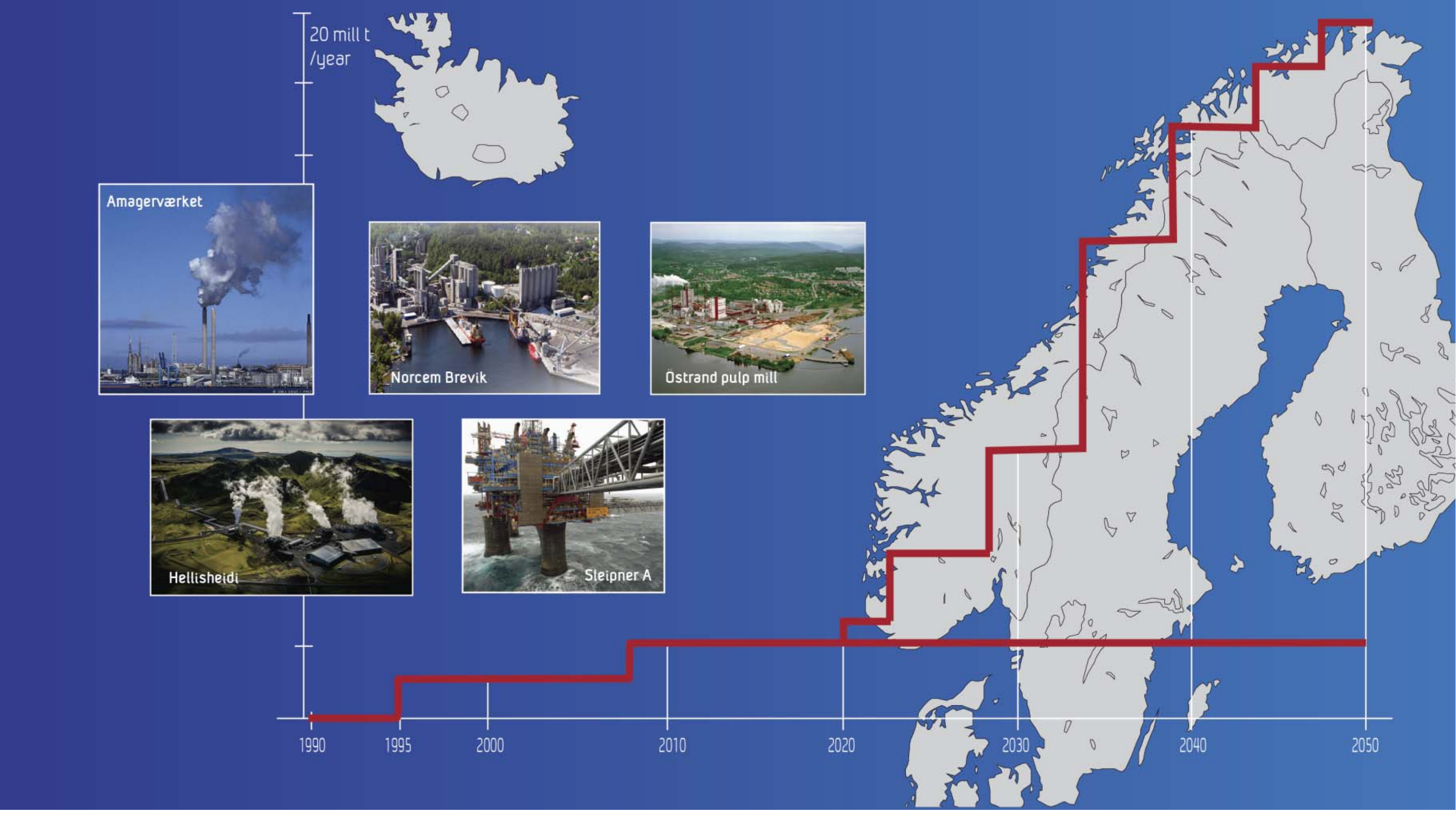

Assessment of reservoir modelling and natural analogue study of the CarbFix site to estimate overall storage potential

