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Modelling the Flow Paths at the Carbfix2 Reinjection Site, Hellisheiði Geothermal Power Plant, SW-Iceland

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ABSTRACT

The CarbFix2 project was developed to dispose of CO_2 and H_2S emissions from the Hellisheiði Power Plant, SW Iceland by mineralization of the injected gases within the subsurface basalts. The gas mixture is dissolved and transported to an injection well where it is co-injected with separated water from the power station. The injection of CO_2 and H_2S takes place in the Húsmúli reinjection area and has been an integral part of the operations at the Hellisheiði Geothermal Power Plant since 2014.

Field scale three-dimensional models of the injection at Húsmúli are developed to characterize and constrain the flow paths between the CarbFix reinjection site and the nearby Skardsmýrarfjall production zone. Mineralization processes occur along the flowpath between these areas and the models will be used to assess the impact of the CarbFix injection on the production wells. The numerical model is centered on the area between the reinjection and production zone. The model is based on the geological and structural model of Húsmúli developed using a multidisciplinary approach combining geological data, induced seismicity and tracer tests conducted in 2013 and 2014. The model results suggest a strong anisotropy control at Húsmúli likely to be associated with extensional faults acting as preferential pathways for the fluid. The model shows a good match to the tracer recovery match from the observation wells and shows limited adverse impact in term of enthalpy decline of the production fluid at Skardsmýrarfjall during the simulation time. The model also suggests that the flow path between the injection and production zones are lengthened due to the density difference of the colder injected fluid which sinks before rising as it heats up. This has a direct impact on surface area of rock that the fluid comes into contact with and the storage potential of the CarbFix reservoir.

1. INTRODUCTION

Carbon capture and storage (CCS) technologies are a combination of technologies that capture and store CO_2 underground preventing its release into the atmosphere. CCS is a key in the transition to a low-carbon future and holds a large role in the global response to climate change (IEA, 2016). The technology developed by the CarbFix project includes the capture and injection of dissolved CO_2/H_2S into fractured rocks for mineral sequestration (Aradóttir *et al.*, 2018). The benefits of this method are twofold; once dissolved, the gases are no longer buoyant, thus reducing potential leakage to the surface, and the dissolved gases are more reactive thus increasing the speed of the CO_2/H_2S mineralization processes within the fractured medium (Matter *et al.* 2016, Aradóttir *et al.*, 2018). Capitalizing on the success of the CarbFix pilot injections (Matter *et al.* 2016, , Snæbjörnsdóttir *et al.*, 2017), the project was scaled up in 2014. Since then, injection CO_2 and H_2S has been an integral part of the operations at the Hellisheiði Geothermal Power Plant in SW-Iceland. In 2017, the capacity of the capture plant was doubled with the addition of a second compressor unit. At current rate, about 10,000 tonnes of CO_2 and 5,000 tonnes of H_2S are injected annually. The injection takes place at the CarbFix2 injection site in Húsmúli, in the northwestern part of the Hellisheiði geothermal field, where the CO_2-H_2S-charged fluid is injected into the fractured basaltic reservoir from well HN-16 in Húsmúli (Figure 1). The EU funded CarbFix2 project currently supports in part ongoing R&D work related to the upscaled injection.

Numerical modeling plays an important role in the CarbFix project as it provides tools to predict and optimize long-term management of the injection of the dissolved gases and ensure the safety of this carbon storage technology. The ability to model the fate of the injected CO_2 as well as to quantify the amount of CO_2 that can be mineralized is also beneficial to increase the overall confidence in the effective long-term sequestration of CO_2. The aim of this paper is to present the preliminary work on the development on a full-scale three-dimensional model of the reactive transport of dissolved mixture of CO_2 and H_2S at Húsmúli. This includes the development of a three-dimensional pure water flow model centered on the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone. This model is used to understand the influence of the tectonic structures found in the subsurface at Húsmúli on the flow-paths of the injected fluid. The model is calibrated against recovery curves from two thermally inert tracer tests conducted in 2013 prior to the gas-enriched injection and 2014 at the start of the CarbFix injection. The 2013 tracer test was performed as a pulse injection of the tracer and the 2014 test as a continuous injection of tracer over the gas-enriched fluid injection period.

The program employed for the numerical simulation is the TOUGH2 software package developed at the Lawrence Berkley National Laboratory (Pruess, 1991). The program is widely used for geothermal applications and is used for the overall model of the Hengill geothermal system (Gunnarsson *et al.* 2011). The TOUGH2 simulator as implemented in forward mode in the iTOUGH2 program, was used here (Finsterle 2007). A range of software (Leapfrog Geothermal) and python scripting tools using the python library pyTOUGH (Croucher, 2011 and Croucher, 2015) were also combined to handle the preparation, running, post-processing, and analysis of the TOUGH2 model with minimal manual input.

2. THE CARBFIX SITE

2.1 Technology and site description

The current operations of the CarbFix project are taking place at Hellisheiði geothermal power plant in SW Iceland. The power plant co-produces electricity and hot water from the geothermal areas of the Hengill central volcano with installed capacity of 303 MW electricity and 133 MW thermal and is operated by ON Power. The CarbFix2 technology captures and injects approximately 1/3 of the CO_2 and 2/3 of H_2S emissions from the power plant. At current rate, about 10,000 tonnes of CO_2 are injected annually along with about 5,000 tonnes of H_2S. CO_2 and H_2S emissions from Hellisheiði power plant are captured in a gas abatement plant through a simple scrubbing process, dissolved in condensate from the power plant (Gunnarsson *et al.* 2018, Sigfússon *et al.* 2018). The gas enriched mixture is then co-injected with the separated water from power station back into the basaltic bedrock. The CarbFix2 mixture is injected into HN-16 located in the Húsmúli reinjection site in the northern part of the Hellisheiði field (Figure 1). Well HN-16 was retrofitted to receive the gas-charged condensate from the CarbFix capture plant. Within the casing of this well is a stainless-steel pipe that reaches 750 m, thus preventing any contact between the carbon steel and the gas-charged water (Gunnarsson *et al.* 2018). The two fluids, separated water and gas-charged water, were injected separately, mixing at the exit of the stainless-steel pipe at a depth of -430 masl (Figure 2). Four production wells (HE-31, HE-48, HE-44, and HE-33) located within 2 km down gradient from the injection well are regularly sampled to monitor the impact of the gas-enriched mixture injection at the CarbFix reinjection site (Figure 1).

This study will focus on wells HN-17 (tracer test carried out in 2013), HN-16 (CarbFix injection and tracer test from 2014) at Húsmúli directionally drilled to depths of -1625 and -1500 masl (Figure 1). Monitoring wells HE-31, HE-48, HE-44, and HE-33 are directionally drilled to depths of -1715, -1319, - 1762, and -813 masl respectively, such that they intersect high permeability fractures at depths below 800 m (Snæbjörnsdóttir *et al.* 2018, Figure 1).

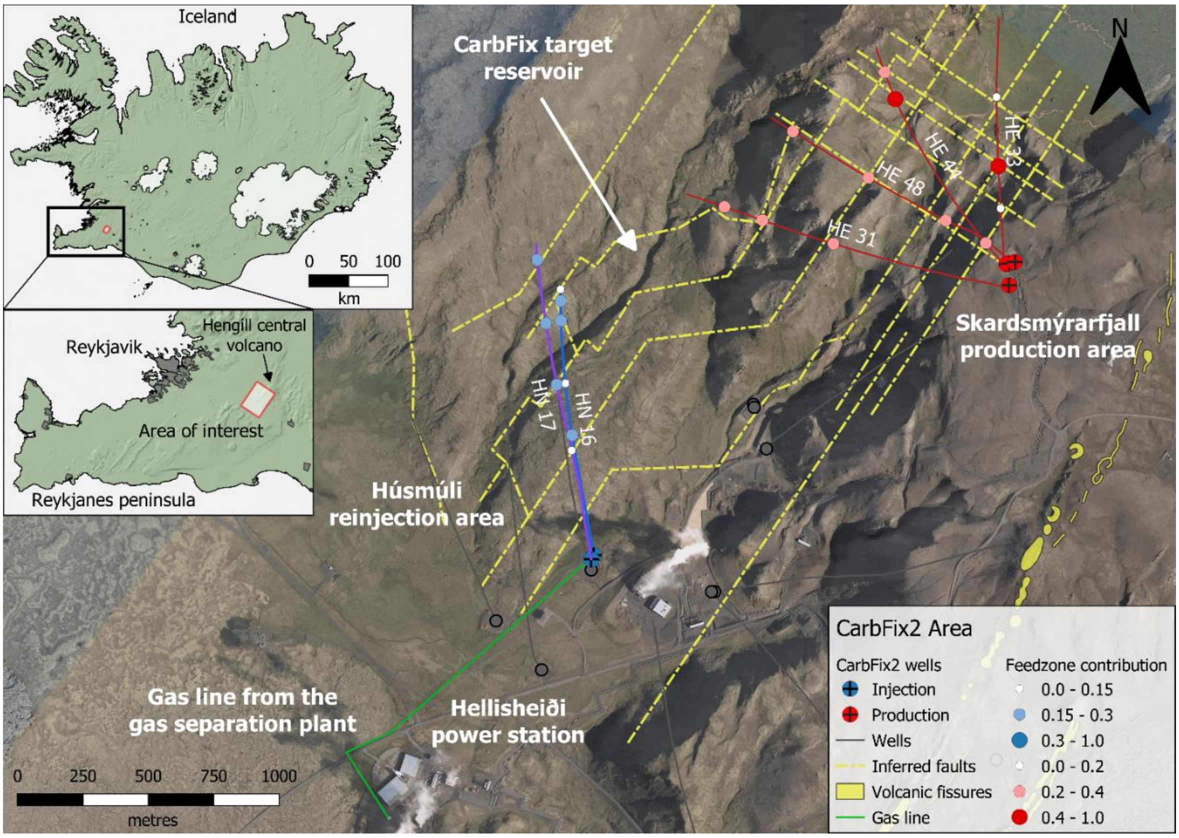

Figure 1: Overview of the CarbFix2 injection site. The gas charged water pipe (shown in green) connects the separation plant to the injection well. Injection was into well HN-16 (shown in blue). The four monitoring wells (HE-31, HE-48, HE-44, and HE-33 each shown in red) are located within 2 km down gradient from the injection well. Inferred faults are shown in yellow and feedzones location and contribution are represent by blue and red circles.

