

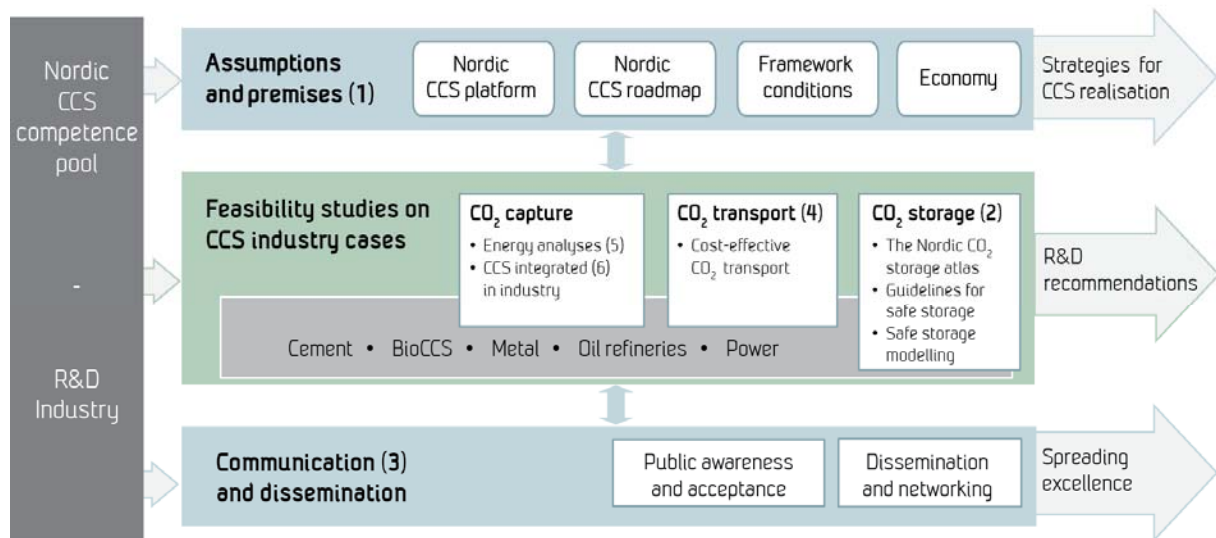
CO₂ storage potential of basaltic rocks in Iceland and the oceanic ridges

Sandra Ó. Snæbjörnsdóttir, Frauke Wiese, Thráinn Fridriksson, Halldór Ármannsson, Sigurdur R. Gislason

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Contact: Centre Director Nils A. Røkke • + 47 951 56 181 • Nils.A.Rokke@sintef.no
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Summary

Iceland is the largest landmass found above sea level at the mid-ocean ridges, about 103,000 km² mostly made of basaltic rocks (~90%). Theoretically much of Iceland could be used for injection of CO₂, fully dissolved in water. Most of the pore space in the older rocks is filled with secondary minerals, thus the young and porous basaltic formations, found within the active rift zone and covering about one third of Iceland, are the most feasible for carbon storage onshore. Studies on mineral storage of CO₂ in basaltic rocks are still at an early stage. Therefore, natural analogues are important for gaining a better understanding of CO₂ fixation in basaltic rocks. Volcanic geothermal systems serve as an applicable analogue since the systems receive considerable amounts of CO₂ from magma in the roots of the systems. The results from this study reveal a large storage potential of basaltic rocks and can be used as a guideline for the theoretical potential of CO₂ storage in basaltic formations. The largest storage potential lies offshore, with long-term advantages for safe and secure CO₂ storage in the mid-ocean ridges.

Keywords Carbon storage, basalt, mineral storage, CarbFix, oceanic ridges

Authors Sandra Ó. Snæbjörnsdóttir, University of Iceland, Iceland, sos22@hi.is
Frauke Wiese, Iceland GeoSurvey, Iceland
Thráinn Fridriksson Iceland GeoSurvey, Iceland
Halldór Ármannsson, Iceland GeoSurvey, Iceland, h@isor.is
Sigurdur Gislason, University of Iceland, Iceland, [sigrg@raunvis.hi.is](mailto:sigr@raunvis.hi.is)

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CO₂ storage potential of basaltic rocks in Iceland and the oceanic ridges

Sandra Ó. Snæbjörnsdóttir^{a*}, Frauke Wiese^b, Thrainn Fridriksson^b, Halldór Ármannsson^b,
Gunnlaugur M. Einarsson^b, Sigurdur R. Gislason^a

^a*Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, Reykjavik 101, Iceland*

^b*ISOR, Iceland GeoSurvey, Grensásvegur 9, Reykjavik 108, Iceland*

Abstract

Iceland is the largest landmass found above sea level at the mid-ocean ridges, about 103,000 km² mostly made of basaltic rocks (~90%). Theoretically much of Iceland could be used for injection of CO₂, fully dissolved in water. Most of the pore space in the older rocks is filled with secondary minerals, thus the young and porous basaltic formations, found within the active rift zone and covering about one third of Iceland, are the most feasible for carbon storage onshore.

Studies on mineral storage of CO₂ in basaltic rocks are still at an early stage. Therefore, natural analogues are important for gaining a better understanding of CO₂ fixation in basaltic rocks. Volcanic geothermal systems serve as an applicable analogue since the systems receive considerable amounts of CO₂ from magma in the roots of the systems. Wiese et al. [1] quantified the amount and spatial distribution of CO₂ stored as calcite within the bedrock of three active geothermal systems in Iceland. The results from this study reveal a large storage potential of basaltic rocks and can be used as a guideline for the theoretical potential of CO₂ storage in basaltic formations. The largest storage potential lies offshore, with long-term advantages for safe and secure CO₂ storage in the mid-ocean ridges. The theoretical mineral CO₂ storage capacity of the ocean ridges, using the Icelandic analogue, is orders of magnitude larger than the anticipated release of CO₂ caused by burning of all fossil fuel on Earth.

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* Corresponding author. Tel.: +354-525-4495; fax: +354-525-4499
E-mail address: sos22@hi.is

1. Introduction

The reduction of CO₂ emissions to the atmosphere is one of the greatest challenges of this century. One solution to this is carbon capture and storage. Therefore, identifying locations for secure CO₂ storage is one of the most pressing scientific problems of our time. Injection of CO₂ into basaltic formations provides significant advantages including permanent storage by mineralisation and a great potential storage volume [2-4].

To date, most subsurface carbon storage projects have injected CO₂ as a separate, buoyant phase into large sedimentary basins; a method that requires high integrity cap-rock for long term storage [4, 5]. Some of the risks associated with CO₂ buoyancy can be mitigated by its dissolution into water during injection [6, 7]. Once dissolved, CO₂ is no longer buoyant, making it possible to inject into fractured rocks, such as the basalts along the ocean ridges.

Basaltic rocks are rich in divalent cations (e.g. Ca²⁺, Mg²⁺ and Fe²⁺). The CO₂-charged water accelerates metal release and the formation of solid carbonate minerals such as Calcite (CaCO₃), Magnesite (MgCO₃) and Siderite (FeCO₃) for long term storage of CO₂ [4, 6, 8, 9].

Iceland is the largest (103,000 km²) landmass found above sea level at the mid-ocean ridges, made mostly (~90%) of basaltic rocks. Carbon capture and storage experiments conducted in Iceland can be used as analogues, along with natural analogues, for carbon storage along the ocean ridges. Theoretically much of Iceland could be used for injection of CO₂, fully dissolved in water. Most of the pore space in the older rocks is filled with secondary minerals, diminishing the transmissivity of the potential injection wells. Thus the young and porous basaltic formations, found within the active rift zone and covering about one third of Iceland, are the most feasible for carbon storage onshore.

