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Modelling the Complex Structural Features Controlling Fluid Flow at the CarbFix2 Reinjection Site, Hellisheiði Geothermal Power Plant, SW-Iceland

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ABSTRACT

Injection of CO_2 and H_2S emissions from the Hellisheiði Geothermal Power Plant, SW-Iceland, as part of the CarbFix project, has been taking place in the Húsmúli reinjection zone since 2014. To study the fate of the dissolved CO_2 and H_2S in the geothermal reservoir, a large-scale three-dimensional model centered on the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone is currently being developed. This model will be used to investigate the flow-paths of the injected fluid, the depth to which the injected fluid circulates, and the geochemical reaction between the injected acidic fluid and the basaltic host-rock along the flow path.

Injection of separated water from the power plant started at the Húsmúli injection site in 2011 and a tracer test was conducted at the site in 2013-2015. Simple flow path models using tracer recovery data from that test indicate that production wells exhibiting significant tracer recovery could be seriously affected by the injection of cooler fluids (cooling of up to 25-30°C). However, monitoring data collected since large-scale reinjection started at Húsmúli in late 2011 doesn't indicate any significant cooling of the production wells monitored, which contradicts the cooling predictions of these simple models. This indicates that a more complex representation of the subsurface at Húsmúli is required to model the flow of the injected fluid.

The work here presents the preliminary efforts to constraint the pure water flow model against the 2013 tracer test data available using the TOUGH2 non-isothermal flow simulator. It was found that to match the tracer returns, strong anisotropy controlled by large extensional and strike-slip faults is necessary in the model, which act as preferential pathways for the fluid. In addition, it was found that a dual porosity approach was required to replicate the fast and strong recovery of tracers found in wells at Skardsmýrarfjall. The method of Multiple Interacting Continua (MINC), a generalization of the dual-porosity concept used here, allows for a better numerical approximation of the flow in a fractured continuum and includes transient fracture-matrix interactions.

This work will be used as the basis for a fully coupled reactive transport model to capture the mineralization processes of the injected, dissolved CO_2 and H_2S along the flow path, and to estimate the extent of the effective storage area of the basaltic host rock at Húsmúli. The impact of long-term reinjection of separated water on the Skardsmýrarfjall production area is also of interest here. This model will be used to estimate any potential adverse effects on the enthalpy of production at Skardsmýrarfjall as part of the resource management of the Hellisheiði geothermal resource.

1. INTRODUCTION

Carbon capture and storage (CCS) technologies are a combination of technologies which captures and stores 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 injection of dissolved CO_2 into fractured rocks for mineral sequestration (Matter *et al.*, 2016). The benefits 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). In 2014, following the success of the CarbFix pilot injections (Matter *et al.*, 2016), the project was scaled up, as part of the EU funded CarbFix2 project. Since then, injection of otherwise emitted CO_2 and H_2S has been an integral part of the operations at the Hellisheiði Geothermal Power Plant in SW-Iceland (Figure 1). At current rate, about 10,000 tonnes of CO_2 are injected annually along with about 5,000 tonnes of H_2S, but this amounts to about 30% of the CO_2 emissions and about 70% of the H_2S emissions from the plant (Sigfússon *et al.*, 2018). 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 (Figure 2).

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 include 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-path of the injected fluid and to estimate the hydrological parameters of the model required to match the available field data. The model is calibrated against recovery curves from a tracer test conducted in 2013, prior to the CO_2 injection. The focus will be on the tracer injection from well HN-17 and recovery curves from wells HE-31, HE-48, HE-44, HE-33, HE-46, and HE-05 in the Skardsmýrarfjall area. This is because well HN-17 intersects the same structures as the injection well currently used for the gas injection, well HN-16, and the recovery return from HN-17 are characteristic of the flow pattern at Húsmúli.

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, graphical post-processing and analysis of the TOUGH2 model which allows minimal manual input editing.

2. GEOLOGICAL CONTEXT

2.1 Regional and Tectonic Settings

The Hellisheiði geothermal field lies within the Hengill volcanic system of the western volcanic zone (WVZ) in SW-Iceland. (Figure 1). Hengill volcanic center is located at a triple junction where two active rift zones meet a seismically active transform zone. It is located between the Western Volcanic Zone (WVZ), the Reykjanes Peninsula Rift (RPR), and the South Iceland Seismic Zone (SISZ) (Figure 1).

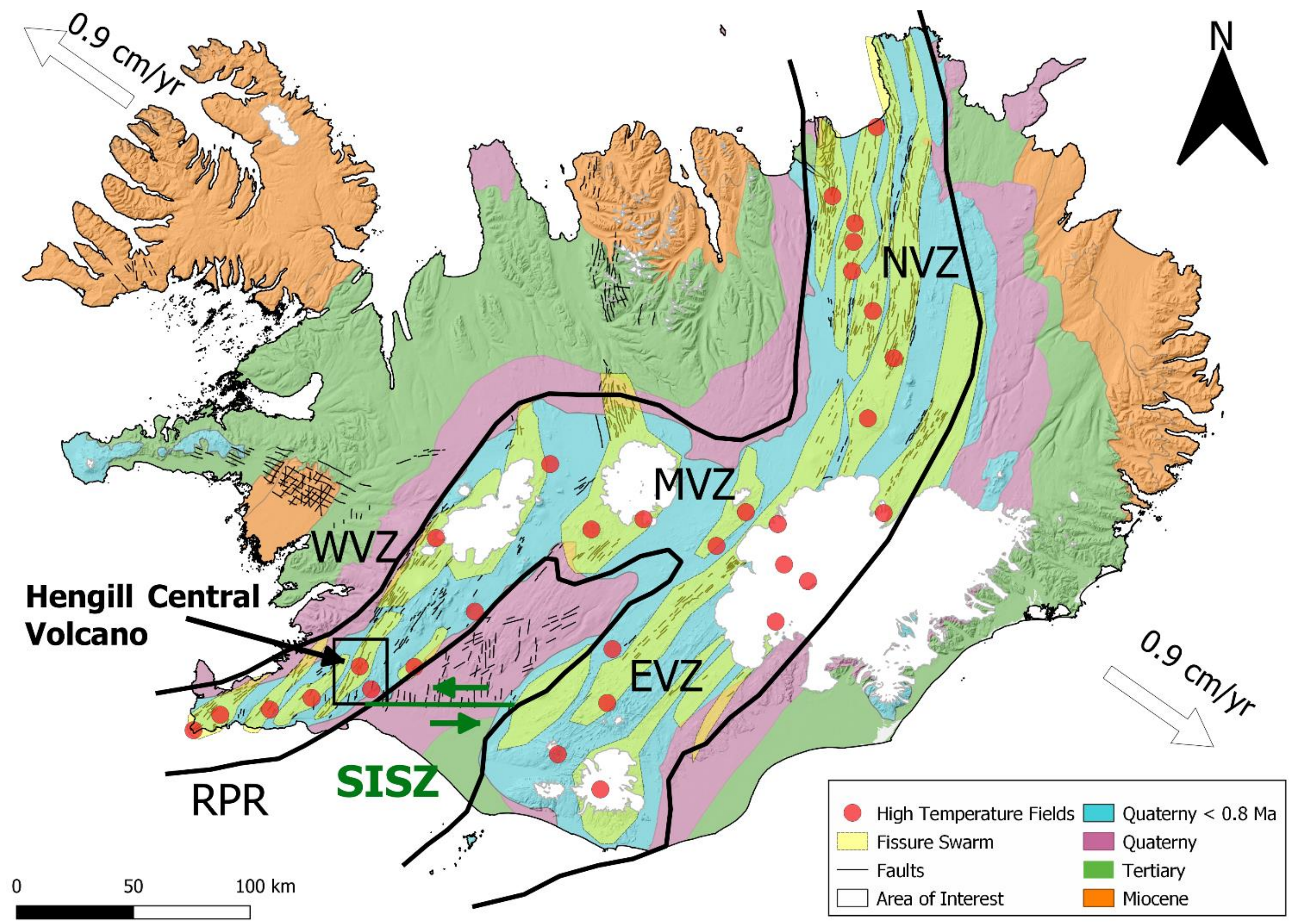

Figure 1: Geological map of Iceland showing the location of the active rift, volcanic, and transform zones (WVZ = Western Volcanic Zone, RPR = Reykjanes Peninsula Ridge, MNZ = Middle Volcanic Zone, EVZ = Eastern Volcanic Zone, NVZ = Northern Volcanic Zone, SISZ = South Iceland Seismic Zone, TFZ = Tjörnes Fracture Zone). The black box shows the location of the Hellisheiði Geothermal Field.

The Hengill central volcano is a complex of fissure swarms and volcanoes resulting from rifting tensional forces causing magmatic intrusions and the formation of a graben structure parallel to the rift (Hardarson *et al.*, 2010). It occupies the central part of a 60-100 km long and 3-5 km wide volcanic NE-SW trending fissure swarm (Franzson *et al.*, 2010). The rift spreads at an average speed of about 2 cm/year and NNE rift-parallel normal faults, eruptive fissures, and dykes develop within the fissure swarm. 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).

The Hengill volcanic system is at the intersection of the rift fissure swarm and the transform zone of SISZ. The SISZ is oriented EW, it is about 10-15 km wide and 70-80 km long and takes up the transform motion between the Western (WVZ) and the Eastern Rift (EVZ). The left strike slip faults of the SISZ is compensated by ruptures mainly along N-S right strike-slip faults, a common phenomenon known as bookshelf faulting (Einarsson, 2008).

