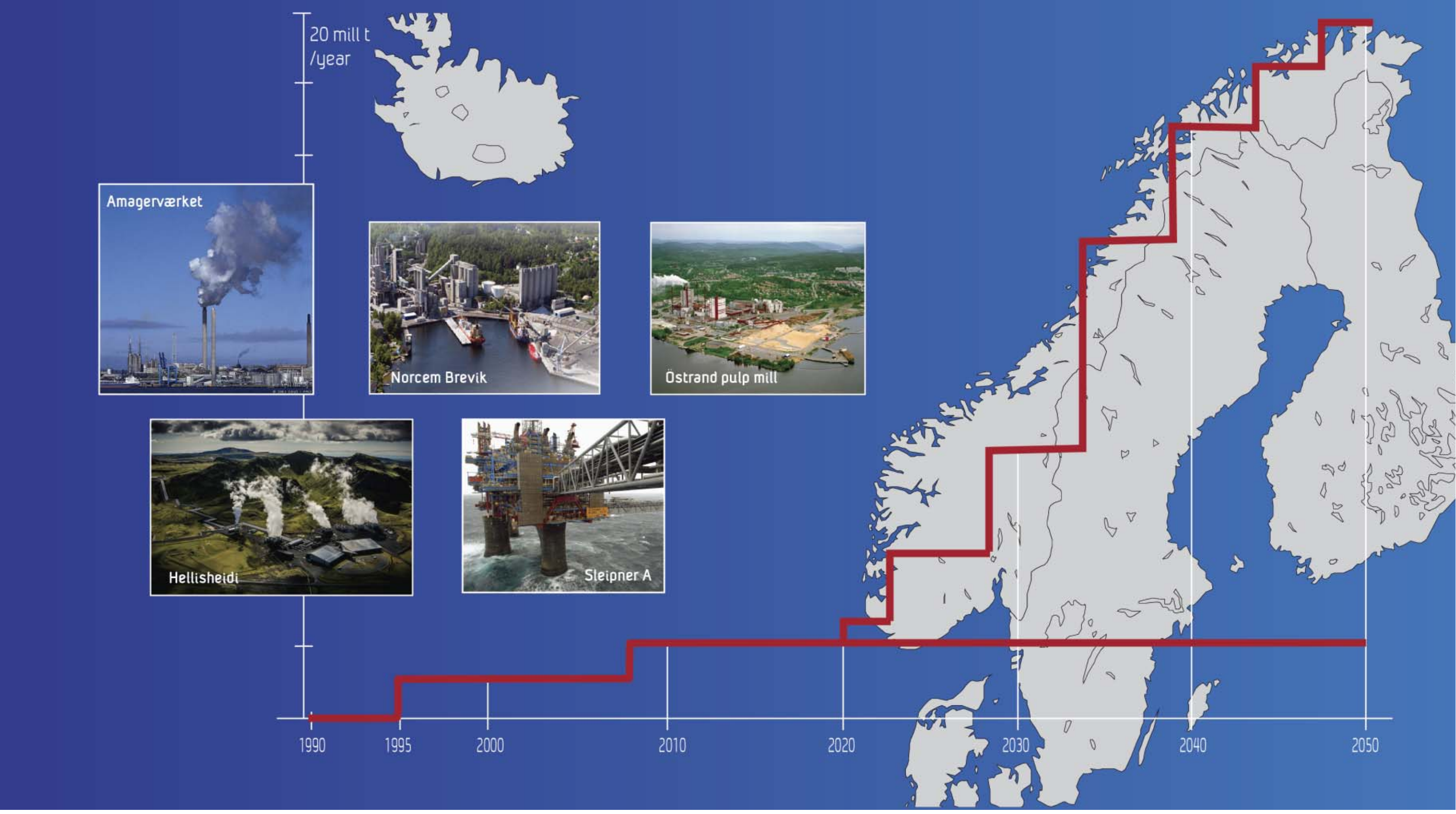

Capacity for mineral storage of CO_2 in basalt

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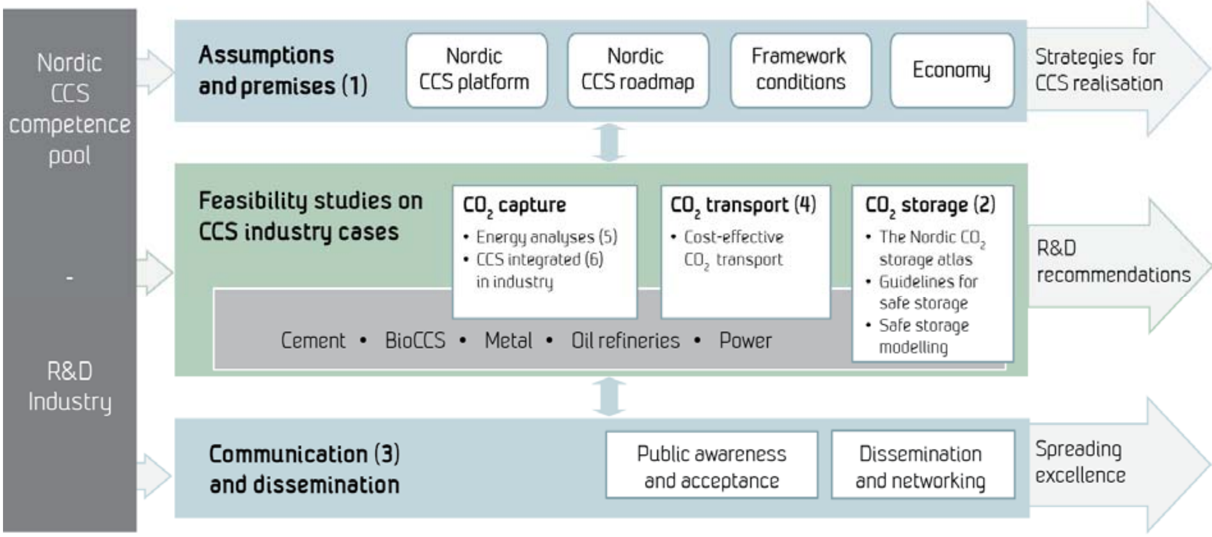

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Summary

Mineral storage of CO_2 in basaltic rocks offers the potential for long-term, safe CO_2 storage. Studies on mineral storage of CO_2 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; the systems receive considerable amounts of CO_2 from magma chambers or intrusions in the roots of the systems and can therefore be considered as a natural experiment to determine the CO_2 storage capacity of the bedrock. 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. *(2008)* estimates that the total CO_2 fixed within the active geothermal high-temperature 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 potential capacity for mineral storage of CO_2 in Icelandic basalts remains theoretical until more experience is gained by up-scaling of ongoing demonstration

Keywords Mineral storage, geothermal, basalts, storage capacity.

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About NORDICCS

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Activity 6.3.3: Capacity for mineral storage of CO_2 on land in Iceland