3. STRUCTURAL CONTROL AT HÚSMÚLI

The Hellisheiði field is located at the southern part of the Hengill volcanic system formed by several volcanic cycles during spreading episodes in the rift zone. The Hengill central volcano occupies the central part of a 60–100 km long and 3–5 km wide volcanic NESW trending fissure swarm with a graben structure. The Hellisheiði geothermal field is characterized by high heat flow and extensive geothermal activity associated with shallow level crustal magma chambers or dyke swarms. Normal faulting is prominent throughout this system and the cumulative vertical displacement of the normal faults in the Hengill area reaches 200 m (Khodayar *et al.* 2015).

3.1 Origin of the permeability at Hellisheiði

The highest temperatures in the field and the largest producers at Hellisheiði are majoritarily located along large rifting faults trending NNE and the two postglacial eruptive fissures. Similarly, sharp boundaries in the formation temperature parallel to the rifting direction are found at Hellisheiði (Gunnarsson *et al.* 2011). These suggest that the geothermal flow is bounded by structural features affiliated with intrusive bodies and sub-vertical faults following an NNE orientation. Modelling studies have showed that a structural control of the geothermal resource at Hellisheiði is consistent with the data available (Gunnarsson *et al.* 2011).

Permeability at Húsmúli shares the same NNE trending features, however recent studies have shown that the tectonic control at Húsmúli is more complicated, highlighted, amongst other things, by the induced seismicity events in 2010-11 during which the start of injection triggered ruptures along N-S and ENE faults (Juncu *et al.* 2018 and Kristjánsdóttir *et al.* 2018). At Húsmúli a shear system linked to the South Iceland Transform Zone (SITZ) meets the NNE rifting system and influences the flow paths (Khodayar *et al.* 2015). The reinjection wells at the Húsmúli site target this heavily fractured area (Figure 1). The permeable zones below the cased section of wellbores have been linked to open fractures and major faults. A high number of fractures striking ENE and NNE have been identified on televiewer logs in wells at Húsmúli including HN-16 (Thordarson *et al.* 2011). These have been linked to the conjugate ENE sinistral strike-slip faults of the SITZ. The NNE set is parallel to the rift fissure swarm (Khodayar *et al.* 2015). The dip of the fractures found in wells at Húsmúli are indicative of steeply dipping structures (Khodayar *et al.* 2015).

3.1 Fracture distribution in HN-16

The rose diagram of the fracture distribution is shown in Figure 2. The fractures have been grouped into three main high fractures density or feedzones. The feedzones range from -650 and -700 masl (feedzone 1), -1350 and -1450 masl (feedzone 2), and -1500 and -1600 masl (feedzone 3). This feedzone distribution is supported by circulation fluid loss during drilling, spinner tests interpretation, as well as fault trace at the surface. Two minor feeds have also been identified but will not be considered in the study. The CarbFix fluid mixture enters the reservoir through fractured zones of the open section of the injection well (Figure 2).

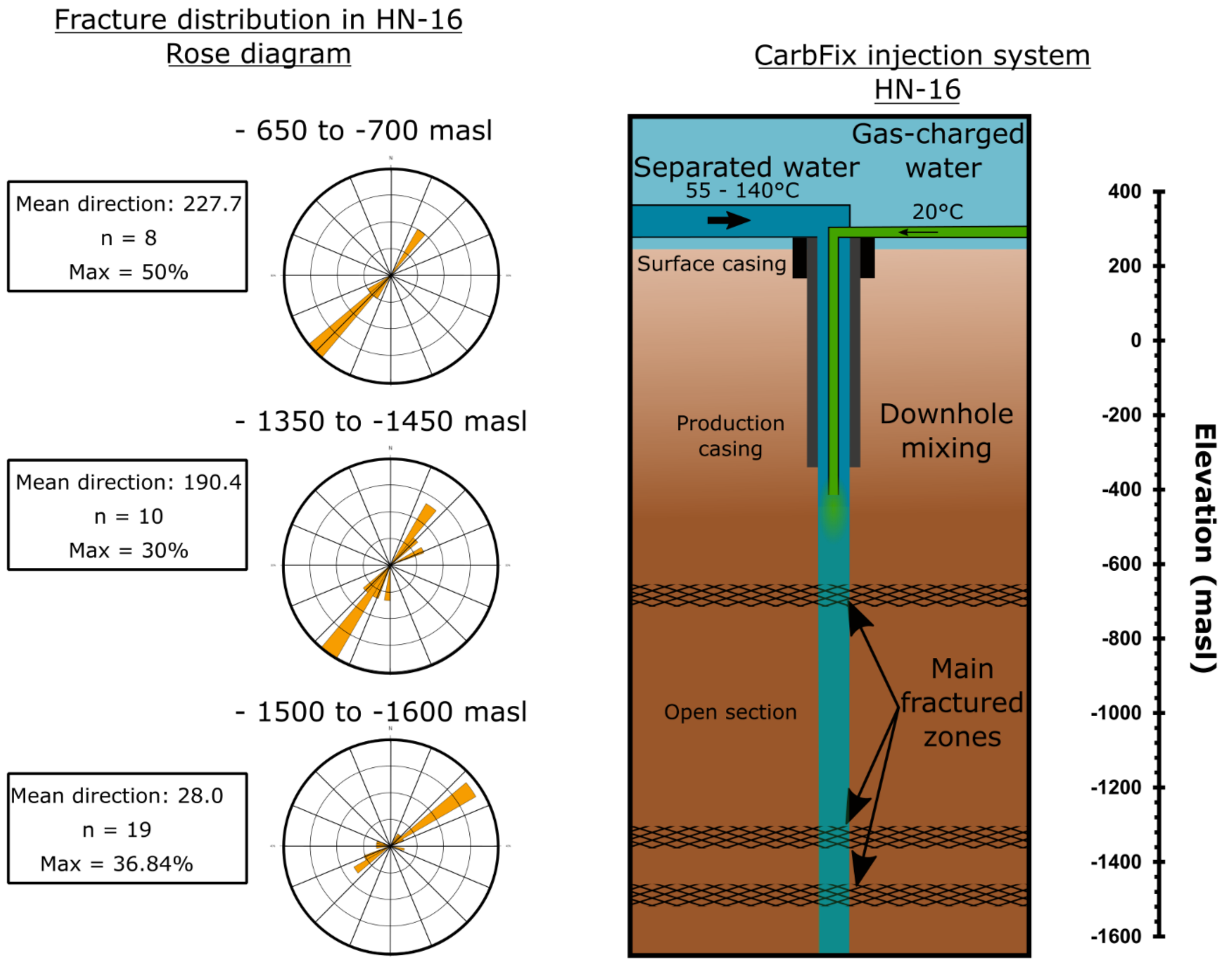

Figure 2: Left: Rose diagram of the fracture distribution for the three main feedzones identified in HN-16. Right: Schematic diagram of the injection system.

Televiewer logs have not been carried out for HN-17, however HN-17 is adjacent HN-16, and it is believed that it intersects the same structures as HN-16 (Figure 1).

3.2 Tracer Tests

Tracer tests have been conducted at the Húsmúli re-injection site to establish flow paths, estimate residence times, and to evaluate the risk of thermal breakthrough between injection wells at Húsmúli and production wells at Skarðsmýrarfjall. A widespread tracer test campaign (pulse injection over a period of two hours) was conducted in 2013 in wells in the Gráuhnúkar and Húsmúli re-injection sites including HN-17 (Kristjánsson et al. 2016). In 2014, at the start of the CarbFix2 injection a thermally stable inert tracer was added to the gas-charged water to monitor the fate of the dissolved gases after their injection in HN-16. The current research focuses on the result of the 2013 and 2014 tracer tests. The recovery curves for each of the monitoring wells are presented and discussed below. The amount of tracer recovered from producing wells are reported in terms of ppb (µg/kg). These values are plotted against time.