These tectonically different zones meet at the Hengill triple-junction and define the structural features found at Hellisheiði, which largely influence the regional and local subsurface flow.

2.2 Hellisheiði geothermal field

The Hellisheiði geothermal field is located on the southern flanks of the Hengill central volcano and is characterized by high heat flow and extensive geothermal activity associated with shallow level crustal magma chambers or dyke swarms. The Hellisheiði Power plant is a combined thermal energy and electricity power plant consisting of six 45 MWe high pressure and one 33 MWe low pressure turbine generator units and a 133 MWth thermal energy production unit. It was commissioned in 2006 with the installment of two 45 MWe turbines, with additional turbines and thermal power plant added in 2010 and 2011. Currently the power plant is in operation at near full capacity. 61 production wells and 17 reinjection wells have been drilled in the Hellisheiði geothermal field to provide steam for the power generation, and for separated water disposal (Figure 2).

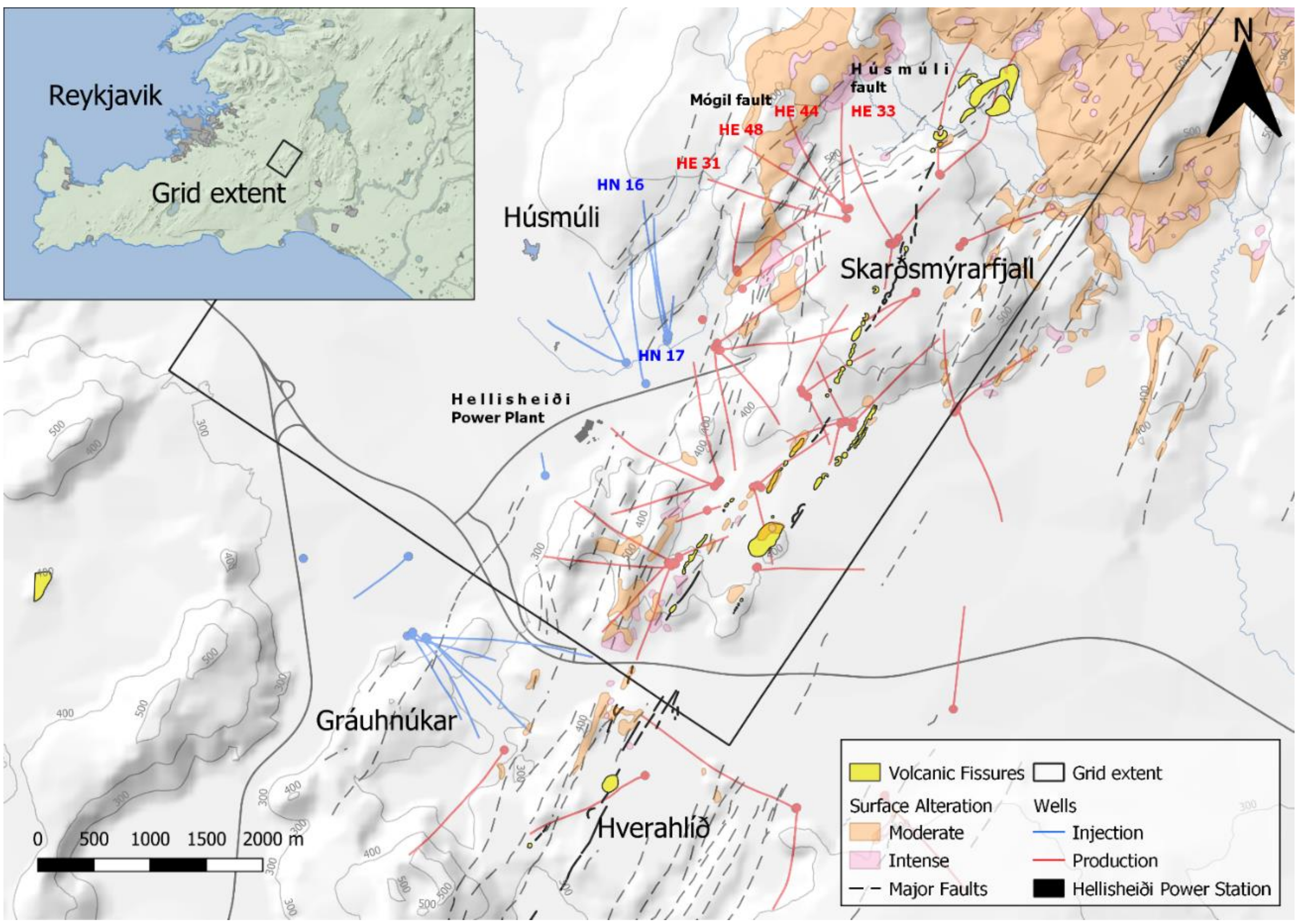

Figure 2: Hellisheiði Geothermal Field and Húsmúli reinjection site in the northwest sector of the field.

The subsurface stratigraphy at Hellisheiði consists of alternating successions of hyaloclastite formations from glacial periods and lava sequences formed during interglacial periods. Intrusive rocks dissect the succession at a depth lower than about -500 meters above sea level (masl) and become dominant part of the strata below ~ -1500 masl (Franzson *et al.*, 2010). Two main reinjection zones are utilized in the Hellisheiði field: Gráuhnúkar and Húsmúli. The Gráuhnúkar reinjection field was commissioned in 2006 and the Húsmúli field in 2011 (Kristjánsson *et al.*, 2016). The Gráuhnúkar field is located SW of the production field and consists of six reinjection wells, and the Húsmúli area is located on the north-western edge of the field (Figure 2). The Húsmúli site is the main injection site for the field and accounts for roughly 60% of the total reinjection, with annual reinjection of about 12 Mt of geothermal brine and condensate (~60-80 °C) (Snæbjörnsdóttir *et al.*, 2018).

2.3 The CarbFix2 Injection Site at Húsmúli

The Carbfix2 injection site is located at the Húsmúli site in the northern part of the Hellisheiði field, at the western flanks of the Hengill volcanic system (Figure 2). The main injection well for dissolved gases, HN-16, is located at the mouth of Sleggjubeinsdalir Valleys and is in close communication with three production wells, HE-31, HE-48, and HE-44 located at the SW-part of the Skardsmýrarfjall Mountain (Figure 2). The wells in the Skardsmýrarfjall production zone reach depths ranging from about 2200-2700 m and typically produce liquid dominated fluids with enthalpies comprised between ~1100-1250 kJ/kg (Snæbjörnsdóttir *et al.*, 2018).

3. STRUCTURAL CONTROL AT HÚSMÚLI

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 (Figure 2). 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 characteristics albeit recent studies has 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).

On the surface two large NNE trending normal faults have been identified at Húsmúli; the Mógil fault and the Húsmúli fault which makes up the western part of the Sleggubeinsdalir Valleys (Figure 2). However, the fracture system at Húsmúli is more complex at depth, where a shear system linked to the SISZ transform zone oriented in various directions influences the flow paths (Khodayar *et al.*, 2015). The reinjection wells at the Húsmúli site target this heavily fractured area. Additional work is currently being carried out to further identify and characterize these tectonic features.

3.2 2013 Tracer Test

A comprehensive tracer test was conducted during the 2013-15 period at the Húsmúli reinjection site to define the hydrological flow paths and to provide data to evaluate the risk of thermal breakthrough between injection and production wells (Kristjánsson *et al.*, 2016). The tracer test involved the injection of different naphthalene sulfonic acid (NTS) tracers into six different injection wells located in both the Húsmúli and Gráuhnúkar reinjection areas (Kristjánsson *et al.*, 2016). This paper will focus on the 1,3,6-NTS tracer injection into well HN-17 located at Húsmúli. However, conclusions from the other tracer injection have been included in the development of the conceptual model of Húsmúli. The tracer injection into well HN-17 occurred on 20 June 2013 and was followed by daily sampling of the 14 closest monitoring wells, starting the same day the first injection took place. Frequent analysis tracked first arrivals of different tracers and gradually additional wells were included to the monitoring program until all producing wells were included (Kristjánsson *et al.*, 2016). 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.

Table 1: Location of major and minor feeders in injection and production wells for tracer injection in HN-17

HN-17 *Elevation (masl)*		*Tracer detected in*	*Elevation (masl)*		*Arrival time*	*% of tracer arrived*
major feeders	*minor feeders*		*major feeders*	*minor feeders*		
-815; -1100; -1426	-510	HE-31	-1044; -1413; -1577	-	14 days	26%
		HE-48	-859; -1222	-465	18 days	21%
		HE-44	-1432	-332; -1609	53 days	8%
		HE-33	-566	-384; -744	115 days	<1%
		HE-46	-725; -790; -1181; -1946	-1810; -1873	222 days	1.7%
		HE-05	-927	769; -1105; -1340	536 days	<1%

Table 1 and Figure 3 show that the tracer arrival time in well HE-31 took 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 (Kristjánsson *et al.*, 2016). After 138 days the tracer reached well HE-33, but only at a very low concentration (Figure 3). Limited recovery observed in the wells adjacent to the south (HE-05 and HE-46) indicates a strongly anisotropic permeability at Húsmúli (Kristjánsson *et al.*, 2016).