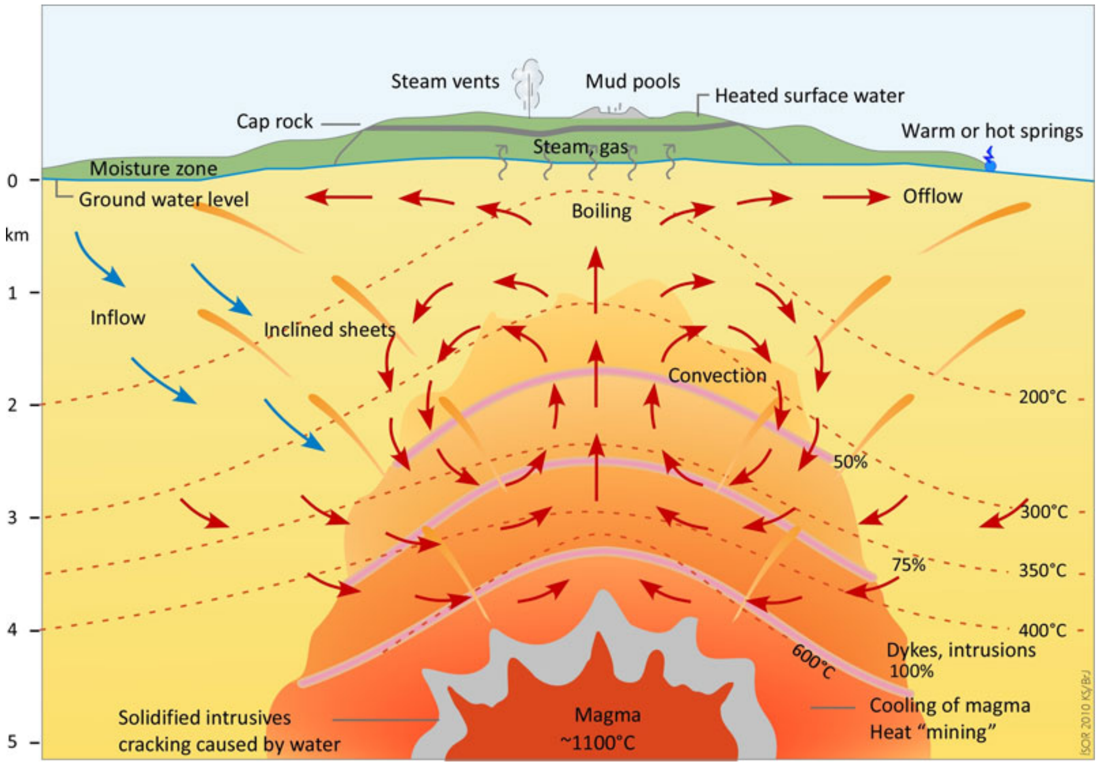

Fig 1. *Geothermal field; conceptual model from Sæmundsson and Jónsdóttir (2010).*

Mineral storage of carbon dioxide (CO_2) in basaltic rocks offers the potential for long-term, safe CO_2 storage. Basaltic rocks are rich in divalent cations, Ca^{2+}, Mg^{2+} and Fe^{2+}, which react with CO_2 dissolved in water to form stable carbonate minerals such as Calcite ($CaCO_3$), Magnesite ($MgCO_3$) and Siderite ($FeCO_3$) *(Oelkers et al., 2008; Gislason et al., 2010).* About 90% of the bedrock in Iceland is basalt *(Jóhannesson and Sæmundsson, 1998).*

Studies on mineral storage of CO_2 are still at an early stage *(e.g. Alfredsson et al. 2013; Aradóttir et al., 2012).* 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; the systems receive considerable amounts of CO_2 from magma chambers or intrusions in the roots of the systems (Fig. 1) and can therefore be considered as a natural experiment to determine the CO_2 storage capacity of the bedrock *(Wiese et al., 2008).*

