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The geology and hydrology of the CarbFix2 site, SW-Iceland

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Abstract

Injection of CO_2 and H_2S emissions from the Hellisheidi Geothermal Power Plant, SW-Iceland, as part of the CarbFix project, is currently taking place in the Húsmúli reinjection zone. Here we present detailed descriptions of the geology of the reservoir rock in Húsmúli including descriptions of its intrusions, secondary mineralogy and sources of permeability. We further present preliminary results from a modelling study of the Húsmúli reinjection zone that was conducted to obtain better understanding of flow paths in the area. The model was calibrated using results from an extensive tracer test that was carried out in 2013-2015.

Keywords: CarbFix; SulFix; CO_2; H_2S; Hellisheidi Power Plant; Húsmúli; numerical modelling; mineralization

1. Introduction

Carbon capture and storage (CCS) technologies need to play a large role in the global response to climate change [1]. The success of CO_2 storage depends on its long-term safety. Rather than injecting captured gas directly into the storage formation, a technology to dissolve the gases in water prior or during injection has been developed through the CarbFix project. Once dissolved, the gases are no longer buoyant, improving considerably the security of the

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injection and making it possible to inject CO_2 into fractured rocks, such as basalts along the ocean ridges and on the continents [2, 3]. Furthermore, this method makes it possible to co-inject water soluble gases such as SO_2, H_2S and HF, and thereby lowering the gas capture costs [2, 4, 5]. For example, results obtained so far from the CarbFix pilot injections [e.g. 6, 7, 8] agree with natural analogues [e.g. 9], laboratory experiments [e.g. 10, 11] and reactive transport simulations [12] indicating rapid mineralization of the injected CO_2.

In 2014, following the success of the CarbFix pilot injections, the project was scaled up, in part 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 Hellisheidi Geothermal Power Plant in SW-Iceland. At current rate, about 10,000 tonnes of CO_2, or about 1/3rd of the plant's emissions, are injected annually along with about 5,000 tonnes, or 2/3rd of the H_2S emissions [13]. The injection takes place at the CarbFix2 injection site in Húsmúli, in the northern part of the Hellisheidi geothermal field, where the CO_2-H_2S-charged fluid is injected below 700 m depth into the fractured basaltic reservoir (Fig. 1). The aim of this paper is to describe the reservoir conditions at the CarbFix2 injection site in Húsmúli, in terms of both its stratigraphical and hydrological settings. This will be done through a review of the geology, the permeable structures, and the alteration in the main involved wells and by presenting results from a recent reservoir modelling study of the site using injection data and tracer test results.

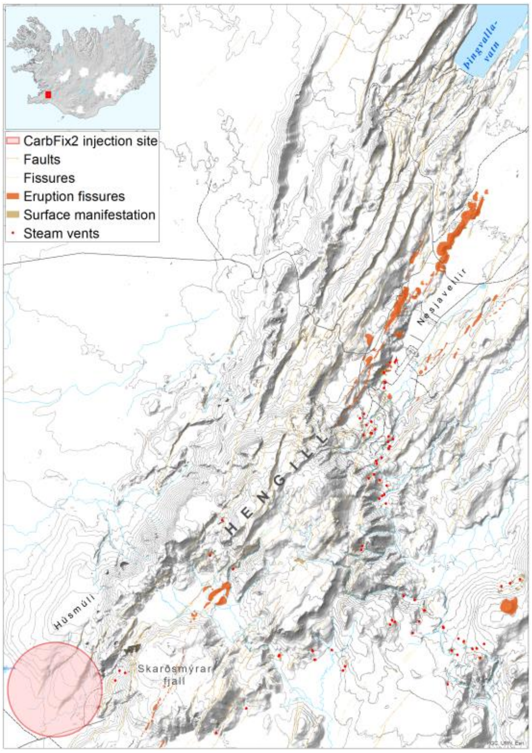

Fig. 1. The Hengill volcanic system. The CarbFix2 injection site is marked with a red circle.