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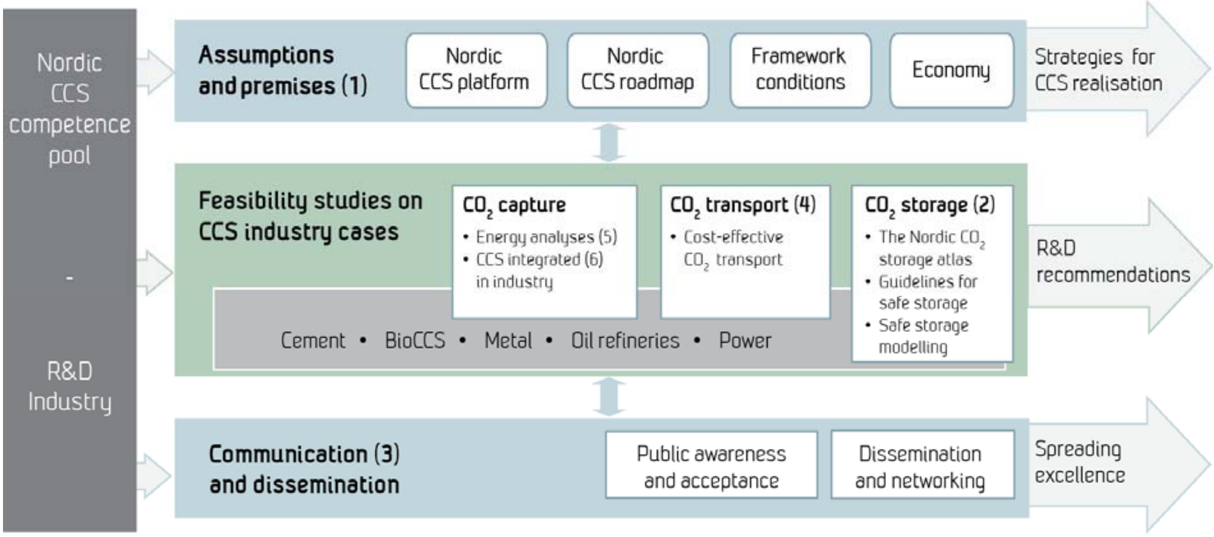

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Summary

Extensive work was carried out prior to two CO_2 injection experiments in Hellisheiði to evaluate the potential for mineral storage of CO_2. Reservoir modelling was used in order to evaluate the CO_2 storage potential of basaltic rocks together with a study using geothermal areas as a natural analogue. Results from these two studies are evaluated and compared with the first results from the field injection experiments to assess the overall storage potential for CO_2 in basaltic rocks. The results from the two studies are in good agreement and show that fresh basaltic rocks may comprise ideal geological CO_2 storage formations

Keywords CO_2 injection, basalts, reservoir modelling, natural analogue, CO_2 storage potential.

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Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.

D 6.3.1402 Assessment of reservoir modelling and natural analogue study of the CarbFix site to estimate overall storage potential

Abstract

Extensive work was carried out prior to two CO_2 injection experiments in Hellisheiði to evaluate the potential for mineral storage of CO_2. Included in the work was a natural analogue study done by Wiese et al (2008) to evaluate the CO_2 storage potential of basaltic rocks using geothermal areas as natural analogs and extensive reservoir modelling carried out by Aradóttir et al. (2012). Here, results from these two studies are evaluated and compared with the first results from the field injection experiments to assess the overall storage potential for CO_2 in basaltic rocks. The results from the two studies are in good agreement and show that fresh basaltic rocks may comprise ideal geological CO_2 storage formations.

Introduction

Two injection experiments have been carried out at the CarbFix site in Hellisheiði, SW-Iceland. In January-March 2012, 175 tons of pure CO_2 were injected into basaltic rocks at about 520 m depth and in June-August 2012 73 tons of 75% CO_2, 24%H_2S and 1%H gas mixture from the Hellisheiði geothermal plant was injected at the same site.

