

# CO<sub>2</sub> sequestration in basaltic rock at the Hellisheidi site in SW Iceland: stratigraphy and chemical composition of the rocks at the injection site

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## ABSTRACT

Storage of CO<sub>2</sub> as solid Ca, Mg, and Fe carbonates in basaltic rocks may provide a long-lasting solution for reduction of industrial CO<sub>2</sub> emissions. Here, we report on the underground stratigraphy of the chemical composition and crystallinity of rocks and their alteration state at a targeted field site for injection of CO<sub>2</sub>-charged waters, the Hellisheidi area in SW Iceland.

## Introduction

THE reduction of industrial CO<sub>2</sub> emissions is one of the main challenges of this century (Metz *et al.*, 2005; Oelkers and Schott, 2005). Storage of CO<sub>2</sub> as solid calcium carbonate in basaltic rocks may provide a long-lasting, thermodynamically stable and environmentally benign solution (e.g. Matter *et al.*, 2007). In nature, the carbonization of basaltic rocks occurs in a variety of well documented settings, such as the hydrothermal alteration at volcanic hot springs (Barnes and O'Neil, 1969; Arnórsson and Gunnlaugsson, 1985), in deep ocean-vent systems (Kelley *et al.*, 2005) and through surface weathering (e.g. Gislason *et al.*, 2006). Estimates suggest that 30–35% of the present-day CO<sub>2</sub> consumption due to silicate weathering on land may be attributable to basaltic rocks, although they constitute <5% of the overall continental area (Dessert *et al.*, 2003). This underscores the high reactivity of the basaltic rocks compared to other silicates. Recent experimental studies of the dissolution rate of natural silicate glasses and silicate minerals have shown that dissolution rates of both minerals and glasses increase with decreasing silica content, and that

glasses dissolve faster than minerals having the same Al/Si ratio (Wolff-Boenisch *et al.*, 2004; 2006). For example, natural glass of basaltic composition dissolves about ten times faster than glass of rhyolitic composition (Wolff-Boenisch *et al.*, 2004).

The University of Iceland, Reykjavik Energy in Iceland, Columbia University in the USA and CNRS, Toulouse, France co-operate on a research project, Carb-Fix, to optimize methods for storing CO<sub>2</sub> in basaltic rocks. The project consists of field-scale injection of CO<sub>2</sub>-charged waters into basaltic rocks, laboratory-based experiments, large-scale plug-flow experiments, study of natural CO<sub>2</sub> waters as a natural analogue, and state-of-the-art geochemical modelling. The targeted field site for the injection of CO<sub>2</sub>-charged water is the Hellisheidi area in SW Iceland (Fig. 1). The surface rocks are of basaltic composition, both glassy and crystalline. The crystalline lava flows were formed after the last glaciation but glassy ridges, referred to as hyaloclastites (broken glass), were formed under ice during the last glaciation 11,500–110,000 y ago (e.g. Saemundsson, 1980). The magma that formed the hyaloclastite ridges was quenched in the meltwater at the eruption site, forming glass, crystalline rock fragments and pillow lavas (e.g. Schopkaa *et al.*, 2006).

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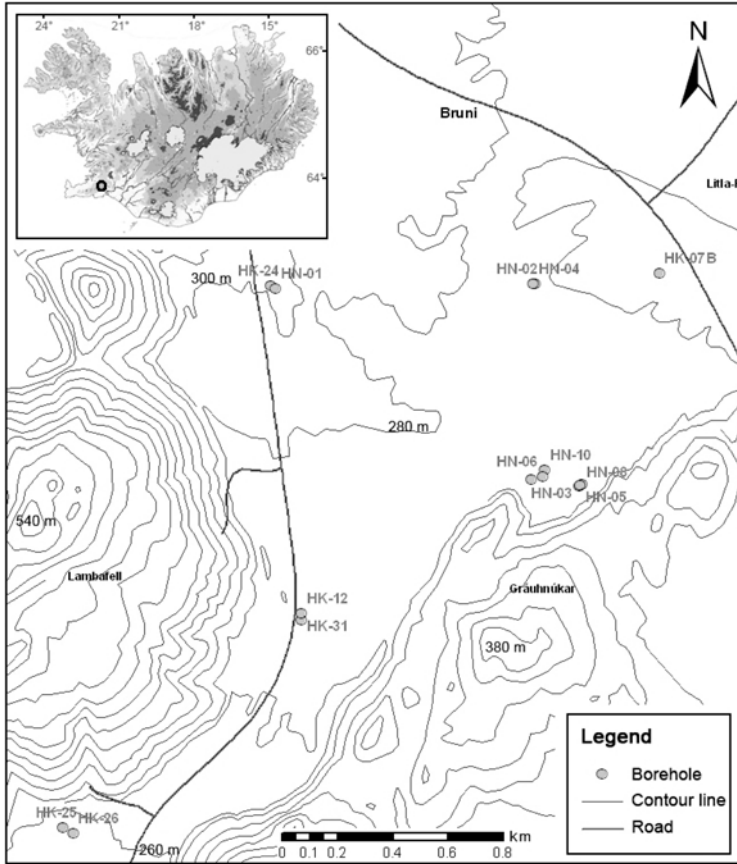


FIG. 1. The Hellisheidi SW Iceland injection site. The CO<sub>2</sub> will be dissolved in water from well HN-1 and injected into well HN-2. Wells HN-4, HK-31 and HK-26 are monitoring wells. Note that well HN-1 is ~1 km west of the injection well HN-2.