2. Mineral storage potential of CO₂ in basaltic rocks

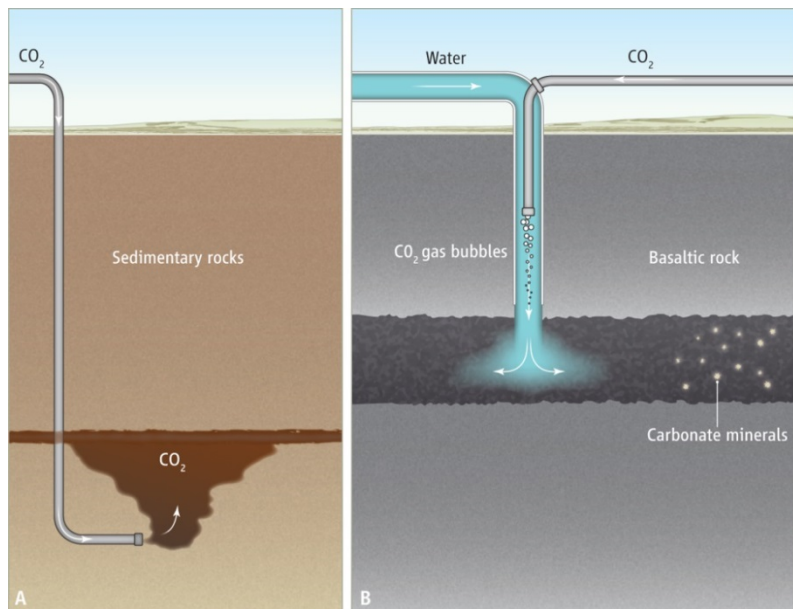


Fig. 1. Carbon storage in sedimentary basins and basaltic rocks. (A) Carbon storage in sedimentary basins; CO₂ is injected as a separate buoyant phase and is trapped below an impermeable cap rock. (B) In the CarbFix method, CO₂ is dissolved into water during its injection into porous basaltic rocks. No cap rock is required because the dissolved CO₂ is not buoyant and does not migrate back to the surface. Figure from Gislason and Oelkers, [4].

There are two ways of injecting CO₂ into rocks for geological storage. In the most common method (Fig. 1A) pure compressed CO₂ is injected as a separate buoyant phase into porous rock layers, such as sandstone or basalt, at more than 800 m depth; it is anticipated that the presence of an impermeable layer will keep the CO₂ from escaping back to the surface (structural trapping) (Fig. 2). Eventually some of this CO₂ becomes trapped in small pores, limiting its mobility (residual trapping). Over time, the CO₂ dissolves in the formation water (solubility trapping). Some of this dissolved CO₂ reacts to form stable carbonate minerals (mineral trapping). As the progress goes from structural to mineral trapping, the CO₂ becomes more immobile and thus the storage more secure. However, this process can take thousands of years or more [10, 11].

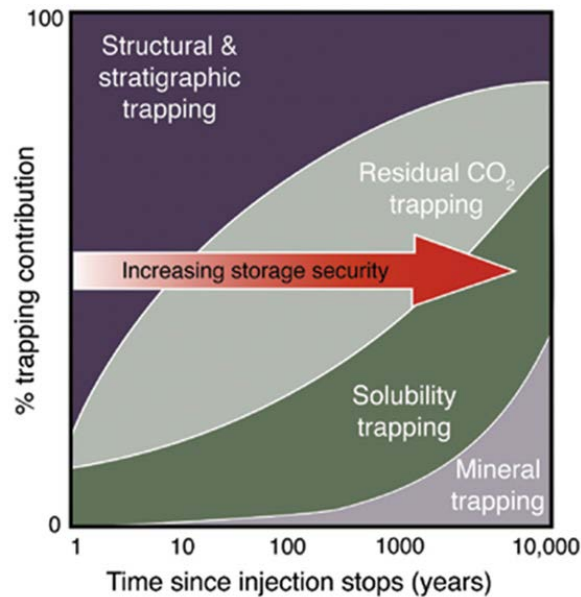


Fig. 2. A general representation by S. Besson of the evolution of trapping mechanism of CO₂ over time when injected as a separate buoyant phase [10]. When CO₂ is dissolved in the water prior or during injection solubility trapping occurs immediately and the bulk of the carbon is mineralized within few years [4, 7, 12, 13].

In Iceland an alternative method is being tested, in a project called CarbFix (www.carbfix.com), where the CO₂ is dissolved during injection into porous basaltic rock (Fig. 1B). CO₂ is aspirated into down-flowing water within the injection well at 350 m depth. The CO₂ bubbles dissolve in the water before it enters the rock. Once dissolved in water, CO₂ is no longer buoyant and does not migrate back to the surface. The CO₂-charged water accelerates both the metal release from the basalt and subsequent formation of solid carbonate minerals. Solubility trapping occurs immediately, and the bulk of the carbon is trapped in minerals within few years [4, 7, 12, 13]. Once stored as a mineral, the CO₂ is immobilised for geological time scales [4, 6, 9].

In addition to CarbFix, one other field injection project is ongoing, assessing the feasibility of carbon storage in basalts; the Big Sky Carbon Sequestration Partnership (BSCP) in north-western USA, near Wallula, Washington [14, 15]. In the BSCP project, pure CO₂ is injected as a separate buoyant phase into a porous basaltic layer, anticipating that the presence of an impermeable layer will keep the CO₂ from escaping back to the surface.

3. Geological settings of Iceland

Iceland is one of the most active and productive sub-areal volcanic regions on Earth with magma output rates of more than five km³ per century [16]. The most voluminous volcanism on the Earth occurs at the mid-ocean ridges where total magma production is about 400 times greater than in Iceland. Seafloor spreading generates about 20 km³ per year of mid ocean ridge basalt (MORB) which is one of the dominant volcanic rock types on Earth [e.g. 17].

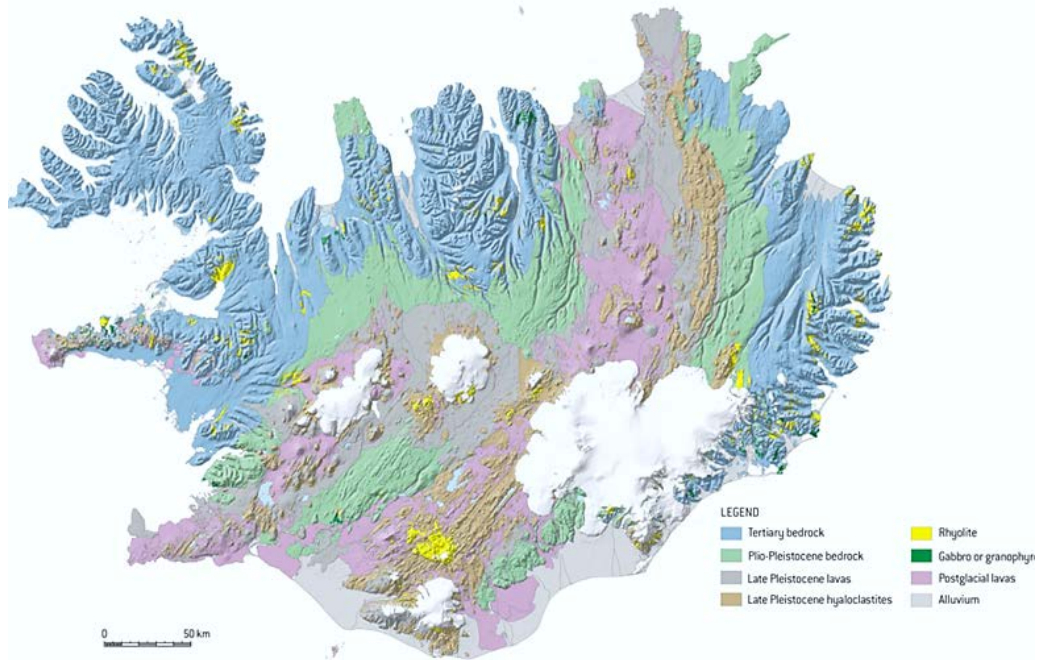


Fig. 3. Map based on Geological map of Iceland [18]. Iceland, 1:1.000.000. Icelandic Institute of Natural History.

The Iceland basalt plateau rises more than 3000 m above the surrounding sea floor and covers about 350,000 km² [16]. Iceland itself is 103,000 km², mostly made of young 0-20 M yr. igneous rocks and sediments thereof. Approximately 90% of the bedrock in Iceland is basalt (Fig. 3) indicating that theoretically much of Iceland could be used for injecting CO₂, fully dissolved in water, into basaltic rocks.

