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Assessing the carbon sequestration potential of basalt using X-ray micro-CT and rock mechanics

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A R T I C L E I N F O

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A B S T R A C T

Mineral carbonation in basaltic rock provides a permanent storage solution for the mitigation of anthropogenic CO_2 emissions in the atmosphere. 3D X-ray micro-CT (XCT) image analysis is applied to a core sample from the main basaltic reservoir of the CarbFix site in Iceland, which obtained a connected porosity of 2.05–8.76%, a reactive surface area of 0.10–0.33ömm^{-1} and a larger vertical permeability (2.07ö×ö10^{-10}öm^2) compared to horizontal permeability (5.10ö×ö10^{-11}öm^2). The calculations suggest a CO_2 storage capacity of 0.33 Gigatonnes at the CarbFix pilot site. The XCT results were compared to those obtained from a hydromechanical test applied to the same sample, during which permeability, electrical resistivity and volumetric deformation were measured under realistic reservoir pressure conditions. It was found that permeability is highly stress sensitive, dropping by two orders of magnitude for a −0.02% volumetric deformation change, equivalent to a mean pore diameter reduction of 5öμm. This pore contraction was insufficient to explain such a permeability reduction according to the XCT analysis, unless combined with the effects of clay swelling and secondary mineral pore clogging. The findings provide important benchmark data for the future upscaling and optimisation of CO_2 storage in basalt formations.

1. Introduction

Mineralisation of CO_2 in basaltic rock formations may provide an effective method of CO_2 sequestration (CCS) (Oelkers et al., 2008; Gislason et al., 2010; Matter et al., 2016), mitigating increased anthropogenic CO_2 emissions in the atmosphere. Basalt has enormous CO_2 storage potential, comprising ∼60% of the Earth's surface, and storage capacities of ∼13,800 to 127,800 Gt of CO_2 have been estimated in deep-sea basalt reservoirs (Gislason et al., 2010; Marieni et al., 2013). CCS in basalt encourages mineral trapping, also referred to as in situ carbonation, providing a permanent storage solution (Sigfusson et al., 2015). Compared to CCS in basalts, conventional CCS in sedimentary rock (e.g. sandstones) requires extensive monitoring and high cap rock integrity, which can degrade over time due to CO_2-fluid-rock interactions (Gaus, 2010).

The CarbFix project at the Hellisheidi geothermal power plant in Iceland is an onshore example of a pilot study in which the mineral carbonation of CO_2 potential of basaltic rocks is investigated (Fig. 1). 40,000 t of CO_2 per year is currently produced by Hellisheidi geothermal power plant (Sigfusson et al., 2015). In addition, Iceland is composed of ∼90% basaltic rocks, providing the ideal location for the pilot study (Hjartarson and Sæmundsson, 2014; Snæbjörnsdóttir et al., 2014). The target formation is composed of basalt lavas with an olivine tholeiite composition, ranging in age from 500,000 to 125,000 years before present, with a low degree of secondary alteration (Alfredsson et al., 2013).

In January 2012, 230 t of CO_2 was coinjected with 7000 t of H_2O into injection well HN-02 (Matter et al., 2016). To allow distinction between native carbon in the basalt reservoir and injected CO_2, Carbon-14 (^{14}C) in the form $NaH^{14}CO_3^-$, in addition to non-reactive SF6 and SF5CF3 tracers, were coinjected with the injected CO_2 (Matter et al., 2013). Proximal to the injection site, the injected CO_2 and H_2O react to form carbonic acid. The dissolution of secondary mineral phases, primary host rock minerals and basaltic glass occurs due to the flow of low pH injection waters. Secondary carbonates are expected to precipitate further from the injection site as reactions ((1) and (2)) proceed to the right (Alfredsson et al., 2013):

$$CO_2 + H_2O = H_2CO_3 \quad (1)$$

$$(Fe, Ca, Mg)^{2+} + H_2CO_3 = (Fe, Ca, Mg)CO_3 + 2H^+ \quad (2)$$

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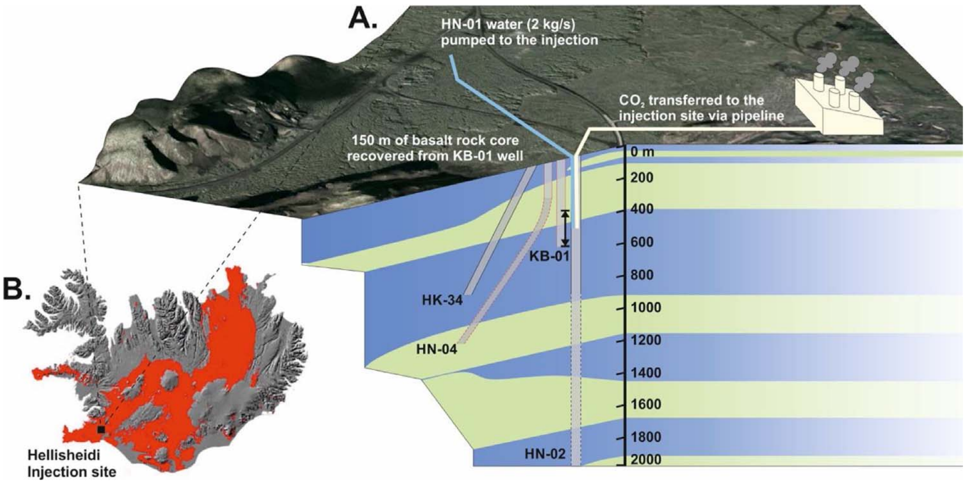