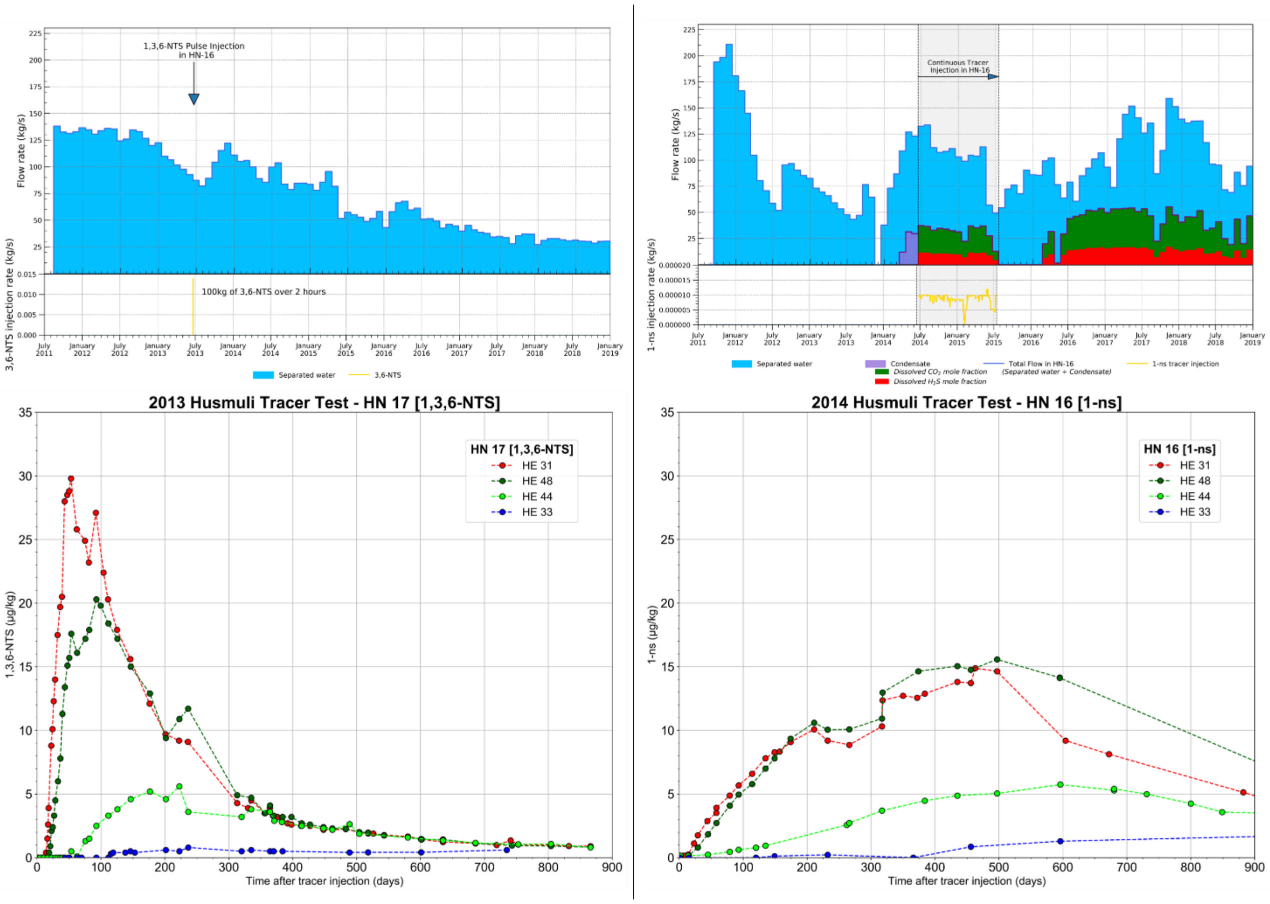

Figure 3: Top: Effluent water and tracer injection (left: HN-17; right:HN-16). Bottom: Recovery curves sampled in wells HE-31, HE-48, HE-44, and HE-33 after the tracer injection (left: 2013 1,3,6 NTS slug test; right: continuous 1-ns tracer test).

100 kg of 1,3,6-naphthalene sulfonic acid (NTS) tracer was injected into HN-17 over two hours on 20 June 2013 (Figure 3). The amount of tracer recovered and the time of first arrival for each production well is summarized in Table 1 and the tracer recovery curves for well HN-17 are presented in Figure 3. The tracer first arrival time in well HE-31 was only 14 days and shortly after (18 days) the tracer appeared in well HE-48. After 53 days the 1,3,6-NTS tracer appeared in the third well, well HE-44. These three wells combined yield a combined recovery of 55 kg of the 100 kg of the1,3,6-NTS tracer injected, corresponding to 55% recovery in this part of the production area. After 138 days the tracer reached well HE-33, but only at a low concentration. Limited recovery observed in the wells adjacent to the south (Kristjánsson *et al.* 2016).

Table 1: Location of major and minor feeders in injection and production wells for tracer injection (1,3,6 NTS) in HN-17

Elevation (masl)		Tracer detected	Elevation (masl)		Arrival time
major feeders	*minor feeders*		*major feeders*	*minor feeders*	
-815; -1100; -1426	-510	HE-31	-1044; -1413; -1577	-	14 days
		HE-48	-859; -1222	-465	18 days
		HE-44	-1432	-332; -1609	53 days
		HE-33	-566	-384; -744	115 days

A thermally stable inert tracer, 1-naftalenesulfonic acid (1-ns), was added to the gas-charged water at the start of the CarbFix injection (Figure 3). During the CarbFix injection in HN-16 from June 20th, 2014 to July 15th, 2015 a total of 291 kg of the 1-ns tracer was injected at a constant proportion to the gas-charged water using a Milton Roy dosing pump (Gunnarsson *et al.* 2018). The amount of tracer recovered and the time of first arrival for each production well is summarized in Table 2 and the tracer recovery curves for well HN-17 are presented in Figure 3. It took the tracer only 14 days to appear in well HE-31 and 29 days to appear in well HE-48. 1-ns appeared in HE-44 after 79 days and appeared in HE-33 between 366 and 456 days after the start of the tracer injection.

Table 2: Location of major and minor feeders in injection and production wells for tracer injection (1-ns) in HN-16

Elevation (masl)		Tracer detected	Elevation (masl)		Arrival time
major feeders	*minor feeders*		*major feeders*	*minor feeders*	
-712; -1380; -1520	-990; -1600	HE-31	-1044; -1413; -1577	-	14 days
		HE-48	-859; -1222	-465	29 days
		HE-44	-1432	-332; -1609	79 days
		HE-33	-566	-384; -744	456 days

3.3 Tracer tests interpretation

The fast tracer recovery in the monitoring wells as well as the lack of tracer return in wells located south of the area indicates a strongly anisotropic permeability at Húsmúli (Kristjánsson et al. 2016). This behaviour is supported by previous modelling studies as well as a study by Khodayar et al. (2015) which analysed the results of the tracer test data with available subsurface data, aerial photographs, and seismic events. This study correlated the feedzones of the injection and production wells in Húsmúli and Skarðsmýrarfjall with subsurface tectonic structures to identify carriers/barriers structures providing preferential pathways for the injected fluid or impeding the flow of the injected fluid. It suggests that the shear system striking mainly northerly, ENE, and NW provide the flow paths between Húsmúli and Skarðsmýrarfjall (Khodayar et al. 2015). The conceptual model of the transport processes developed here is based on some of the tectonic configurations identified by Khodayar et al. (2015).

- An ENE set appears to be the most favourable flow path for the tracer (showed in green in Figure 4). The main feeders of the re-injection wells (HN-17 included) fall on the hanging walls of the ENE faults. These faults extend from the re-injection zone to the edge of the Skarðsmýrarfjall production zones and intersect wells HE-31, HE-48, HE-44, and HE-33 facilitating a relative short travel time from HN-17 to HE-31.
- The NS faults (shown in purple in Figure 4) are also good carriers and channel the flow to and from the ENE faults.
- The NW faults (shown in red in Figure 4) south-westward dipping and lay perpendicular to the flow direction of tracers and act as barriers for the tracers coming from the opposite direction, i.e., from the southwest. These faults act as barrier or semi barrier structures, delaying the tracers travel time across the faults.

The NNE trending faults identified at the surface in the vicinity of Húsmúli re-injection site (Gunnarsdóttir and Poux, 2016) have also been included in the model (Figure 4) to model the field-wide interrelationship between structures and the operation at the Hellisheiði geothermal power plant.

