

Aquifer characterization with tracer test technique; permanent CO₂ sequestration into basalt, SW Iceland

M. REZVANI KHALILABAD¹, G. AXELSSON² AND S. R. GISLASON¹

¹ Institute of Earth Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavík, Iceland

² ÍSOR, Iceland GeoSurvey, Grensasvegur 9, IS-108, Reykjavík, Iceland

ABSTRACT

Mineral sequestration is among several promising methods of CO₂ reduction. It involves incorporation of CO₂ into a solid phase via precipitation of carbonate minerals. A prerequisite to carbonate precipitation is the availability of aqueous metal cations and a network of porous media for fluid flow and water-rock interactions. The Hellisheidi-Threngsli lava field in SW Iceland comprises ideal conditions for studying the feasibility of permanent CO₂ storage as minerals in basaltic rocks. In this paper we report on a tracer test conducted between two wells at the Hellisheidi-Threngsli site to characterize the physical properties of the main aquifers. The results suggest that most of the water flow between the wells is through an homogenous thick layer with high tortuosity along flow paths and a high reactive surface area for water-rock interactions.

KEYWORDS: tracer test, Na-fluorescein, mineral sequestration, basaltic aquifer, Iceland.

Introduction

CO₂ emission and its effect on global warming is the most controversial issue in the scientific world today. In an attempt to reduce atmospheric CO₂ a number of innovative methods have been suggested over the last few years. Mineral trapping is among several promising methods. Many authors have referred to mineral trapping as permanent CO₂ sequestration because of the ability of many carbonate phases to remain stable for geologically significant timeframes (e.g. Perkins and Gunter, 1995). A prerequisite to carbonate precipitation is the availability of aqueous divalent metal cations, which can combine with dissolved CO₂. One potential source of these cations is the dissolution of metal-bearing silicate rocks like basalt. Moreover, a large potential storage capacity in basaltic porous media will provide tortuosity in the flow path and large potential reactive surface area. Risks are nevertheless present. CO₂ might leak from the subsurface before carbonate

precipitation. Furthermore, precipitation of secondary minerals too close to the injection site can lead to lower permeability arresting further CO₂ injection (Oelkers and Schott, 2005).

The University of Iceland, Reykjavik Energy in Iceland, Columbia University in the USA, and CNRS in Toulouse, France, have agreed on co-operation in a research project, Carb-Fix, to optimize methods for storing CO₂ in basaltic rocks. CO₂ gas will be dissolved in water at elevated pressure at ~25°C and injected into a basaltic target zone at a depth of 400 to 800 m. The CO₂ gas used in the study will be that emitted by the Hellisheidi geothermal power plant which is located in the study area, i.e. the Hellisheidi-Threngsli area, SW Iceland. The target zone is cut by a number of shallow and deep wells, which will facilitate the injection and monitoring during the study (Fig. 1).

It is essential to understand the hydrogeological structure of the subsurface layers prior to injection. Therefore, this study attempts to define the governing flow paths in the target zone regarding the type of permeability and amount of effective porosity. A detailed description of the target aquifer will help to delineate

* E-mail: mar7@hi.is

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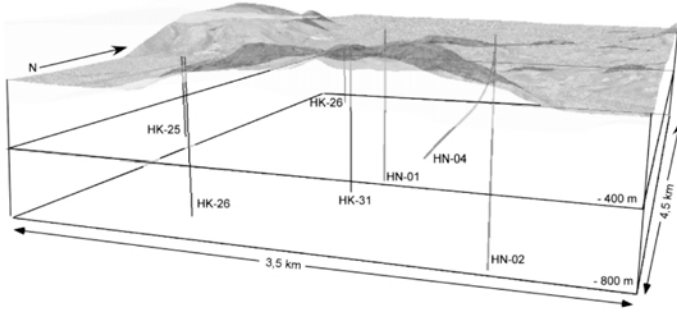


FIG. 1. A simplified three-dimensional sketch of the reservoir volume under consideration for CO₂ injection. Wells in the area are shown by vertical lines. A preliminary tracer test, a dipole test, was conducted between wells HN-02 and HN-04.

injection strategy and to plan precise monitoring of the field during and after CO₂ injection.

