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CO_2 storage potential of basaltic rocks offshore Iceland

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Abstract

Injection of CO_2 into basaltic formations provides significant benefits including permanent storage by mineralisation and large storage volume. The largest geological storage potential lies offshore and in the case of basalt, along the mid-oceanic ridges where CO_2 could be stored as carbonate minerals for thousands of years. Most of the bedrock, both on land and offshore Iceland consists of basalt that could theoretically be used for injection of CO_2, fully dissolved in water. The most feasible formations are the youngest formations located within the active rift zone. It is estimated that up to 7000 $GtCO_2$ could be stored offshore Iceland within the Exclusive Economic Zone. Site specific geological research and pilot studies are required for refining the concept and offshore pilot scale projects should be considered as the next steps in evolving the method.

1. Introduction

The reduction of carbon dioxide (CO_2) emissions to the atmosphere is one of the greatest challenges of this century and multiple approaches are needed for halting climate change by reversing the rise in emissions. One solution to this is carbon capture and storage (CCS). In fact, the International Energy Agency estimates that under the 2°C scenario, CCS will provide one sixth of required emission reduction in 2050 [1]. Injection of CO_2 into basaltic formations provides significant benefits including permanent storage by mineralisation and a great potential storage volume [2-5]. Mineral carbonation requires combining CO_2 with divalent metal cations to form carbonate minerals, such as Calcite ($CaCO_3$), Dolomite ($CaMg(CO_3)_2$), Magnesite ($MgCO_3$), siderite ($FeCO_3$), and solid

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solutions thereof [3, 6]. Basaltic rocks contain over 25 wt% Ca, Mg, and Fe-oxides and are reactive in water, thus the metals contained in basalts are readily available to combine with the injected CO_2 to form carbonate minerals [7-12]. Once dissolved in water, CO_2 is no longer buoyant and does not migrate back to the surface. The CO_2-charged water accelerates both the metal release from the basalt and subsequent formation of solid carbonate minerals for long term storage of CO_2 (fig 1.) [3].

The method of dissolving the CO_2 during injection into reactive basaltic rocks changes the time scale for mineral storage significantly with solubility trapping occurring immediately, and the bulk of the carbon trapped in minerals within only few years [3, 13, 14]. Once stored as a mineral, the CO_2 is immobilised for geological time scales [3, 6, 11, 15]. This method will be referred to as the CarbFix method, named after the project that pioneered it.
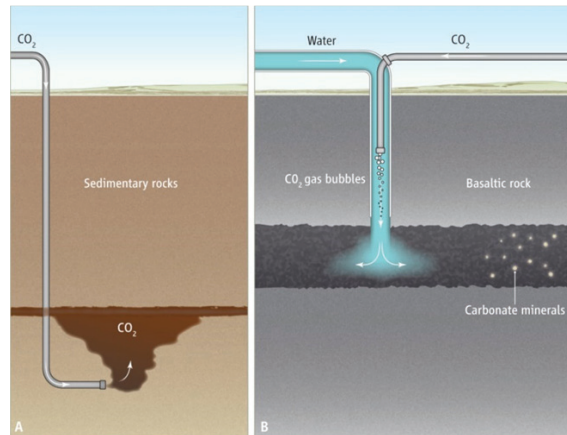

Fig. 1. Carbon storage in sedimentary basins and basaltic rocks. (A) Carbon storage in sedimentary basins; CO_2 is injected as a separate buoyant phase and is trapped below an impermeable cap rock. (B) In the CarbFix method, CO_2 is dissolved into water during its injection into porous basaltic rocks. No cap rock is required because the dissolved CO_2 is not buoyant and does not migrate back to the surface. Figure from Gislason and Oelkers [3].