Studies on the permeability and porosity of Icelandic bedrock show that porosity and permeability generally decrease with progressive alteration, gradual burial and increasing rock age since most of the pore space in the older rocks is filled with secondary minerals [19, 20]. Thus, the youngest basaltic formations, found in the active rift zone, are the most feasible for carbon storage onshore in Iceland. These basalt formations consist of lavas, hyaloclastic (glassy) formations and associated sediments younger than 0.8 M yr covering about one third of Iceland.

4. Key parameters for mineral storage of CO₂

Mineral carbonation requires combining CO₂ with divalent metal cations to form carbonate minerals, such as calcite (CaCO₃), dolomite (CaMg(CO₃)₂), magnesite (MgCO₃), siderite (FeCO₃), and Ca-Mg and Mg-Fe carbonate solid solutions [4, 8].

With few exceptions, the required metals are divalent cations, including Ca²⁺, Mg²⁺ and Fe²⁺. The availability of divalent metal cations for carbonate precipitation is enhanced by rapid dissolution rates of Ca, Mg, Fe-rich silicate rocks such as basaltic and ultramafic rocks. These dissolution rates can be enhanced in several ways including increasing the mineral-fluid interfacial surface area, injecting into glassy rather than crystalline rocks, and choice of temperature/injection fluid composition. These enhancement methods are described in detail in Gislason et al. [6, 9].

The most abundant cation sources for mineral storage of CO₂ are silicate minerals and glasses [6, 21]. Basalt contains about 25% by weight of calcium, magnesium, and iron oxides [22, 23]. Basaltic rocks are reactive in water, thus the metals contained in basalts are readily available to combine with the injected CO₂ to form carbonate minerals [6, 22, 24, 25, 26, 27, 28].

Basaltic rocks are abundant at Earth's surface; a little less than 10% of the continents and much of the ocean floor is composed of basalt [6, 29, 30].

Whilst the availability of divalent metal cations remains the limiting factor for mineral storage of CO₂ it is not the only concern. For successful injection and mineral carbonation, other key parameters must also be considered.

4.1. Availability of water for injection

Mineral storage of CO₂ via the CarbFix method requires a substantial amount of water. The water demand to fully dissolve one ton of CO₂ at 25 bar pressure and 25°C is 27 tons of pure water. About 4% of the injected mass is CO₂. The CO₂ solubility increases, and thus the amount of water required for its dissolution decreases, by elevating the CO₂ partial pressure and lowering the temperature [6].

On the continents, the water present in the target storage formation can be pumped up and used to dissolve the CO₂ during the injection. Although the pumping of water from the subsurface may increase costs, water pumping is also necessary during the later stages of pure CO₂ injection into sedimentary basins, when a large portion of the pore space has been filled with CO₂.

The amount of water required could pose a problem in some areas, for example in places with insufficient ground water sources, low recharge rates or inefficient water management. In some cases seawater might be the only viable option. Porous basalts near the continental margins have enormous storage capacities adjacent to nearly unlimited supplies of seawater [31]. The CO₂ solubility decreases by about 10% at elevated partial pressure of CO₂ and therefore the amount of water required for its dissolution increases by 10% at seawater salinity.

The basaltic ocean ridges are porous and vast amounts of seawater are circulated annually through them by natural processes. Every year, about 100 Gton of water is circulated through the oceanic ridges; this is about three time's greater than the present mass of anthropogenic release of CO₂ to the atmosphere [32, 33].

Dissolution of basalt, basaltic glass and peridotite in seawater has been studied to some extent [25, 34]. The results show that dissolution of CO₂ into seawater prior to or during injection appears to be a promising approach but further modelling and experimental work is required to refine the concept.

4.2. Temperature

The release of the divalent cations needed from glassy basaltic rocks for carbonate formation can be enhanced by raising the temperature. Increasing the temperature from 0 to 100°C, at pH 3.5 and fixed total concentration of dissolved aluminum (10⁻⁶ mol/kg), increases dissolution rates by a factor of 60. The same temperature increase, at pH 9, results in a 4.5 order of magnitude increase in rates [35]. The dissolution rates of the secondary minerals present in altered basaltic rocks, such as zeolites and clays, are also raised at elevated temperature. They become unstable in the CO₂-charged injection waters resulting in their dissolution and thereby creating additional porosity in the near vicinity of injection wells [23]. The temperature can be raised by increasing the depth of injection wells and/or drilling into areas of high geothermal gradients.

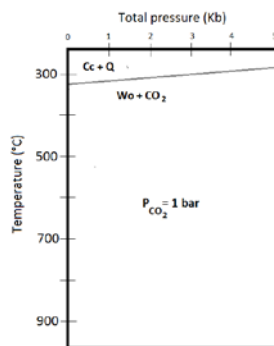


Fig. 4. Simple, thermodynamic system of calcite (Cc), quartz (Q) and wollastonite (Wo); total pressure (Kb) vs. temperature at fixed CO₂ pressure of 1 bar. Modified figure from Skippen et al. [36].

The lower boundary for mineral storage of carbon in basalt is dictated by the thermal gradient and the thermodynamic stability of carbonates such as calcite rather than the availability of divalent cations from the dissolution of basaltic rocks. At high temperatures the primary porosity of reactive rocks and therefore reactive surface area tend to decrease and the solubility of carbon dioxide in water decreases with increasing temperature.

The thermodynamic stability of carbonates is limited at temperature in excess of 300°C. Observations of hydrothermally altered basaltic rocks from Iceland show that calcite does not form at temperatures above 290°C [e.g. 37]. This finding is in a good agreement with thermodynamic data [36] as shown in Fig. 4 for the simplified calcite, quartz and wollastonite system.

Geothermal systems in Iceland typically have a thermal gradient above 200°C/km and a very similar overall pattern of calcite distribution has been reported by Wiese et al. [1] and Tómasson and Kristmannsdóttir [38] showing that, with some exceptions, generally below about 1000-1500 m depth very little calcite is present.

In terms of temperature, mineral storage of CO₂ could theoretically be executed at depths greater than 1500 m in basaltic rocks outside of the geothermal systems where carbonates remain stable at greater depths due to a lower temperature gradient, but other factors like decreased porosity and permeability with increased depth would have to be considered for it to be beneficial.

4.3. The partial pressure of CO₂

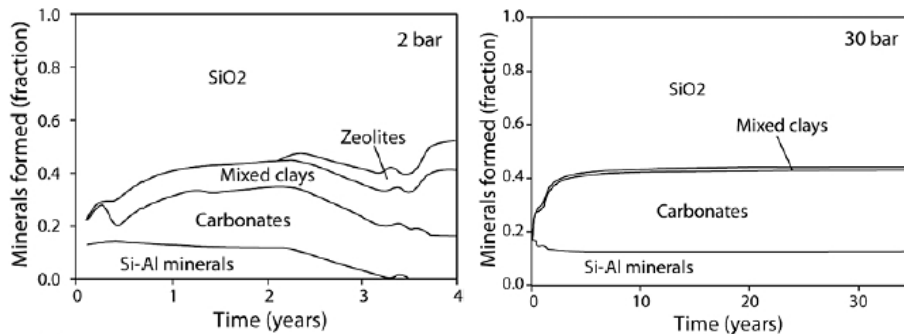


Fig. 5. The results of reaction progress modelling of basaltic glass-CO₂ water interactions. Mole fractions of secondary minerals formed as a function of reaction progress for groundwater in contact with basaltic glass saturated at 25 °C with 2 and 30 bars CO₂ pressure. Carbonate fraction increases relative to clays and zeolites with increasing pCO₂. Figure from Gysi and Stefansson, [39].

Thermodynamic model calculations suggest that elevated partial pressure of CO₂ will enhance the efficiency of carbon mineralisation as shown in Fig. 5 [39, 40]. The higher the partial pressure of CO₂ the higher the fraction of released divalent cations that precipitate as carbonates rather than zeolites and clays.

Natural analogues for CO₂ injection into basaltic rocks at moderate temperature in West-Greenland suggest that at relatively high partial pressure of CO₂, Fe and Mg rich carbonates are stable; at intermediate CO₂ pressure Mg-Ca carbonates dominate and at the lowest partial pressure Ca-carbonates are most common [41].