Tracer test analysis and interpretation

Tracer tests involve injecting a chemical tracer into a hydrological system and monitoring its recovery, through time, at various observation points. Results are used to study flow paths and quantify fluid flow. A preliminary tracer test was conducted between two wells at the Hellisheidi-Threngsli site; HN-02 and HN-04. As shown in Fig. 1, well HN-04 is not straight. The distance between the two wells is ~60 m at 400 m depth and 360 m at 800 m depth (Fig. 1). A flow field was induced by the continuous injection of water into HN-02 at a rate of 5 kg/s, and continuously pumping of water out of well HN-04 at a rate of 10 kg/s. Operation of the doublet commenced 3 days prior to tracer injection to develop a steady state flow field. 0.5 kg of a Na-fluorescent dye, a conservative tracer material, was then released as a slug into well HN-02. The fluorescent dye background level was negligible and it is detectable at extremely low concentrations. The Na-fluorescein detection limit was ~10 ppt (Smith and Pretorius, 2002).

In order to define the sampling plan and to simulate the observed concentration, a one-dimensional dispersion transport process was assumed. Such a model ignores diffusion, adsorption and retardation (Axelsson *et al.*, 2005). Based on the theory of solute transport the following equation simulates the mass flow of the tracer (e.g. Bear *et al.*, 1993; Javandel *et al.*, 1984).

$$F_{x,\text{dispersion}} = -\phi \cdot D_x \cdot \partial C / \partial x \quad (1)$$

This is Fick's law where ϕ is the material porosity, C the solute concentration (kg/m³) and D_x is the dispersion coefficient (m²/s) which is defined as:

$$D_x = a_x \cdot u_x + D^* \quad (2)$$

Here a_x is the dispersivity of the material (m), u_x denotes the fluid particle velocity (m/s) and D^* is the coefficient of molecular diffusion (m²/s). Comparable equations apply for the y and z directions.

The differential equation for solute transport is derived by combining the flow equations above and the conservation of mass of the solute involved. For an homogeneous, isotropic and saturated medium the differential equation is:

$$\frac{\partial}{\partial x} \left[D_x \frac{\partial C}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_y \frac{\partial C}{\partial y} \right] + \frac{\partial}{\partial z} \left[D_z \frac{\partial C}{\partial z} \right] - \frac{\partial}{\partial x} [u_x C] - \frac{\partial}{\partial y} [u_y C] - \frac{\partial}{\partial z} [u_z C] = \frac{\partial C}{\partial t} \quad (3)$$

Theoretically a mathematical solution should exist for any such problem, but in practice their solutions are often very complicated (Javandel *et al.*, 1984). Some simpler analytical solutions are possible after very simplifying assumptions on the geometry, dispersion, etc. of the flow. In the case of the simple geometry of a flow-channel with one-dimensional flow connecting an injection well and a production well, equation 3 simplifies to:

$$D_x \frac{\partial^2 C}{\partial x^2} = u \frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \quad (4)$$

Where D_x is the dispersion coefficient (m²/s) and C the tracer concentration in the flow-channel

(kg/m³). Molecular diffusion is ignored, thus $D = \alpha_L u$ with α_L the longitudinal dispersivity of the channel (m) and u the average fluid velocity in the channel (m/s) given by $u = q/\rho A\phi$, with q the channel flow rate (kg/s), ρ the water density (kg/m³), A the average cross-sectional area of the flow-channel (m²) and ϕ flow-channel porosity. Based on the conservative nature of the tracer material the tracer mass-balance between flow-channel and production well can be written as $c \cdot Q = C \cdot q$ where c is the observed tracer concentration in the production well, Q the production rate (kg/s). Assuming instantaneous injection of a mass M (kg) of tracer at time $t = 0$ the solution is given by:

$$c(t) = \frac{u\rho M}{Q} \frac{1}{2\sqrt{\pi Dt}} e^{-(x-ut)^2/4Dt} \quad (5)$$

Here $c(t)$ is the tracer concentration in the production well fluid and x the distance between the wells involved. Equation 5 was used for the tracer test analysis presented in this paper. In the case of two or more flow channels, the analysis yields estimates of parameters for each channel. The tracer interpretation software TRINV was used for the simulation and interpretation (United Nations University Geothermal Training Programme, 1994).