Most of the oceanic floor and about 10% of the continents is composed of basalt which is the dominant rock type on Earth's surface [16, 17]. The most voluminous volcanism on the Earth occurs at the mid-ocean ridges where seafloor spreading generates about 20 km^3 per year of mid-ocean ridge basalt (MORB) [18]. The offshore formations offer a unique environment for CO_2 storage with a vast volume of pore space, and fresh and reactive rocks. The ridges extend through all of the major ocean basins, with a total length in excess of 60,000 km [29]. The theoretical integrated CO_2 storage capacity of the ridge system has been estimated to be of the order of 100,000-250,000 $GtCO_2$ [2] considerably larger than the estimated CO_2 emission from burning all fossil fuels on Earth [19].

The physical properties of the mid-oceanic ridges have been studied extensively, mainly through scientific drilling, and geophysical and bathymetric surveys [e.g. 20]. The flanks of the ridges are known to contain highly fractured and permeable basaltic layers [21] with pervasive circulation of seawater initiating at the spreading axis and continuing for millions of years as the oceanic crust moves away from the axis and cools and ages [22]. The advective heat flow for the entire oceanic ridge system is estimated to be about 10^{13} W, with about two thirds of the heat loss occurring in seafloor younger than 8 Ma. The mass flow of seawater necessary to produce this heat loss at the oceanic ridges is about 1,000 GtH_2O/yr [23].

A vast amount of water is required to dissolve the CO_2, depending mostly on pressure, temperature, and salinity [11]. At 25 bar CO_2 pressure and 4°C, about 20 tonnes of seawater of average salinity (35‰) are required for dissolving each tonne of CO_2 [24, 25]. The 2014 anthropogenic CO_2 emissions to the atmosphere were 36 $GtCO_2$/yr [26]. It would take about 720 GtH_2O to dissolve all of that CO_2 in seawater at 25 bar CO_2 pressure, about three-quarters of the amount that percolates into the ridge system every year.

Here, a first attempt is made to estimate the theoretical capacity for mineral storage of CO_2 in young basaltic

formations offshore Iceland, within the Icelandic Exclusive Economic Zone which extends 200 nautical miles from the coastal line, covering area of about 740,000 km^2. Observations made during screening of basaltic formations onshore are initially used to calculate a first order estimate of the offshore potential. However, further work and a more thorough study of the available data is required for selection of suitable formations for mineral storage of CO_2 and estimation of the CO_2 storage potential, including lab and field injection experiments using seawater and extensive monitoring and characterization of current onshore injection experiments.

2. Geological settings of Iceland and the North Atlantic Basin

Iceland sits astride the North Atlantic Ridge where the North American and the Eurasian plates are separated (fig. 2). Iceland is one of only two places on Earth where an oceanic spreading centre rises above sea level and is the largest area of sub-aerially exposed mid-ocean ridge on Earth [27].

Fig. 2. Iceland and the Mid-Atlantic ridge. Based on map from Amante and Eakins [28].

The plate boundary in, and close to Iceland is composed of several rift segments and transform zones, forming an overlapping spreading centre with propagating rifts both at the southern and northern parts of the island (fig. 2 and 3) [29, 30], with a spreading rate of about 18-20 mm/yr [31]. In SW-Iceland, at the tip of the Reykjanes peninsula, the offshore Reykjanes Ridge (RR) meets the on-land Reykjanes Oblique Rift which extends to form the West Volcanic Zone (WVZ) as shown in Fig. 3. In N-Iceland the Northern Volcanic Zone (NVZ) is linked to the offshore Kolbeinsey Ridge (KR) by the NW-trending Tjörnes Fracture Zone (TFZ) [e.g. 32, 33] (fig. 3).