4.4. Porosity, Permeability

Studies on permeability and porosity show that generally porosity and permeability decrease along with progressive alteration, gradual burial and increasing age. The oldest bedrock in Iceland, in NW- and E-Iceland, is so dense it is almost impermeable (Fig. 6). The permeability increases towards the active rift zone where the rocks are younger. The youngest formations in the active rift are made of highly porous and permeable basaltic lavas and hyaloclastic (glassy) formations with abundant groundwater flow [43].

Hydrothermal alteration and formation of secondary minerals takes place when the rocks are buried under younger formations and are then exposed to more heat and pressure. Most of the pore space in the older rocks is filled since the molar volume of secondary minerals is larger than the molar volume of primary minerals and some secondary

minerals contain water and CO₂. Gradual burial of the strata also causes compression on the underlying layers making them even less permeable [e.g. 19, 20].

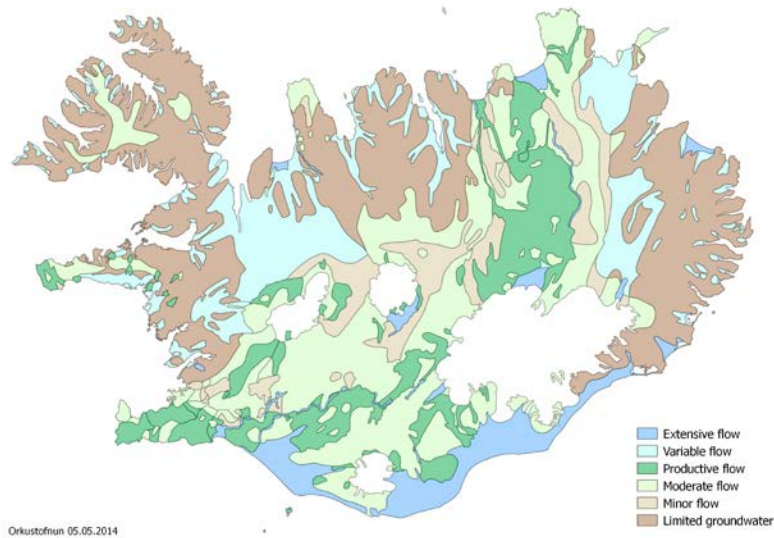


Fig. 6. Map based on hydrogeological map of Iceland from Hjartarson [42]. The most permeable rocks are situated within the active rift zone (blue and green colors). The permeability decreases towards the older formations, the oldest formations situated in the NW and E parts of Iceland (brown colors) are nearly impermeable. Prepared by the National Energy Authority.

Since 1992 the National Energy Authority of Iceland and later the Iceland GeoSurvey have carried out systematic sampling of fresh to highly altered igneous rocks of variable composition in order to define the petro-physical properties of Icelandic bedrock [e.g. 20, 44, 45]. The average permeability of the basaltic lava samples was measured to be 367 mD. The average porosity of the lavas was measured to be 8.09 %, however, the porosity of the unaltered lavas was measured to be 27.8% but as soon as secondary minerals started to appear the porosity dropped below 7% and was measured to be 6.13% in samples of highly altered basaltic lavas (Table 1).

Table 1. The effect of alteration on the porosity of basaltic lavas from Stefánsson et al. [45]

	Average porosity (%)	# of samples
All samples	8.09	108
Unaltered lavas	27.8	9
Smectite-zeolite alteration (alteration temperatures below 200°C)	6.69	31
Chlorite-epidote-actinolite alteration (alteration temperatures above 200°C)	6.13	56

Hyaloclastites are clastic, glassy rocks formed dominantly in sub-glacial phreatic eruptions. Hyaloclastic formations are extremely heterogeneous and show very broad variation both in porosity and permeability (Table 2). Frolova et al. (2004) analysed 80 samples of basaltic hyaloclastic tuffs of variable burial depth (0-1000 m) and age (>2.5 M yr). The porosity of the samples analysed varied between 14 and 57% and permeability between $1 \cdot 10^{-3}$ mD to $6.4 \cdot 10^3$ mD. The wide dispersion is mainly the result of different degree of alteration, with a general decrease both in porosity and permeability with increasing depth, although some exceptions are present.

Table 2. The average porosity and permeability of the main rock types in Iceland and the range in porosity and permeability measured in 80 samples of hyaloclastic tuffs.

	# of samples	Average porosity (%)	Standard Deviation	Average permeability, Klinkenberg (mD)	Standard deviation
Basaltic lavas ¹	52	8.09	9.14	3.75	14.67
Basalt intrusions ¹	19	3.68	3.71	0.157	0.263
Acid rocks ¹	20	12.09	6.39	0.028	0.044
Hyaloclastic formations ²	80	14-57		$1 \cdot 10^{-3}$ - $6.4 \cdot 10^3$	

Data from Stefánsson et al.¹ [45] and Frolova² [20].

These results establish the large effect alteration and formation of secondary minerals have both on porosity and permeability of both crystalline basalt and glassy formations.

The most feasible formations for carbon storage onshore in Iceland are situated within the active rift zone where the basaltic rocks are young and still porous and normal faults are common. These formations are younger than 0.8 M yr. and cover about 34,000 km², which is about one third of Iceland.

It should be noted that the initial porosity and permeability of the bedrock prior to injection of dissolved CO₂ will be affected. As stated before, secondary minerals, such as zeolites and clays, present in altered basaltic rock become unstable in the CO₂-charged injection waters resulting in their dissolution and thereby creating additional porosity in the near vicinity of injection wells [23].

4.5. Depth

The minimum depth for injection of CO₂ using the CarbFix method is dictated by dissolution of CO₂ and water demand for injection. The CO₂ has to be dissolved at minimum pressure of 25 bars, which is 250 m below the water table, and some distance is needed for the descending CO₂-gas-bubbles to dissolve [6, 7]. The ideal depth for injection of CO₂ is therefore below 350 m.

Geothermal systems typically have a thermal gradient above 200°C/km compared to 50 to 150°C/km in dense and permeable rocks outside of them [43].

Defining the lower boundary for mineral storage of carbon at 1500 m depth allows inclusion of the areas with the highest thermal gradient, considering that stability of carbonates is limited at temperature in excess of 300°C, and therefore gives a rather conservative estimate of the storage potential.

The benefit of injecting deeper than at 1500-2000 m is uncertain due to the rapid decrease of permeability with depth and temperatures over 300°C in areas with high temperature gradient. The targeted depth range for injection of fully dissolved CO₂ into basaltic rocks is therefore 500-1500m.

When injecting into high-temperature geothermal systems with steep thermal gradients it is important to stay below the liquid-vapour curve for water to prevent boiling.

4.6. Risk of contamination of groundwater

The reaction between the CO₂-charged water and the basaltic rocks not only releases divalent cations that end up in carbonates, but also other metals that can be harmful for the biota. The metals of main concern are Al and Cr, but some other elements, such as Fe and Mn, can be both essential for life and toxic depending on their concentration. The toxic metal release is the most dangerous at the early stage of CO₂ injection into basalt [46-48]. Natural analogues have shown the secondary minerals, such as carbonates, effectively scavenge the potential toxic metals that are released at early stages [46, 48].

A novel high pressure column reactor [49] was used to study the mobility of metals at the early stage (hours) of CO₂ injection into basalt. Dissolved Al, Fe, Cr and Mn exceeded the allowable drinking water limits according to the European Directive relating to the quality of the water intended for human consumption [47, 50].

Samples analysed from monitoring wells after injection of 175 tons of CO₂ at the CarbFix site in Hellisheiði, SW-Iceland showed that no dissolved metals exceeded the allowed drinking water limits during the field experiment.