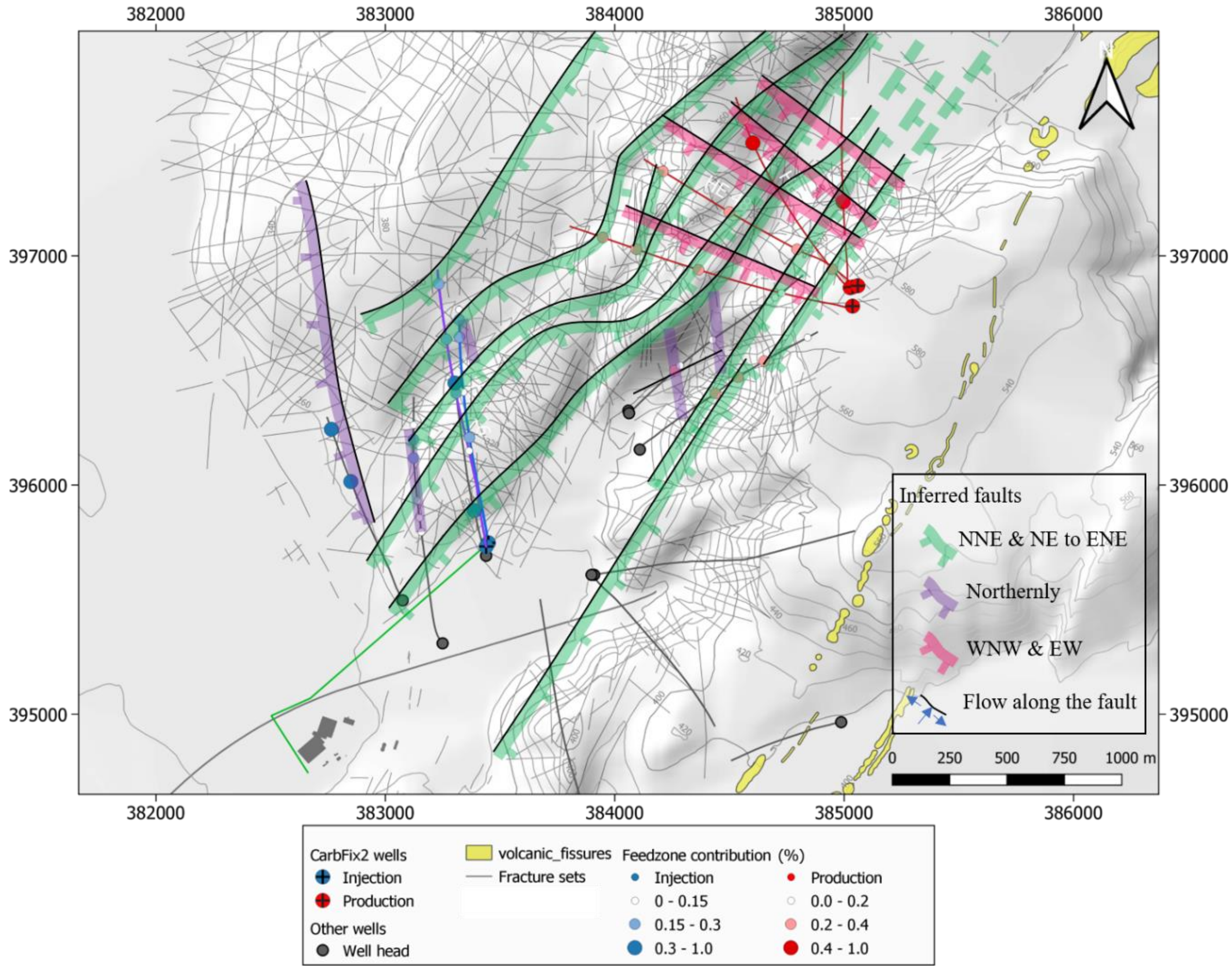

Figure 4: Conceptual model of the flow paths at the Húsmúli re-injection site (based and adapted from Khodayar et al. 2015)

4. DESCRIPTION OF THE NUMERICAL MODEL

4.1 Grid Structure

The model developed in this study is a three-dimensional model centered on the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone. The model is set to cover an area of 42 km^2 (6 km x 8 km) and the lateral extent of the model was set large enough to encompass the flow paths between Húsmúli and Skardsmýrarfjall while avoiding boundary effects (Figure 5). The grid used is irregular with four levels of refinement. Blocks range from 1 km by 1 km at the outskirts of the model to 250 m by 250 m in the area of interest, between Húsmúli reinjection site and the Skardsmýrarfjall production zone (Figure 5). The model is made up of 67 layers ranging from 400 masl to -2700 masl and with a thickness comprised between 100 m and 25 m. Layers with a high feedzone density were set to have the minimum thickness of 25 m (Figure 5). The present model has a total of 81,600 active blocks, 242,808 connections, and is referred as model HU_81600. The grid was rotated and aligned along an NE direction parallel to the rift and some of the large NE faults found in Húsmúli.

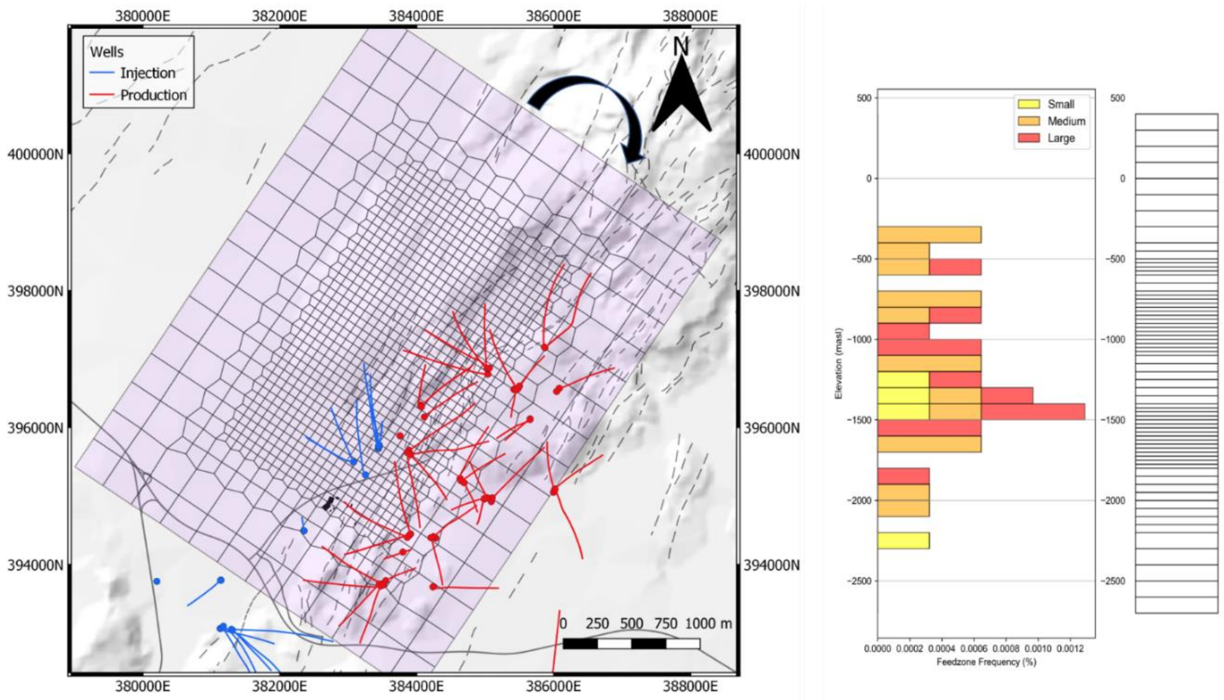

Figure 5: Grid structure, feedzones distribution, and layer structure of the model for the Húsmúli model HU_81600.

4.2 Rock-Type Assignment

The geological structure of the Húsmúli reinjection site is represented in the numerical model by defining a rock-type for each geological unit which populate the three-dimensional array of blocks that covers the model area. The rock-type distribution and parameters represent the geological units and their associated properties: lava flows, hyaloclastites/hyaloclastic formations, dyke intrusions, faults and clay cap (Figure 6). It is directly based on the leapfrog geological model of Hellisheiði provided by the Geoscience team from ISOR (Gunnarsdóttir and Poux, 2016).