The plate boundary is affected by the existence of a mantle plume located beneath Iceland [34]. The mantle plume has profoundly influenced the creation of the oceanic crust along the North Atlantic basin. The thickness of the crust along the Reykjanes Ridge is of 10-11 km [35] which is about 6–7 km higher than normal oceanic crust [36] but the influence of the mantle plume appears to extend less far north along the Kolbeinsey Ridge with 1-2 km thinner crust than along Reykjanes Ridge [37]. The effect of the mantle plume results in the anomalously shallow bathymetry of the Reykjanes Ridge and Kolbeinsey Ridges compared to mid-oceanic ridges in general; the depth of the Iceland sea north of Iceland is about 1000-2000 m and as shallow as 500 m at Reykjanes Ridge closest to land and up to 1500-2000 m at the southern end of the ridge [38]. These areas, north and south of Iceland, are shown by the shaded part of the ridges in Figure 3.

The excessive volcanism associated with the combination of a mantle plume and divergent rifting has led to the forming of the Iceland basalt plateau shown in Fig. 2 and Fig. 3. The plateau rises more than 3000 m above the surrounding sea floor and covers about 350,000 km^2 including the terrestrial 103,000 km^2 of Iceland [39]. Iceland is mostly made of young 0-20 M yr. igneous rocks and sediments thereof, but approximately 90% of the bedrock is basalt [40]. The relatively flat shelf around Iceland is generally at depths of between 100-200 m and its average width is 80 km [41]. Sediments, mostly originate onshore and are abundant at the edge of the shelf, close to and below the slope of it. The thickness of the sediments below the slope are estimated to be up to 1000-2000 m, except in one area north of Iceland within the TFZ, between Skjálfandi bay and Eyjafjörður fjord in Figure 3, where the sedimentary pile is estimated to be as thick as 4000 m [42].

The ridges consist, as stated before, of MORB but are somewhat covered with sediments; very thin layers, or none at all, above the axis of the ridges where new crust is being formed but thickening towards the seafloor as the rocks gets older, reaching 1000-1500 m at the end of the slope of the ridges [38].
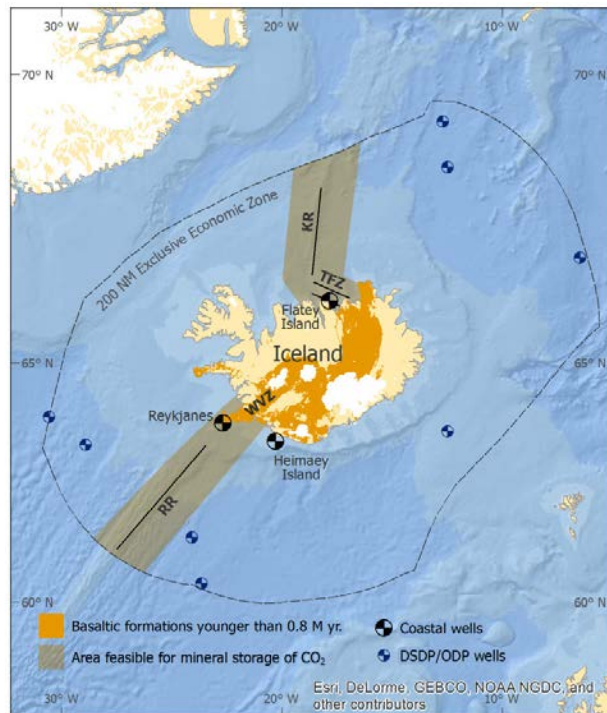

Fig. 3. General outlines of the plate boundary in Iceland. Reykjanes Ridge (RR) enters Iceland at the tip of the Reykjanes Peninsula which extends to form the Western Volcanic Zone (WVZ). The Northern Volcanic Zone (NVZ) extends north where it is linked to the offshore Kolbeinsey Ridge (KR) by the NW-trending Tjörnes Fracture Zone (TFZ). Large hourglass circles indicate wells drilled in the coastal areas and small hourglass circles indicate wells drilled offshore as a part of DSDP and ODP. The area that fits our criteria as feasible for CO$_2$ mineral storage offshore Iceland is shaded. It extends 30 km to each side of the axis of the Reykjanes Ridge SW of Iceland and the Kolbeinsey Ridge N of Iceland, from the costal line and to the boundary of the Iceland Economic Zone. Modified after Einarsson and Sæmundsson, [43], map based on data from Esri, GEBCO and NOAA [44].