2. Site description

2.1. The geological settings of the Hellisheidi field

The Hellisheidi geothermal field lies within the Hengill volcanic system of the western volcanic zone of Iceland, at a location where the western rift zone meets the volcanic zone of Reykjanes peninsula, and is intersected there by the South Iceland Seismic Zone (SISZ) forming a triple junction (Fig. 1). Hengill central volcano occupies the central part of a 60-100 km long and 3-5 km wide volcanic NE-SW trending fissure swarm [14, 15]. The area has been studied intensively in connection with geothermal utilization [e.g. 16-18]. The Hellisheidi power plant was commenced in 2006 and currently utilizes the field for production capacity of 303 MWe of electricity and 133 MWth of thermal energy. In total, 61 production wells and 17 injection wells have been drilled in the area ranging from about 1500 to 3300 m in depth. The injection wells are located at two distinct injection sites, where reinjection of the geothermal brine and condensate after production takes place. Due to the intensive drilling in the area, the subsurface geology is well known [e.g. 14, 15, 19-21] and hydrothermal alteration and alteration zones in the top-most 2-3 km have been studied to some extent [22-24]. An age of about 0.4 million years has been estimated for Hengill, which puts an upper age limit on the geothermal system [14, 15]. Postglacial volcanism at Hengill has been confined to three fissure eruptions dated at ~10,300 yrs., ~5,700 yrs. and ~1,800 yrs. [25].

The largest part of the Hengill central volcano is built up of hyaloclastic (glassy) formations, formed by magma-water interaction during glacial periods that dominate the top-most 1,000 m of the center of the Hengill area [14, 19]. In the less mountainous areas, the stratigraphy 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 m below sea-level (mbsl) and become dominant part of the strata below ~1500 mbsl [e.g. 19]. Olivine-tholeiite is by far the most common rock type in the Hengill system. Olivine tholeiitic lavas usually have simple mineralogies, characterized by the early formation of olivine followed by the crystallization of plagioclase and later clinopyroxene, which dominate the groundmass together with Fe-Ti oxides [26]. Olivine tholeiitic lavas are usually rich in volcanic glass, especially on rapidly chilled surfaces of lava flows and hyaloclastites. Intermediate and felsic rocks are found on surface at the western edge of the volcano and as intrusive rocks in wells throughout the geothermal field where most of the intrusions are of basaltic composition [14, 19].

Studies of geothermal alteration of basaltic rocks in Iceland show sequences of alteration mineral assemblages that change with increased depth and temperature; these are identified as zones of alteration as described below, reflecting the dominant temperature of the system when the minerals were formed [19, 27, 28]. The first sign of hydrothermal alteration is the formation of smectites and zeolites along with chalcedony. With increased depth and temperature, quartz starts forming at about >180 °C, and the smectites become interlayered with chlorite, forming mixed layer clays (MLC) at temperatures around >200 °C. The high temperature hydrothermal alteration is characterized by the formation of chlorite and epidote, but these minerals are believed to form at >230-250 °C. Epidote becomes more abundant with increased temperature and depth, along with prehnite, and at temperatures above 280 °C actinolite is expected to form. The geothermal wells in the Hellisheidi field are cased off down to the chlorite-epidote zone. Calcite is among the most common alteration minerals in the Hellisheidi field, and is expected to form at temperatures below 300 °C. It has been estimated that about 1,600 Mt of CO_2 are already bound in calcite within the bedrock in the area [9]. Sulfides are also quite abundant in the secondary mineral assemblage; mostly pyrite but also pyrrhotite. Calcite and sulfides within the bedrock reflect the volcanic CO_2 and H_2S gas content derived from magma, respectively, and may thus be an indirect measure of the magnitude of intrusive activity in the field [e.g. 29].

2.2. The CarbFix2 injection site at Húsmúli

The Carbfix2 injection site is located at the Húsmúli site in the northern part of the Hellisheidi field, at the western flanks of the Hengill volcanic system (Fig. 1). The Húsmúli site is the main injection site for the field, with annual re-injection of about 12 Mt of geothermal brine and condensate (~60-80 °C). It lies ~270 m above sea-level (masl). 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 Skarðsmýrarfjall Mountain, at some 570 masl (Fig. 2). The wells' depths range from about 2200-2700 m, and they are cased off down to a depth of 660-837 m depth (134-343 mbsl). The maximum down-hole temperature in the production wells ranges from ~260-285 °C. The well paths are shown in Fig. 2. The depths, depths of casings, and azimuth of the four wells are shown in Table 1.