5. Natural analogues for mineral storage of CO₂

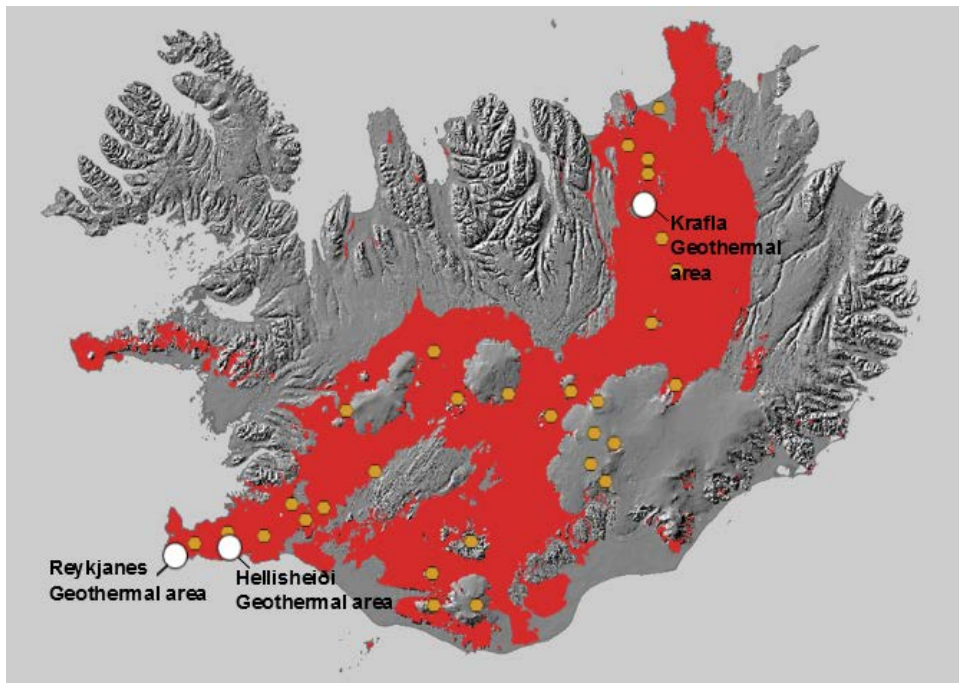


Fig. 7. Theoretical area feasible for CO₂ mineral storage in Iceland: Basaltic formations younger than 0.8 M yr within the active rift zone. Volcanic geothermal systems are marked with white dots but they serve as an applicable analogue as they receive considerable amounts of CO₂ from magma chambers or intrusion in their roots. High-temperature geothermal systems studied by Wiese et al. [1] are marked with orange dots.

Studies on mineral storage of CO₂ in basalts are still at an early stage [e.g. 4, 23, 51]. Therefore, natural analogues are important for gaining a better understanding of CO₂ fixation in basaltic rocks. Volcanic geothermal systems serve as an applicable analogue; the systems receive considerable amounts of CO₂ from magma chambers or intrusions at the roots of the systems and can therefore be considered as a natural experiment to determine the CO₂ storage capacity of the bedrock [1, 52].

The large amounts of CO₂ that are already naturally fixed within the geothermal systems underscore the storage potential of basaltic rocks. Wiese et al. [1] estimate that the total CO₂ fixed within the active geothermal high-temperature systems in Iceland shown by orange dots in Fig. 7 amounts to 30–40 GtCO₂.

Wiese et al. [1] quantified the amount and spatial distribution of CO₂ stored in calcite within the bedrock of three active geothermal systems in Iceland: Krafla in the north-east of Iceland and Hellisheiði and Reykjanes in the south-west (Fig 7.). The CO₂ content was measured in 642 drill cutting samples from a total of 40 wells, located in the three geothermal systems.

The values measured in the Reykjanes geothermal system, which is considered to be the youngest of the three geothermal systems (active for 10,000–100,000 years), were significantly lower than elsewhere in this study, on average 28.2 kg m⁻³ of CO₂ fixed in the uppermost 1500 m of the wells. The average CO₂ load in the uppermost 1500 m in Hellisheiði geothermal system was measured 65.7 kg m⁻³. The highest values are measured in the Krafla geothermal system, which is considered to have been active for the longest, between 110,000 and 290,000 years, on average 73.1 kg m⁻³ in the uppermost 1500 m [1] (Fig 8., Table 3).

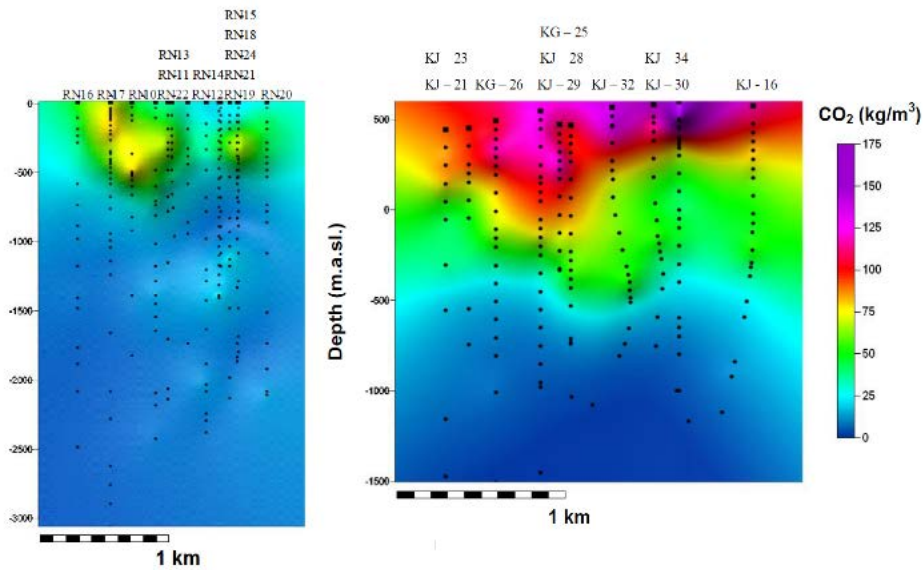


Fig. 8. Cross-sections extending from west to east (looking north) showing the distribution of CO₂ fixed in the bedrock at Reykjanes (left) and Krafla (right) geothermal systems. Concentration of fixed CO₂ is indicated by different colors, see bar for scale (From Wiese et al. [1]).

Table 3. Average CO₂ load (kg/m³) and suggested age (years of activity) of the three geothermal systems of interest (from Wiese et al. [1])

	CO ₂ fixed in uppermost 1500 m (kg/m ³)	Activity of Geothermal system (years)
Reykjanes	28.2	10.000-100.000
Hellisheiði	65.7	>70.000*
Krafla	73.1	110.000-290.000

*Franzson, et al. [53]

The amount of CO₂ fixed in the bedrock of the three geothermal systems obtained from this study can be used as a guideline for the theoretical CO₂ storage potential in onshore basaltic formations in Iceland.

5.1. Storage potential of the Icelandic rift zone

The active rift zone covers about 34,000 km², or about one third of Iceland (Fig. 9). By using the average CO₂ load in the uppermost 1500 m of the Reykjanes system as a minimum and the average CO₂ load in the uppermost 1500 m of the Krafla system as a maximum (Table 3) and applying these to a 1000 m thick segment at 500-1500 m depth, of the relatively fresh basaltic formations within the rift zone yields a very large value; 2,470 Gt of CO₂ as a maximum (Krafla analogue) and 953 Gt as a minimum (Reykjanes analogue). This scenario is highly theoretical but underscores the large mineral storage potential within the rift zone of Iceland where the rocks are young and still porous and normal faults are common.

Other attempts have been made to estimate the capacity for mineral storage of CO₂ in basalt. McGrail et al. [2] estimated that the Colombia River basalts alone have the capacity to store over 100 Gt of CO₂, assuming an interflow thickness of 10 m, average porosity of 15% and 10 available interflow zones at an average hydrostatic pressure of 100 atm. Anthonsen et al. [54] applied McGrail's assumptions to all the bedrock of Iceland, giving an estimated capacity of about 60 Gt CO₂. Using the same assumption to calculate the potential capacity of mineral storage of CO₂ within the active rift zone in Iceland the number goes down to about 21 Gt CO₂.