Extensive work was carried out prior to the injection experiments to optimize and describe the thermodynamic and kinetic basis for mineral storage of CO_2 in basaltic rocks (Gislason et al. 2010), characterize the geology and water chemistry of the CarbFix site (Alfredsson et al., 2013) and study the amount and spatial distribution of CO_2 already naturally stored within the basaltic rocks at Hellisheiði (Wiese et al., 2008). Other tasks included among other things wide-ranged experimental work on dissolution (e.g. Gudbrandsson et al. 2011), plug flow experiments (e.g. Galezcka et al. 2014), reaction path geochemical modelling (e.g. Gysi et al 2012) and reactive transport modelling (e.g. Aradóttir et al. 2012).

The main aim of this report is to assess the reservoir modelling and natural analog study done at the CarbFix site to estimate overall storage potential.

Natural analog study at the Hellisheiði geothermal area

Wiese et al. (2008) quantified the amount and spatial distribution of CO_2 stored as calcite ($CaCO_3$) within the bedrock of three active high-temperature geothermal systems in Iceland; Krafla in the north–east of Iceland and Reykjanes and Hellisheiði in the south-west (Figure 1). The geothermal waters are meteoric in the Krafla and Hellisheiði systems, but seawater in the Reykjanes system. The geothermal systems receive considerable amount of CO_2 from magma deep in their roots that partly gets fixed within the bedrock as carbonate minerals such as calcite, but the magma serves as a heat-source for the systems. The geothermal systems can therefore be used as natural analogues to determine the capacity of basaltic rocks for mineral storage of CO_2.