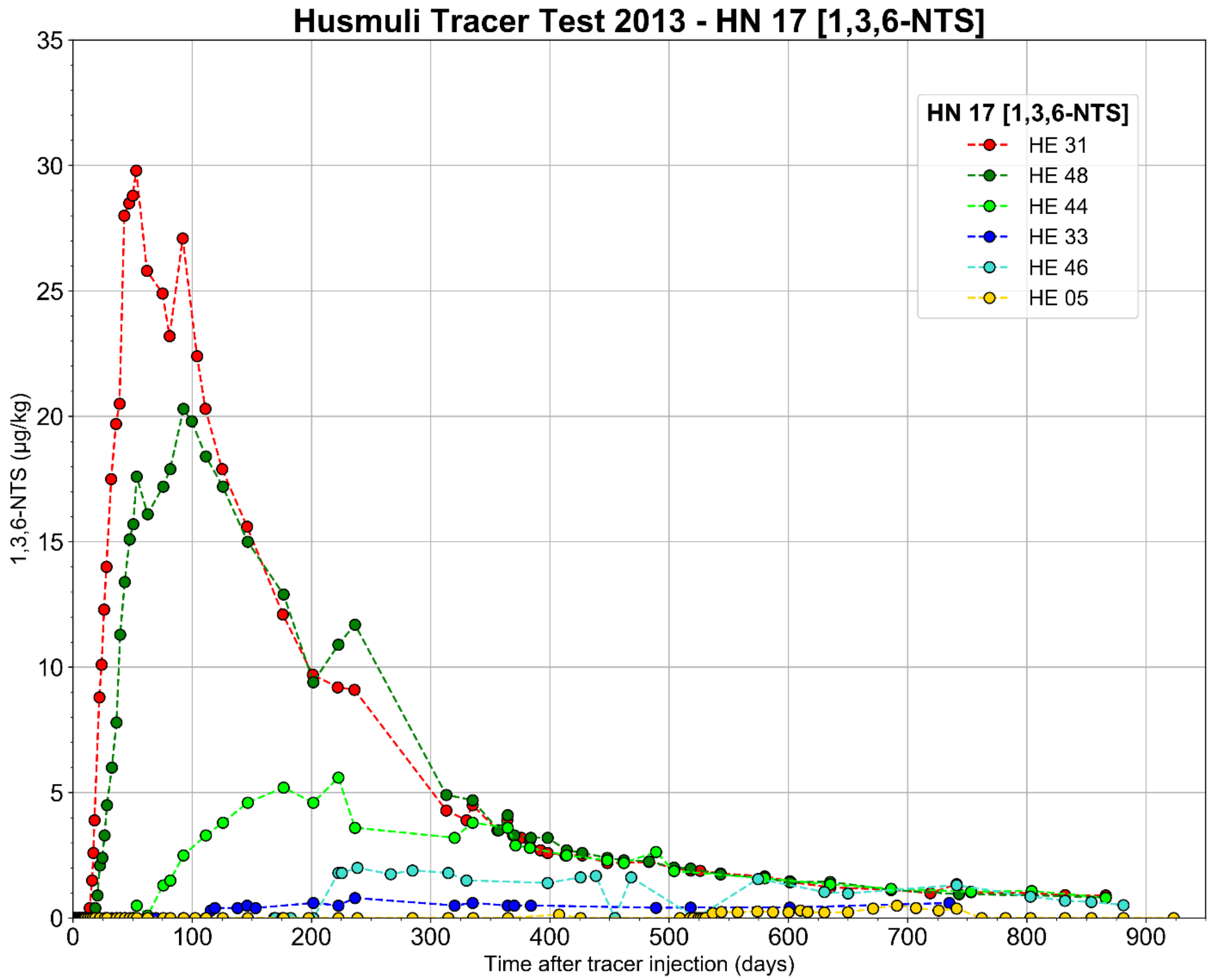

Figure 3: Recovery of 1,3,6 NTS injected into well HN-17 in Húsmúli through Hellisheiði production wells.

3.3 Flow paths at Húsmúli

The multidisciplinary study presented by Khodayar et al. (2015) analyzed the results of the tracer test data with available subsurface data, aerial photographs, and seismic events. This work has helped identifying the fracture system(s) which appear to guide the tracer flow paths. It correlated the feedzones of the injection and production wells in Húsmúli and Skardsmýrarfjall with subsurface tectonic structures in order to characterize the flow path of the tracer and identifying carriers/barriers structures. This study has found that out of the two fracture systems identified at Húsmúli, an NNE extensional rift-parallel structures blended with Riedel shears of the transform zone striking mainly northerly, ENE, and NW, the latter controls the tracer flow paths at Húsmúli (Khodayar et al. 2015).

The analysis suggests that the following structures of the Riedel shears system controls the tracer flow paths and tracer return from the re-injection to the receiving wells (Khodayar *et al.*, 2015):

- The ENE set (structure 1-5 in Figure 4) seen among secondary fractures on tele viewer image logs is the main carrier of tracer and appears to be the most favorable flow path for the tracer. The main feeders of the reinjection well (HN-17 included) fall on the hanging walls of the ENE faults. These faults extent from the reinjection zone to the edge of the Skardsmýrarfjall 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 (structures 6-8 in Figure 4) are also good carriers and channel the flow to and from the ENE faults.
- The NW faults (structures 9-11 in Figure 4) southwestward 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/semi barrier structures, delaying the tracers travel time across the fault.

This tectonic configuration will be included in the modelling study of the flow at the CarbFix2/Húsmúli reinjection site. NNE trending faults identified at the surface in the vicinity of Húsmúli reinjection site have also been included in the model (Figure 6) to follow the overall structures of the area (Gunnarsdóttir and Poux, 2016).

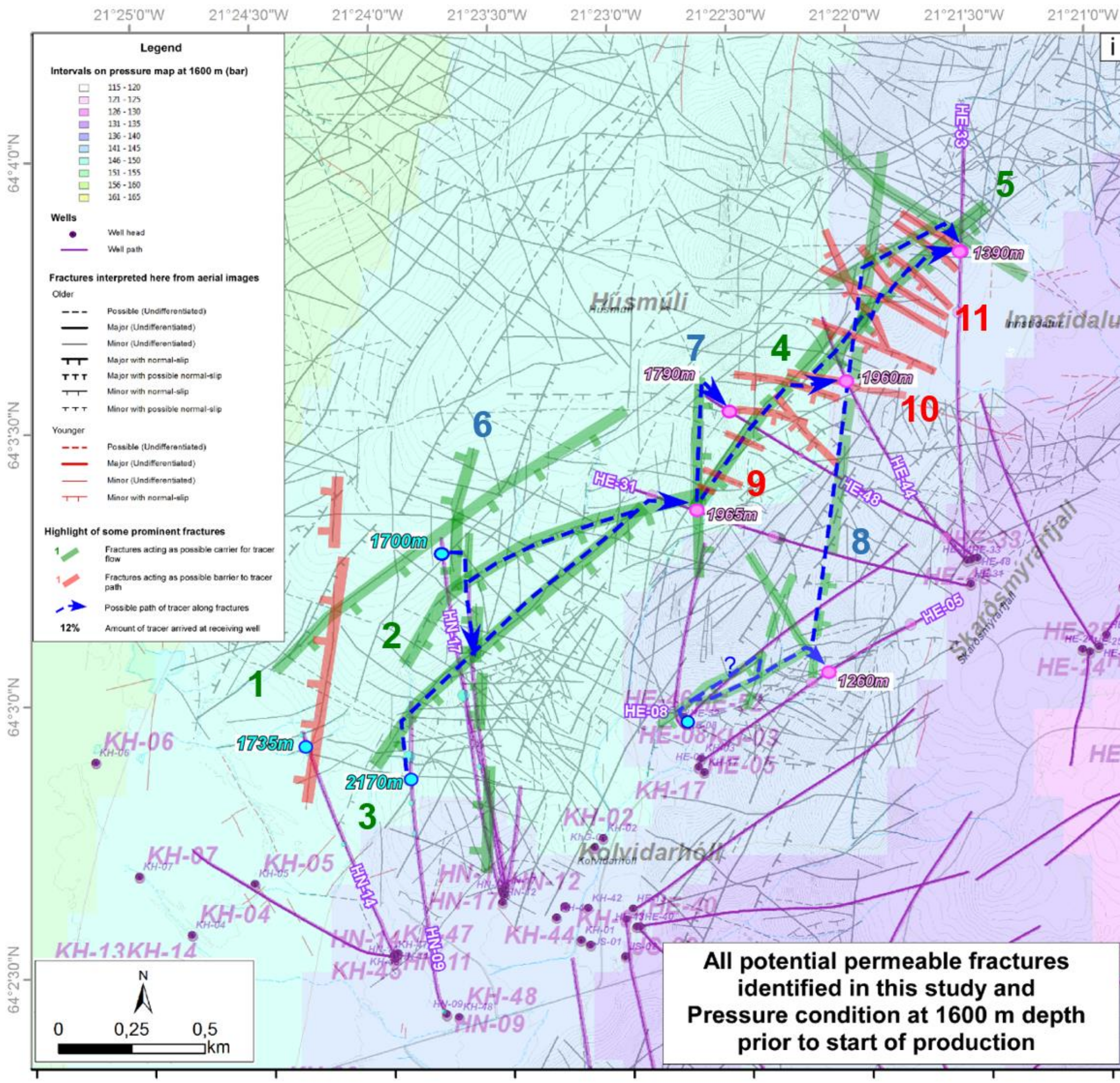

Figure 4: Structural interpretation of possible tracer flow paths from individual injection well (modified from Khodayar *et al.*, 2015).

