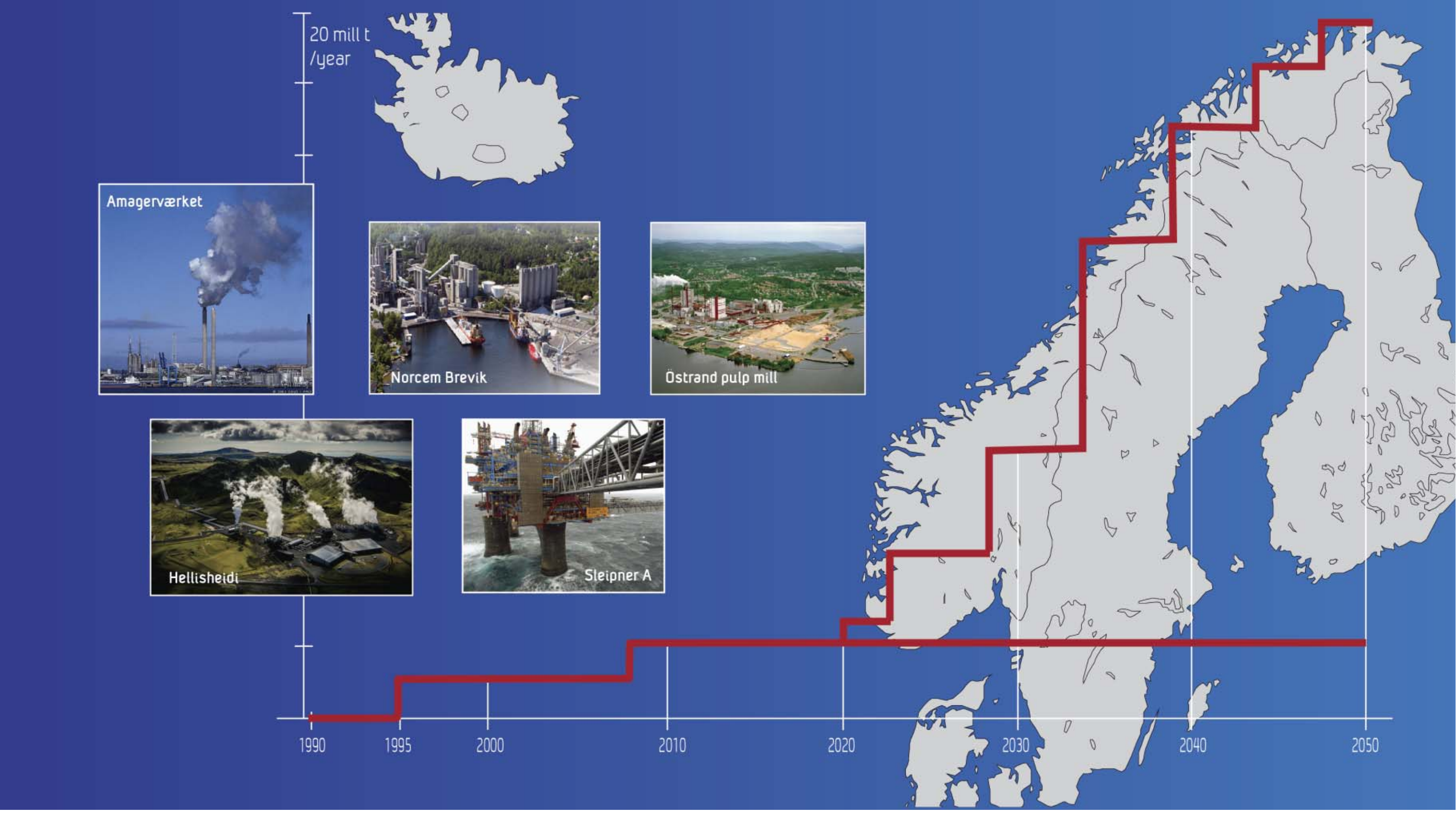

Screening of basalt formations onshore Iceland

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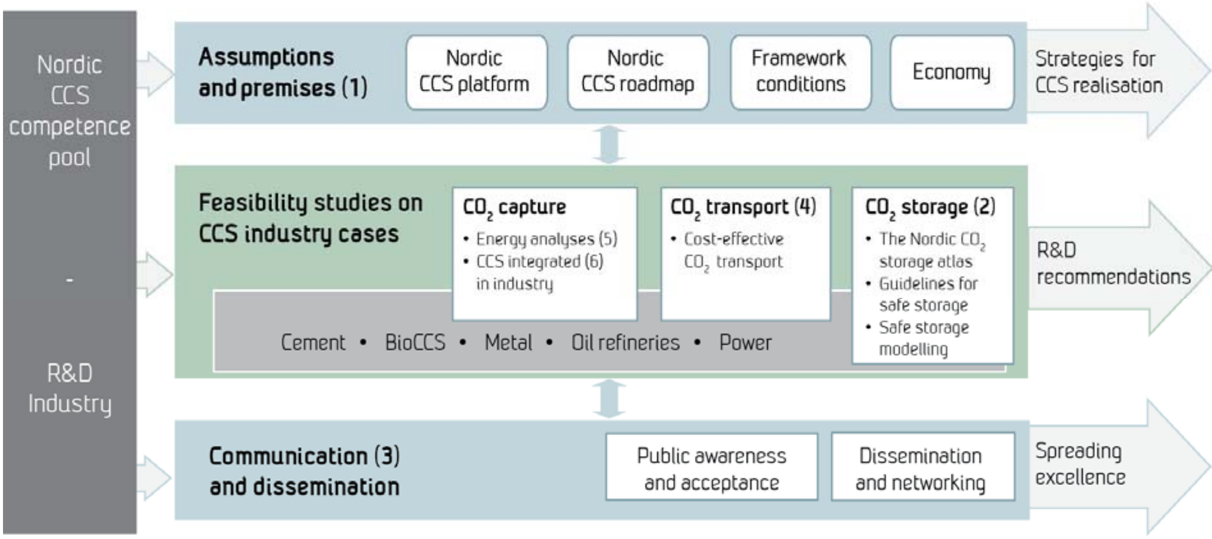

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Summary

Iceland is 103,000 km2, mostly made of young 0-20 M yr. igneous rocks and sediments thereof. National Energy Authority and later Iceland GeoSurvey have since 1992 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. Studies on permeability and porosity show that generally porosity and permeability decrease along with progressive alteration, gradual burial and increasing