Fig. 1. (A) geological cross section of the Hellisheidi injection site, showing the location of drill core KB-01. Blue represents basalt rock and green represents hyaloclastite formations. 150 m of core section have been taken from the basalt CO_2 storage formation. The drill core is located between injection well HN-02 and monitoring well HN-04, which are 10 m apart at the surface. The figure is modified from Alfredsson et al. (2013). (B) The location of Hellisheidi injection site is shown on a map of Iceland. The area in red highlights basaltic rock formations < 0.8 Myr within the active rift zone. These basalt rock formations are expected to have the greatest reservoir potential due to a low degree of secondary mineralisation and compaction. The figure is modified from Snæbjörnsdóttir et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To characterise storage reservoir parameters subsequent to the injection, 150 m of core KB-01 have been drilled between injection well HN-02 and monitoring well HN-04 (Fig. 1). From geochemical studies using the tracers, > 95% of the injected CO_2 is believed to have mineralised between wells HN-02 and HN-04, within a couple of months of the initial CO_2 injection (Matter et al., 2016).

Up to now there has been a lack of research undertaken to characterise the reservoir properties of basalt. In previous reservoir scale studies by Khalilabad et al. (2008) using a Na-Fluorescein tracer it was found that only 3% of the injected tracer was channelled by a discrete fracture system between HN-02 and HN-04. The remaining injected tracer was interpreted to have flowed through the vesicles (matrix flow), highlighting the importance of understanding matrix flow in the basalt reservoir (Gislason et al., 2010). In this study we characterise the reservoir properties of the target basalt formation at Hellisheidi through the analysis of porosity, reactive surface area, pore network modelling and the permeability of KB-01 core samples using X-Ray micro-CT (computer tomography) and hydromechanic flow-through tests on a laboratory scale. The ultimate aim is to provide a reliable and robust quantification of the CO_2 sequestration potential of the basalt rock reservoir. This is the first ever study to combine analysis of a vesicular pore network of basalt rock using 3D X-ray micro-computed tomography, connected (effective) porosity determinations and reactive surface area values for calculations of CO_2 mineral carbonation. The ultimate aim of this work is to provide a reliable and robust quantification of the CO_2 sequestration potential of basalt rock reservoirs. The study also highlights a number of important issues regarding the potential effect of secondary mineral pore clogging in the presence of high salinity fluids, of great importance since the most suitable basaltic CO_2 storage sites are found offshore (Goldberg and Slagle, 2009).

2. Materials and methods

2.1. X-ray micro-CT analysis

2.1.1. Image acquisition

3D X-ray micro-CT (XCT) scans were conducted using a micro-focus Custom Nikon HMX ST Scanner at the μ-VIS X-Ray Imaging Centre, University of Southampton. The scanner has a 225 kV X-ray source and a 2000 × 2000 pixel flat panel dector (Fig. 2).

Data was acquired using an electron accelerating potential of 200 kV and a tube current of 128 μA. The X-ray beam was filtered using 0.250 mm of tin. 3143 equiangular projections were acquired through 360° with 8 frames per projection taken to reduce noise. 3D reconstruction of the projections was performed using a proprietary filtered back-projection algorithm implemented in CTPro 3D (Nikon Metrology, Tring, UK). The reconstructed 3D data had an isometric voxel size of 0.026 mm.

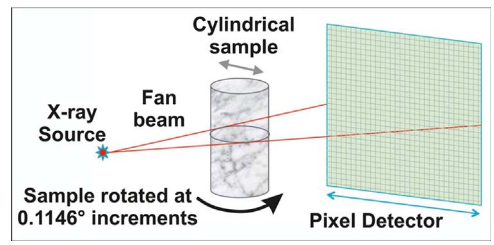

Fig. 2. Diagram of the micro-computer tomography (micro-CT) imaging of the core samples. X-rays propagate through the sample with a fan geometry from the X-ray source and are detected by a 2 × 2000 pixel detector. 2D image slices are reconstructed from projections made at 0.1146° increments, to produce a 3D.

The study was performed using the 436.1–436.4 m depth section of cylindrical basalt core KB-01, measuring 44 mm diameter × 106 mm length (Fig. 3A).

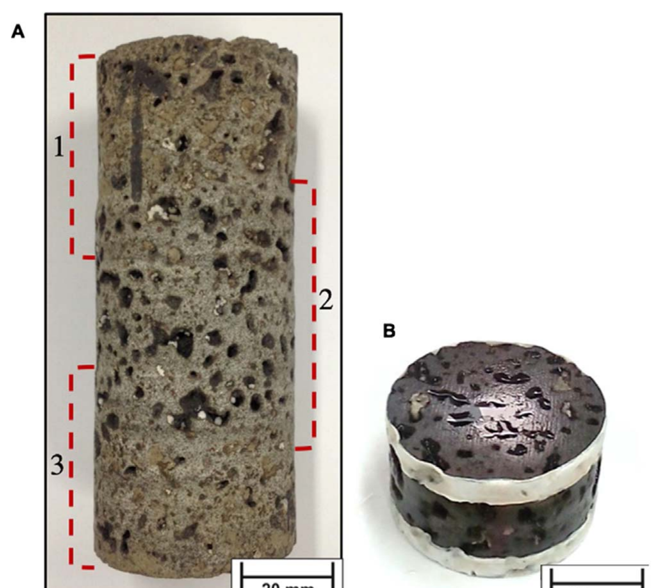

Fig. 3. (A) Original photograph of basalt sample, KB-01, 12-1, 52-81. The dashed red lines (1–3) highlight three 52 mm length, 4.45 cm diameter overlapping sub-regions. During the 3D X-ray micro-CT (XCT) scan the sample was held vertically in place within a plastic container, suspended with polystyrene. (B) For the hydromechanic experiment a 2.63 cm length, 4.45 cm diameter sub-sample was used, most representative of sub-region 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)