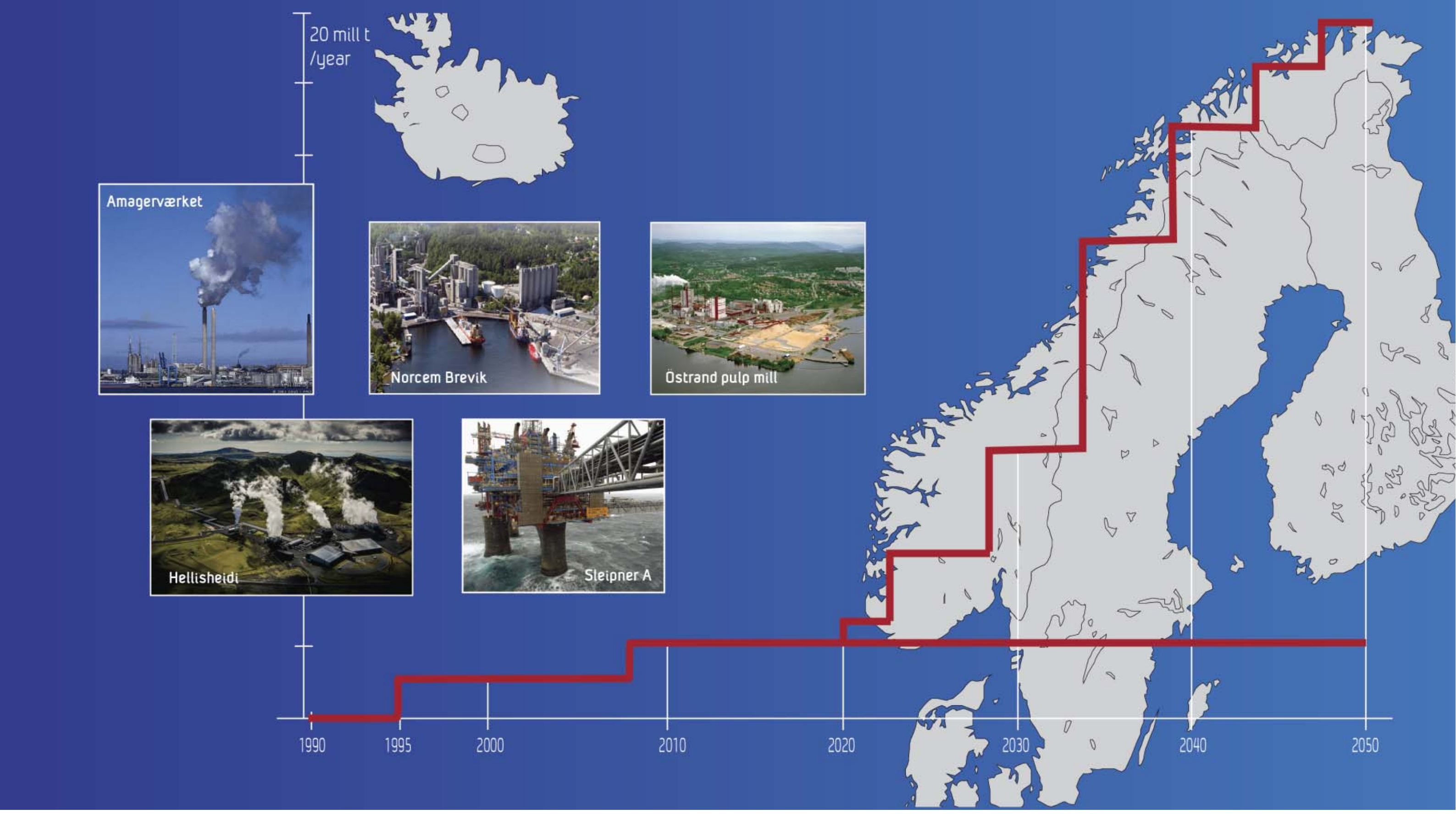

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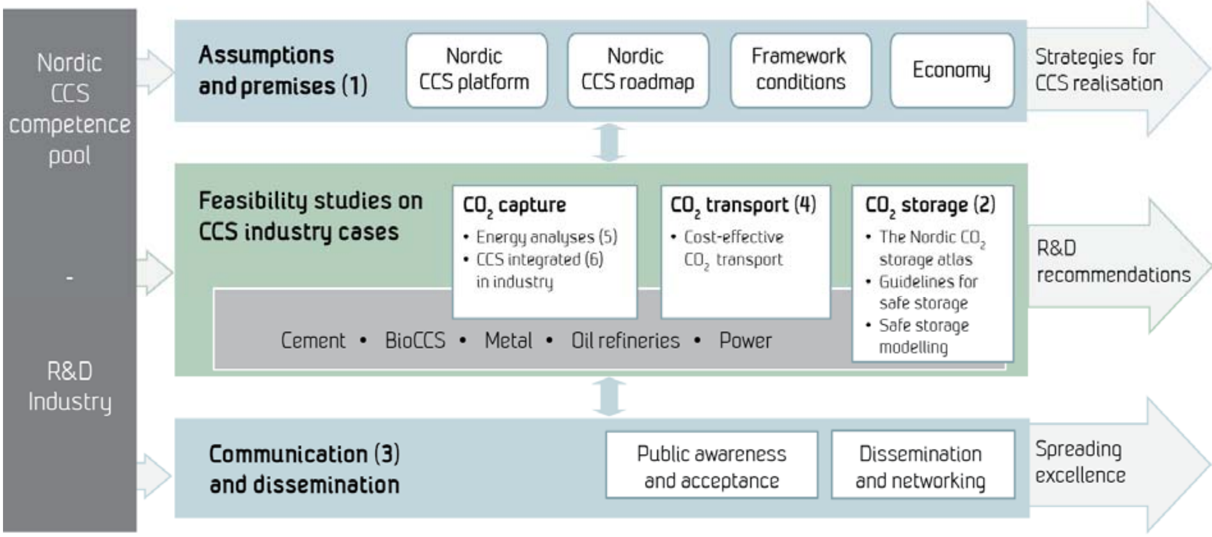

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Summary

Methodology for injection of CO_2 into basalts and evaluation of the theoretical storage capacity for Iceland.

Contribution to the International Carbon Conference, Reykjavik, Iceland, August 2014.

Keywords Storage potential, basalts, Iceland, ocean ridges, geothermal

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About NORDICCS

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.

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CO_2 storage potential of basaltic rocks in Iceland and the oceanic ridges

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The reduction of CO_2 emissions to the atmosphere is one of the greatest challenges of this century. One solution to this is carbon capture and storage (CCS). Some of the risks associated with CCS stem from the buoyancy of CO_2. This risk can be can be mitigated by dissolving CO_2 in water during its injection into basaltic rocks. Once dissolved, CO_2 is no longer buoyant and the CO_2-charged water accelerates metal release and formation of solid carbonate minerals for long term storage CO_2 [1].
Iceland is the largest landmass found above sea level at the mid-ocean ridges, about 103,000 km^2 mostly made of basaltic rocks (~90%). Theoretically much of Iceland could be used for injection of CO_2, 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 CO_2 in basaltic rocks are still at an early stage. Therefore, natural analogues are important for gaining a better understanding of CO_2 