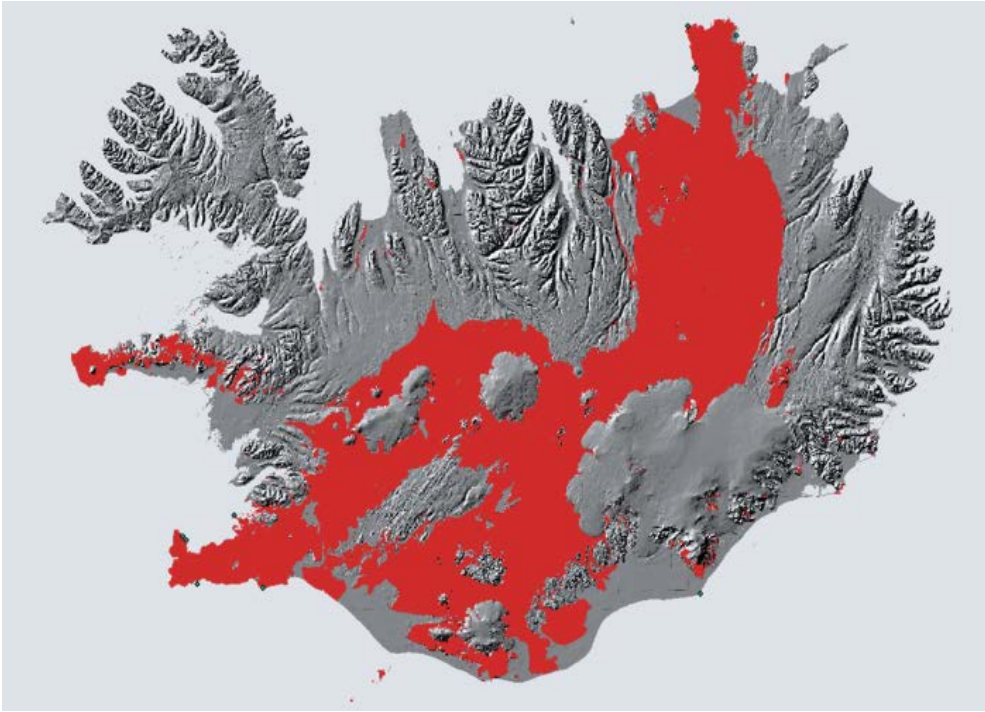


Fig. 9. Theoretical area feasible for CO₂ mineral storage in Iceland: Young and porous basaltic rocks (>0.8 M yr) within the active rift zone covering about one third of Iceland.

Furthermore, Goldberg et al. [3, 31] revealed the large storage capacity of sub-oceanic basalt formations at the Juan De Fuca plate west of Oregon, USA. The geologically feasible area at suitable depth for mineral storage of CO₂ there is calculated to be about 78,000 km². Assuming a channel system dominating permeability over one-sixth of the uppermost 600 m of the area, it is estimated to contain 7800 km³ of highly permeable basalt. Given an average channel porosity of 10%, 780 km³ of potential pore volume will be available for CO₂ storage. Anthonsen et al. [54] also applied Goldberg et al. [31] calculations to all of Iceland, resulting in an enormous number of about 1,200 GtCO₂. If these calculations are limited to the bedrock of the active rift zone in Iceland, over 400 Gt CO₂ could still be stored.

5.2. Storage potential for CO₂ transportation via pipeline

To get a more realistic value of the capacity for mineral storage in Icelandic basalt formations, transportation of CO₂ via pipeline was taken into consideration. The 30 km long, hot water pipeline from Nesjavellir to Reykjavík was used as an approximation and the area within 30 km radius of eight of the largest harbours proximal to the rift zone was selected (Fig. 10).

The formations included were, as in the previous scenario, basaltic lavas, hyaloclastic formations and associated sediments, younger than 0.8 M yr. Three harbours in the north-east were included (Húsavík, Kópasker, Raufarhöfn), one in the south-east (Höfn í Hornafirði) and four in the south-west (Reykjavík, Reykjaneshafnir, Grindavík, and Þorlákshöfn). In addition, an industrial harbour which is under construction in Helguvík, in SW-Iceland, was included. Population centres, water protection areas, national parks, natural monuments, nature reserves and country parks were excluded from the area. The area that fits the criteria is about 2390 km², close to 2% of Iceland.

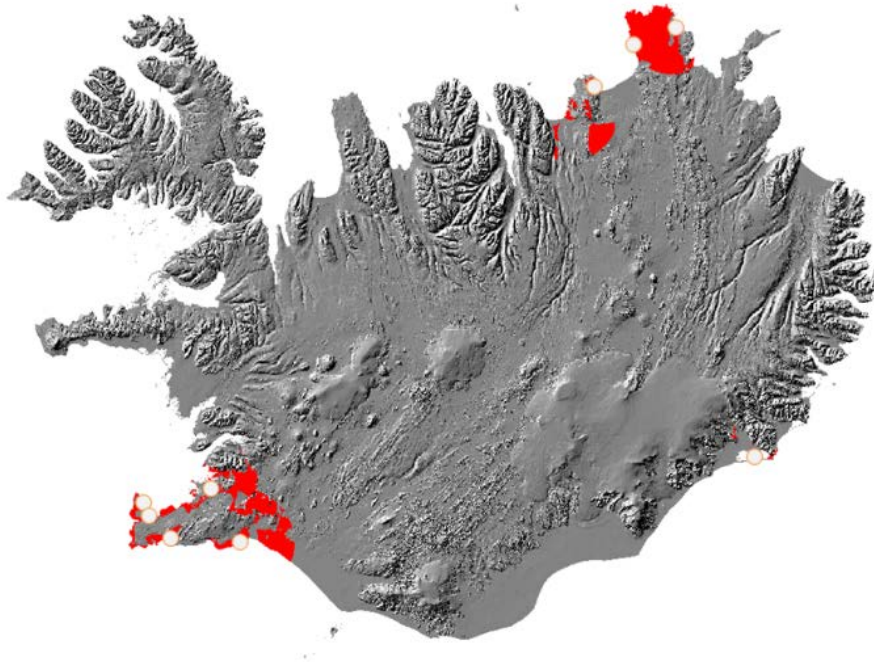


Fig. 10. Theoretical area feasible for CO₂ mineral storage in Iceland; Basaltic formations from Holocene and upper Pleistocene in the vicinity (radius of 30 km) of a large-scale harbour (white dots). Population centers, water protection areas, national parks, natural monuments, nature reserves and country parks were excluded from the area.

Using the results from Wiese et al. [1], as done in the previous example, and applying the average CO₂ load in the uppermost 1500 m of the Reykjanes system as a minimum and of the Krafla system as a maximum to a 1000 m thick segment of the defined area generates a maximum capacity of 175 Gt CO₂ and minimum of 67 Gt CO₂. For comparison, in 2012 the global CO₂ emissions to the atmosphere were 35.6 Gt from fossil fuel burning, cement production and land-use change [33].

Applying the study of McGrail et al. [2] and assuming an interflow thickness of 10 m, average porosity of 15% and 10 available interflow zones at an average hydrostatic pressure of 100 bar, the estimated capacity of the defined area goes down to about 1.4 GtCO₂.

Using the study of Goldberg et al. [31] and assuming a channel system dominating permeability over one-sixth of the uppermost 600 m of the area and average channel porosity of 10%, we get a number of 28.5 GtCO₂.

5.3. The Icelandic analogue and the oceanic ridges

The length of the rift zone in Iceland, the largest landmass found above sea level at mid-ocean ridges, is about 600 km. The oceanic ridges rise on average 1000–3000 m above the adjacent ocean floor (Fig. 11). The ridges extend through all of the major ocean basins, with a total length in excess of 60,000 km [29]. The theoretical mineral CO₂ storage capacity of the ocean ridges, using the Icelandic analogue, is of the order of 100,000–250,000 Gt CO₂. This theoretical storage capacity is significantly larger than the estimated 18,500 Gt CO₂ stemming from burning of all fossil fuel carbon on Earth [55].

Using the assumptions of McGrail et al. [2] and applying them to the ocean ridges gives an estimate of about 2,000 GtCO₂ and applying Goldberg's et al. [31] study gives an estimate about 40,000 GtCO₂.



Fig. 11. Iceland and the Mid-Atlantic ridge. (Based on map from Amante and Eakins [56]).