Table 1. The measured depths, depths of casings and azimuth of the CarbFix2 injection and monitoring wells.

	HN-16	HE-31	HE-48	HE-44
Type of well	Injection	Monitoring/production	Monitoring/production	Monitoring/production
Azimuth	350°	280°	300°	330°
Depth of casing	660 m/-343 mbsl	727 m/-134 mbsl	837 m/-238 mbsl	837 m/-256 mbsl
Measured depth	2204 m	2703 m	2288 m	2606 m
True vertical depth	1902 m	2292 m	1850 m	2340 m

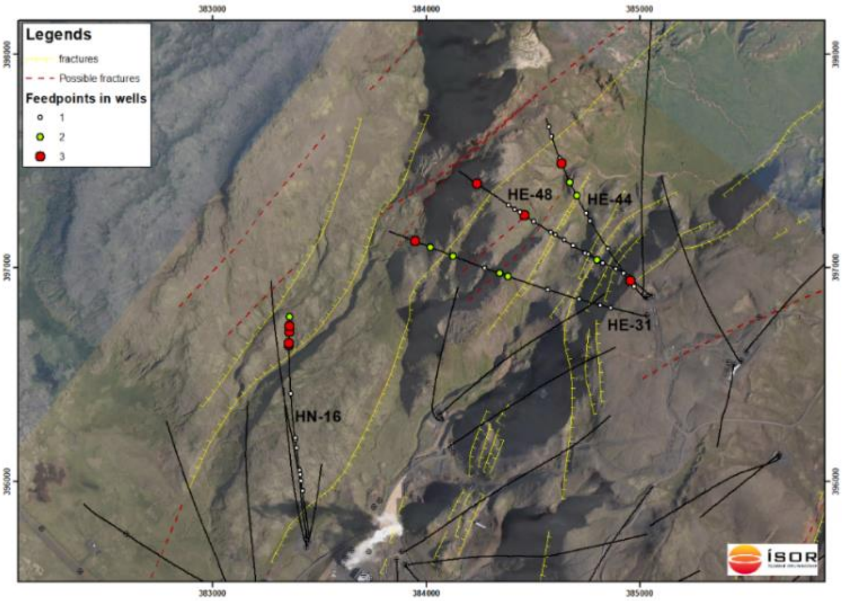

Fig. 2. The CarbFix2 site at the Húsmúli injection site. The feedzones (feedpoints) of the injection well HN-16, and the monitoring wells HE-31, HE-48, and HE-44 are labelled with circles. The color and size of the circles indicates the size of the feedzones.

3. Geological settings of the CarbFix2 site at Húsmúli

3.1. The stratigraphy of the host rocks

The general stratigraphy of the CarbFix2 wells at Húsmúli is shown in Fig. 3. The stratigraphy of well HN-16 is based on binocular microscope analysis of drill cuttings as described by Gudfinnsson et al. [30], supported by thin section analysis of drill cuttings from wells near HN-16 [31]. The stratigraphy of wells HE-31, HE-48, and HE-44 is based on binocular microscope analysis of drill cuttings from the wells and thin section analysis of drill cuttings from the wells and other wells in the vicinity [31].

Hyaloclastic formations dominate the stratigraphy. These formations are very heterogeneous, ranging from almost completely crystalline pillow basalts with only minor amounts of volcanic glass to almost pure volcanic glass (tuffs). The formations are typically more crystalline at the base, consisting of pillow basalt or pillow basalt breccias formed when the water pressure was sufficient to limit the water interaction with the magma, and overlain by more glass-rich layers of breccias or tuffs formed by the rapid quenching of magma upon mixing with the external water.

In well HN-16, which is situated in a topographic low of the area, the stratigraphy consists of alternating hyaloclastic formations, formed during glacial periods, and lava flows from sequences from interglacial periods which have flowed from the highlands down to the lowlands and surrounded the hyaloclastic ridges. Plagioclase phenocrysts are common in both glassy and crystalline formations and in some cases plagioclase and olivine phenocrysts appear together.