age since most of the pore space in the older rocks is filled with secondary minerals. Thus, the youngest basaltic formations in the active rift zone are the most feasible for carbon storage onshore in Iceland. Since CO2 emissions in Iceland are considerably low compared to the vast potential storage capacity, potentially CO2 could be shipped to Iceland and transported via pipeline to suitable storage areas.

Keywords Basaltic rocks, porosity, permeability, secondary minerals, geothermal gradient, rift zone, CO_2 storage.

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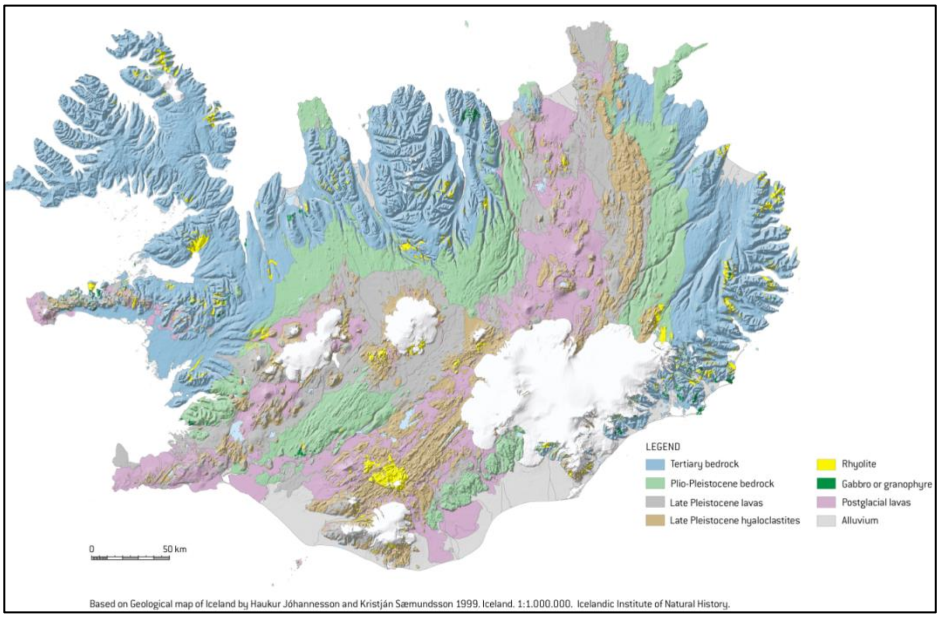