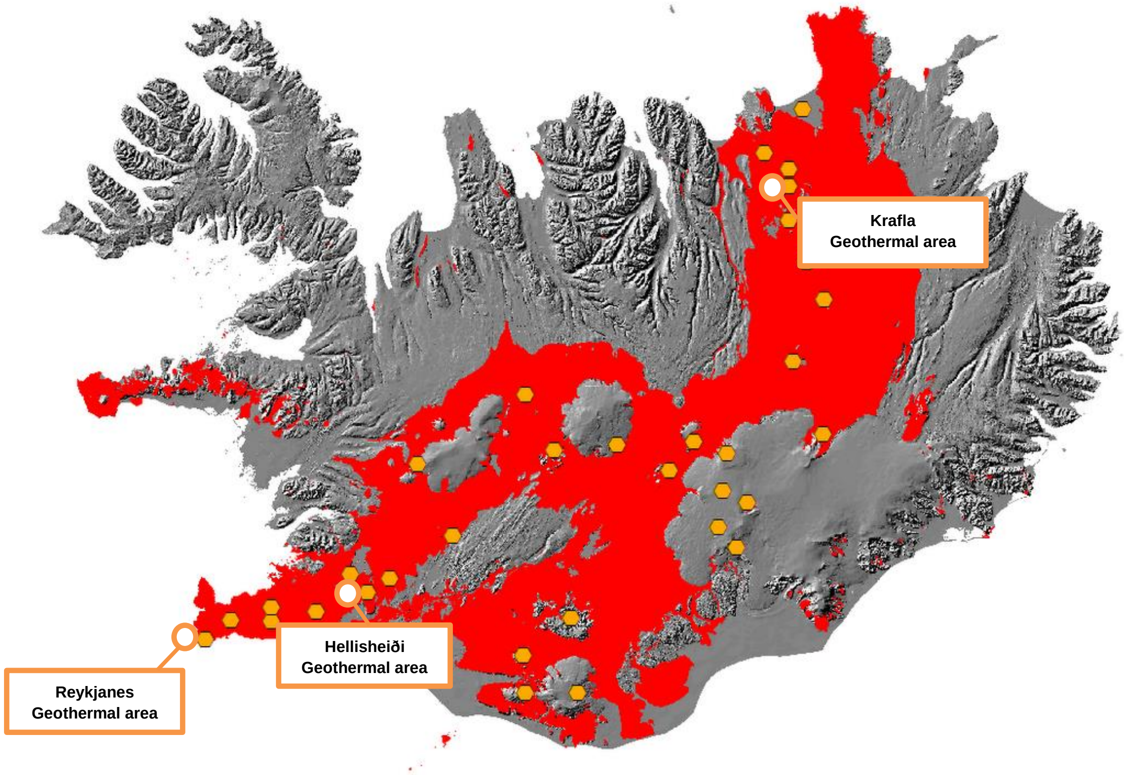


Figure 1. *The three geothermal areas studied by Wiese et al. (2008); Krafla in the north-east of Iceland and Reykjanes and Hellisheiði in the south-west of Iceland.*

The values measured in the Reykjanes geothermal area, which is considered to be the youngest of the three geothermal areas (active for 10,000-100,000 years), were significantly lower than elsewhere in this study; on average 18.8 kg/m^3 of CO_2 fixed in the uppermost 1500 m of the wells. The highest values are measured in the Krafla geothermal area, which is considered to have been active for the longest (between 110,000 and 290,000 years) on average 48.7 kg/m^3 in the uppermost 1500 m.

It is estimated that about 43.8 kg/m^3 of CO_2 is already naturally fixed within basaltic rocks at the Hellisheiði geothermal system (Figure 2), but the rate of mineral sequestration of CO_2 in the area is estimated to be about 4,100–23,500 tonnes/year. Natural fixation per unit surface area in Hellisheidi was estimated to have accumulated to 650,000 tonnes/km^2 over the past 70,000–140,000 years. This represents the total amount of CO_2 that is fixed in the crust, down to 1500 m, beneath a given area of the surface. This value is a significant estimate of the amount of CO_2 fixed in the bedrock, since almost all CO_2 has accumulated above 1500 m in these systems.