3.3 Previous modelling work

3.3.1 Simple flow-channel model

The first effort to model the tracer test data was done using simple flow-channel model connecting respective feed-zones in the reinjection and production wells showing the largest tracer recovery. These results are presented along with cooling predictions for the production wells (Kristjánsson *et al.*, 2016).

The properties of each flow channel, along with injection and production rates, include flow channel length (fixed), flow channel cross-sectional area (Aφ) and flow channel dispersivity (αL). The model results show a good correspondence between the observed and simulated tracer recovery. The dispersion term in the model for the flow channel is relatively large which may indicate that the flow path consists of a complex fracture networks rather than simple fracture flow paths. In addition, thermal predictions from the flow-channel models predicted significant cooling in wells HE-31 and HE-48. Monitoring data has, however, hardly shown any cooling after six years of large-scale re-injection of geothermal brine and condensate.

The modelling work reported in Kristjánsson *et al.* (2016) concludes that although it was able to match the tracer recovery, the cooling predictions are too pessimistic in some cases and a more complex representation of the subsurface at Húsmúli may be required to model the flow of the injected fluid. The paper suggests the flow paths may consist of fracture networks where the fluid is in contact with much greater rock surface area the simple flow-channel models assume. It also indicates that the distance and the temperature encountered between the injection and production may be influenced by the injected fluid sinking to greater depth, due to higher density is not captured appropriately by a simple flow channel.

3.3.2 Homogeneous, single, and mutli-channel model

A simplified three-dimensional reservoir model of the tracer injection to investigate the flow paths at Húsmúli was developed in 2018 as a requirement for a Master of Science degree (Tómasdóttir, 2018, Snæbjörnsdóttir *et al.*, 2018).

The first approach tested whether the tracer recovery curves could be reproduced by a homogeneous model. The second approach "single channel model" tested whether the inclusion of a more permeable flow channel extending from the injection well to the production wells could result in a more realistic recovery. The third approach "multi-channel model" tested a system with two narrower flow channels directly connecting the two individual feedzones in the wells.

The results showed that the recovery cannot be simulated with a homogeneous approach. Good results for both the tracer arrival times and concentration peaks were obtained using the single and multiple flow channel approaches. The best fits were obtained by assigning high permeability and low porosity values in different section of the flow channel(s) (Tómasdóttir, 2018, Snæbjörnsdóttir *et al.*, 2018). The low porosity represents the active pore volume within the channel bounds, i.e. the volume of the actual permeable fractures. The channels therefore represent of fractured zones within the medium.

4. DESCRIPTION OF THE NUMERICAL MODEL

A three-dimensional model centered on the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone was developed as part of the CarbFix2 project. The goal is to develop a field scale fully coupled reactive transport model of the reinjection of the mixture of dissolved gases (65% CO_2 and 35% H_2S) and to simulate the fate of the injected gas-charged fluid. To identify and characterize the flow path at Húsmúli and estimate hydrological parameters such as permeability and porosity a transport model was developed to constraint the flow at Húsmúli and calibrated against the available data prior to the inclusion of the reactive chemistry.

4.1 Grid Structure

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). Local refinement of the grid was made to improve the representation of the geological structures and to better handle the dense spacing of the wells in the field (e.g. reduce the number of wells and feedzones located in the same block) while limiting the number of blocks used (and thus minimizing the computational cost of the simulation). 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 NNE direction parallel to the rift and some of the large NNE faults.

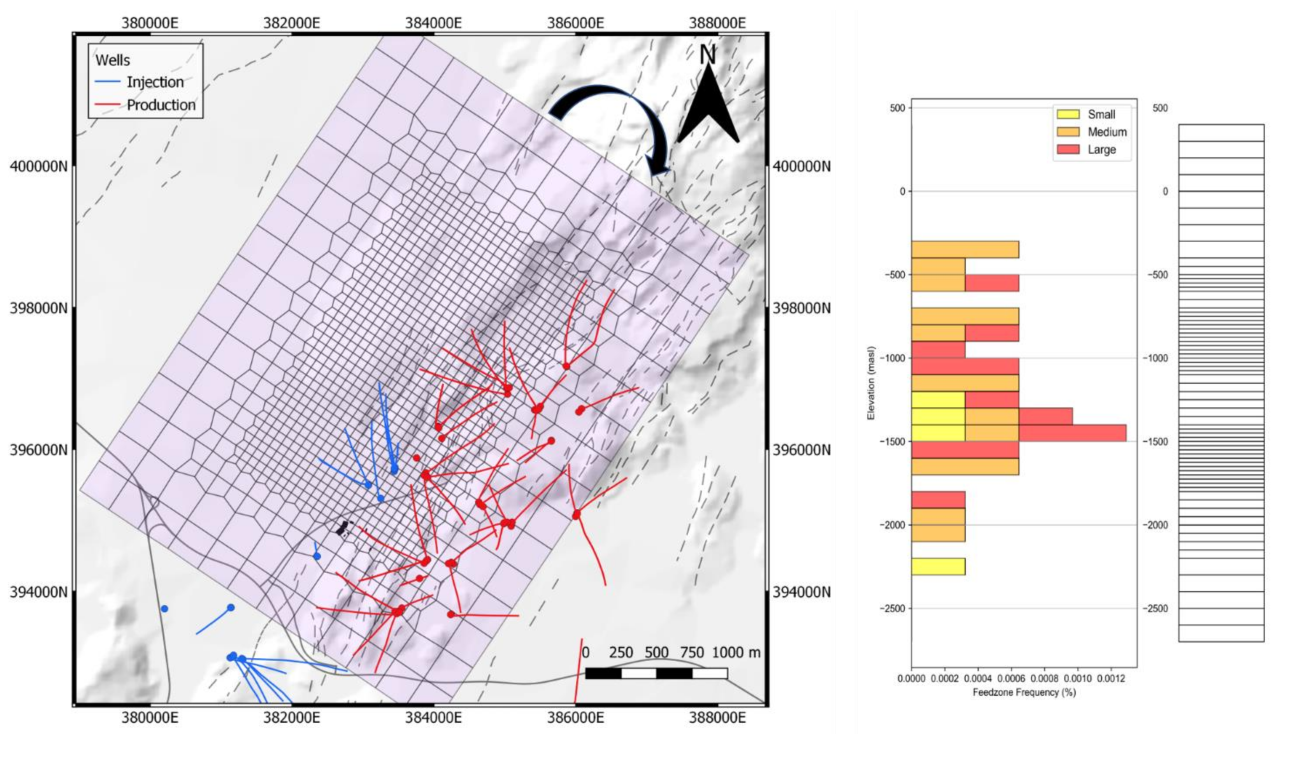

Figure 5: Grid structure, feedzones distribution, and layer structure of the model for the Húsmúli model HU_81600.

4.2 Single Porosity Approach - Rock-Type Assignment

The flow in the fractured media at Húsmúli in the numerical model is idealized and the physical parameter of the fracture and the rock matrix in each block (such as permeability and porosity) are averaged over the model blocks and defined as a rock-type parameter. This is known as a single porosity approach and is commonly used for geothermal applications.

4.2.1 Rock-type distribution and permeability

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, hyaloclastic, dyke intrusions, faults, alteration layers, etc. It is directly based on the leapfrog geological model of Hellisheiði provided by the Geoscience team from ISOR (Gunnarsdóttir and Poux, 2016). 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 2).

The permeability specified in the rock-type parameters defines the ability of the porous material to allow fluids to pass through it. It consists of the following parameters: permeability 1, permeability 2, and permeability 3 which represent the permeability in the (x, y, z) space respectively (Pruess, 1991). The rock-types of the volcanic sequence are characterized here by a traverse isotropy; permeability 1 and permeability 2 values are set as equal, meaning each rock-type has the same ability to let fluid flow through in the (x, y) space (Table 2).

Table 2: 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	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		

The grid for HU_81600 was imported in Leapfrog Geothermal and the geological sequence was assigned to the relevant blocks of the model as rock-types (Table 2).

The grid was then exported as a TOUGH2 input file with the volcanic sequence implemented. This model was then used as the base for all futures models.

4.2.2 Introducing Anisotropy: Implementation of a fault network

Individual tectonic structures are believed to be critical to describe the fluid flow at Húsmúli (§3.3) and were explicitly represented in the numerical model (Figure 6). This introduces the anisotropy in the model and reflects our current understanding of the tectonic structures and resulting impact on the flow paths at Húsmúli. The anisotropy in the permeability values of the fault was introduced by modifying the values of permeability 1 and permeability 2 in the rock-type parameter section. Permeability 1 is assigned a high value and represents the flow along the fault strike, whereas permeability 2 is set at a small value and represents the flow across the fault face (Table 3). This captures the ability of the fault to act as a carrier structure and channel the flow along the fault (Figure 7 a).

In the present model, faults are set as vertical as literature suggest the structures are near-vertical.