The objective of this study is to define the underground stratigraphy at the injection site, the chemical composition of the rocks, their crystallinity and alteration state. These results will be used to define and select the most suitable horizons for CO<sub>2</sub> injection and in assessing the reactivity of the rocks. Furthermore, the chemical composition of the rocks will be used in reactive transport modelling of the system before and after injection.

## Methods

The samples used in this study consist of drill cuttings which were collected at 2 m depth intervals during drilling of the wells at the injection site (Hardarson *et al.*, 2007; Alfredsson *et al.*, 2007). No cores are available. The source-

depth estimate error for the drill cuttings is variable. It is within 1 m at shallow depths, but ~2–5 m at 1000 m depth. Individual drill cuttings were studied at the drill site with a binocular microscope to define the types of primary and secondary minerals, properties such as grain size, rock types such as hyaloclastite, lava, picrite, and olivine tholeiite, etc. Basaltic lava flows tend to form a flat horizontal landscape, whereas hyaloclastite formations form elongated high-standing ridges, e.g. the Lambafell and Gráuhnúkar formations shown in Fig. 1. Stratigraphic interpretation of drill cuttings is clear when lava flows replace hyaloclastite formations, at similar depths, in neighbouring wells. The Hengill volcanic system at the Hellisheidi site is a rather narrow and very active volcanic system consisting of a continuous

stratigraphic series covering the inter-glacial and glacial periods for the last 400 ka (e.g. Franzson *et al.*, 2005). Because of the continuous record, the age of each inter-glacial and glacial formation can be estimated by counting the periods.

Whole-rock chemical analyses were made of fresh and altered rocks, glassy and crystalline, from several wells, at various depths in the study area. Fifty drill-cutting samples were prepared for chemical analysis. All the samples were cleaned of external material such as mica and mud used during drilling. From some of the samples, basaltic grains were handpicked to represent ‘fresh’ rock.

These samples were powdered in an agate shatter box and analysed for major and trace elements using a Panalytical PW2404 wavelength-dispersive sequential X-ray spectrometer at the University of Edinburgh. During the ignition process, the loss on ignition (LOI) was analysed to evaluate the alteration state of the samples.

**Results and discussion**

The stratigraphy of the rocks at the injection site is shown by a NE–SW cross-section in Fig. 2. The surface rocks are 300 m.a.s.l. in the NE end of the section but 260 m.a.s.l. at the SW end of the section. The rock formations consist of basaltic hyaloclastite formations and lava flows. A thick hyaloclastite formation appears at 200 m depth in the middle of the section but at 100 m depth in

HN-2, the injection well. During drilling of borehole HK-31, there was a loss of drill fluid at 400 m, which indicates high permeability in the rock formation at that depth.

The upper level of alteration minerals appears at 100–300 m depth. Calcite and Ca-rich zeolites appear a little lower, at ~200 m deep. In general, the alteration forms at shallower depths in the eastern part of the injection site, probably due to more frequent faulting of the bedrock, and the geothermal system of the Hengill area is towards the east. The sequence of the alteration minerals shown in Fig. 1 indicates a progressive increase in temperature during alteration with depth. The present bedrock temperature, as measured within the wells, ranges from 25°C at a depth of 500 m to 180°C at a depth of 1500 m. The estimated ages of the first 800 m of the rock formations are shown in the upper left of the section in Fig. 2. The youngest rock formations are the lava flows enclosing the Lambafell hyaloclastite ridge (Figs 1, 2) and are 2000–5000 y old. The hyaloclastite formation at 600–800 m depth could have formed 300,000 to 500,000 y ago. For the proposed field-scale injection, CO<sub>2</sub> will be dissolved in water from well HN-1 and injected into well HN-2. The rest of the wells are monitoring wells (Fig. 1). Note that well HN-1 is west of injection well HN-2, as can be seen in Fig. 1 and is therefore not downstream from the injection well.