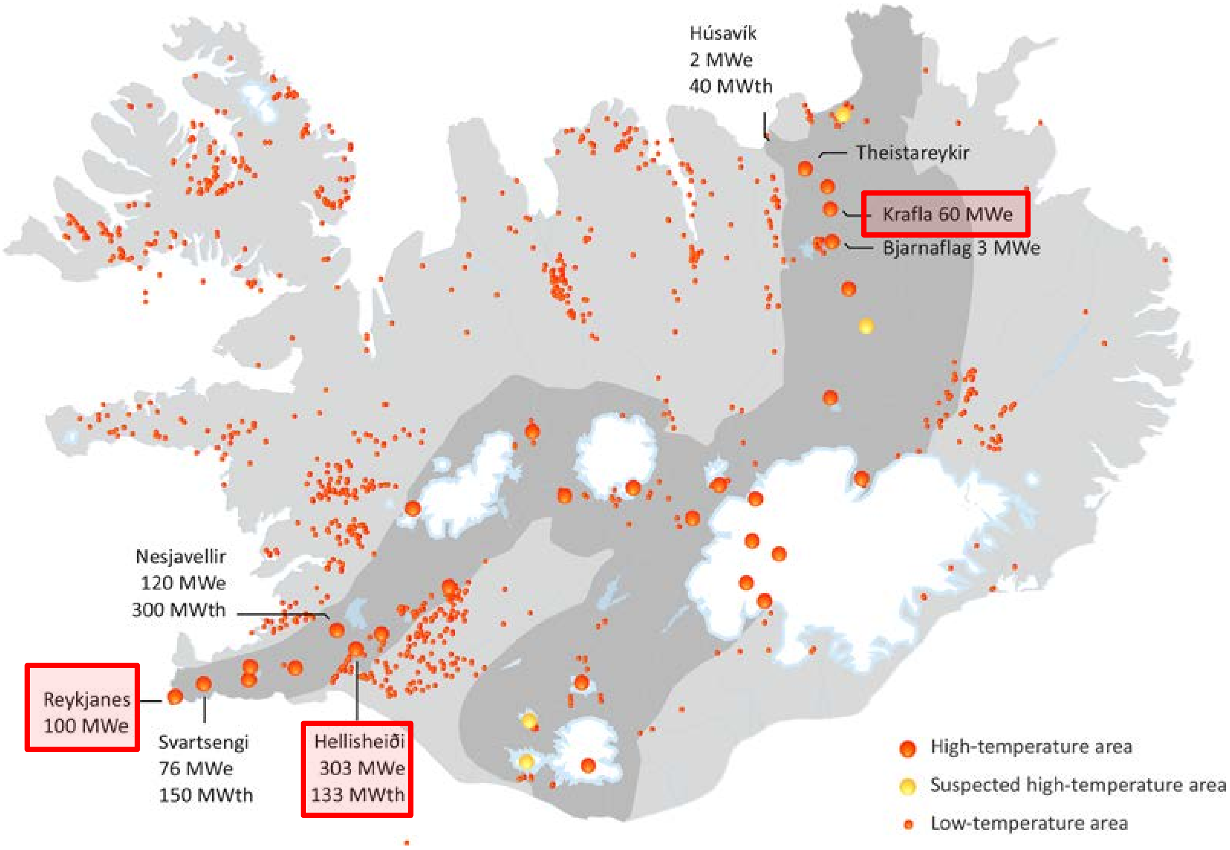

Fig. 2 *Geothermal map of Iceland (ÍSOR, 2013). High-temperature geothermal areas of concern in Wiese's study are marked with a red box as well as the present energy harnessed from the field in megawatts electricity production (MWe) and megawatts thermal water production (MWth).*

Wiese et al. *(2008)* quantified the amount and spatial distribution of CO_2 stored in calcite ($CaCO_3$) 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 2). The CO_2 content was measured in 642 drill cutting samples from a total of 40 wells, located in the three geothermal areas. The results are presented as kg of CO_2 per m^3 rock (Table 1).

The values measured in the Reykjanes geothermal area were significantly lower than elsewhere in this study, on average 28.2 kg m^{-3} of CO_2 fixed in the uppermost 1500 m of the wells. The Reykjanes system is considered to be the youngest of the three geothermal areas, having been active for between 10,000 and 100,000 years *(Wiese et al., 2008)*. The average CO_2 load in the uppermost 1500 m in Hellisheiði geothermal area was measured 65.7 kg m^{-3}, with estimated age between 70,000 and 400,000 years *(Franzson et al. 2005)*. 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 *(Wiese et al., 2008)*, on average 73.1 kg m^{-3} in the uppermost 1500 m.