Fig 1. *Geological map of Iceland (Jóhannesson and Sæmundsson, 1998)*

Iceland is one of the most active and productive sub-areal volcanic regions on Earth, with magma output rates of >5 km^3 per century. The Iceland Basalt plateau rises more than 3000 m above the surrounding sea floor and covers about 350,000 km^2 *(Thordarson and Höskuldsson, 2008)*. Iceland is 103,000 km^2, mostly made of young 0-20 M yr. igneous rocks and sediments thereof.

Approximately 90% of the bedrock in Iceland is basalt *(Jóhannesson and Sæmundsson, 1998)* indicating that theoretically much of Iceland could be used for injecting CO_2, fully dissolved in water, into basaltic rocks (Fig 1). Basaltic rocks are rich in divalent cations (Ca^{2+}, Mg^{2+} and Fe^{2+}). These ions can react with dissolved CO_2 to precipitate carbonate minerals such as Calcite, Dolomite, Magnesite and Siderite for in situ mineral storage of CO_2 *(Oelkers et al., 2008; Gislason et al., 2010).*

National Energy Authority and later Iceland GeoSurvey have since 1992 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. Franzson et al., 2010; Frolova et al., 2004; Stefánsson et al., 1997).*

Studies on permeability and porosity show that generally porosity and permeability decrease along with progressive alteration, gradual burial and increasing age since most of the pore space in the older rocks is filled with secondary minerals *(e.g. Frolova et al. 2004; Neuhoff et al., 1999).* Thus, the youngest basaltic formations in the active rift zone are the most feasible for carbon storage onshore in Iceland. The uppermost ± 1000 m are made of highly porous and permeable basaltic lavas and hyaloclastitic (glassy) formations with heavy flow of groundwater *(Flóvenz and Saemundsson, 1993).*

These formations are younger than 0.8 M yr., from upper Pleistocene and Holocene, and cover about 34,000 km^2, which is about one third of Iceland (Fig 2).

In order to define the petro-physical properties of basaltic lavas, Stefánsson et al. *(1997)* collected 162 samples of fine to coarse grained basaltic lavas, basalt scoria and porphyritic lavas. As stated before, alteration and formation of secondary minerals has a large effect on both porosity and permeability since the molar volume of secondary minerals is larger than the molar volume of primary minerals and some secondary minerals contain water and CO_2. 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 27.81% 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.