The stratigraphy of wells HE-31, HE-48, and HE-44 on Skarðsmýrarfjall Mountain consists of different hyaloclastic formations, sometimes separated by thin sedimentary layers, but no lava flows are identified in the top 1500 m of the wells. The top ~250 m consist of the Skarðsmýrarfjall formation, which is characterized by plagioclase and olivine porphyritic pillow basalts. Below the Skarðsmýrarfjall formation, five different hyaloclastic formations have been identified, with plagioclase phenocrysts apparent in most of them.

Overall, at about 1300-1500 m depth, a lava sequence is found in the wells in the field which consists of highly altered crystalline rocks. The formation is frequently intersected by intrusions. As anticipated for the Hellisheidi geological setting, this formation is the "base" of the Hengill volcano, formed prior to the onset of central volcanic activity in the Hengill area and puts a maximum age on the Hengill hydrothermal system (Fig. 3). The lava succession is believed to belong to the extinct Grensdalur central volcano some 5 km east of Hengill [19].

The presence of lava sequences in the stratigraphy of well HN-16 and other wells at Sleggjubeinsdalir Valleys indicates that the area at Sleggjubeinsdalir has been, as it is today, lower than the surrounding area. No lava sequences are intersected in the wells on Skarðsmýrarfjall Mountain, but the stratigraphy of the wells drilled from the mountain consists of hyaloclastic formations with different characteristics down to about 1500 m, indicating that the area was mountainous before the formation of the Skarðsmýrarfjall Mountain.

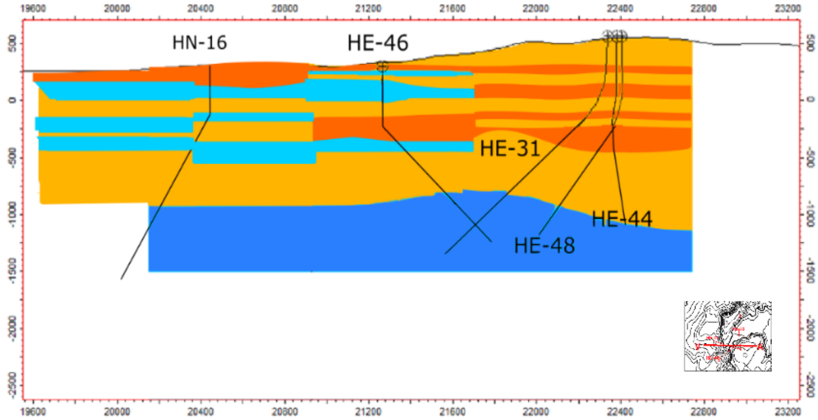

Fig. 3. The general stratigraphy of the CarbFx2 injection site at Húsmúli: a simplified cross-section from W-E. Hyaloclastic formations are marked with different orange colors, lava sequences are marked with blue colors. The anticipated "base" of the Hengill volcano is marked with dark blue. Note that intrusions are identified in samples from about 500 m depth and become more common with increased depth. The wells are cased off down to 134-343 m b. s. (Table 1).

3.2. Intrusive rocks

In Hengill, intrusive rocks become noticeable below ~500 mbsl and dominant below ~1500 mbsl [e.g. 19]. In the upper part of the wells the intrusions are usually thin and fine-grained, but thicker doleritic intrusions are common in the deeper parts. Intrusive rocks are often less altered and denser than the surrounding host rock. They are believed to contribute substantially to the permeability in the field, because the fracture networks created by their emplacement are a major control on aquifer permeability within the geothermal reservoir [e.g. 32].

Intrusive rocks are observed from below ~500 mbsl in all the four wells and become more common with depth, but are never the dominant part of the stratigraphy. In the Skarðsmýrarfjall-wells, this can be explained by the fact that these wells don't reach as deep as most of the wells in the Hellisheidi field. Several intrusions are intersected but they appear to be very thin, probably due to the deviation of the wells. The largest feed-points in the wells are in several instances associated with intrusions. Intrusions of intermediate composition are intersected by all wells but are especially common in well HE-31 compared to other wells in the Hengill area [e.g. 33], probably due to its vicinity to Sleggja Mountain, which is the only formation of intermediate and acidic composition on the surface at Hellisheidi [16].