Results and discussion

The tracer slug was injected into well HN-2 on 13.11.07. Sampling from well HN-4 was carried out at a rate of four samples per day for two weeks and one sample per day for the remaining 125 days in this study. Samples were also taken from wells HN-01 and HK-31 (Fig. 1). Well HN-01 supplied the water for the injection well HN-02, and HK-31 is located 1.5 km downstream, to the south. No tracer has been detected in the latter two wells. The tracer test results for well HN-04 together with model results are shown in Fig. 2. The sum of the three channels fits the measured concentrations well (coefficient of determination is 96.8%).

The model simulates the measurements quite accurately if three flow channels are used; the first channel at 400 m depth and with 60 m distance between the wells, the second at 650 m depth with 150 m distance, and the third at 850 m depth, with 360 m distance from well HN-02. Note that well HN-04 is deviated as shown in Fig. 1. The locations of these channels are based on

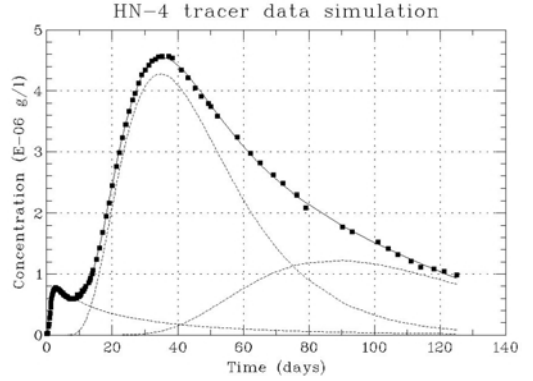


Fig. 2. Observed and simulated Na-fluorescein recovery in well HN-04 assuming three distinct flow channels.

stratigraphy (Alfredsson *et al.*, 2008, this volume), well logging and circulation losses during drilling of the wells (Helgadóttir *et al.*, 2007). The distances between the wells were calculated based on the known inclination of well HN-02 at each depth. As the adopted solution is not unique, geological information and well logging data must be taken into account to find the possible depth of aquifers.

The total mass recovery during the first 125 days of the tracer test was 50%. The parameters of the three assumed channels are shown in Table 1. The first hump in Fig. 2 shows the contribution of a thin aquifer to the total observed concentration, which may have been caused by a thin inter layer or a fracture between the wells at shallow depth. The calculated mass recovery of tracer through this flow channel was small, 3.2% (Table 1). The second pulse in Fig. 2 is believed to be caused by a much larger aquifer in the well cross section with 34.5% calculated mass recovery (Table 1). The classic shape of the curve is characteristic of an homogeneous porous media in the channel which is assumed to represent the effect of an aquifer at ~850 m depth, which was well defined during drilling and logging. This aquifer responded much later as a consequence of its depth and greater distance between wells (Fig. 2). The mass-recovery contribution calculated for this aquifer is 12.3% (Table 1).

The highest velocity is in channel one (Table 1); this is a sign of fracture flow. The velocity was slower in channel 2 and the third channel showed a greater velocity than channel 2 but its contribution arrived towards the end of the total concentration curve due to its greater

TABLE 1. Model parameters used to simulate the tracer recovery with three channels; flow path distance (x), the calculated mass-recovery of tracer through the corresponding flow channel, until infinite time over the total injected tracer (Mi/M), dispersion coefficient (D_L), fluid velocity (u_x), the simulated product of flow channel area A and porosity ϕ (m^3), longitudinal dispersivity (α_L).