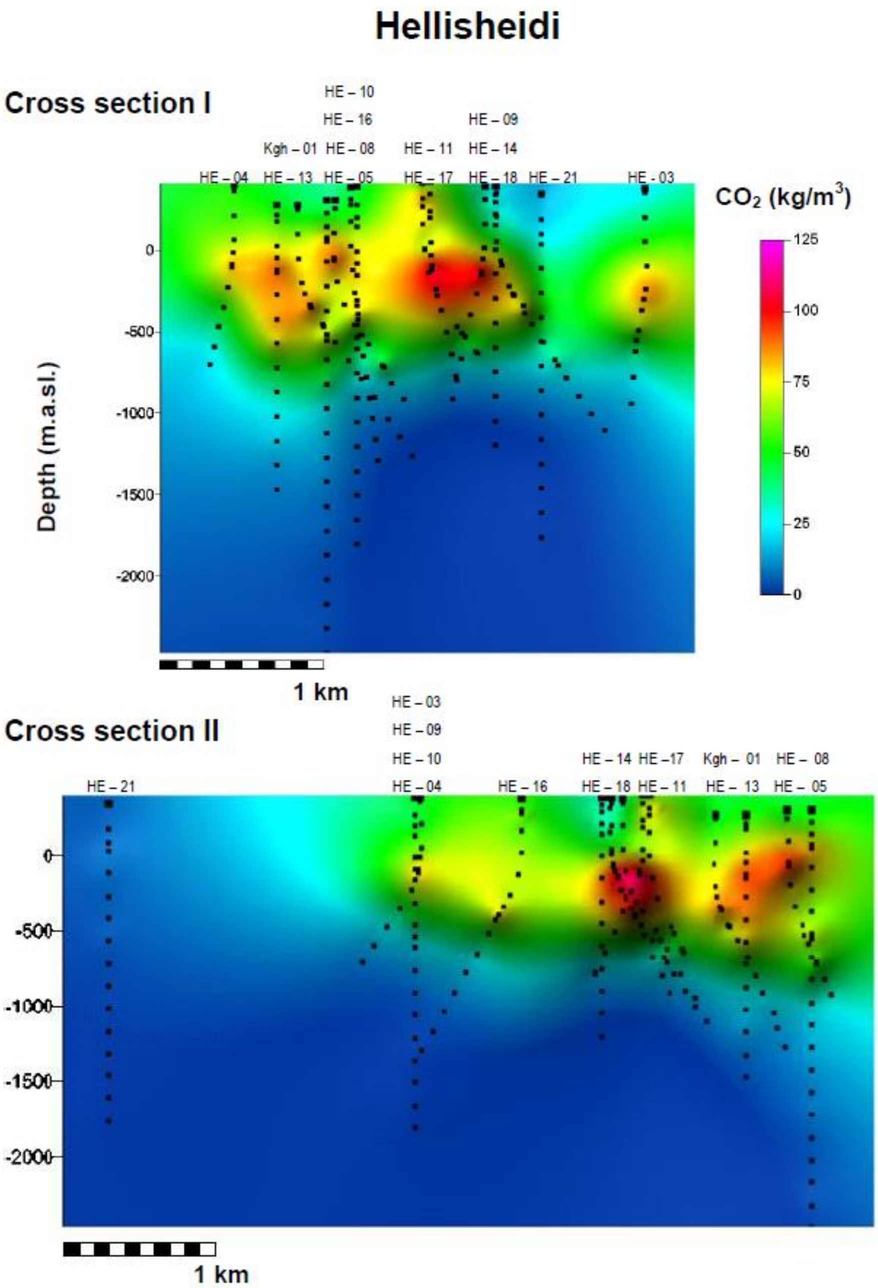


Figure 2. *Cross sections from Hellisheiði geothermal field showing the distribution of CO_2 fixed within the bedrock. Cross section I extend from W to E and cross section II from S to N. Concentrations of fixed CO_2 (kg/m^3) are indicated by different colours, see bar for scale. Modified figure from Wiese et al. (2008).*

The CarbFix site is situated outside of the high-temperature geothermal area at Hellisheiði and therefore there is no direct influx of magmatic CO_2 from below as is the case within the high-temperature area. Therefore, less CO_2 is stored within the basaltic rocks at the CarbFix site and the CO_2 profile from the CarbFix site (Figure 3) does not show the same distribution pattern as the wells located within the high-temperature areas. An outflow zone from the geothermal system has been identified in the area where the CarbFix site is located, so the occurrence of calcite at the CarbFix site is probably resulting from mixing of deep and shallow CO_2-bearing geothermal fluids causing mineral precipitation.

The natural analogue study underscores the high potential for mineral storage of CO_2 within basaltic rocks but it is estimated that about 30-40 $GtCO_2$ are already naturally fixed within the active high-temperature geothermal areas in Iceland (Wiese et al., 2008). The physical and hydrological conditions above the geothermal reservoirs are though not considered the most favourable for mineral storage of CO_2. This is due to the thermodynamic stability of calcite which is not stable at temperatures above 290°C in the geothermal areas. Another disadvantage is the convection and boiling taking place within the areas which provide a mechanism for vertical transport of CO_2 from the core of the system toward the surface.

The CarbFix site is therefore considered more suitable for mineral storage of CO_2, but in addition to lower thermal gradient there is less CO_2 already stored within the basaltic rocks leaving more pore space for injection and mineralisation of CO_2 at the site.