fixation in basaltic rocks. Volcanic geothermal systems serve as an applicable analogue since the systems receive considerable amounts of CO_2 from magma in the roots of the systems. Wiese et al. [2] quantified the amount and spatial distribution of CO_2 stored as calcite within the bedrock of three active geothermal systems in Iceland. The average kg m^{-3} of CO_2 fixed in the uppermost 1500 m varied from 28.2 kg m^{-3} in the area considered to be the youngest of the three to 73.1 kg m^{-3} in the oldest one. The results from this study can be used as a guideline for the theoretical potential of CO_2 storage in basaltic formations. By using the lowest average as a minimum and the highest average as a maximum and apply these values to a 1000 m thick segment of the relatively fresh basaltic formations within the rift zone of Iceland yields 2,470 Gt of CO_2 as a maximum mineral storage potential and 953 Gt as a minimum. This scenario is highly theoretical but underscores the enormous mineral storage potential within the young and porous basaltic rocks.
The length of the rift zone in Iceland is about 600 km. The oceanic ridges rise on average 1000–3000 m above the adjacent ocean floor and extend through all of the major ocean basins, with a total length in excess of 60,000 km. The theoretical mineral CO_2 storage capacity of the ocean ridges, using the Icelandic analogue, is of the order of 100,000–250,000 Gt CO_2. This theoretical storage capacity is significantly larger than the estimated 18,500 Gt CO_2 stemming from burning of all fossil fuel carbon on Earth [3]. The question remains; how much of this storage potential is practical to use?