3. Data available on offshore formations

The areas offshore of Iceland have been studied to some extent, especially the areas north and north-east of Iceland, in connection with oil and gas exploration. The research includes gas-analysis, multi-beam bathymetry, side scan sonar, seismic surveys, seafloor photography, and coring of sediments in selected areas [45]. The most concrete

information on offshore formations is from wells drilled at the coastal line of Iceland, on the shelf, and seafloor which could give valuable information on formations for mineral storage of CO_2 offshore of Iceland (fig. 3)

Wells drilled in Heimaey Island south of Iceland and Flatey Island in the Skjálfandi Bay north of Iceland can give information on the formations at the shelf south and north of Iceland. Wells drilled at the coast at the Reykjanes peninsula can somewhat represent the stratigraphy offshore SW-Iceland. Several wells have also been drilled offshore of Iceland as a part of the Deep See Drilling Project (DSDP) in 1970-1976 and Ocean Drilling Program (ODP) in 1993-1995, ranging from about 120 to about 620 m in depth from the seafloor These are mostly sedimentary cores, but in some cases cored down to the basalt basement at about 300-600 m depth [e.g. 20].

Two deep wells have been drilled in Heimaey Island, the largest island of the Vestmannaeyjar Islands south of Iceland; 1565 m and 2277 m deep (fig. 3). The stratigraphy of the wells consists mostly of alternating sedimentary formations and basaltic hyaloclastites; glassy formations formed under water resulting in fragmentation of the magma. The chemical composition of the sediments indicates that the formations are derived from weathering of volcanic rocks on land, located within the East Volcanic Zone north of Vestmannaeyjar Island [46].

A 554 m deep well was drilled in Flatey Island in the bay of Skjálfandi north of Iceland in 1982 (fig. 3). The stratigraphy of the well is mostly sedimentary rocks formed in shallow water or on land during glaciation and three 10-20 m thick basaltic lava sequences [e.g. 42, 47]. Seismic- and gravity-surveys conducted in the area indicate that the island is located on top of the sedimentary formation located between Skjálfandi bay and Eyjafjörður fjord which is estimated to be about 4 km thick [42].

Several wells have been drilled at the south-western tip of the Reykjanes peninsula (fig. 3), in connection with geothermal utilisation in the area, which show some trends in stratigraphy. Below about 100 m and down to about 900-1000 m depth the formation consists of glassy basaltic hyaloclastic formations and marine sediments indicating eruptions under water and formations of sediments in water depth less than 50 m. The dominant rock type below 900-1000 m depth is crystalline basalt, most likely pillow basalt formed offshore, but hyaloclastites and sedimentary tuff-units are also cut by the wells [e.g. 48].

4. Most feasible formations for CO_2 mineral storage offshore Iceland

Seismological studies on the internal structure of the oceanic crust reveal a remarkably homogeneous structure compared to the continental crust. Two igneous crustal layers are identified; layer 2 characterized by low velocities and steep velocity gradients and layer 3 by high velocities and low velocity gradient. These seismic velocities are related to bulk porosity and rock composition within the oceanic crust [22].

The feasible formations for mineral storage of CO_2 lie within the so called layer 2 which is associated with the upper crust. The top-part of layer 2 consists of a few hundred metres thick extrusive section that caps the crust along the ridges with the highest bulk porosities (20-40%) within the oceanic crust. Below this section lies a 1.5-2 km thick sheeted dike section with porosities of less than 10%. The permeability and porosity structure of the crust is the result of both tectonic and magmatic processes [22]. Little is published on the mean thickness of the porous top-part of layer 2 at the Mid Atlantic ridges but the thickness at the Reykjanes Ridge is measured to be 400 ± 100 m, decreasing with crustal ages over 5 Ma [49].