The values of CO_2 fixed in the bedrock of the three geothermal systems obtained from this study can be used as a guideline for the theoretical potential of CO_2 storage in onshore basaltic formations in Iceland.

Table 1 CO_2 load (kg m^{-3}) in the uppermost 1500 m of production wells in Reykjanes, Hellisheiði and Krafla geothermal fields (from Wiese et al., 2008).

Reykjanes Well id	CO_2 load (t/m^2)	Hellisheidi Well id	CO_2 load (t/m^2)	Krafla Well id	CO_2 load (t/m^2)
RN - 10	42.5	HE - 03	70.1	KJ – 16	72.9
RN - 11	36.0	HE - 04	48.9	KJ – 21	37.4
RN - 12	16.7	HE - 05	72.9	KJ – 23	60.5
RN - 13	44.4	HE - 08	73.5	KG – 25	92.3
RN - 14	15.4	HE - 09	53.2	KG – 26	73.3
RN - 15	20.1	HE - 10	51.5	KJ – 28	81.9
RN - 16	19.0	HE - 11	103.4	KJ – 29	82.3
RN - 17	41.7	HE - 13	60.0	KJ – 30	59.2
RN - 18	28.3	HE - 14	71.7	KJ – 32	89.0
RN - 19	32.6	HE - 16	61.4	KJ – 34	82.0
RN - 20	24.6	HE - 17	93.4		
RN - 21	15.3	HE - 18	53.6		
RN - 22	36.6	KHG - 01	100.9		
RN - 24	22.1	HE - 21	5.0		
Reykjanes average	**28.2**	**Hellisheidi average**	**65.7**	**Krafla average**	**73.1**

Theoretically, since about 90 % of Icelandic bedrock is basalt, much of Iceland could be used for mineral sequestration of CO_2 *(e.g. Gislason et al. 2010)*. The most feasible storage sites are the youngest basaltic formations in the active rift zone, since their porosity has not been as affected by secondary mineralisation as in the older formations *(e.g. Neuhoff et al., 1999*). These formations consist of basaltic lavas, hyaloclastic formations and associated sediments younger than 0.8 M yr., from upper Pleistocene and Holocene, covering about 34,000 km^2 of Iceland (Fig 3).

Observations of hydrothermally altered basaltic rocks show that calcite is not expected to form at temperatures above 290°C *(Franzson, 1998)*. Wiese et al. *(2008)* and Tómasson and Kristmannsdóttir *(1972)* report a very similar overall pattern of calcite distribution in geothermal systems in Iceland with increasing abundance of calcite with depth to a maximum at about 200-400 m depth. Below that a gradual decrease in calcite is noted and below about 800-1000 m depth very little calcite is present.

By using the average CO_2 load in the uppermost 1500 m of the Reykjanes system as a minimum and the average CO_2 load in the uppermost 1500 m 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 we get a gigantic value of 2,470 Gt of CO_2 as a maximum and 953 Gt as a minimum. This scenario is highly theoretical but underscores the enormous 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 CO_2. McGrail et al. *(2006)* 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. *(2013)* applied McGrail's assumptions to the bedrock of Iceland, giving an estimated capacity of about 60 Gt CO_2. Using the same assumption to calculate the potential capacity of mineral storage of CO_2 within the active rift zone in Iceland the number goes down to about 21 Gt CO_2.

Furthermore, Goldberg et al. *(2008, 2010)* revealed the large storage capacity of sub-oceanic basalt formations at the Juan De Fuca plate east of Oregon, USA. The geologically feasible area at suitable depth for mineral storage of CO_2 is calculated to be about 78,000 km^2. Assuming a channel system dominating permeability over one-sixth of the uppermost 600 m of the area, it is estimated to contain 7800 km^2 of highly permeable basalt. Given an average channel porosity of 10%, 780 km^3 of potential pore volume will be available for CO_2 storage. Anthonsen et al. *(2013)* also applied Goldberg et al. *(2008)* 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 Gt CO_2 could be stored.