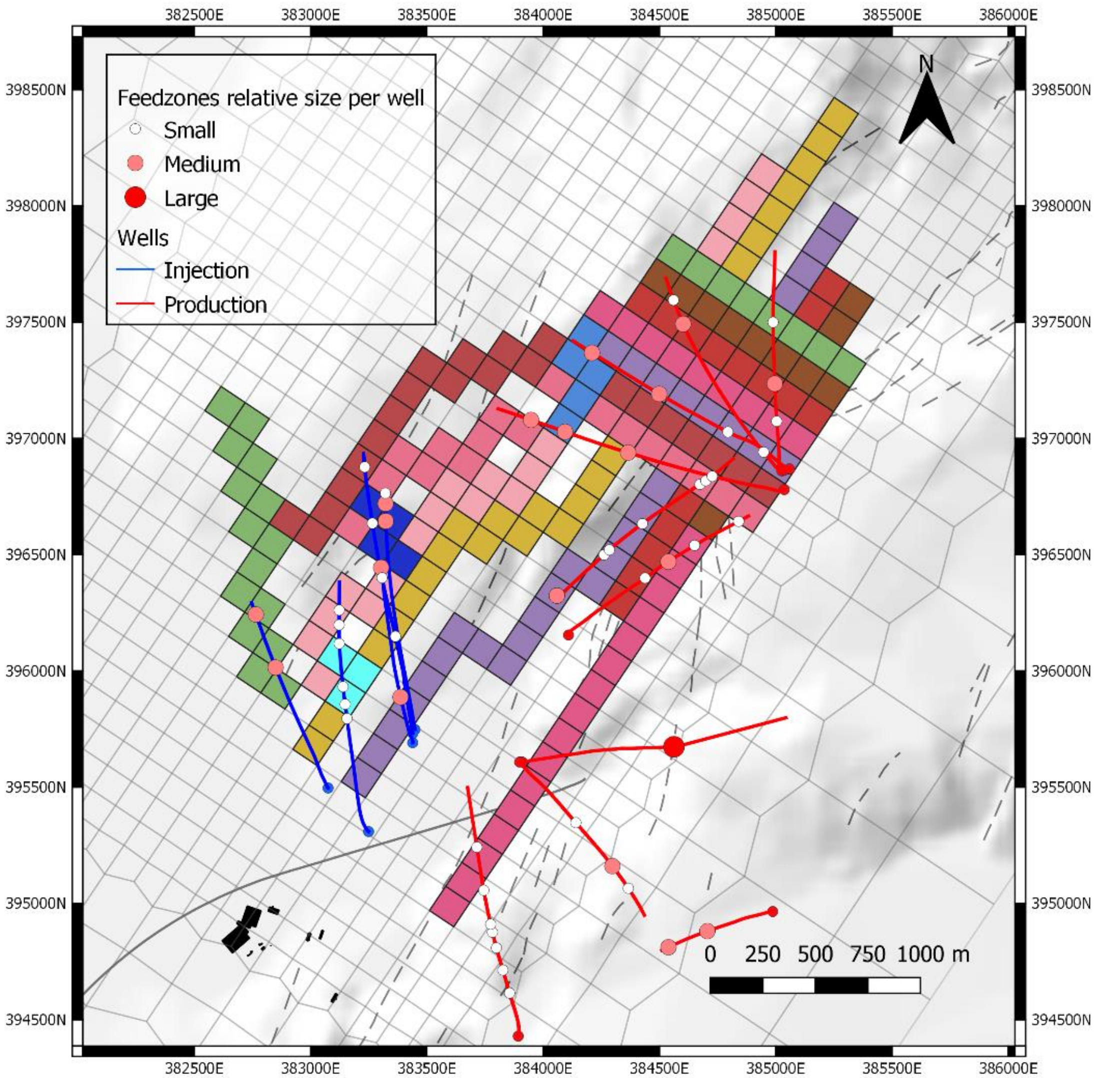

Figure 6: Rock-type distribution of the tectonic features implemented in HU_81600.

4.2.3 Fault intersection

Fault geometry and fault intersection are also an important aspect to consider and impact the flow direction in a complex fault network; If the flow path is parallel to a fracture plane and runs on the hanging wall block of the fault, the structure acts as a carrier (ENE, and northerly structures) (Khodayar et al. 2015), facilitating the travel path (Figure 7 a). But if the tracer flow path is perpendicular to the fracture plane the fracture may acts as a barrier of the flow (Khodayar et al. 2015) (NW structures) (Figure 7 a). General characteristics such as the orientation of the hanging wall were defined for each fault (Table 3). The "open face" of the fault intersection was assigned the permeability 1 value whereas the "closed face" is assigned a permeability 2 value (Figure 7 b).

Table 3: Example of the characterization of the tectonic structure in the modelling workflow.

Name	*Type*	*Hanging wall*	*Order*	*Permeability 1* [$\times 10^{-15}$ m^2]	*Permeability 2* [10^{-15} m^2]
Fault_diver_001	Extensional	SE	1	1000	50
Fault_barr_001	Transform	SW	2	150	15
Fault_barr_002	Transform	SW	3	150	15

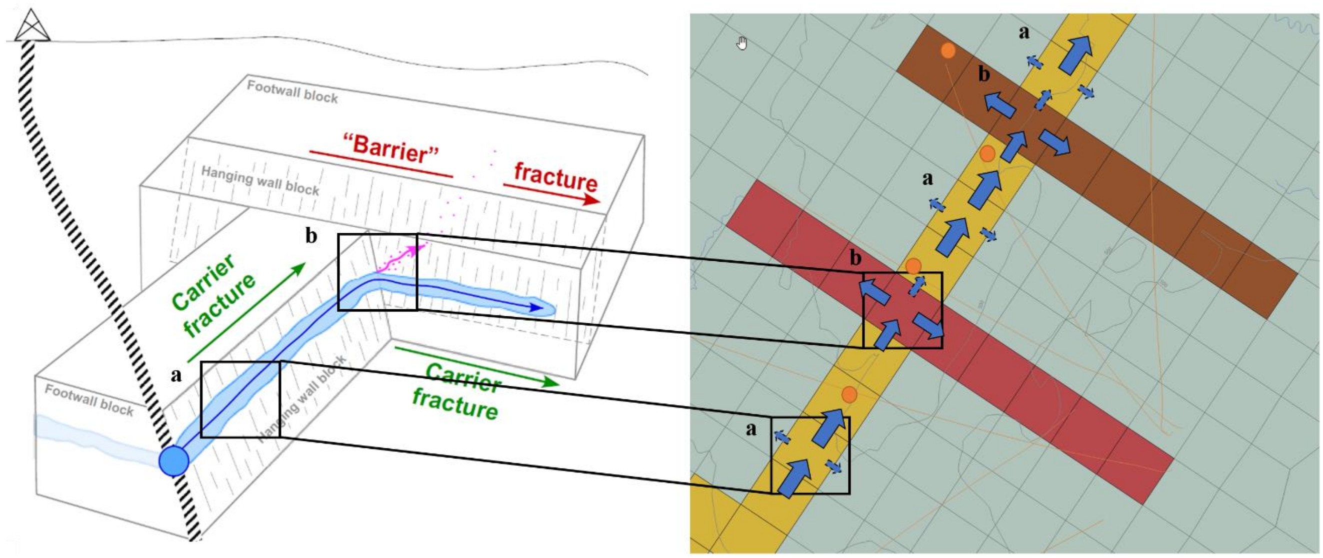

Figure 7: Conceptual model of a fault intersection (left) and implementation in the model (right). (a) Represents the ability of the fault to act as a carrier or barrier and channel the flow along the fault (modified from Khodayar *et al.*, 2015). (b) Represent the permeability assigned to the connection face of fault blocks and fault intersection blocks allowing the flow to be channeled or redirected along the strike of the fault. Blue arrows represent the mass flow between the connection faces controlled by Permeability 1 and Permeability 2.

This workflow is grid independent and only requires as input the fault strike and dipping orientation and the order of the faults. This flexibility allows testing of a wide range of structural model at a small cost with no manual input.

4.2 Dual porosity approach

In addition to the single porosity approach and after reviewing the preliminary results of the single porosity model (§5.1 and Figure 10) a dual porosity representation of the model was implemented to improve the match of the model to the tracer recovery curves. The dual porosity representation was used to capture the flow in a fractured media at Húsmúli in order to reproduce the tracer breakthrough more accurately.

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 (§4.1). The concept was introduced by Barenblatt et al. (1960) to represent the seepage of homogenous fluids in fissured rocks. In the dual porosity approach for representing a fracture network in a low permeability rock matrix, it is assumed that the fluid flows mainly through the fractures and hence 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.

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 initial 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):

$$\theta_{eff} = \theta_f V_f + \theta_m (1 - V_f)$$

Where $\theta_{eff}, \theta_f, \theta_m$ the effective, fracture, and matrix porosities respectively and V_f is the fraction of the total block volume occupied by the fractures. The matrix permeabilities were assigned a value of 1 micro-Darcy. The initial 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	2%
	Matrix 1	20%
	Matrix 2	78%
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

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 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 (Figure 8). The bottom layer of the model has been set as fixed pressure boundary to allow for pressure and temperature support during the simulation.