[1] S.R. Gislason, Eric H. Oelkers (2013). *Science 25 April 2014: Vol. 344 no. 6182 pp. 373-374.*
[2] Wiese, F., et al. (2008). *CO_2 fixation by calcite in high-temperature geothermal systems in Iceland. Report, ISOR 2008/003.*
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Mineral storage of CO_2

The reduction of CO_2 emissions is one of the greatest challenges of this century. One solution to this is carbon capture and storage (CCS).

Some of the risks associated with CCS stems from the buoyancy of CO_2. That risk can be can be mitigated by dissolving CO_2 in water during its injection into basaltic rocks **(fig. 1)**. Once dissolved, CO_2 is no longer buoyant, making it possible to inject into fractured rocks, such as basaltic rocks along the oceanic ridges.

The CO_2-charged water accelerates metal release and formation of solid carbonates for long term storage of CO_2 **[1]**

Iceland is the largest landmass found above sea level at the mid-ocean ridges, about 103,000 km² mostly (~90%) made of basaltic rocks. Theoretically much of Iceland could be used for injection of CO_2, 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 within the active rift zone, covering about one third of Iceland, are the most feasible for carbon storage onshore **(fig. 2)**.

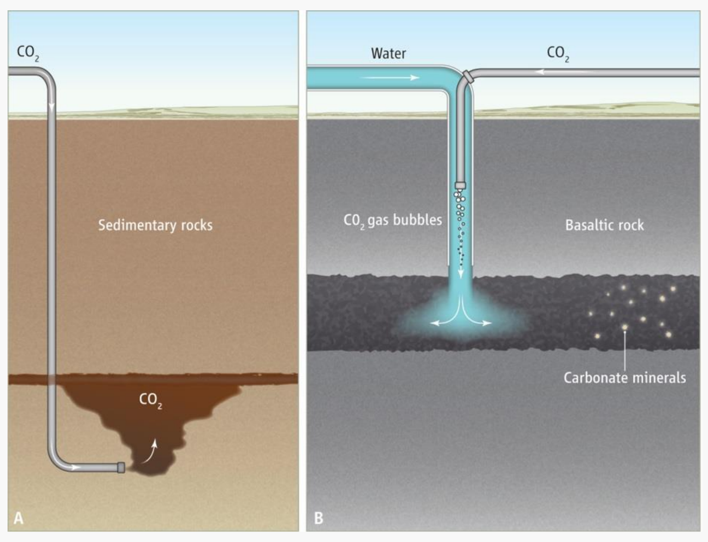
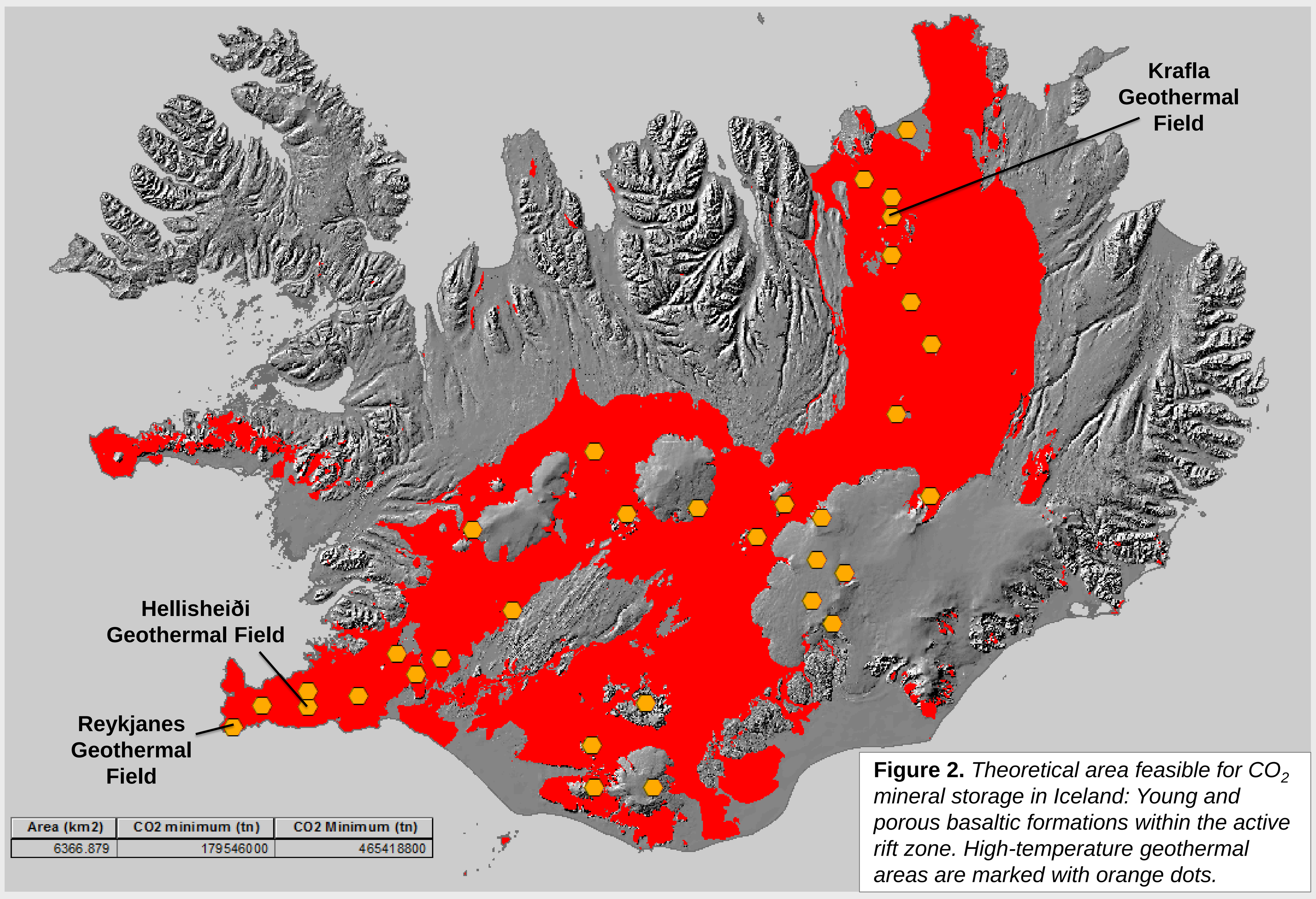