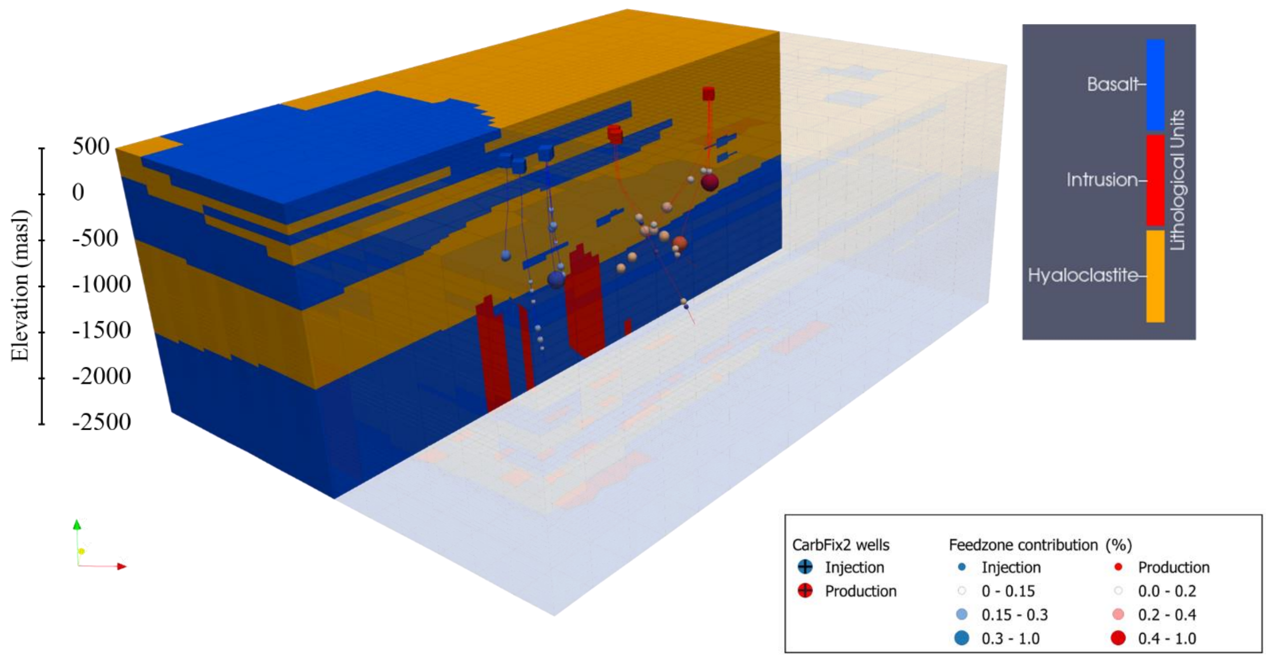

Figure 6: Rock types assignment of the lithology at the CarbFix 2 re-injection site.

The rocktypes were further divided into three groups; the rocks located within the geothermal system subject to alteration and stress of varying permeability, rocks located above the geothermal system within the cold-water ground system and referred to as "Fresh", and formations surrounding the geothermal system known as "Outer" of limited permeability (Table 3). The rock-types of the volcanic sequence are characterized here by a traverse isotropy; permeability 1 and permeability 2 values are equal, meaning each rock-type has the same ability to let fluid flow through in the (x, y) space (Table 3).

Table 3: Permeability and Porosity values for the rocktype defined in the base model. The permeability values for these formations are isotropic in the (x, y) space.

Name	*Porosity*	*Permeability (1&2 and 3) [10^{-15} m^2]*		
		Geothermal System	Fresh	Outer
Basalt	0.1	5-10, 0.5-2	100, 20	0.5-1, 0.2-0.5
Hyaloclastic Formations	0.1	15-50, 2-10	100, 20	1-5, 0.5-1
Intrusion	0.1	1-5, 2-10	100, 20	0.05-0.1, 0.1-0.2
Clay Cap	0.1	1, 1, 1		

Individual tectonic structures are believed to be critical to describe the fluid flow at Húsmúli (section 3.3) and were explicitly represented in the numerical model (Figure 7). This introduces anisotropy in the model and reflects our current understanding of the tectonic structures and flow paths at Húsmúli. The anisotropic nature of the faults was introduced by assigning the parameter permeability 1 along the fault strike and permeability 2 to the face across the fault face. Permeability 1 is then assigned a high value and permeability 2 is set at a small value. This captures the ability of the fault to act as a carrier structure and channel the flow along the fault. Fault intersection was also considered by assigning the open face of the fault intersection the permeability 1 value and the closed face is assigned a permeability 2 value. In the present model, faults are set as vertical as televiewer data analysis suggests.

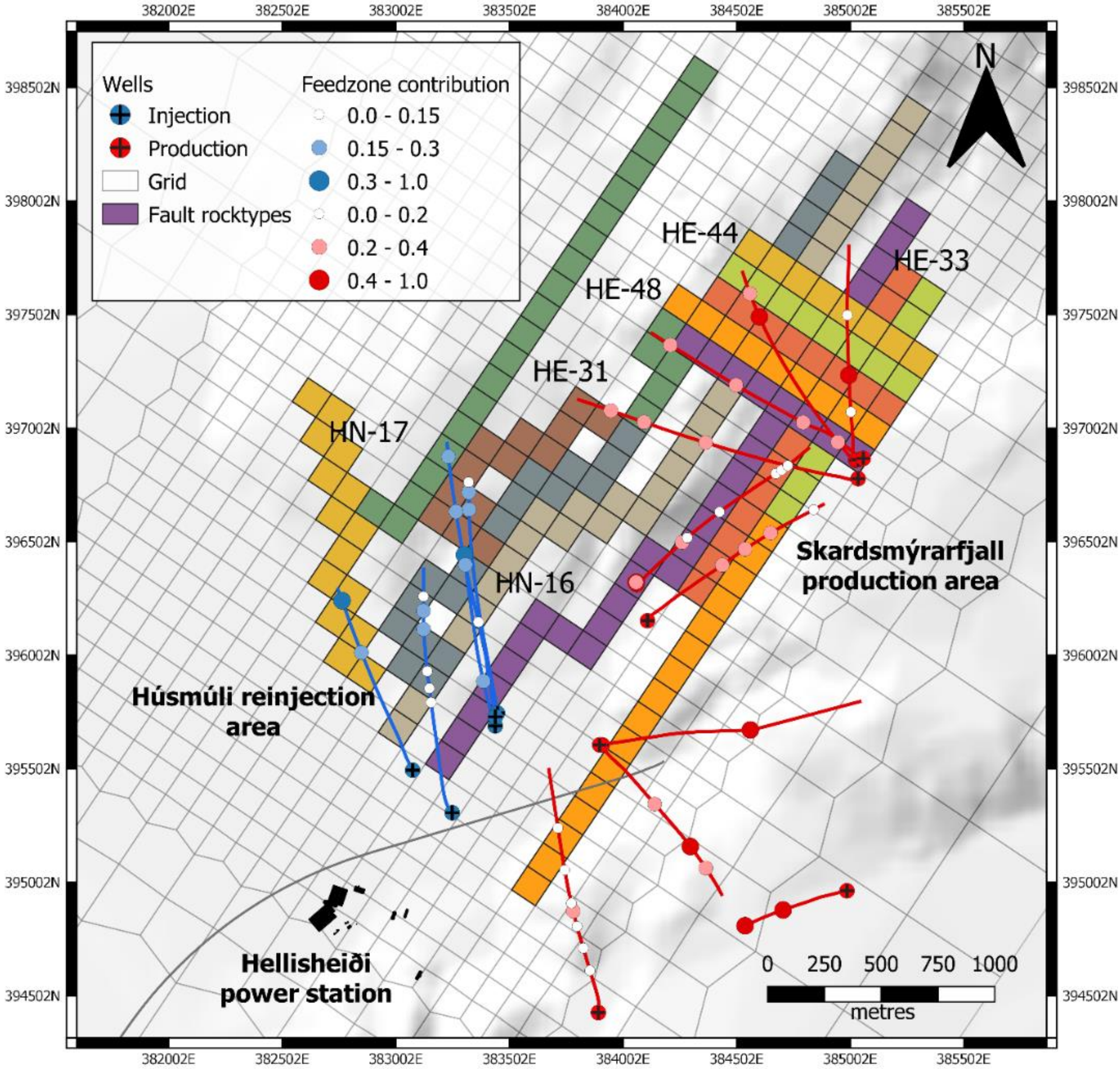

Figure 7: Rock-type distribution of the tectonic features implemented in HU_81600.

4.2 Dual Porosity Approach

A dual porosity representation of the flow was used to capture the fractured nature of the subsurface at Húsmúli. The dual porosity approach idealizes the flow region as two interacting continua, namely the fractures and the matrix as opposed to averaging the parameters over the entire block (section 4.2). To represents a fracture network in a low permeability rock matrix, the dual porosity approach assumes that the fluid flows mainly through the fractures and the matrix flow is small (Warren and Root, 1963; Zimmerman *et al.* 1996). The multiple interacting continua or MINC method in TOUGH2 adds further complexity to the dual porosity approach by allowing the matrix to be subdivided into nested blocks (Pruess and Narasimhan, 1985), thus representing gradients of pressure, temperature or concentration inside the matrix.

The dual porosity model developed here is based on the single porosity model of Húsmúli and will not be discussed in this study (Ratouis *et al.* 2018). Partitioning of the single porosity mesh into two computational volume elements to create a double-porosity grid was generated using the MINC function in the PyTOUGH library (Croucher, 2015). The PyTOUGH library also provides a utility for generating a dual porosity initial condition file from a single porosity INCON or SAVE file. The dual porosity model of Húsmúli used three interacting continua (one fracture and two matrix blocks) with corresponding volume fractions of 2%-10%-88% and fracture spacing was set to 150 m (Table 4). The fracture was assigned a very high porosity fixed at 90%. The matrix porosity values were based on porosities used in the single porosity production history model. The matrix porosity was chosen such that effective porosity of the dual porosity model is the same as the porosity of the single porosity model (See Eqn. 1):

$$\theta_{eff} = \theta_f V_f + \theta_m (1 - V_f) \qquad \textit{Eqn. 1}$$

Where $\theta_{eff}, \theta_f, \theta_m$ are the effective, fracture, and matrix porosities and V_f is the fraction of the total block volume occupied by the fractures (here 2%). The matrix permeabilities were assigned a value of 1 micro-Darcy. The parameters used with the dual porosity model are summarized in Table 4. The MINC grid was applied only to the grid blocks within the central area. The dual porosity model has a total of 183,440 grid blocks and 344,648 connections.

