chair, Lamont-Doherty Earth Observatory of Columbia University, USA. [jmatter@ldeo.columbia.edu](mailto:jmatter@ldeo.columbia.edu)
- Ingvi Gunnarsson, geochemist at Natural Resources and Research, Division of Research and Development, Orkuveita Reykjavíkur, Iceland. [ingvi.gunnarsson@or.is](mailto:ingvi.gunnarsson@or.is)

### 3 Student involvement

One of the main goals within CarbFix has been to train young scientists in the fields related to carbon capture and storage. As a result, a large part of the research carried out within the consortium is carried out by graduate students. The project funded by GEORG for the 3<sup>rd</sup> year of the grant; Effect of ionic strength on the dissolution rates of basaltic glass and basaltic minerals at pH 3.6 and temperature 25°C was carried out by the PhD student Kiflom Gebrehiwot Mesfin.

In 2012-2014, nine PhD students were working on science projects, within the CarbFix project. One PhD student, Therese Flaathen, was the first one to finish in 2009, then Edda S. Aradóttir, 2011, Alexander Gysi 2012, Gabrielle Stockmann 2012, Iwona Galeczka 2013 and Snorri Guðbrandsson 2012. A list of PhD students for the period 2012-2014 is given below.

Name	Title of Ph.D. thesis	University	Start	Finish
Gabriella Stockmann	Experimental determination of the effect of precipitated mineral coatings on the rates of basaltic glass and minerals; effect of bacteria on the dissolution of basaltic glass	University of Iceland and Paul Sabatier Toulouse	Sept 2007	May 2012
Helgi Arnar Alfreðsson	CO <sub>2</sub> storage in basaltic rock: Pre-injection studies of the injection field and development of a piston-type down hole sampler for CO <sub>2</sub> rich fluids and tracers	University of Iceland	Sept 2007	Sept 2014
Iwona Galeczka	Experimental studies on CO <sub>2</sub> sequestration in basaltic rocks with plug flow reactor and natural analogue studies	University of Iceland	Sept 2009	Sept 2013

Snorri Guðbrandsson	Dissolution rates of crystalline basalt and plagioclases and precipitation rates of Al-silicates.	University of Iceland and Paul Sabatier Toulouse	Sept 2007	October 2013
Jonas Olsson	Natural analogue of toxic metals scavenging into carbonates and the environmental effects of the Grimsvötn 2011 volcanic ash.	University of Copenhagen and University of Iceland	June 2010	June 2014
Kiflom Gebrehiwot Mesfin	Dissolution of basaltic glass and basaltic minerals in seawater. The effect of ionic strength.	University of Iceland	June 2010	?
Sandra Snæbjörnsdóttir	Field injection of pure CO <sub>2</sub> and gas mixture into the CarbFix Hellisheiði injection site and CO <sub>2</sub> storage capacity of Iceland and the oceanic ridges	University of Iceland	June 2012	June 2016
David Stevens	Reactive transport approach to studying CO <sub>2</sub> -H <sub>2</sub> S-H <sub>2</sub> water-basalt interaction: Modelling, designing and optimizing mineral storage in basaltic rocks at elevated temperature	Reykjavík Energy and University of Iceland	March 2014	March 2017
Deirdre Clark	Experimental studies on CO <sub>2</sub> sequestration in basaltic rocks with plug flow reactor and field injection of gas mixture into the Hellisheiði geothermal system	University of Iceland	March 2014	March 2017

>

#### 4 Publications and disseminations

- Kiflom G. Mesfin, Domenik Wolff-Boenisch and Sigurdur R. Gislason (2011). Dissolution rates of basaltic glass as a function of cation concentration. Poster, GEORG open-house presentations, Reykjavik University, 20 October 2011.
- Kiflom G. Mesfin, Domenik Wolff-Boenisch and Sigurdur R. Gislason (2012a). Effect of ionic strength on the dissolution rates of basaltic glass at pH 3.6 and 25°C. Poster presentation. 30th Nordic Geological Winter Meeting, Reykjavik, 9-12 January 2012.
- Kiflom G. Mesfin, Domenik Wolff-Boenisch and Sigurdur R. Gislason (2012b). Effect of ionic strength on the dissolution rates of basaltic glass and bytownite at pH 3.6 and 25°C. Abstract Goldschmidt conference 2012, Montreal, Canada.
- Kiflom G. Mesfin, Domenik Wolff-Boenisch and Sigurdur R. Gislason (2012c). Effect of Ionic Strength on the Dissolution rates of Basaltic glass and Bytownite at pH 3.6 and temperature 25°C. Poster VoN Research Symposium 2012, Reykjavik, Iceland.
- Kiflom G. Mesfin, Ingvi Gunnarsson, Bergur Sigfusson, Edda S. Aradóttir, Einar Gunnlaugsson, Martin Stute, Juerg M. Matter, Eric H. Oelkers, Sigurður R. Gíslason (2012d). Pure CO<sub>2</sub> injection at Hellisheiði: Results. Poster, Georg open-house presentations, Reykjavik, 2012.

## 5 Cost statement

*University of Iceland received 100% of the GEORG grant to CarbFix in the 3 year of the contract, total of 3.500.000,- iskr. It was used to pay 12 month salary for the PhD student Kiflom G. Mesfin.*

*The carbfix project funded the rest of the experimental cost, total of one and a half million iskr.*

*In total University of Iceland spent close to 10 million iskr on various parts of the CarbFix project during the third year of the contract, June 2012-June 2013.*