Figure 1. ***(A)*** *Carbon storage in sedimentary basins; CO_2 is injected as a separate buoyant phase and is trapped below an impermeable cap rock.* ***(B)*** *CO_2 dissolved in water during its injection into porous basaltic rocks. No cap rock is required because the dissolved CO_2 is not buoyant and does not migrate back to the surface (from Gislason and Oelkers 2014).*



Area (km2)	CO2 minimum (tn)	CO2 Minimum (tn)
6366.879	179546000	465418800

Figure 2. *Theoretical area feasible for CO_2 mineral storage in Iceland: Young and porous basaltic formations within the active rift zone. High-temperature geothermal areas are marked with orange dots.*

Natural analogs

Since studies are still at an early stage, volcanic geothermal systems serve as an applicable natural analogue for gaining a better understanding on mineral storage of CO_2. The systems receive considerable amounts of CO_2 from their heat source and can therefore be considered as a natural experiment to determine CO_2 storage capacity of the bedrock.

Wiese et al. **[2]** quantified the amount and spatial distribution of CO_2 stored as Calcite within the bedrock of three active geothermal systems in Iceland: Krafla in the north–east of Iceland and Hellisheidi and Reykjanes in the south-west. The geothermal waters are meteoric in the Krafla and Hellisheidi systems , but seawater in the Reykjanes system. The CO_2 content was measured in drill cutting samples from 40 wells, located in the three geothermal areas.

Average CO_2 load

The values measured in the Reykjanes geothermal area (considered the youngest of the three) were significantly lower than elsewhere in this study; on average **28.2 kg m^{-3}** of CO_2 fixed in the uppermost 1500 m. The average CO_2 load in the uppermost 1500 m in Hellisheiði geothermal area was measured **65.7 kg m^{-3}**. The highest values are measured in the Krafla geothermal area (considered to have been active for the longest) on average **73.1 kg m^{-3}** in the uppermost 1500 m **[2].**