Fifty samples were measured for major and trace elements. A total of 30 chemical constituents

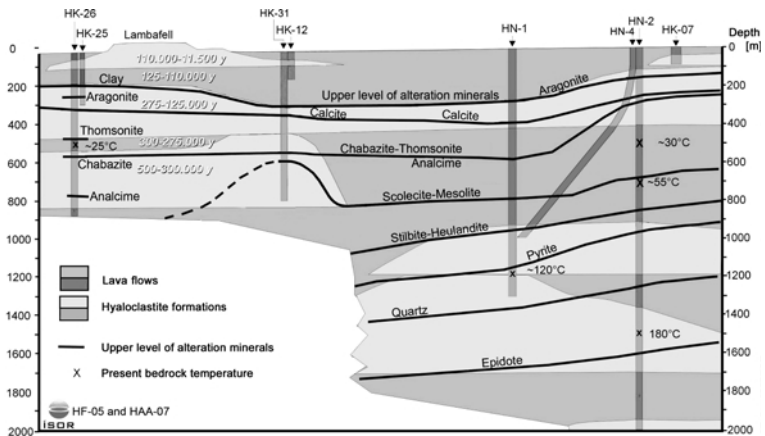


FIG. 2. NE–SW cross-section of the rocks at the injection site. Boreholes are marked as columns, basaltic lava flows are dark grey, and basaltic hyaloclastite formations are light grey. The first appearance of alteration minerals with depth are marked as black lines labelled with the mineral name. Estimated ages of the first 800 m of the rock formations are shown in the upper left of the section.

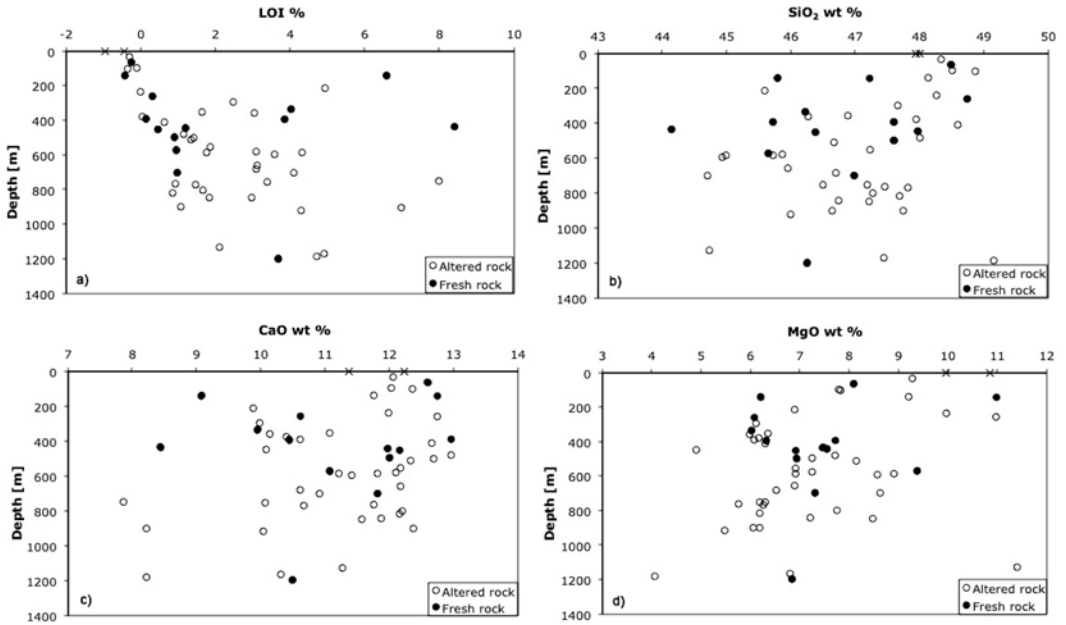


FIG. 3. (a) % LOI; (b) silica; (c) Ca and (d) Mg concentration, plotted vs. depth. Fresh rocks are shown as black dots, altered as white dots. The compositions of the same elements from Stapafell glass and dyke are shown as x.

were measured. The alteration state, estimated by loss on ignition (LOI), is low, as shown in Fig. 3a, and it increases with depth. The LOI, at 400–800 m, ranges from 0 to 5%. The silica compositions range from ~45 to 49% SiO<sub>2</sub> (Fig. 3b). The overall chemical composition range spans the picrite to tholeiite rock types (e.g. Jakobsson, 1980). The majority of the rocks are of olivine tholeiite composition (Fig. 3b–d). The majority of the rocks below 400 m, the zone targeted for the injection, are poorer in silica than the Stapafell formation. The composition of the Stapafell glass and crystalline dyke used in dissolution-rate experiments (Gislason and Oelkers, 2003) is superimposed on the diagrams at zero depth. The dissolution rate of the Stapafell glass has been used for water/rock chemical modelling of the proposed CO<sub>2</sub> injection (Gysi and Stefansson, 2008). As shown by Wolff-Boenisch *et al.* (2004), the dissolution rate of natural glasses increases with decreasing silica content. Thus the rocks below 400 m are reactive due to the small silica content and will readily react with the proposed CO<sub>2</sub>-charged injection waters. Model calculations indicate precipitation of Mg- and Fe carbonates at low pH, and Ca carbonates at high pH, following CO<sub>2</sub> injection (Gysi and Stefansson, 2008). The

target-zone rocks are both poorer and richer in Ca than the Stapafell rocks; they are poorer in Mg but richer in total Fe. Thus there should be an ample source of divalent cations from the rocks to combine with CO<sub>2</sub> and form carbonates during the proposed injection.

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