As stated before, seafloor spreading generates about 20 km^3 per year of mid ocean ridge basalt (MORB). A minimum of about 9 tons of basaltic glass is required for mineralising one ton of carbon, assuming all calcium, magnesium and iron are converted into calcite, magnesite and siderite [8]. If the annual production of MORB by seafloor spreading would be used for mineral storage of CO_2 , about 25 GtCO_2 could be stored per year, which is about 70% of the annual global anthropogenic CO_2 emission to the atmosphere in 2012.

6. Conclusions

There is a high potential for mineral storage of CO_2 in Icelandic basalts and $30\text{-}40 \text{ GtCO}_2$ are estimated to be already naturally fixed within the active geothermal systems [1]. This amounts to the anthropogenic global annual emission of CO_2 to the atmosphere in 2012 [33].

Onshore projects on mineral storage of CO_2 in basalt, such as the CarbFix project in SW-Iceland and the Big Sky Carbon Sequestration Partnership in the northwest United States near Wallula, Washington are yet the only projects where CO_2 is stored in basalt.

Results from CarbFix injection experiments on rapid mineralisation of injected CO_2 when dissolved prior or during injection [4, 7, 12, 13] show a very promising outcome for mineral storage of CO_2 in basaltic rocks.

The largest storage potential lies offshore, where theoretically all CO_2 from burning of fossil fuel carbon could be stored with long-term advantages for safe and secure CO_2 storage in the mid-ocean ridges. The question remains; how much of this storage potential is practical to use?

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References

- [1] Wiese F, Fridriksson Th, Armannsson H. CO₂ Fixation by Calcite in High-temperature Geothermal Systems in Iceland. Tech. Rep., ISOR–2008/003, Iceland Geosurvey, www.os.is/gogn/Skyrslur/ISOR-2008/ISOR-2008-003.pdf (2008).
- [2] McGrail BP, Schaef HT, Ho AM, Chien Y-J, Dooley JJ, Davidson CL. Potential for carbon dioxide sequestration in flood basalts. *J. Geophys. Res.* 2006; 111: B12201
- [3] Goldberg DS, Kent DV, Olsen PE. Potential on-shore and off-shore reservoirs for CO₂ sequestration in Central Atlantic magmatic province basalts. *Proceedings of the National Academy of Sciences of the United States of America* 2010; 107: 1327–1332
- [4] Gislason SR, Oelkers EH. Carbon Storage in Basalt. *Science* 2014; 344: 373–374.
- [5] Rutqvist J, Birkholzer J, Cappa F, Tsang C-F. Estimating maximum sustainable injection pressure during geological sequestration of CO₂ using coupled fluid flow and geomechanical fault-slip analysis. *Energy Conversion and Management*; 2007; 48, 1798–1807
- [6] Gislason SR, Wolff-Boenisch D, Stefansson A, Oelkers EH, Gunnlaugsson E, Sigurdardottir H, Sigfusson B, Broecker WS, Matter JM, Stute M, Axelsson G, Fridriksson T. Mineral sequestration of carbon dioxide in basalt: A preinjection overview of the CarbFix project. *Int. J. Greenhouse Gas Control* 2010; 4: 537–545
- [7] Sigfusson B, Gislason SR, Matter JM, Stute M, Gunnlaugsson E, Gunnarsson I, Aradottir ES, Sigurdardottir H, Mesfin KG, Alfredsson HA, Wolff-Boenisch D, Arnarson MT, Oelkers EH. Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO₂ injection system. *Int. J. Greenhouse Gas Control* 2014 (in press).
- [8] Oelkers EH, Gislason SR, Matter J. Mineral carbonation of CO₂. *Elements* 2008; 4: 331–335
- [9] Gislason SR, Broecker WS, Gunnlaugsson E, Snæbjörnsdóttir SÓ, Mesfin KG, Alfredsson HA, Aradottir ES, Sigfusson B, Gunnarsson I, Stute M, Matter JM, Arnarson MTH, Galeczka IM, Guðbrandsson S, Stockman G, Wolff-Boenisch D, Stefansson A, Ragnheidardottir W, T. Faathen, Gysi AP, Olssen J, Didriksen K, Stippe S, Menez B and Oelkers EH. Rapid solubility and mineral storage of CO₂ in basalt. *Energy Procedia*; 2014: This issue
- [10] Benson S, Cook P, Anderson J, Bachu S, Nimir H, Basu B, Bradshaw J, Deguchi G, Gale J, von Goerne G, Heidug W, Holloway S, Kamal R, Keith D, Loyd P, Rocha P, Senior B, Thomson J, Torp T, Wildenborg T, Wilson M, Zarlenga F, D. Zhou D, Celia M, Gunter B, King JE, Lindeberg E, Lombardi S, Oldenburg C, Pruess K, Rigg A, Stevens S, Wilson ES Whittaker S. In: Metz B, Davidson O, Coninck H, Loos M, Meyer L. editors. *IPCC Special Report on Carbon Dioxide Capture and Storage*, New York :Cambridge Univ. Press; 2005), p. 195–276
- [11] Gilfillan SMV, Sherwood Lollar B, Holland G, Blagburn D, Stevens S, Schoell M, Cassidy M, Ding Z, Zhou Z, Lacrampe-Couloume, Ballentine CJ. Solubility trapping in formation water as dominant CO₂ sink in natural gas fields. *Nature* 2009; 458: 614–618
- [12] Matter JM, Stute M, Hall J, Mesfin K, Snæbjörnsdóttir, Gislason SR, Oelkers EH, Sigfusson B, Gunnarsson I, Aradottir ES, Alfredsson HA, E. Gunnlaugsson E.H.and Broecker WS. Monitoring permanent CO₂ storage by in situ mineral carbonation using a reactive tracer technique. *Energy Procedia* 2014; (this issue).
- [13] Snæbjörnsdóttir SÓ, Mesfin KG, Gunnarsson I, Aradottir ES, Sigfusson B, Gunnlaugsson, Oelkers EH, Stute M, Matter J, Gislason SR. CarbFix: Injection of CO₂ and CO₂-H₂S gas mixture at Hellisheidi SW-Iceland. First results on chemical monitoring. *International Carbon Conference, Reykjavik, Iceland.* <http://www.or.is/en/projects/international-carbon-conference-2014> (2014)
- [14] McGrail BP, Spane FA, Sullivan EC, Bacon DH, Hund G. The Wallula basalt sequestration pilot project. *Energy Procedia* 2011; 4: 5653–5660
- [15] McGrail BP, Freeman CJ, Brown CF, Sullivan EC, White SK, Reddy S, Garber RD, Tobin D, Gilmartin JJ, Steffensen EJ. Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: Case study at the Boise White Paper Mill. *Int. J. Greenhouse Gas Control* 2012; 9: 91–102
- [16] Thordarson Th, Höskuldsson Á. Postglacial volcanism in Iceland. *Jökull*; 2008; 58, 197-228.
- [17] Searle R. *Mid-Ocean Ridges*. Cambridge: Cambridge University Press; 2013
- [18] Jóhannesson H and Sæmundsson K. Geological map of Iceland, 1:500.000; 1998. Icelandic Institute for Natural History.
- [19] Neuhoﬀ PS, Fridriksson Th, Arnorsson S, Bird DK. Porosity evolution and mineral paragenesis during low-grade metamorphism of basaltic lavas at Teigarhorn, Eastern Iceland. *Am. J. Sci.*; 1999; 299, 467–501.
- [20] Frolova J, Franzson H, Ladygin V, Sigurdsson O, Stefánsson V, Shustrov V. Porosity and permeability of hyaloclastites tuffs, Iceland. *Proceedings of International Geothermal Workshop IGW2004 “Heat and light from the heart of the earth”*; 2004 August 9-16; Petropavlovsk-Kamchatsky, Russia. 2004. 10 p.
- [21] Matter JM, Kelemen PB. Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. *Nature Geoscience* 2009; 837–841