Channel	x (m)	Depth (m)	Mi/M	D_L (m^2/s)	u_x (m/s)	$A\phi$ (m^2)	α_L
1	60	400	3.2	52.0E-03	8.20E-05	2.3	63.3
2	150	650	34.5	7.40E-04	4.50E-05	47	16.5
3	360	850	12.3	1.00E-01	5.20E-05	14	20.4

distance and deeper location in the well (Table 1 and Fig. 2). Channel 1 had the smallest pore volume, as expected for a fracture where the pore volume is the product of the channel area A , distance x and porosity. Channel 2 represents a thicker layer with greater volume of pore space interpreted as a network of homogenous interconnected porosity. Channel 3, the deep aquifer, has a large amount of pore space. Therefore, despite its depth, its contribution to the measured concentration was considerable. Stepwise simulation of future data points will provide a better understanding of its behaviour (Table 1 and Fig. 2).

The filled squares are the measured tracer concentration; the individual dashed-curves represent the concentration contribution of each channel with flow through the first, second and third channels, starting at \sim days 0, 8 and 23 respectively. The solid curve is the sum of the three calculated concentrations. The computer model TRINV was used to simulate the observations. (coefficient of determination = 96.8%).

Conclusions

The preliminary aquifer characterization of the CO₂ injection target zone in the Hellisheidi-Threngsli field was successful. The tracer test provided high-quality data and the interpretation presented here was able to address the main factors characterizing the zone. Inferred flow-channel volumes, dispersivity values and the shape of the tracer breakthrough curve imply that most of the basaltic bed rock, providing the flow paths, consists of a large volume of relatively homogeneous porous media. Single path fractures are believed to play only a minor role in the flow path system. A uniform network of interconnected porosity thus provides high tortuosity and large cumulative reactive surface area for water-rock

interactions available for the planned CO₂ basalt sequestration. The test conducted furthermore provides valuable information that will be used for design and pre-modelling of the large-scale tracer test planned in the area prior to the initiation of the CO₂ injection.

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References

- Alfredsson, H.A., Hardarson, B.S., Franzson, H. and Gislason, S. R. (2008) CO₂ sequestration in basaltic rock at the Hellisheidi site in SW Iceland: Stratigraphy and chemical composition of the rocks at the injection site. *Mineralogical Magazine*, **72**, 1–5 (this volume).
- Axelsson, G., Björnsson, G. and Montalvo, F. (2005) Quantitative interpretation of tracer test data (R. Horne and E. Okandan, editors). *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey.
- Bachu S., Gunter, W.D. and Perkins, E.H. (1995) Aquifer disposal of CO₂ – hydrodynamic and mineral trapping. *Energy Conservation Management*, **35**, 269–279.

- Bear, J., Tsang, C.F. and de Marsily, G. (editors) (1993) *Flow and Contaminant Transport in Fractured Rock*. Academic Press Inc., San Diego, 560 pp.
- Helgadóttir, M.H., Hardarson, B.S., Franzson, H., Sigurdsson, Ó., Kristinsson, B. and Sigurdsson, S. (2007) *Hellisheidi-HN-04*. Iceland GeoSurvey report ISOR-2007/016, Reykjavik, 34 pp.
- Javandel, I., Doughty, C. and Tsang, C.F. (1984) *Groundwater Transport. Handbook of Mathematical Models*. Water Resources Monograph Series, **10**. American Geophysical Union, 228 pp.
- Oelkers, E. and Schott, J. (2005) Geochemical aspects of CO₂ sequestration. *Chemical Geology*, **217**, [183–186](#).
- Perkins, E.H. and Gunter, W.D. (1995) Aquifer disposal of CO₂-rich greenhouse gases: Modeling of water–rock interaction paths in a siliciclastic aquifer. Pp. 895–898 in: *Water–Rock Interactions* (Y.K. Kaharaka and O.V. Chudeav, editor). Brookfield, Rotterdam.
- Smith, S.A. and Pretorius, W.A. (2002) The conservative behaviour of fluorescein. *Water SA*, **28**, 403–406.
- United Nations University Geothermal Training Programme (1994) *ICEBOX*. 2nd edition, compiled by Th. Arason and G. Bjornsson, Orkustofnun, Reykjavik, 66 pp.