The velocity of the top-part of layer 2 increases as the crust ages away from the spreading axis, reaching typical levels of deeper crustal rocks by <10 Ma [22]. The young (<3.2 Ma) DSDP basalts are pervasively altered [50-52] indicating that the alteration must commence very soon after the crust is formed [53]. The first stages of alteration of the oceanic crust are formation of palagonites and later smectites but both processes are the results of seawater-basalt interaction. This involves large amounts of water and can produce major chemical fluxes between layer 2 and the oceanic reservoir, but these processes typically occur in Atlantic type crust younger than 3 Ma [52]. Radiometric dating of vein smectites from MORB also indicates that most of the alteration occurs within 3 Ma [54]. Porosity data from DSDP and ODP sites show a similar relationship for samples with crustal ages >5 Ma [55] but the crust retains roughly half of its porosity after 10-15 Ma with continuing alteration at decreasing rate [56].

Studies on Icelandic bedrock show that, as with oceanic crust porosity and permeability generally decrease with progressive alteration, gradual burial, and increasing rock age since most of the pore space is filled with secondary minerals in the older rocks [57, 58]. Average porosity of young and un-altered basaltic lavas has been measured to be about 27% compared to 6-7% in highly altered samples [59]. Thus, the youngest basaltic formations found within

the active rift zone (<0.8 Ma), have been evaluated as the most feasible for carbon storage onshore Iceland [2]. As for the porosity and permeability, the structure of the top-part of the Icelandic crust, as studied in wells drilled within the active rift zone, also reveals a similar structure as the oceanic crust with the top few hundred meters dominated by extrusive rocks; glassy formations and pillow basalts erupted during glacial times and lava flows during inter-glacials, sheeted dykes becoming more dominant with increasing depth and finally gabbro or granophyre-like intrusions in the deepest parts [e.g. 60].

The same criteria are therefore used here for the assessment of mineral carbon storage potential offshore as for the onshore formations in Iceland. The selected area for the storage estimate reaches from the axis of the Reykjanes Ridge SW of Iceland and the Kolbeinsey ridge NE of Iceland and extends 30 km to each side of the ridge axis which is the width of the active rift zone in Iceland (fig. 3). Using the spreading rate of about 18-20 mm/yr it can be estimated that the age of the formations is <3 Ma, eliminating the more altered and less porous formations. This includes area from the costal line and to the boundary of the Iceland Economic Zone which covers about 93,000 km^2.

The difference between injecting CO_2 dissolved in water and in a buoyant supercritical stage is underscored in Figure 1 and discussed in chapter 1 of this paper. Supercritical CO_2 is kept trapped below an impermeable cap rock, but since dissolved CO_2 is heavier than the formation fluids, the injection wells are not dependent on cap-rocks or seals. In fact, the dissolved CO_2 can be injected into fractured and even open aquifers, as long as the flow path is long enough for alkalinity generation and eventually mineralisation of the CO_2. As stated before, the time required for mineralisation is of the orders of months to years [3, 13, 14]. The total depth of injection, including the seawater column, should be at least 300 m yielding about 30 bar pressure, enough for considerable solubility of the CO_2 in the seawater, as also discussed in chapter 1. Site specific studies and further experience with the CarbFix method will inform how far the injection wells would have to reach into the basalt formation for successful injection. However, the experience from the on-shore injection experiments of the CarbFix project in Hellisheiði has shown that 200 m below the water table in the basalt formation is more than enough [13].

5. Storage potential estimates

Few attempts have been done to estimate the mineral storage potential of CO_2 in basaltic rocks. The first attempt was made by McGrail et al. [61] that estimated the storage potential of continental flood basalts for storage of buoyant, supercritical CO_2 assuming that the Columbia River basalts which cover more than 164,000 km^2 of Washington, Oregon, and Idaho, have the capacity to store over 100 GtCO_2. The targeted depth of the injection was 1000 m assuming interflow thickness of 10 m, average porosity of 15% and 10 available interflow zones at an average hydrostatic pressure of 100 atm.