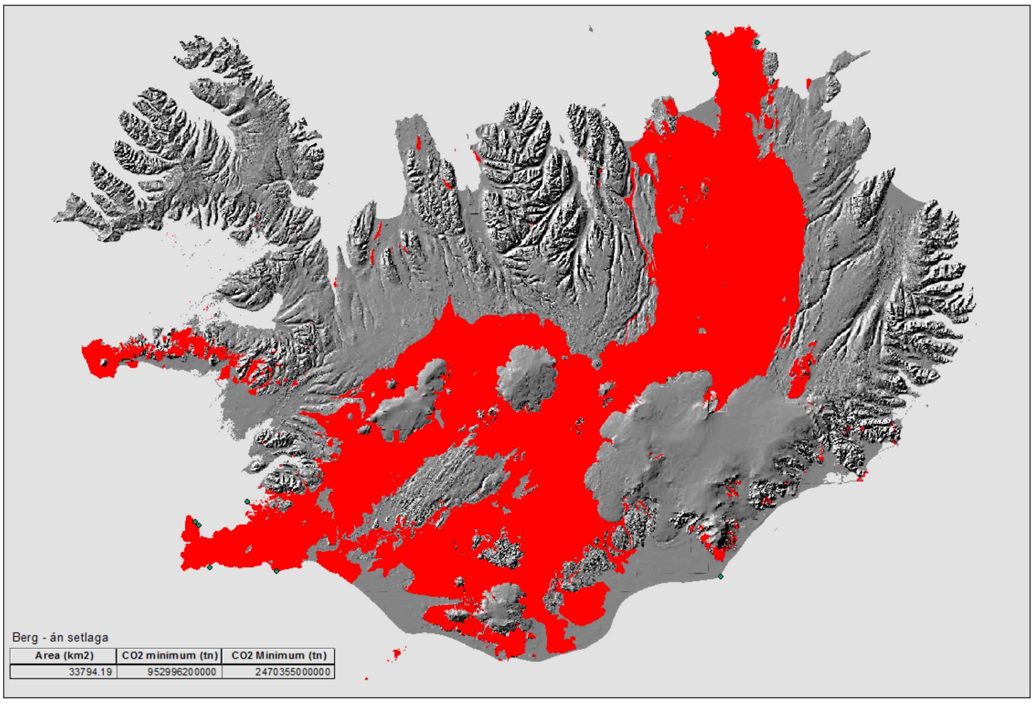

Fig 3. *Theoretical area feasible for CO2 mineral storage in Iceland; Basaltic formations from Holocene and upper Pleistocene, younger than 0.8 M yr.*

Since studies on mineral storage of CO_2 are still at an early stage all values obtained by different approaches to the subject are theoretical.

To get a more realistic value of the capacity for mineral storage in Icelandic basalt formations, transportation of CO_2 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 of the rift zone was selected.

The formations included were, as in the previous scenario, basaltic lavas, hyaloclastic formations and associated sediments from upper Pleistocene and postglacial lavas. 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. National parks, natural monuments, nature reserves and country parks were excluded from the area. The area that fits the criteria is about 3700 km^2, close to 3% of Iceland (Fig 4).

Using the results from Wiese et al. *(2008)* as done in the previous example and applying the average CO_2 load in the uppermost 1500 m of the Reykjanes system as a minimum and the average CO_2 load in the uppermost 1500 m of the Krafla system as a maximum and to a 1000 m thick segment of the defined area generates a maximum capacity of 272 Gt CO_2 and minimum of 105 Gt CO_2 . For comparison, in 2012 the global CO_2 emissions to the atmosphere were 35.6 Gt from fossil fuel burning and cement production. *(The Global Carbon Project, 2013).*