3.3. Secondary mineralogy

The most common secondary minerals identified within the reservoir of the four wells are shown in Table 2. The wells of this study are, as previously mentioned, cased down to the chlorite-epidote zone. The rocks of the reservoir are therefore affected by high temperature alteration (>230 °C). The formation of secondary minerals corresponds with the breakdown of primary phases, as shown in Fig. 4. Volcanic glass and olivine in the host rock are fully altered long before the chlorite-epidote zone is reached, and the first sign of the alteration of plagioclase to albite, and pyroxene to chlorite is within this zone of alteration, along with the alteration of Fe-Ti oxides to titanite ($CaTiSiO_5$). When the epidote-actinolite zone is reached (>280 °C), with the first appearance of actinolite (Table 2), the oxides are largely altered, and alteration of plagioclase to albite, epidote, calcite, and wairakite has been identified in wells both at Skarðsmýrarfjall and near well HN-16. The intrusive rocks intersected in the wells are usually less altered than their host rocks.

Calcite is abundant in all the four wells and is identified both as a secondary replacement mineral (e.g. by carbonation of volcanic glass), as alteration of pyroxenes and plagioclase, and as direct deposition in pores and veins. It is present in almost all samples from its first appearance in all four wells. Calcite is, however, unstable at temperatures above 280 °C and is not expected to form at temperatures above 300 °C [e.g. 19]. Sulfides are not abundant in the wells, apart from few zones of high permeability, but as for calcite they are identified in samples throughout the wells.

Table 2. The most common secondary minerals identified in the CarbFix2 reservoir, together with their chemical formula, minimum formation temperatures based on [17, 25] and depths of first appearances.

	Chemical formula	T °C	HN-16	HE-31	HE-48	HE-44
Quartz	SiO_2	180	660 m	580 m	450 m	510 m
Epidote	$Ca_2(Al,Fe)_2(SiO_4)_3(OH)$	230-250	1100 m	830 m	728 m	742 m
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2{\cdot}(Mg,Fe)_3(OH)_6$	230	700 m	680 m	~650 m	620 m
Prehnite	$Ca_2Al_2Si_3O_{12}$ (OH)	240	1020 m	900 m	840 m	780 m
Wollastonite	$CaSiO_3$	270	1450 m	1370 m	-	-
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	280	1800 m	1700 m	1550 m	1980 m
Calcite	$CaCO_3$	<300	180 m	350 m	450 m*	450 m*
Sulfides	FeS_2, $Fe_{(1-x)}S$, $CuFeS_2$, …			300 m	450 m*	450 m*