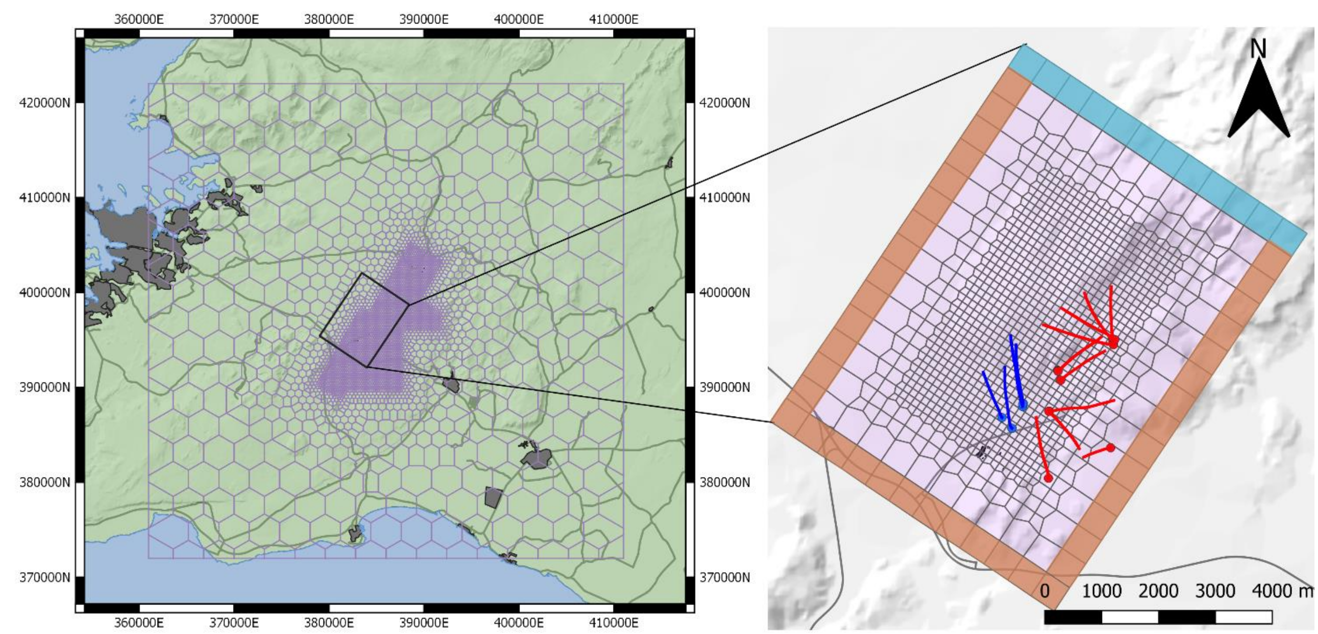

Figure 8: Grid used for the Hengill Model (Hengill_2018) (left) Lateral boundary conditions for HU_81600 (right). The blue blocks represent an open boundary whereas the brown blocks represent the edge where a closed boundary was implemented.

4.4 Initial conditions, production data and tracer injection

The simulation starts on the 15/09/2011 when reinjection of separator water started at Húsmúli and runs to December 2017 (last data available). 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. For every primary variable an interpolated value is computed for that grid point, using the barycentric coordinates, and the values of the function at the vertices of the enclosing simplex. These values were then written to an initial condition file to be used by HU_81600.

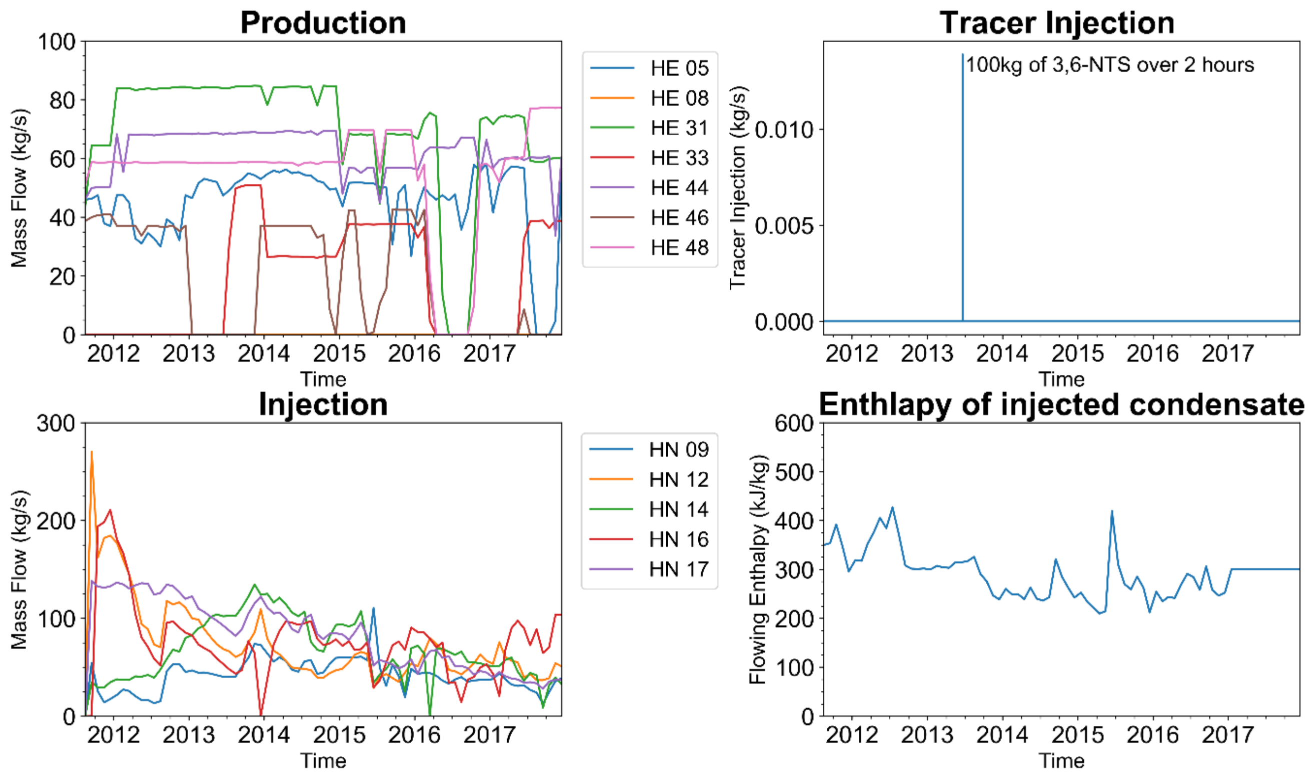

Figure 9: Production rates, injection rates, tracer injection rates (1,3,6 1,3,6-NTS), and enthalpy of the injected condensate used for the model.

Production and reinjection from the active wells at Húsmúli and the Skardsmýrarfjall production zone were implemented in the model and aim to model accurately the dynamic state of the system during the tracer test (Figure 8). Monthly mean values of injection and production rates were supplied by Reykjavík Energy as well as the enthalpy of the injected fluid. The injection and production rates over the simulation time as well as the enthalpy of the injected water for the wells which shows tracer returns is shown in Figure 9.

The simulation the tracer test is run in two successive stages; the first stage is a single water component flow simulation from September 2011 until June 2013 pre-tracer injection. This set of results provide the initial condition at the time of the tracer injection. The second stage introduces a second water component (water #2) and is run until the of the simulation period. The injection of tracer took place on 20//06/2013 when a 100 kg of tracer was injected in the system via well HN-17 over two hours and was modelled by a source term in the model. 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.

5. NUMERICAL MODEL OF THE REINJECTION AT HÚSMÚLI

5.1 Single Porosity Model results

The single porosity model produced poor results in terms of matching the tracer recovery curves (Figure 10). The tracer only appears in well HE-33 400 days after injection. After 900 days the tracer return has reached less than 1% of the recorded peak value in HE-31 (Figure 10). In the other observation wells the model results show no tracer recovery for the first three years after the tracer injection. The model results are more than an order of magnitude smaller than the observed return, both in term of arrival time and the peak concentration thus failing to capture the tracer fluid flow from Húsmúli to Skardsmýrarfjall. Attempt to increase the permeability along the main carrier were not successful.

Figure 11 shows that the flow paths of the tracer are accurately represented in the model. The tracer travels along the fault line from Húsmúli to the Skardsmýrarfjall production area as described in the conceptual model. This suggests that our conceptual understanding of the impact of the tectonic features may be appropriate but that the single porosity computational grid is not adapted to represent flow in fractured volcanic rocks.