Table 4: Parameters used with the dual porosity model DP HU_81600

Parameters		Dual Porosity HU_81600 Model
Volume fraction	Fracture	5%
	Matrix 1	15%
	Matrix 2	80%
Permeability	Fracture	Varies according to single porosity model values
	Matrix	1.0×10^{-18}
Porosity	Fracture	90%
	Matrix	Varies according to single porosity model values
Fracture spacing		250
Rock grain density (kg/m^3)		2600
Rock specific heat (J/kg K)		900
Rock conductivity (W/m K)		1.5

4.3 Boundary Conditions and Initial Conditions

The top boundary of the model was set at the approximate elevation of the top of the water table and is connected to a large atmospheric block. The lateral boundaries to the NW, SW, and SE have been set as closed boundaries; the regional flow suggest very limited flow from these directions (Figure 8). A recharge boundary condition was chosen to allow flow from the northern side of the model as fixed pressure boundary. The bottom layer of the model has been set as fixed pressure boundary to allow for pressure and temperature support during the simulation.

The simulation starts on September 15th, 2011 when reinjection of separator water started at Húsmúli and runs to December 31st, 2018. The initial conditions (temperature, pressure and gas saturation) for HU_81600 were extracted from the numerical model of the Hengill geothermal resource (Gunnarsson *et al.* 2011). This model is developed and maintained by Reykjavik Energy and simulates the production from Hellisheiði and Nesjavellir geothermal fields for resource management purposes (Gunnarsson *et al.* 2011). The Hengill model covers a larger area and the grid is coarser than the grid developed in this study (Figure 8). The values were interpolated using a spatial three-dimensional Delaunay triangulation.

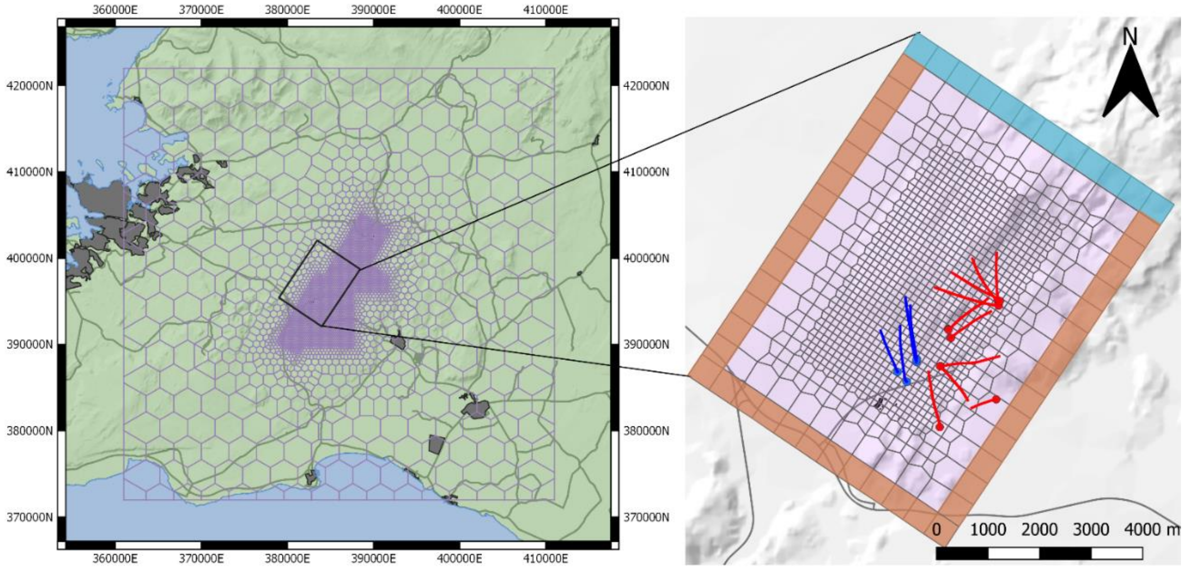

Figure 8: Grid used for the Hengill Model (Hengill_2018) (left) Lateral boundary conditions for HU_81600 (right). The blue blocks represent an open boundary whereas the brown blocks represent the edge where a closed boundary was implemented.

4.4 Production Data and Tracer Injection

Production and reinjection from the active wells at Húsmúli and the Skardsmýrarfjall production zone were implemented in the model from September 2011 to December 2018. Monthly mean values of injection and production rates were supplied by Reykjavík Energy as well as the enthalpy of the injected fluid (Figure 9). A pure water Equation of State (EOS1) was used for the simulation. The first stage of the simulation is a single water component flow simulation from September 2011 until the start of tracer injection. This provide the initial condition at the time of the tracer injection. The second stage starts at the start of the tracer test considered and introduces a second water component (water #2) to represent the inert tracer and is run until the end of the simulation period. Two set of models were run simultaneously to model the pulse tracer injection (1,3,6 NTS) in 2013 and continuous tracer injection (1-ns) in 2014. Both simulations use the same injection and production data. The injection of the 2013 pulse tracer injection took place on June 20th, 2013 and the 2014 continuous tracer injection was modelled by injecting tracer from July 24th, 2014 to July 15th, 2015. A background value of 10^{-10} kg/kg for the second water component was defined for the second stage of the model to avoid convergence problems resulting from zero values.

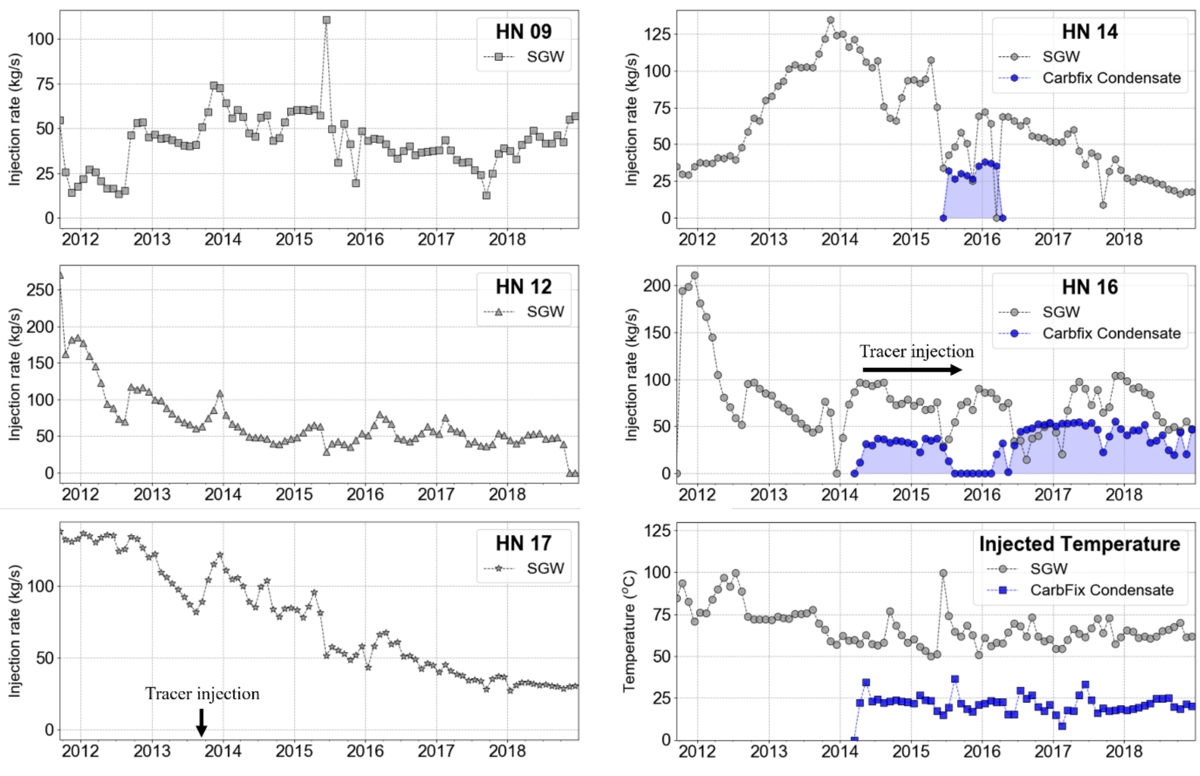

Figure 9: Monthly injection rates in the injection wells considered and temperatures of the injected water during the simulation period.

5. NUMERICAL MODEL OF THE REINJECTION AT HÚSMÚLI

Figure 10 shows the tracer recovery curves for the two tracer tests carried out at Húsmúli in 2013 and 2014. The arrival time, peak concentration and shape of the curves are correctly matched for all wells in the 2013 pulse tracer injection. The long tail of the recovery recorded in well HE-31 is well captured. The match for the 2014 continuous tracer test is not as satisfactory highlighting different flow path characteristics. Pore scale behavior and retention of the solute by the host rock or the presence of slower flow paths between the injection and the monitoring wells are both an area of current work.