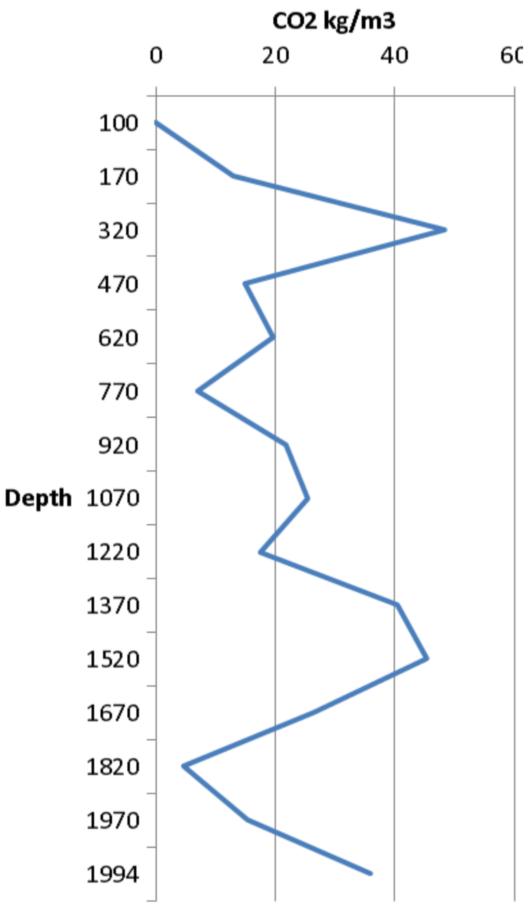


Figure 3. *CO_2 profile from the injection well HN-02 at the CarbFix site, showing the amount of CO_2 (kg/m3) already naturally fixed within the basaltic rocks, modified figure from Wiese et al. (2008).*