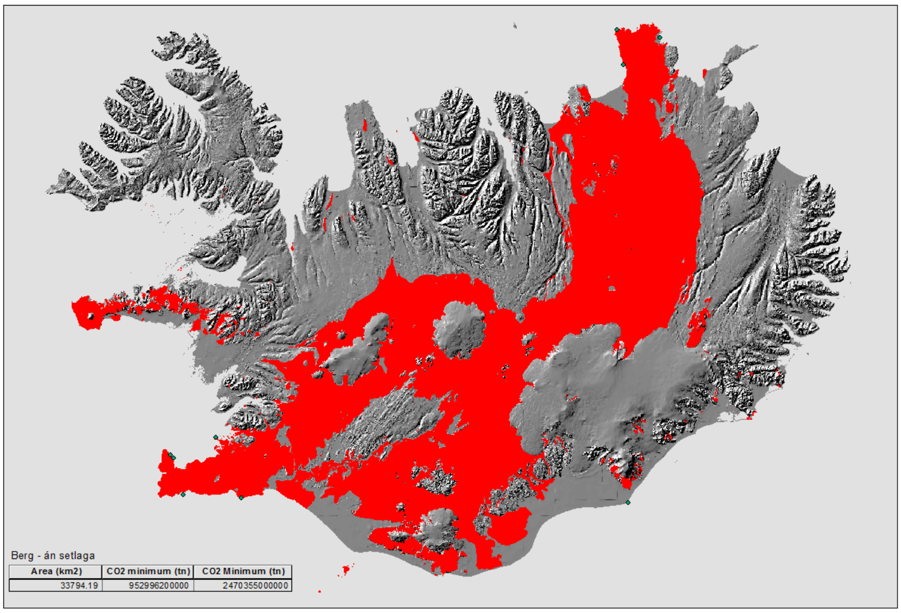

Fig 2. *Theoretical area feasible for CO_2 mineral storage in Iceland: Basaltic formations younger than 0.8 M yr.*

Hyaloclastites are clastic, glassy rocks formed dominantly in subglacial phreatic eruptions. Hyaloclastic formations are extremely heterogeneous by their porosity and permeability. 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 $1*10^{-3}$ mD to $6,4*10^{3}$ 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.

The lower boundary for mineral storage of carbon is dictated by the thermal gradient and the stability of carbonates such as calcite rather than availability of basaltic rocks. Observations of hydrothermally altered basaltic rocks show that calcite is not expected to form at temperatures above 290°C *(Franzson, 1998)*. This is in a good agreement with thermodynamic data *(e.g. Skippen, 1981)*.

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 this a gradual decrease in the abundance of calcite is noted and below about 800-1000 m depth very little calcite is present.

Technically, mineral storage of carbon could be executed at depths greater than 1000 m in basaltic rocks outside the geothermal areas where calcite remains stable to greater depths. Geothermal areas typically have a thermal gradient above 200°C/km compared to 50 to 150°C/km in dense and permeable rocks outside of them. In the fresh and porous basaltic lavas within the rift zone the heat is mainly transported by convection and therefore a very low temperature gradient is observed *(Flóvenz and Saemundsson, 1993)*. Defining the lower boundary for mineral storage of carbon at 1000 m depth allows inclusion of the areas with the highest thermal gradient, giving a rather conservative estimate of the storage potential. Considering the availability of basaltic rocks and the additional costs in going deeper, that possibility is not included in this evaluation.

As stated before, the youngest basaltic rocks, situated within the active rift zone, cover about 34,000 km^2. National parks, natural monuments, nature reserves and country parks cover in total 16,860 km^2 of area in Iceland *(Statistics Iceland, 2013)*. By excluding these protected areas from previous criteria the total area is reduced to about 26,000 km^2 (Fig 3).

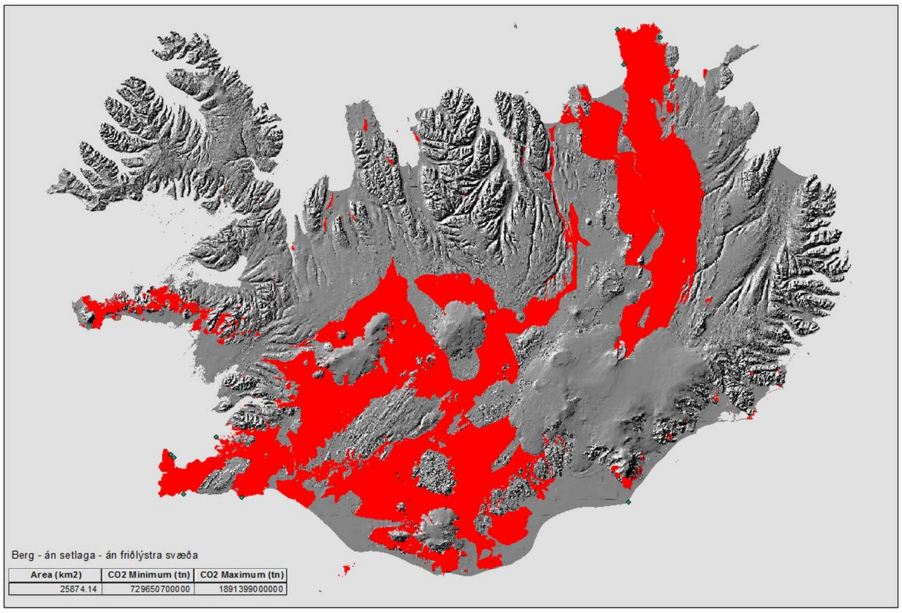

Fig 3. *Theoretical area feasible for CO_2 mineral storage in Iceland: Basaltic formations younger than 0.8 M yr., excluding protected areas in Iceland.*