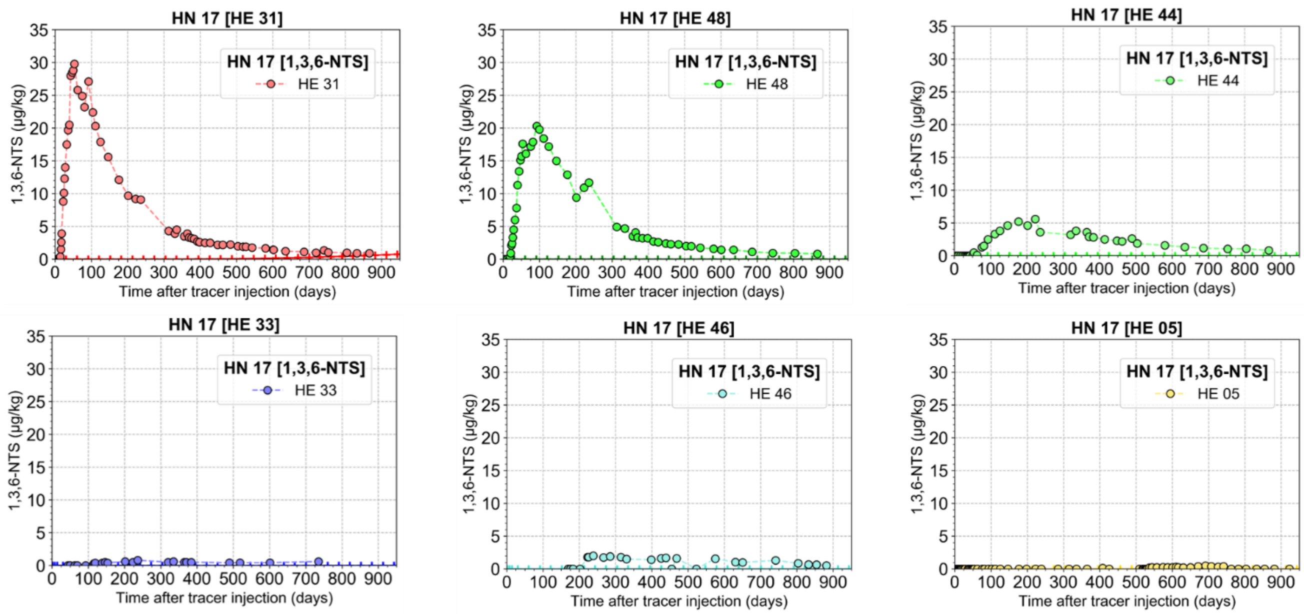

Figure 10: Single porosity model results - Tracer recovery curves for 1,3,6-NTS tracer injection. The data is represented by the colored dots and the dotted line and the model results by the colored plus sign symbol and the solid line.

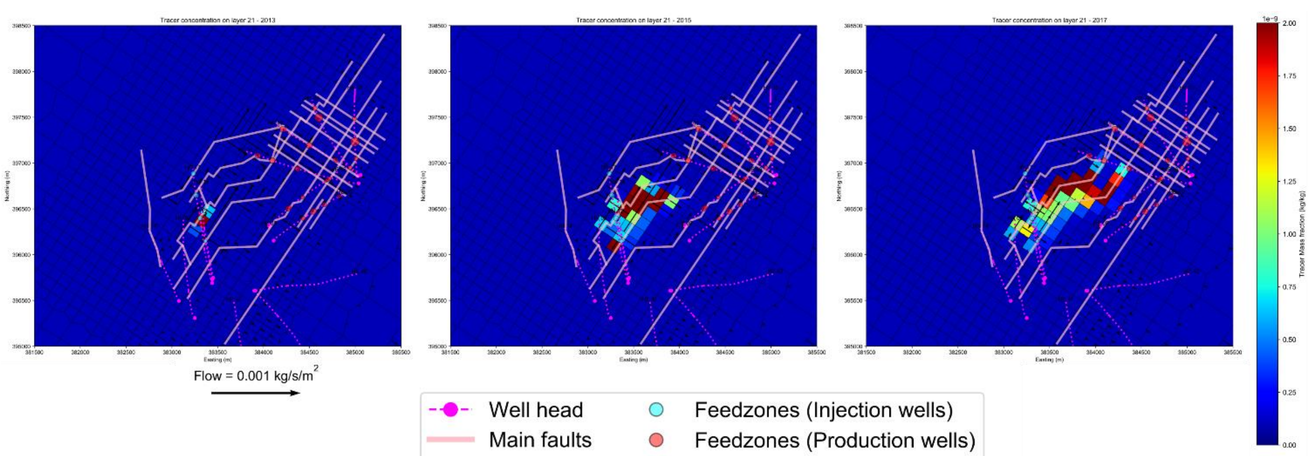

Figure 11: Single porosity model results - Tracer content in in 2013. 2015, and 2017 at an elevation of -825 masl (layers 21). The fault trace is shown in pink and the feedzones are represented by blue (injection) or red (production) dots.

5.2 Dual Porosity Model results

The dual porosity model was generated from the single porosity model using the values in Table 4. The production simulation including the 2013 tracer injection was run from 2011 to 2017. This section presents the model results for the dual porosity model. Figure 12 shows the tracer recovery curves for the double porosity model.

The match is significantly better than for the single porosity model. Both the arrival time for wells HE-33 and HE-44 are correctly matched by the model (Figure 12). The model is not capturing the tracer return for well HE-48 accurately. We believe that currently the model is not capturing the vertical flow of the tracer within the faults. The feedzones in HE-48 are significantly shallower than wells HE-33 and HE-48 (Table 1) and it appears that currently the tracer is not reaching the shallow feedzone blocks for well HE-48.

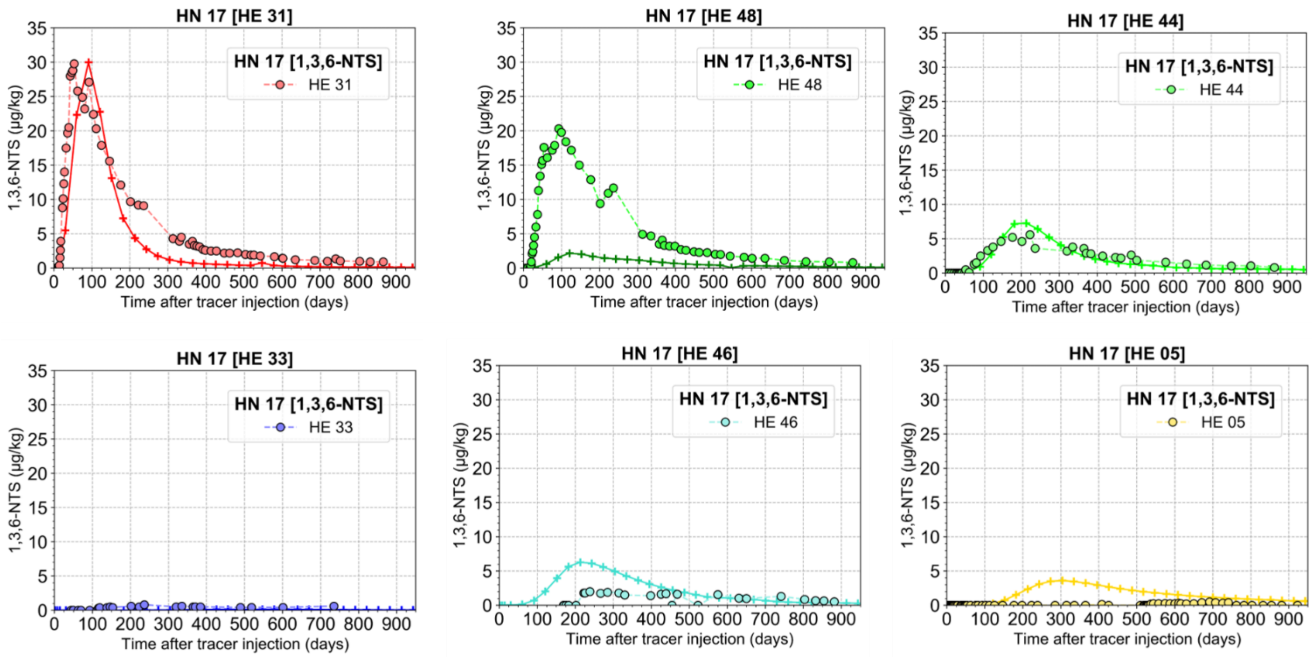

Figure 12: Dual porosity model results - Tracer recovery curves for 1,3,6-NTS tracer injection. The data is represented by the colored dots and the dotted line and the model results by the colored plus sign symbol and the solid line.

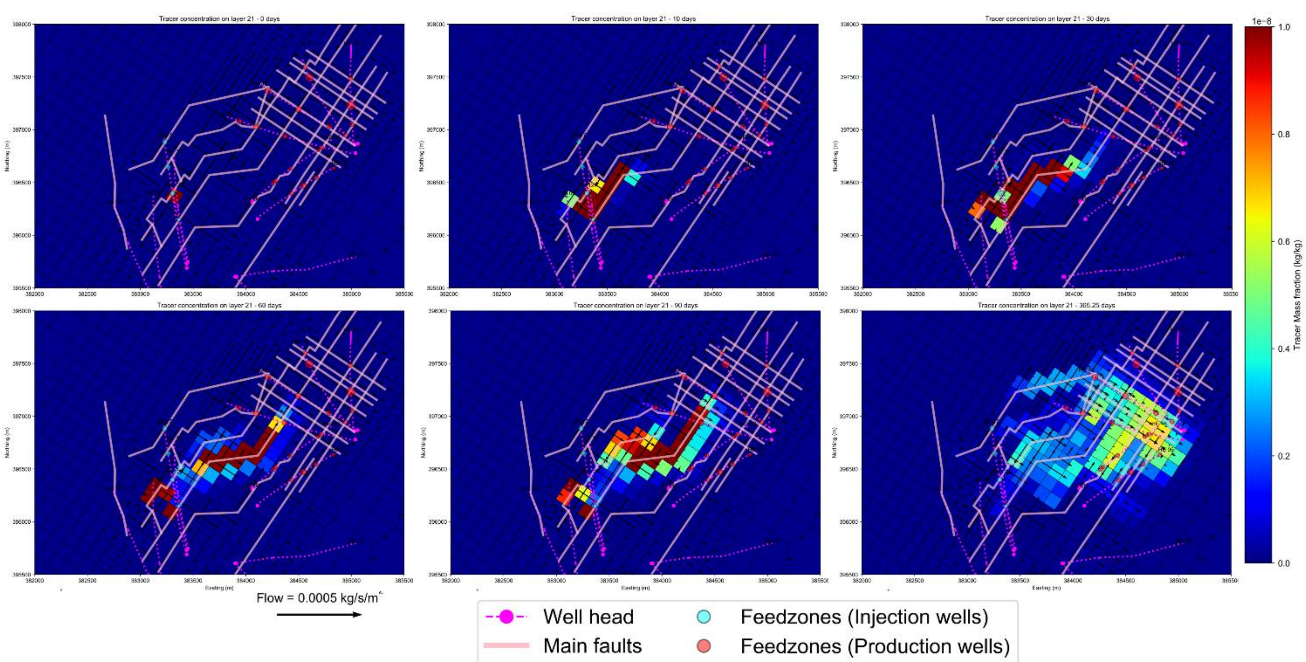

Figure 13: Dual porosity model results - Tracer content 0, 10, 30, 60, 90, and 365 days after the tracer injection at an elevation of -825 masl (layer 21). The faults are shown in pink and the feedzones are represented by blue (injection) or red (production) dots.