Storage potential estimates at the CarbFix site

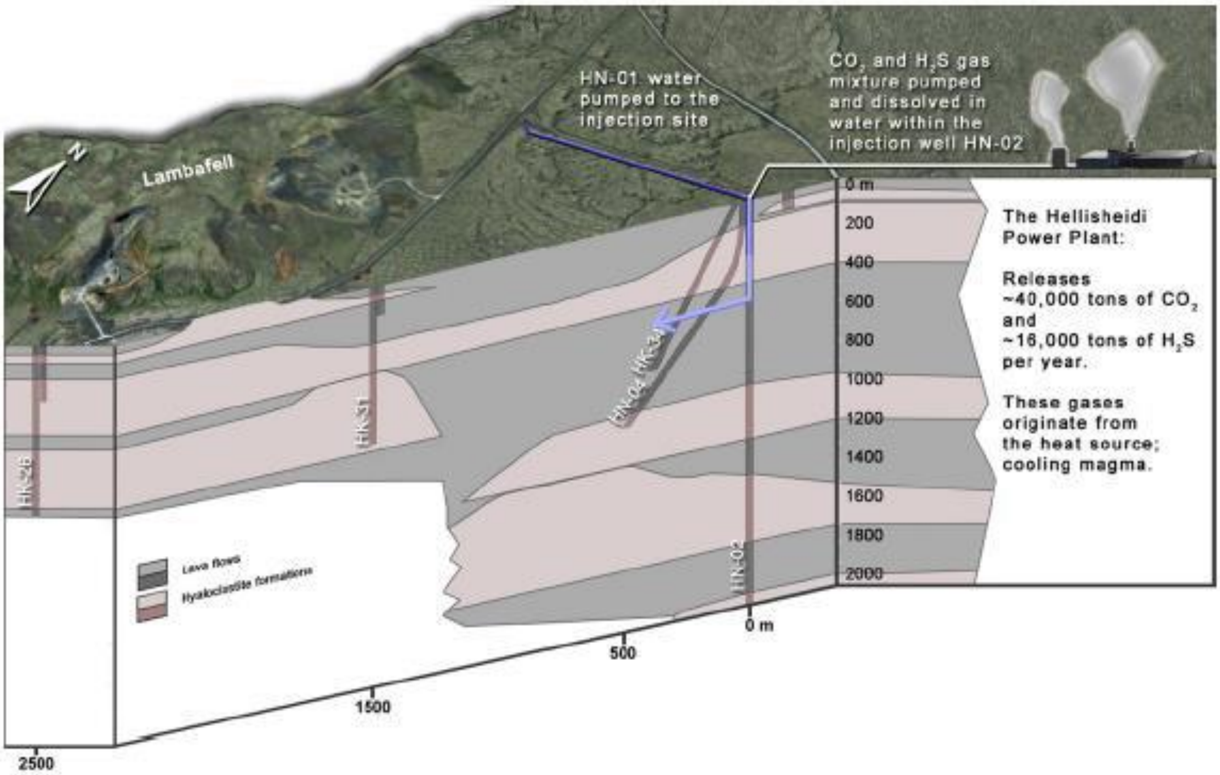


Figure 4. *Geological cross section of the CarbFix injextion site. The CO_2 and CO_2-H_2S-H_2 gas mixture were pumped towards the injection site and co-injected in well HN-02 with water from well HN-01. The gas is dissolved in the water and enters the storage formation as a single phase. Modified from Alfredsson et al. 2013.*

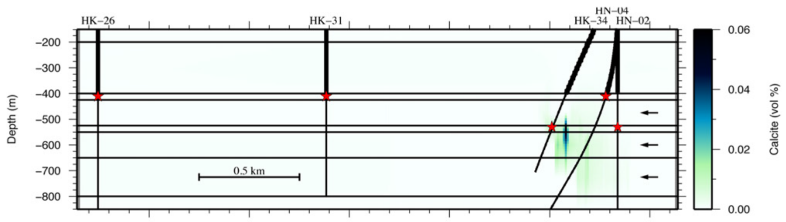
The first attempt to estimate the potential for mineral storage of CO_2 at the CarbFix site (Figure 4) was done by Gislason et al. (2010). The target zone of the injection is more than 2000 m long, 1000 m wide and 500 m thick, resulting in over one cubic km of basaltic rocks. Assuming 10% porosity of the rocks of which only 10% would eventually be filled with calcite yields in 0.01 km^3 volume for calcite precipitation, or about 12 kg/m^3 of CO_2. This volume can accommodate 12 million tons of CO_2. The present CO_2 emission rate of magmatic CO_2 from the geothermal power plant at Hellisheidi Iceland is 40,000 tons/year. With the present rate it would take about 200 years to fill this available pore space.

The assessment of Wiese et al (2008) on the amount of CO_2 already naturally stored within basaltic rocks at Reykjanes, Hellisheiði and Krafla geothermal areas can also be used for estimating the storage potential of the CarbFix site. By applying the average values of CO_2 (kg/m^3)fixed within the bedrock at the three geothermal areas and applying them to the target zone at the CarbFix site the numbers go up to 18.8-48.7 million tons of CO_2. The amount of CO_2 per unit surface area at Hellisheiði geothermal system applied to the target zone of the injection yields 65,700 tons/km^2.

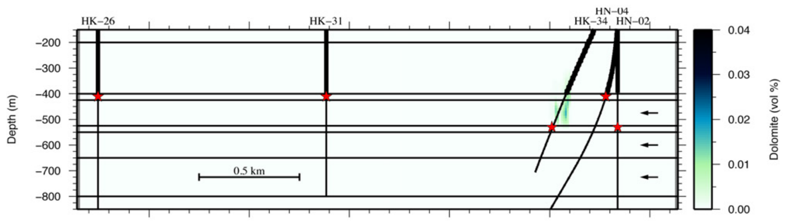
Reservoir modelling of the CarbFix site

Aradóttir et al. (2012) developed two and three-dimensional field scale reservoir models of CO_2 mineral sequestration in basalts and calibrated against a large set of field data.

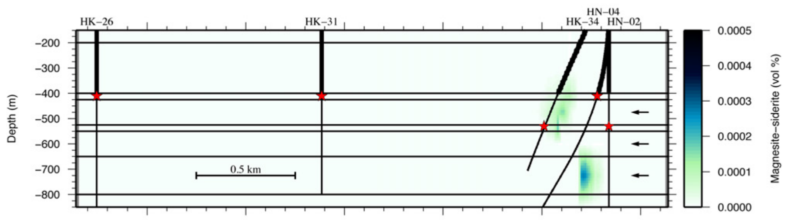
Resulting principal hydrological properties were lateral and vertical intrinsic permeabilities of 300 and 1700 × 10−15 m^2, respectively, effective matrix porosity of 8.5% and a 25 m/year estimate for regional groundwater flow velocity. Reactive chemistry was coupled to calibrated models and predictive mass transport and reactive transport simulations carried out for both a 1200-tonnes pilot CO_2 injection and a full-scale 400,000-tonnes CO_2 injection scenario. Results for HCO3- concentrations in the CO2 pilot injection after 1 year, 5 years and 10 years as predicted by the three-dimensional reactive transport simulations are shown in Figure 5.