Iceland's primary energy supply is 85% renewable energy from hydro and geothermal sources. Close to 100% of its electricity is generated from renewables, 75% of which is hydropower and the rest geothermal. Hot water and heat for an extensive district heat system is mainly harnessed from geothermal fields

In 2010 the total annual CO_2 emission was 4.5 Mt; 41% from the energy sector (fossil fuel combustion 37% and geothermal energy 4%) and 40% from industrial processes. The metal industry, aluminium production (1.2 Mt CO_2 from three smelters) and ferroalloy production (0.23 Mt CO_2 from one smelter), was the source of 85% of the emission from industrial processes in the year 2010. Iceland's goal is a 50-70% reduction in GHG by 2050 compared to 1990 *(Hallsdóttir et al, 2012)*.

Since CO_2 emissions in Iceland are considerably low compared to the vast potential storage capacity, potentially CO_2 could be shipped to Iceland and transported via pipeline to suitable storage areas. Several large-scale harbours are located in the coastal area of the active rift zone; three in the north-east (Húsavík, Kópasker, Raufarhöfn), one in the south-east (Höfn í Hornafirði) and four in the south-west (Reykjavík, Reykjaneshafnir, Grindavík, and Þorlákshöfn). In addition, constructions are ongoing for an industrial harbour in Helguvík in southwest of Iceland.

To get a more realistic or pragmatic estimate of onshore basaltic formations feasible for CO_2 storage in Iceland, basaltic formations younger than 0.8 M yr. situated within 30 km radius of the above mentioned harbours were selected. As before protected areas were excluded. For the 30 km radius the Nesjavellir hot water transmission main, a 30 km long pipeline from Nesjavellir to Reykjavík, was taken into consideration for potential transportation of CO_2 via pipeline. The area that fits these criteria is about 3700 km^2 (Fig 4).

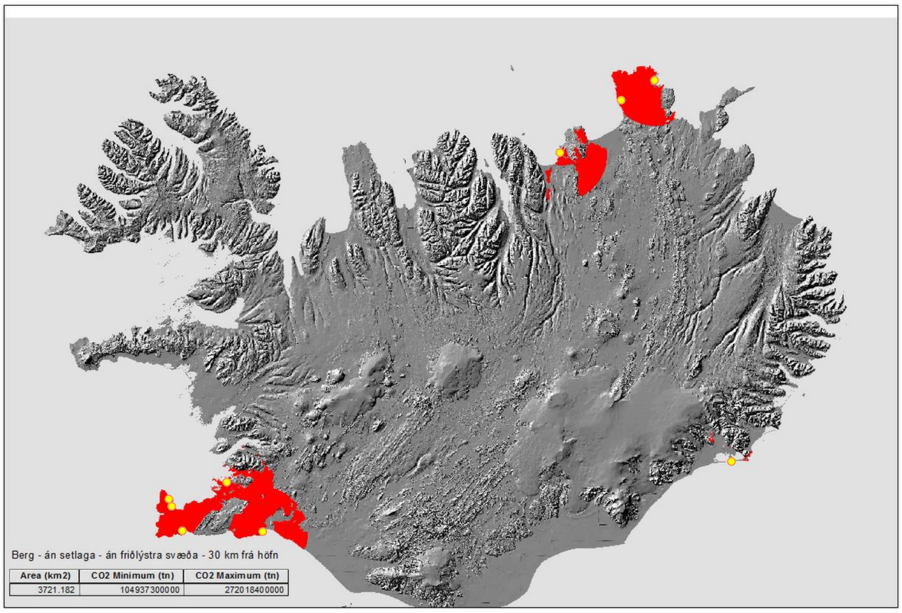

Fig 4. *Theoretical area feasible for CO2 mineral storage in Iceland: Basaltic formations younger than 0.8 M yr. within a 30 km radius of a large-scale harbor (marked with yellow dots).*

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