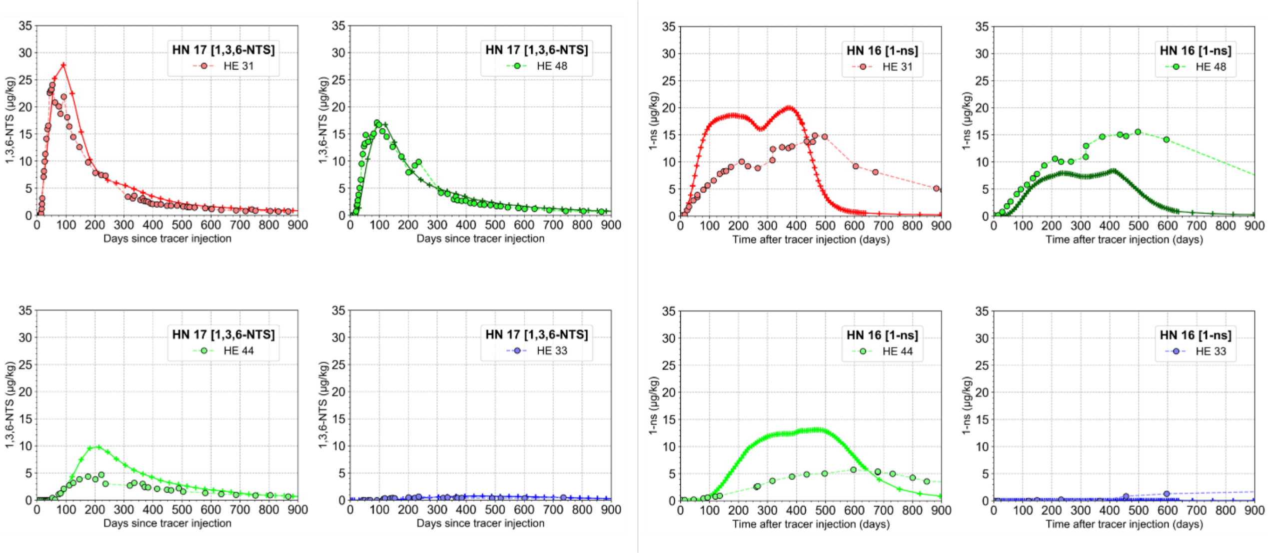

Figure 10: Dual porosity model results - Tracer recovery curves for 1,3,6-NTS tracer injection. The data is represented by the colored dots and the dotted line and the model results by the colored plus sign symbol and the solid line.

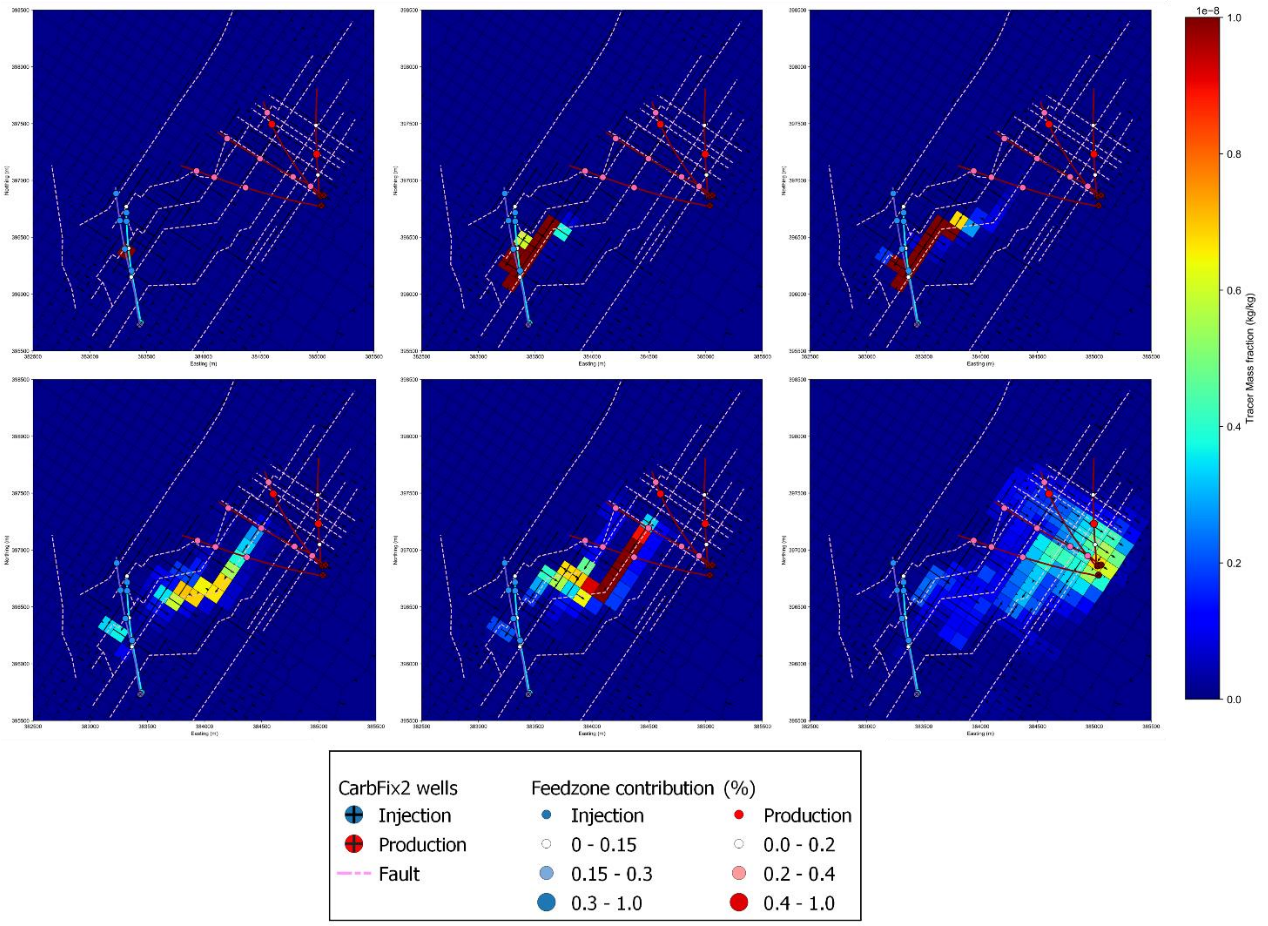

Figure 11: Model results - Tracer content 0, 10, 30, 60, 90, and 365 days after the tracer injection at an elevation of -825 masl (layer 21). The faults are shown in pink and the feedzones are represented by blue (injection) or red (production)

Figure 11 shows the tracer content distribution in the model at an elevation of -825 masl (layer 21) 10, 30, 60, 90 days, and one year after the tracer injection. It shows the progression of the tracer along the carrier faults in the model. The tracer reaches well HE-33 and HE-48 approximately 15 days after tracer injection. The chemical front is then slower and takes approximately 60 days to reach HE-44, as it reaches some of the barrier structures in the model diverting the flow along the NW-SE barrier faults. The impact of the faults on the transport of the tracer is very clear.