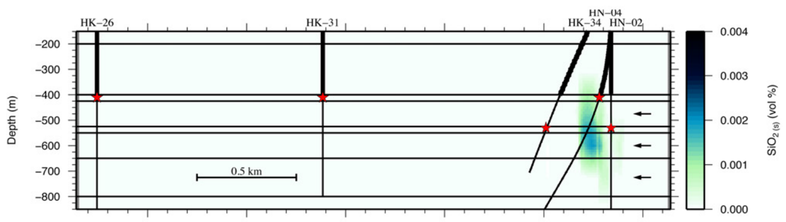
(a) Calcite



(b) Dolomite



(c) Magnesite-siderite



(d) SiO_2 (s)

Figure 5. *From Aradóttir et al. (2012) showing cross sectional view of modeled reservoir HCO^{-3} concentration in the CO_2 pilot injection after (a) 1 year, (b) 5 years, and (c) 10 years, as predicted by three-dimensional reactive transport simulations. The cross section is drawn NE-SW. The figure shows how injected carbonated water travels downstream as a plume with regional groundwater flow. Carbonate precipitation and molecular diffusion lead to significant dilution of the plume within 5 years and its disappearance within 10 years. (a) 1 year. (b) 5 years. (c) 10 years.*

Reactive transport simulations of the pilot injection predict 100% CO_2 mineral capture within 10 years and cumulative fixation per unit surface area of 5000 tonnes/km^2. Corresponding values for the full-scale scenario are 80% CO_2 mineral capture after 100 years and cumulative fixation of 35,000 tonnes/km^2. CO_2 sequestration rate is modelled to range between 1,200 and 22,000 tonnes/year in both scenarios, a value in good agreement with the natural sequestration rate of the Hellisheidi geothermal system, which was estimated by Wiese et al. (2008) to be about 4,100–23,500 tonnes/year.

Field injection experiments at the CarbFix and the CarbFix II sites

175 tonnes of pure CO_2 were injected in January-March 2012 to test the injection system and the rate of solubility and mineral storage at the target zone at about 400-800 m depth and 20°-50°C. 73 tonnes of CO_2-H_2S-H_2 gas mixture (75%-24%-1%) were injected in June-August 2012 at the same site. Mass balance calculations show that most of the injected CO_2 has been mineralized within one year (Matter et al. 2014).

By mid-year 2014, CO_2-H_2S gas mixture (70%-30%), was captured and separated from the gas stream of the Hellisheiði power plant, dissolved in water at the surface at about 20°C and 5 bar pressure and injected down to about 700 m depth and 250-270°C at the CarbFix II site close to the Hellisheiði geothermal plant. By October 2014 about 2,500 tonnes of the gas mixture had been injected. CarbFix II and Reykjavik Energy are aiming at injecting 8,000 - 10,000 tonnes of the gas mixture per year during this experiment.

Conclusions

The natural analogues studied by Wiese at al. (2008) underscore the enormous storage potential for CO_2 within young basaltic rocks where pore-space has not been filled with secondary minerals, with 28.2-73.1 tons of CO_2 stored per unit surface area (m^2) in the uppermost 1500 m at the three high-temperature geothermal systems of the study.

The natural analogue study, the reservoir modelling and the first results from the field injection experiments done at the CarbFix site at Hellisheiði are all in relatively good agreement in regard to storage capacity estimates and the high rate of CO_2 sequestration.

These results show that fresh basaltic rocks may comprise ideal geological CO_2 storage formations.

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