Figure 13 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 after approximately 30 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 in these figures.

Figure 14 shows a SW-NE cross section of the temperature (top) and tracer (bottom) distribution between the Húsmúli reinjection zone and the nearby Skardsmýrarfjall production zone intersecting the bottom feedzone of HN-17 30 (left in Figure 14) and 90 (right in) 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 14). As it travels along the fault line its temperature increases and slowly rises (Figure 14). 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 occurs much slower than changes in tracer concentration along the flow path. The area of cooling around Husmuli after two year of reinjection is present but does not spread as fast as the chemical front (Figure 14).

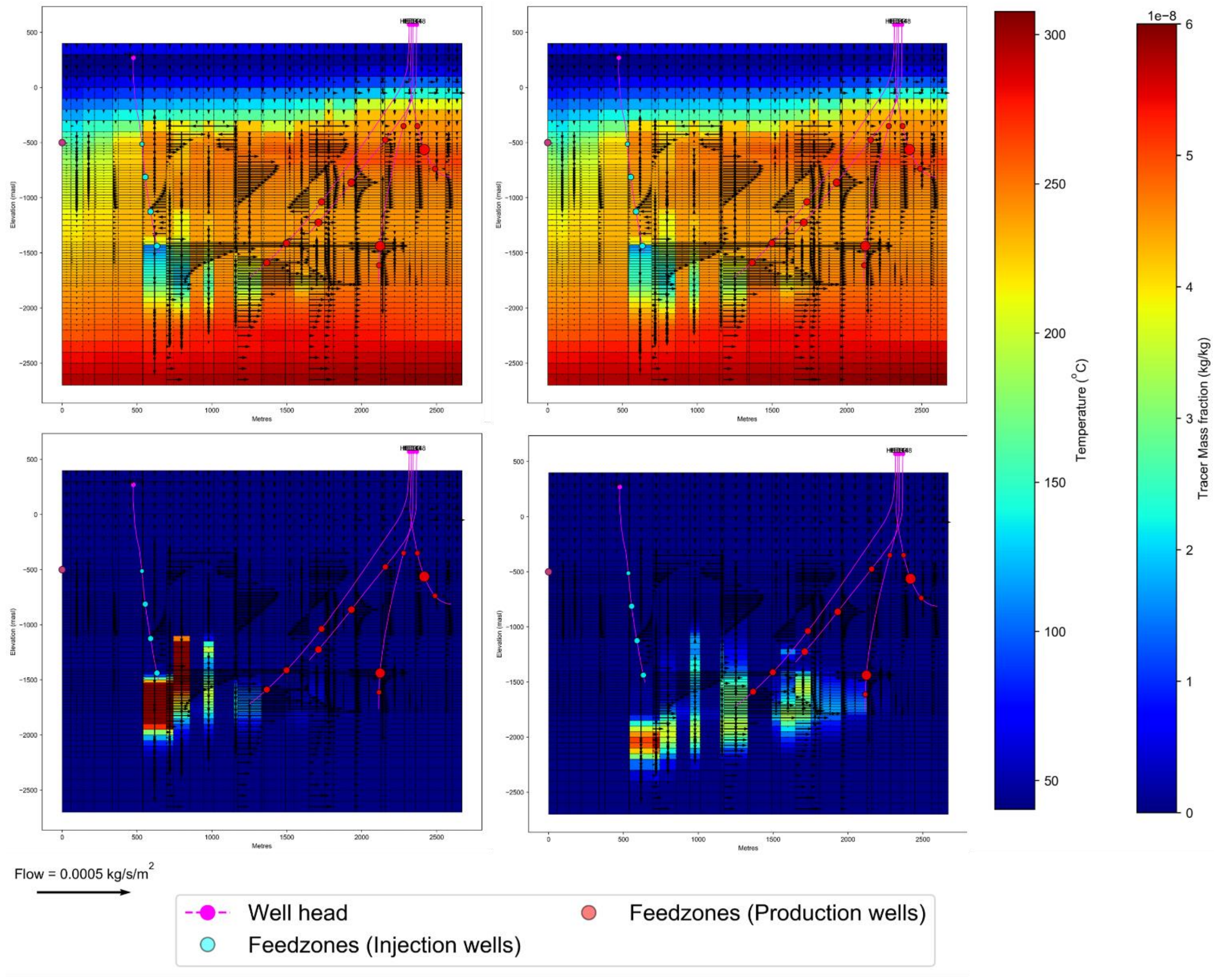

Figure 14: Dual porosity model results – SW-NE cross section of the Temperature (top) and Tracer content distribution (bottom) after 0 (a), 30 (b) and 90 (c) days after the tracer injection. The feedzones are represented by blue (injection) or red (production) dots.

Error! Reference source not found. 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 only well with a cooling trend is well HE-31with a decrease of 70 kJ/kg over the simulation period which may be too pessimistic.

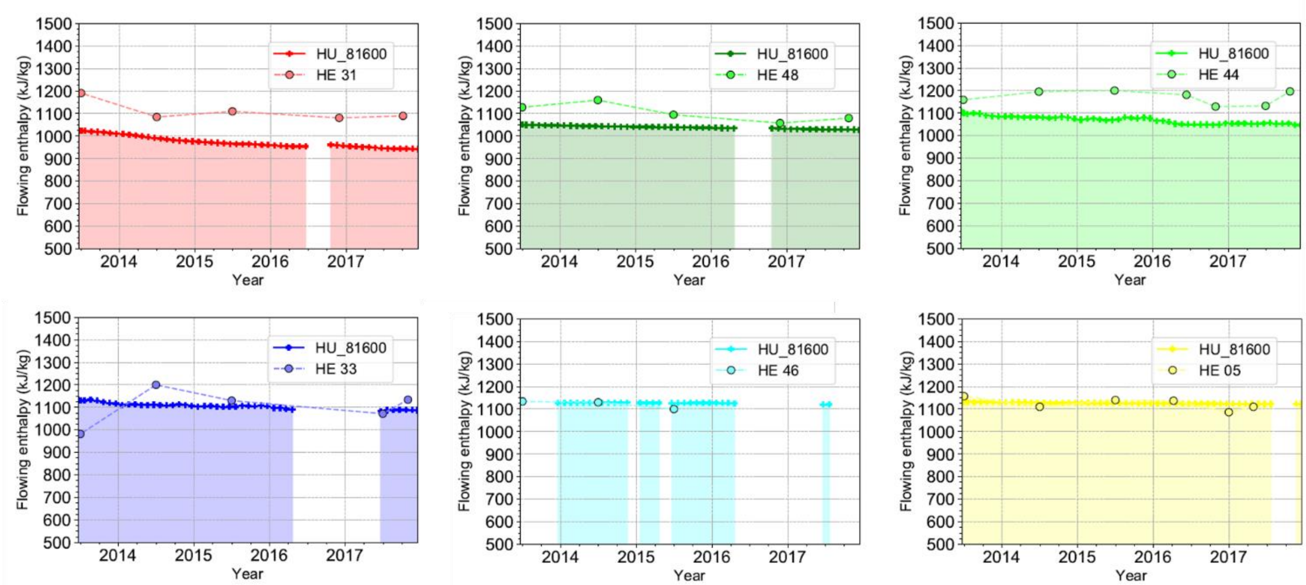

Figure 15: Dual porosity model results – Weighted flowing enthalpy evolution for the monitoring wells. The data is represented by the colored dots and the dotted line and the model results by the colored plus sign symbol and the solid line.

The impact of dual porosity approach is clear and the flow within the fractured rock at Húsmúli seems to be accurately captured. This is mainly due to the MINC partition of the grid which reduces the effective volume of the block that the fluid flows through (fractures) and here accounts for 2% of the volume of the entire block. This causes the tracer travel time between the injection well and the production wells to be significantly shorter.

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 pathway for the reinjected fluid. The flow is largely confined within these tectonic features found between the Husmuli reinjection zone and the Skardsmýrarfjall area. In addition, the flow at Husmuli is best represented by a dual porosity approach which 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 cool injected fluid and the surrounding reservoir formation; the reinjection fluid first sinks in the vicinity of the injection well 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 will be 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 and potential cooling of production wells at Skardsmýrarfjall.

The application of the work-flow 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 analyses 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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