- [22] Schaeff HT, McGrail BP, Owen AT. Carbonate mineralization of volcanic province basalts. *Int. J. Greenhouse Gas Control* 2010; 4: 249–261.
- [23] Alfredsson HA, Oelkers EH, Hardarsson BS, Franzson H, Gunnlaugsson E, Gislason SR. The geology and water chemistry of the Hellisheiði, SW-Iceland carbon storage site. *Int. J. Greenhouse Gas Control* 2013; 12: 399–418
- [24] Wolff-Boenisch D, Gislason SR and Oelkers EH. The effect of crystallinity on dissolution rates and CO₂ consumption capacity of silicates. *Geochimica et Cosmochimica Acta*; 2006: 70, 858-870.
- [25] Wolff-Boenisch D, Wenau S, Gislason SR, Oelkers EH. Dissolution of basalts and peridotite in seawater, in the presence of ligands, and CO₂: Implications for mineral sequestration of carbon dioxide. *Geochim. Cosmochim. Acta*. 2011; 75: 5510–5525
- [26] Rosenbauer RJ, Thomas B, Bischoff JL, Palandri J. Carbon sequestration via reaction with basaltic rocks: Geochemical modeling and experimental results. *Geochim. Cosmochim. Acta* 2012; 89: 116–133
- [27] Gysi AP, Stefansson A. CO₂–water–basalt interaction. Low temperature experiments and implications for CO₂ sequestration into basalts. *Geochim. Cosmochim. Acta* 2012; 81: 129–152
- [28] Galeczka I, Wolff-Boenisch D, Oelkers EH, Gislason SR. An experimental study of basaltic glass–H₂O–CO₂ interaction at 22 and 50 °C: implications for subsurface storage of CO₂. *Geochim. Cosmochim. Acta* 2014; 126: 123–145.
- [29] Wilson, M. *Igneous Petrogenesis. A global Tectonic Approach*. Springer, 1989.
- [30] Dessert C, Dupre B, Gaillardet J, Francois LM, Allegre CJ. Basalt weathering laws and the impact of basalt weathering on the global carbon cycle. *Chem. Geol.* 2003; 202: 257–273
- [31] Goldberg DS, Takahashi T, Slagle AL. Carbon dioxide sequestration in deep-sea basalt. *Proc. Nat. Acad. Sci.* 2008; 105(29): 9920–9925.
- [32] Wolery TJ and Sleep NH. Hydrothermal circulation and geochemical flux at mid-ocean ridges. *J. Geol.* 1976; 84: 249-275
- [33] The Global Carbon Project. [internet] [cited 2nd of May 2014] Available from: <http://www.globalcarbonproject.org/carbonbudget/13/hl-compact.htm>
- [34] Mesfin KG, Wolff-Boenisch D, Gislason SR. Effect of ionic strength on the dissolution rates of basaltic glass and bytownite at pH 3.6 and 25°C. Poster presentation. 30th Nordic Geological Winter Meeting; 2012 9th-12th of January; Reykjavík. (2012).
- [35] Gislason SR and Oelkers E. Mechanisms, rates and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of temperature. *Geochim. Cosmochim. Acta*; 2003: 67, 3817-3832.
- [36] Skippen GB. Dehydration and decarbonation equilibria. In Greenwood H. J. ed. *Application of thermodynamics to petrology and ore deposits*, Mineralogical Association of Canada Short Course. Toronto, Canada: Evergreen Press; 1980. p 66-83.
- [37] Franzson, H. Reservoir Geology of the Nesjavellir High-Temperature Field in SW-Iceland. *Proceedings 19th Annual PNOG-EDC Geothermal Conference*; 1998 March 5-6th; Manila, Philippines; 1998. p. 13-20.
- [38] Tómasson J and Kristmannsdóttir H. High temperature alteration minerals and thermal brines, Reykjanes, Iceland. *Contributions to Mineralogy and Petrology* 1972; 36: 132–134.
- [39] Gysi AP, Stefansson A. Numerical modelling of CO₂–water–basalt interaction. *Miner. Mag* 2008; 72: 55–59
- [40] Gysi AP, Stefansson A. CO₂–water–basalt interaction. Numerical simulation of low temperature CO₂ sequestration into basalts. *Geochim. Cosmochim. Acta* 2011; 75: 4728–4751
- [41] Rogers KL, Neuhoff PS, Pedersen AK, Bird DK. CO₂ metasomatism in a basalt-hosted petroleum reservoir, Nuussuaq, West Greenland. *Lithos* 2006; 92: 55–82
- [42] Hjartarson Á, Sigbjarnarson G, Karrenberg H. *International Hydrogeological Map of Europe*; 1980. Sheet B2. Island. Bundesanstalt für Geowissenschaften und Rohstoffe. Hannover and UNESCO. Paris.
- [43] Flóvenz ÓG, Saemundsson K. *Tectonophysics*; 1993: 225, p. 123-138. [http://dx.doi.org/10.1016/0040-1951\(93\)90253-G](http://dx.doi.org/10.1016/0040-1951(93)90253-G)
- [44] Franzson H, Guðfinnsson GH, Helgadóttir HM, Frolova J. Porosity, density and chemical composition relationships in altered Icelandic hyaloclastites. *Water-Rock Interaction – Birkle & Torres-Alvarado*; 2010: 199-202
- [45] Stefánsson, V, Sigurðsson, Ó, Guðmundsson, Á, Franzson, H, Friðleifsson GÓ, Tulinius, H. Core measurements and geothermal modelling. *Second Nordic Symposium on Petrophysics; 1997: Fractured reservoirs. Nordic Petroleum Technology Series One*, 199-220.
- [46] Flaathen TK, Gislason SR, Oelkers EH, Sveinbjörnsdóttir ÁE. Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO₂ sequestration in basaltic rocks, *App. Geochem.* 2009; 24: 463–474.
- [47] Galeczka I, Wolff-Boenisch D, Gislason SR. Experimental studies of basalt–H₂O–CO₂ interaction with a high pressure column flow reactor: the mobility of metals. *Energy Procedia* 2013; 37: 5823–5833
- [48] Olsson J, Stipp SLS, Makovicky E, and Gislason SR. Metal scavenging by calcium carbonate at the Eyjafjallajökull volcano: A carbon capture and storage analogue. *Chem. Geol.* 2014; 384: 135–148.
- [49] Galeczka I, Wolff-Boenisch D, Jonsson, Th, Sigfusson B, Stefansson A, Gislason SR. A novel high pressure column flow reactor for experimental studies of CO₂ mineral storage. *Applied Geochemistry*; 2013: 30; 91-104.
- [50] European Community. Council directive 80/778/EC of 15 July 1980 relating to the quality of water intended for human consumption as amended by Council Directives 81/858/EEC and 91/692/EEC (further amended by Council Regulation 1882/2003/EC).
- [51] Aradóttir ES, Sonnenthal EL, Björnsson G, Jonsson H. Multidimensional reactive transport modeling of CO₂ mineral sequestration in basalts at the Hellisheiði geothermal field, Iceland. *Int. J. Greenhouse Gas Control* 2012; 9: 24–40
- [52] Ármannsson H, Fridriksson Th, Wiese F, Hernández P, Pérez N. CO₂ budget of the Krafla geothermal system, NE Iceland. *Water-Rock Interaction* (Editors T.D. Bullen and Y. Wang); 2013. Taylor and Francis Group, London, 189-192
- [53] Franzson H, Kristjánsson BR, Gunnarsson G, Björnsson G, Hjartarson A, Steingrímsson B, Gunnlaugsson E, Gislason, G. The Hengill-Hellisheiði Geothermal Field. Development of a Geothermal conceptual model. *Proceedings World Geothermal Congress*; 2005 24-29. April; Antalya, Turkey: 7 p.

- [54] Anthonen KL, Aagaard P, Bergmo PES, Erlström M, Fareidei JI, Gislason SR, Mortensen GM, Snæbjörnsdóttir, SÓ. CO₂ storage potential in the Nordic region. *Energy Procedia*; 2013; 37, 5080-5092.
- [55] Archer D. Fate of fossil fuel CO₂ in geologic time. *J. Geophys. Res.* 2005; 110(C9): C09S05
- [56] Amante C and Eakins BW. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA; 2009. doi:10.7289/V5C8276M [accessed 9.9.2014]