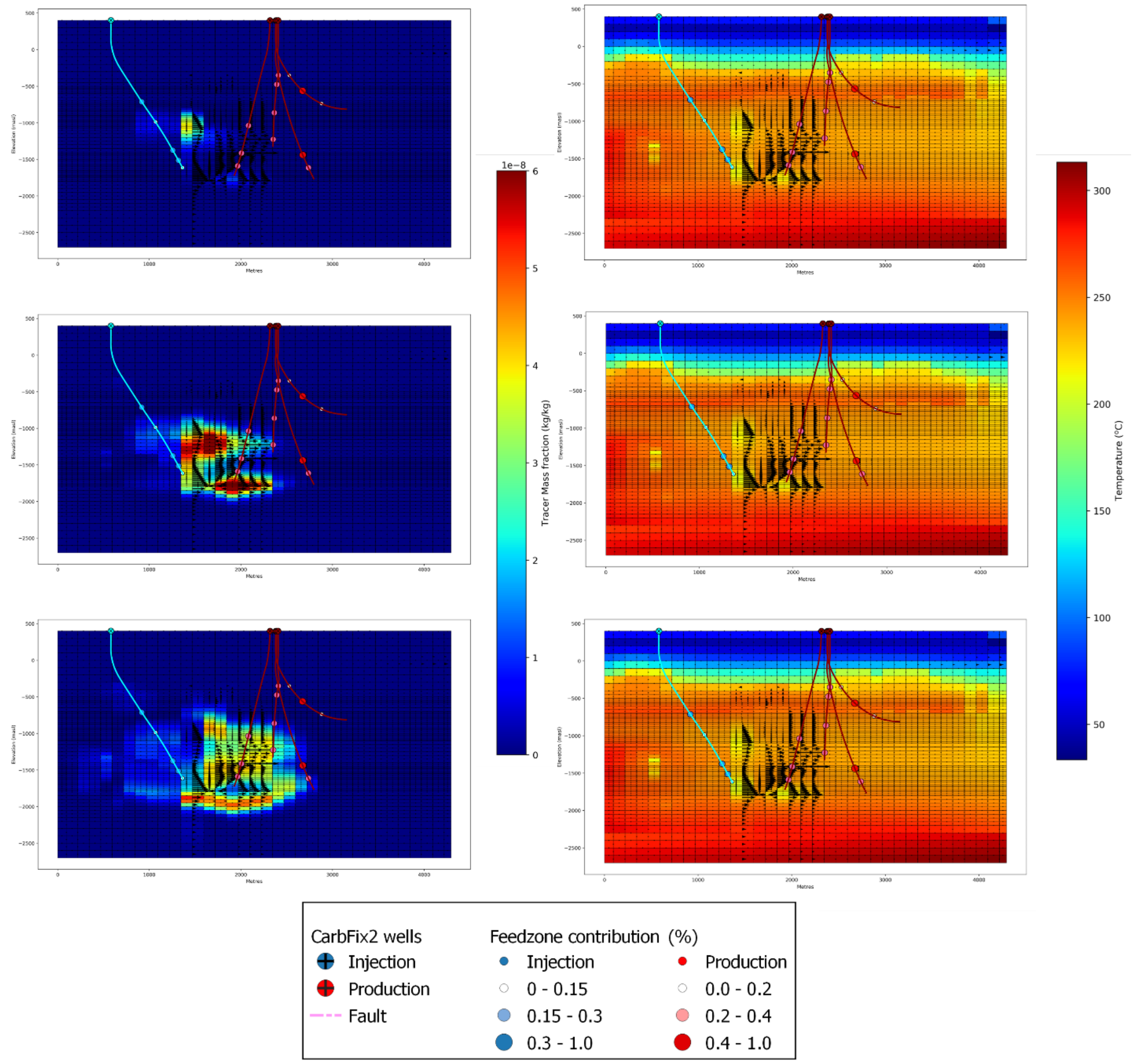

Figure 12: SW-NE cross section along the flow showing the tracer content distribution (left) and temperature (right) after 15, 45, and 100 days after the tracer injection.

Figure 12 shows a SW-NE cross section of the tracer (left) and temperature (right) distribution between the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone intersecting the bottom feedzone of HN-17 15,45, and 100 days after the injection of tracer. It shows that the tracer initially sinks (the cold fluid is denser than the reservoir fluid) in the vicinity of the reinjection well (Figure 12). As it travels along the fault line its temperature increases and slowly rises (Figure 12). This shows that the fluid does not flow in a straight line from the reinjection area to the Skardsmýrarfjall production zone. Instead the fluid first sinks driven by buoyancy and then gradually, as it heats up, rises back as it reaches the Skardsmýrarfjall production zone. This directly impacts the length of the flow path of the injected fluid. Temperature changes in the reservoir also occur much slower than changes in tracer concentration along the flow path. The area of cooling around Húsmúli after two year of reinjection is present but does not spread as fast as the chemical front (Figure 12).

Figure 13 shows the temporal evolution of the weighted enthalpy from the production wells at Skardsmýrarfjall. The model results predict little to no cooling during the simulation period in most wells. The model predicts a slight cooling trend in well HE-31 (decrease of 70 kJ/kg) over the simulation period which may be too pessimistic.

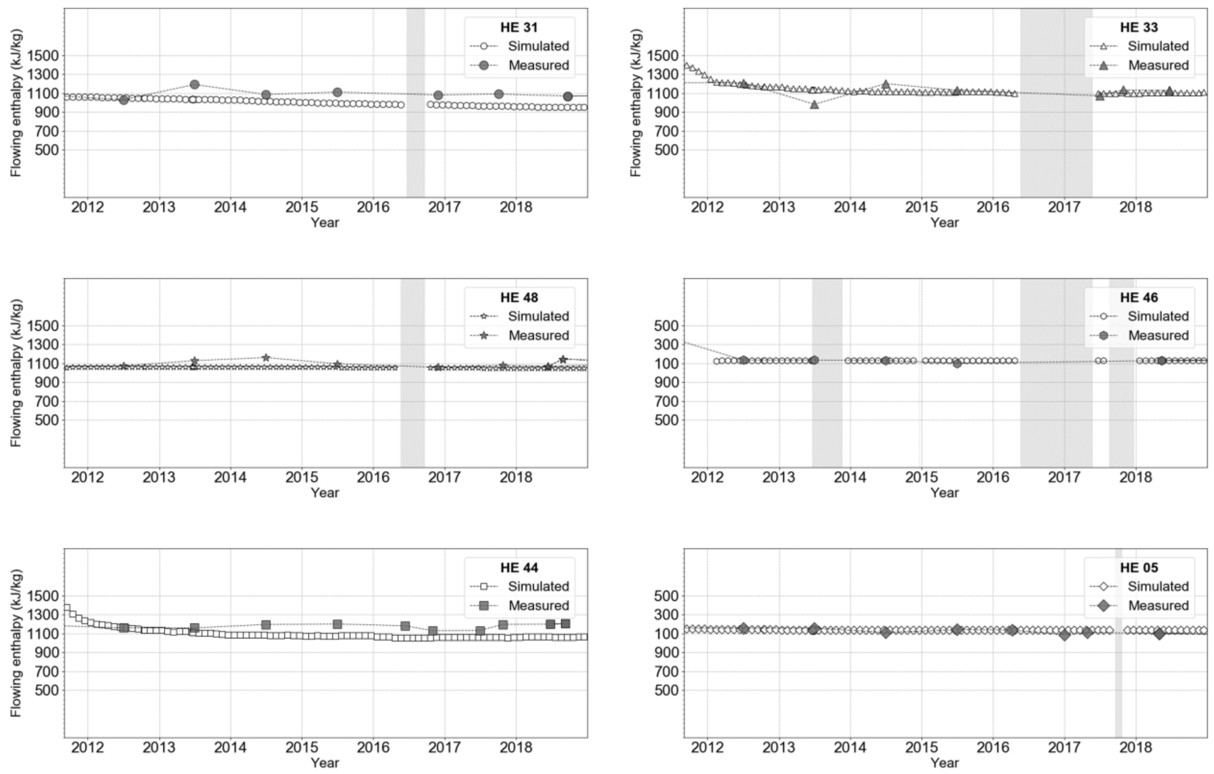

Figure 13: Weighted discharge enthalpy evolution for the monitoring wells. The sampled value is represented by the dark markers and the simulated results by the white markers. The shaded areas represent the time where the flow was not flowing.

6. Concluding remarks

The work presented here shows that the flow at the CarbFix2 reinjection site is strongly anisotropic and large extensional and strike-slip faults act as preferential pathways for the reinjected fluid. The flow is largely confined within these tectonic features found between the Húsmúli reinjection zone and the Skardsmýrarfjall area. A dual porosity representation of the flow at Húsmúli captures successfully the fast and strong recovery of tracers found in wells at Skardsmýrarfjall. The partition of the grid into nested matrix and fracture blocks allows for a better numerical approximation of the flow in a fractured continuum.

The modelling also shows that the flow is driven by the difference in buoyancy between the colder gas-charged fluid and the surrounding reservoir formation; the reinjection fluid first sinks in the vicinity of the injection well down to an approximate depth of -2500 masl and gradually rises back up along the flow paths as it heats up. The flow path from the CarbFix2 reinjection site and the Skardsmýrarfjall production zone is therefore lengthened. This also implies that the reinjected fluid is in contact with a greater rock surface area and hotter rocks. This is a significant observation as it has a direct impact on the size of the carbon storage capacity of the CarbFix2 reservoir, mineralization processes, and on the long-term thermal effect on production wells at Skardsmýrarfjall.

The application of the workflow described in this paper and the use of tools including PyTOUGH enabled us to automate the different stage of the model development from grid generation and model set up through execution and post processing of the simulation results. The use of python scripts makes the transition from a geological model and conceptual model to the numerical model more straightforward. For example, changes in the conceptual model such as a different fault strike or orientation can be immediately modified, and the model updated. This speeds up significantly the calibration process, allows for various model configuration to be tested effortlessly and improves the communication with the geoscientists team involved in the CarbFix2 project.

This paper also highlights areas of improvement and future work:

- Our understanding of the geology and tectonic controls on the fluid flow at depth needs to be further refined. This includes data from fluid-pressure induced seismicity, tracer concentration and arrival time at the production wells, as well as incorporating the fault network into a more detailed geological model of the CarbFix2 reservoir using the 3/4D visualization capabilities of Leapfrog Geothermal.

- The functionality of iTOUGH2 extends beyond what was used in this work and further experimentation with the inverse modelling capabilities for the TOUGH2 code may help to further constraint model parameters. More particularly parameter sensitivity analysis as well as uncertainty propagation analysis will be performed to quantify the impact of the grid and rocktype parameters on the size of the carbon storage reservoir at the CarbFix2 site, and the thermal breakthrough at the production zone.

- The work presented here lays the groundwork for the development of a fully coupled reactive transport model of the CO_2 and H_2S injection into the CarbFix2 reservoir. Once geochemistry is implemented, the model will aim to evaluate the fluid-rock interactions under reservoir conditions, quantify mineral sequestration processes in basalts, as well as determine the impact on the reservoir porosity and permeability.

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