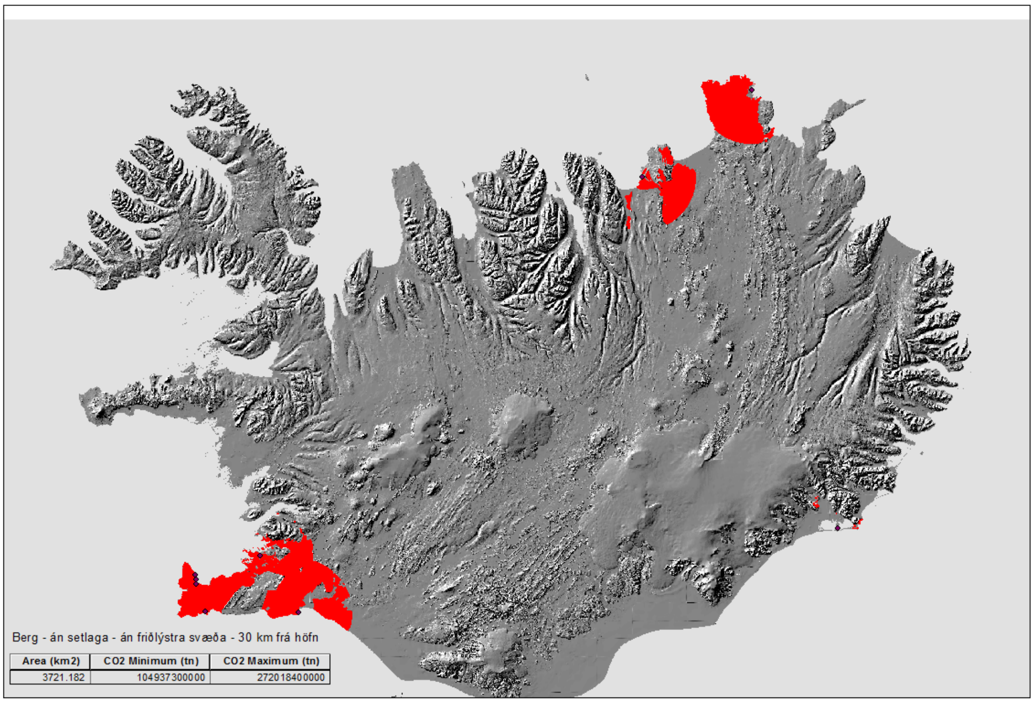

Fig 4. Theoretical area feasible for CO2 mineral storage in Iceland; Basaltic formations from Holocene and upper Pleistocene in the vicinity (radius of 30 km) of a large-scale harbor.

Applying the study of McGrail et al. *(2006)* and assuming an interflow thickness of 10 m, average porosity of 15% and 10 available interflow zones at an average hydrostatic pressure of 100 atm, the estimated capacity of the defined area goes down to about 2 $GtCO_2$.
Using the study of Goldberg et al. *(2008)* 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 45 $GtCO_2$.

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. *(2008)* estimates that the total CO_2 fixed within the active geothermal high-temperature 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 Global Carbon Project, 2013).* The potential capacity for mineral storage of CO_2 in Icelandic basalts remains theoretical until more experience is gained by up-scaling of ongoing demonstration projects *(Gislason et al. 2010).*

Table 2. Summary of the potential for mineral storage of CO_2 using methods from Wiese et al. *(2008)*, McGrail et al. *(2006)* and Goldberg et al. *(2008)* for estimation.

	Basaltic rocks within in the active rift zone, younger than 0.8 M yr. (34.000 km^2)	**Basaltic rocks in 30 km radius of seven of the largest harbors in Iceland (3.700 km^2)**
	$GtCO_2$	**$GtCO_2$**
Wiese et al. *(2008)*	953-2470*	105-272*
McGrail et al. *(2006)*	21	2
Goldberg et al. *(2008)*	400	45

*Using CO_2 load in the uppermost 1500 m of the Reykjanes system as a minimum and the average CO_2 load in the uppermost 1500 m of the Krafla system as a maximum

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