Applying the same criteria to the selected area of 93,000 km^2 offshore Iceland gives storage potential estimate of about 60 GtCO_2 (fig. 4, Scenario 1). This is a rather conservative estimate considering that the total CO_2 measured to be fixed within the active high temperature geothermal systems in Iceland, an area which covers less than 1 km^2 of Iceland, amounts to 30-40 GtCO_2 [62]. McGrail's study [61] differs from this study in two fundamental ways. Firstly, the basaltic formations of the study are continental basalts with different structure and petro-physical properties than the young and glassy basaltic formations of the oceanic crust. Secondly and more importantly, they anticipate that the CO_2 is injected as a supercritical buoyant phase into the basaltic rocks which requires deeper wells and a cap rock to prevent the supercritical CO_2 from leaking out of the reservoir. Injecting supercritical CO_2 also results in orders of magnitude lower mineralisation rate than if the CO_2 is dissolved in water prior to or during the injection using the CarbFix method [3, 14].

Goldberg et al. [63] revealed the large storage capacity of sub-oceanic basalt formations at the Juan de Fuca plate east of Oregon, USA. Assuming a channel system dominating permeability over one-sixth of the uppermost 600 m of the area, it is estimated to contain 7800 km^3 of highly permeable basalt feasible for mineral storage. Given an average channel porosity of 10%, 780 km^3 of potential pore volume will be available for CO_2 storage. If liquefied CO_2 is injected to fill this volume and it remains in liquid form, about 750 GtCO_2 could be stored in this area. If the CO_2 reacts with the basalt and is mineralised about 900 GtCO_2 could be stored in the area.

The Goldberg et al. study is done on oceanic crust which makes it more applicable to the area offshore Iceland. However, with McGrail et. al, Goldberg et al. assume injection of buoyant supercritical CO_2 which puts more

constrains on the targeted area, requiring more than 200 m thick sediment cover as a seal and water depth greater than 2700 m. If the petro-physical criteria from Goldberg et al. [63] are applied to the 93,000 km^2 area offshore Iceland, estimating 9300 km^3 of permeable basaltic rocks along the ridge axis, with 10% average channel porosity., then 930 km^3 of potential pore volume would be available, yielding to a mineral storage potential of 1100 $GtCO_2$ (fig. 4, Scenario 2).

Snæbjörnsdóttir et al. [2] used a study done by Wiese et al. [62] on the amount and spatial distribution of CO_2 stored as calcite within the bedrock of three active high-temperature geothermal systems in Iceland, as a natural analog for mineral storage of CO_2 in young basaltic formations. A significant amount of CO_2 is naturally fixed within basaltic rocks in geothermal areas which receive CO_2 from their heat source; magmatic intrusions in their roots. The amount of CO_2 stored as calcite in the three geothermal systems; Krafla in the north–east of Iceland and Hellisheiði and Reykjanes in the south-west, was estimated by measuring the CO_2 content of about 700 samples of drill cuttings from 42 wells in these three areas. The results indicate that about 28.2 to 73.1 tonnes of CO_2 per m^2 of surface area are already naturally fixed in the uppermost 1500 m of the three areas. The lowest values are 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) and the highest values are measured in the Krafla geothermal area, considered to have been active for the longest (between 110,000 and 290,000 years). These time scales are orders of magnitude larger than the time scales CCS requires, but considering how fast these reactions occur when CO_2 is dissolved in water during injection [3, 15, 64] the results can be used as a guideline for the theoretical CO_2 storage potential.

The CO_2-load in the uppermost 1500 m of the Reykjanes system was used to as a minimum and the Krafla system as a maximum and the values applied to the uppermost 1500 m of the relatively fresh basaltic formations within the active rift zone of Iceland [2]. If the same method is used to estimate the storage potential offshore Iceland gives values of 2600 $GtCO_2$ (fig. 4, Scenario 3) and 6800 $GtCO_2$ (fig. 4, Scenario 4) respectively.