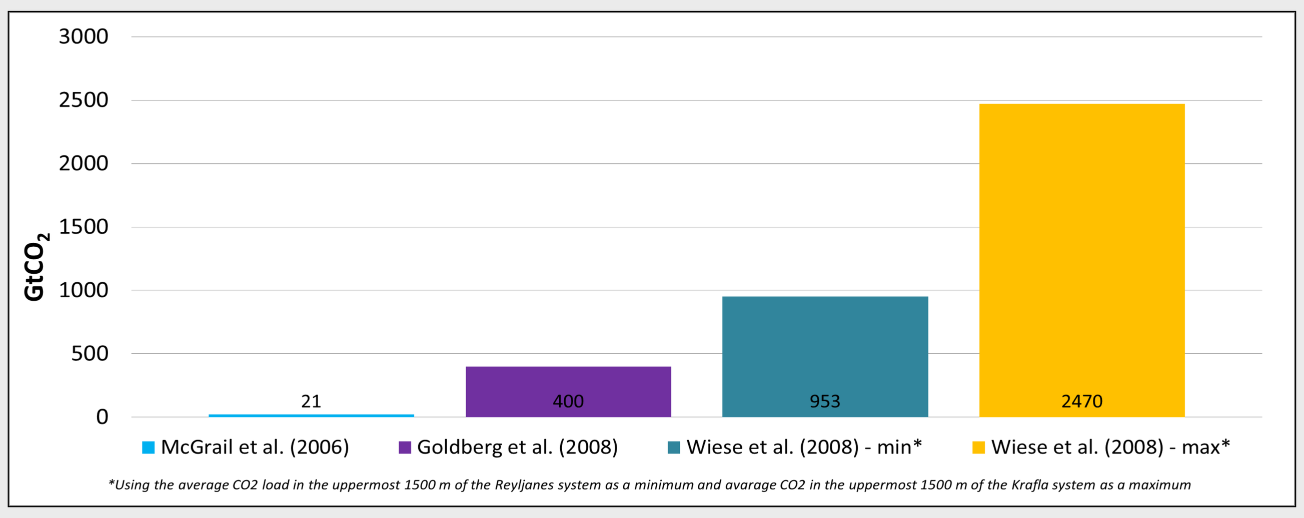


Figure 3. *Theoretical mineral storage potential ($GtCO_2$) of basaltic rocks within the rift zone (34.000 km²) using methods from McGrail* ***[3]****, Goldberg* ***[5]*** *and Wiese* ***[2]****.*

Storage capacity

The amount of CO_2 fixed in the bedrock of the three geothermal systems obtained from Wiese's study **[2]** can be used as a guideline for the theoretical potential of CO_2 storage in relatively young basaltic formations.
By using the average CO_2 load in the uppermost 1500 m of the Reykjanes system as a minimum of the Krafla system as a maximum and applying these to a 1000 m thick segment of the relatively fresh basaltic formations within the rift zone of Iceland yields **953 $GtCO_2$** as a minimum mineral storage potential and **2.470 $GtCO_2$** as a maximum. **(fig. 3)**
This scenario is highly theoretical but underscores the enormous mineral storage potential within the rift zone of Iceland where the basaltic rocks are young and still porous and normal faults are common.

Other estimations

Other attempts have been made to estimate the capacity for mineral storage of CO_2 (table 2). **McGrail et al. [3]** estimated that the Colombia River basalts alone have the capacity to store over 100 Gt of CO_2, 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. **[4]** applied McGrail's assumptions to the bedrock of Iceland, giving an estimated capacity of about 60 Gt CO_2. Using the same assumption for active rift zone in Iceland the number goes down to about **21 $GtCO_2$**.

Furthermore, **Goldberg et al. [5, 6]** 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 km² of highly permeable basalt feasible for mineral storage. Given an average channel porosity of 10%, 780 km³ of potential pore volume will be available for CO_2 storage. Anthonsen et al. **[4]** also applied Goldberg et al.'s **[5]** calculations to the bedrock of Iceland, resulting in an enormous number of about 1,200 $GtCO_2$. If these calculations are limited to the bedrock of the active rift zone in Iceland over **400 $GtCO_2$** could be stored.

Iceland and the oceanic ridges

There is a high potential for mineral storage of CO_2 in Icelandic basalts and large amounts of CO_2 are already naturally fixed within the geothermal systems. Wiese et al. **[2]** estimates that the total CO_2 fixed within the active geothermal systems in Iceland amounts to 30-40 $GtCO_2$. This is equal to the anthropogenic global annual emission of CO_2 to the atmosphere in 2012.
The large potential for mineral storage of CO_2 in Icelandic basalts remains theoretical until more experience is gained by up-scaling of ongoing demonstration projects *(e.g. Gislason and Oelkers, 2014).*
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. The ridges extend through all of the major ocean basins, with a total length in excess of 60,000 km.
The theoretical mineral CO_2 storage capacity of the ocean ridges, using the Icelandic analogue, is of the order of **100,000–250,000 $GtCO_2$**. This theoretical storage capacity is significantly larger than the estimated 18,500 $GtCO_2$ stemming from burning of all fossil fuel carbon on Earth **[7]**.

The question remains; how much of this storage potential is practical to use?

Atlantic Ocean Floor map from Heezen and Tharp (1968), painted by Berann for the National Geographic Magazine

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