As stated before, the permeability, porosity and general structure of the Icelandic crust within the active rift zone is similar to the oceanic crust. The formations on-shore can therefore give valuable information on offshore storage of CO_2. The storage potential estimates using the Icelandic analogue give results of the same order of magnitude as Goldberg et al. [63]. The main difference lies within the different approaches: Goldberg et al. estimate the storage potential from petro-physical properties of the oceanic crust for injection of supercritical CO_2 whilst Snæbjörnsdóttir et al. [2] use natural analog for mineral storage of CO_2.
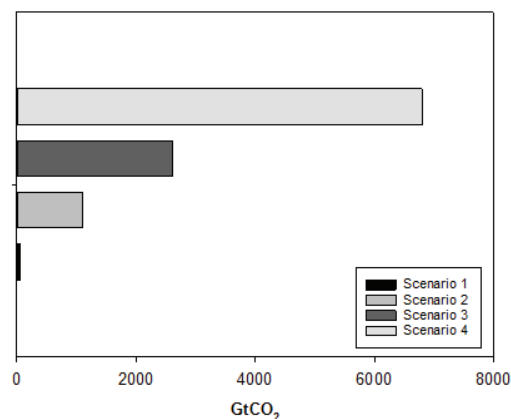

Fig. 4. Storage potential estimates of the selected area feasible for mineral storage of CO_2 offshore Iceland along the of the axis of the Reykjanes Ridge SW of Iceland and the Kolbeinsey Ridge N of Iceland within the Exclusive Economic Zone using criteria from McGrail et al. [61] as scenario 1, Goldberg et al. [63] as Scenario 2 and Snæbjörnsdóttir et al. [2] as Scenario 3 and 4.

6. Conclusions

The largest geological storage potential for CO_2 lies offshore, and in the case of basalt along the oceanic ridges where theoretically CO_2 from burning of all fossil fuel on Earth could be stored as carbonate minerals for thousands of years [2]. There is a large storage potential of CO_2 within basaltic rocks offshore Iceland, which is underscored by the theoretical storage potential estimates ranging from about 60 to about 7,000 $GtCO_2$. There are however large uncertainties due to lack of data and experience within the field which require site-specific geological research and pilot studies.

A significant challenge faced by the CarbFix method is the vast amount of water that is required to dissolve CO_2 during injection. The total mass initially injected will be about 15 to 25 times greater when compared to the conventional method. Both methods run into risks of overpressure in the aquifers when scaled up to millions of tonnes and the great mass injected using the CarbFix method increases this risk. At Hellisheiði geothermal field in SW-Iceland about 22 Mt of waste water from the Hellisheiði geothermal power plant have been re-injected into the fractured reservoir annually for the last four years using 12 injection wells. The injection initially led to some overpressure and induced seismicity which faded out with time during operation [65]. Today it is an ongoing operation that continues to show the feasibility of injecting large volumes of fluid into young and fractured basaltic rocks.

One of the advantages of going offshore is that the oceans provide an unlimited reservoir for the required water. In addition to that, the flanks of the ridges contain highly fractured and permeable basaltic layers with great circulation of seawater, or about 1,000 GtH_2O/yr [23], as mentioned in chapter 1 of this paper. Considering that the CO_2-charged water is heavier than seawater and does therefore not migrate back to the surface, and the fast reactions between the carbonated water and the basaltic rocks [3] it could be a feasible option to extract and re-inject the same water about five years after injection, thus accelerating flow through the formation.

On-shore pilot studies on CO_2 storage within basaltic rocks such as the two CarbFix field injection experiments [e.g. 11, 13, 66] and Big Sky Carbon Sequestration [67, 68] give valuable information on the feasibility of the concept together with modelling work and laboratory injection experiments, since offshore drilling and monitoring is both more expensive and harder to conduct. However, offshore pilot scale projects should be considered as the next steps in evolving the CarbFix method.

Acknowledgements

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