*no cuttings between 220-450 m in well HE-44, and 286-452 m in well HE-48

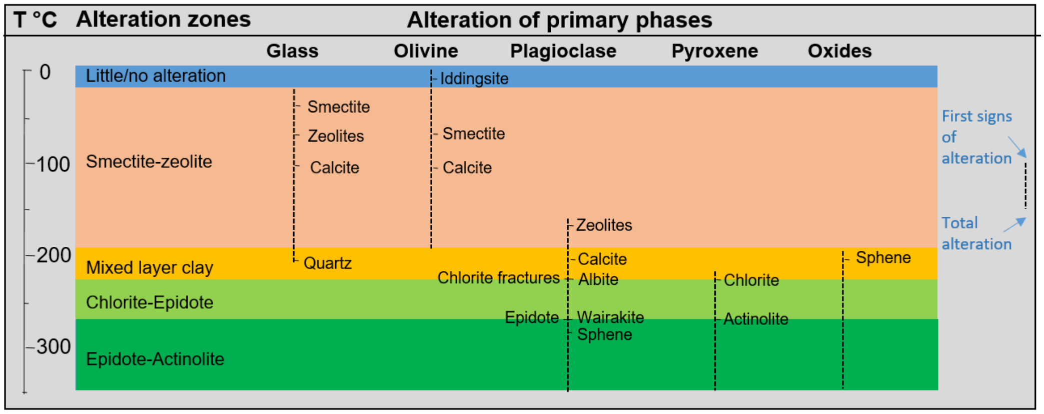

Fig. 4. The alteration zones and the breakdown of the primary phases

3.4. Permeability

The permeability of the Húsmúli site is mainly fracture-dominated. The site has a complicated fracture system, consisting of NNE trending extensional faults and fault segments as well as shears connected to the SISZ transform zone oriented in various directions [e.g. 34]. This fracture network highly affects the permeability in Húsmúli which appears to be very anisotropic along the fault lines [35]. Two NNE trending normal faults are notable on the surface; the western one, the Mógil fault, runs through the Mógil gully, and the eastern one, the Húsmúli fault, makes up the western part of the Sleggubeinsdalir Valleys. The reinjection wells at the Húsmúli site target these faults [36]. Other sources of permeability in the area are believed to be lithological boundaries in the top ~1000 m of the system, and intrusive rocks below ~1000 m [e.g. 19].

Feedzones in geothermal wells are located using down-hole temperature and pressure logs but loss of circulation during drilling, increased alteration of the bedrock and increase in the abundance of secondary minerals can also give valuable information on the size and location of these feedzones. The depths of the main feedzones identified in the CarbFix2 wells are shown in Table 3, along with the injectivity indices of the wells. Injectivity index ((kg/s)/bar) is a simple parameter, approximately reflecting the capacity of a well, serving as the first indicator of well productivity. It is determined at the end of drilling by logging the downhole pressure response near the dominating feedzones to different injection rates [37].

Table 3. The depths of the main feedzones identified in the CarbFix2 wells along with the injection indices of the wells.

Well #	Depth of main feedzones		Injectivity index
	Measured depth (m)	Relative depth (mbsl)	((kg/s)/bar)
HN-16	1900-1920	1366 – 1384	12
	2030	1480	
	2080	1524	
	2170	1603	
HE-31	1754	1008	26
	1778-1802	1027 – 1047	
	1998	1206	
	2496	1582	
HE-48	1720-1760	916-945	15
	2130-2230	1215-1278	
HE-44	920	326	7
	2160-2190	1392-1418	

4. Reservoir modelling of the Húsmúli – CarbFix2 injection site

A simplified reservoir model was developed for this injection site and its interaction with the nearby production wells to investigate the flow paths at Húsmúli. The model was calibrated using the data from a tracer test carried out at Húsmúli during 2013-2015. Fast recovery of tracers injected into the wells at Húsmúli was observed in wells HE-31, HE-44, and HE-48, indicating a principal flow direction parallel to the Mógil and Húsmúli faults. Limited recovery was observed in production wells to the south of well HE-31 indicating somewhat channelized flow and anisotropy in the system permeability [35].

Fracture models presented by Kristjánsson et al. [35] using tracer recovery data from the above mentioned test showed good correspondence between observations and modelled results. The results, however, showed a large dispersion in the channels indicating fracture networks rather than simple fracture flow paths. Thermal predictions from the fracture models predicted significant cooling in wells HE-31 and HE-48 by the injection of the cooler fluids (~60-80 °C). Monitoring data has, however, hardly shown any cooling after six years of large-scale re-injection of geothermal brine and condensate. The results from the fracture models indicate that the flow path is likely more complex than assumed in the original models [35].

The following subsections will describe the software used for the modelling, the model setup, the simulation procedure, and lastly the calibration approaches and the results obtained. Tracer recovery from well HN-17 was used for the simulation model calibration, as described below. Wells HN-16 and HN-17 are drilled in a similar direction and from the same drill pad and therefore cut the same geological structures. A study of the flow paths from HN-17 to the production zone will therefore be highly relatable to the flow paths for the fluid injected into HN-16.

4.1. Software, model setup and simulation procedure

The TOUGH2 simulator [38], as implemented in forward mode using the iTOUGH2 program, was used to solve the model's governing mass and energy balance equations [39]. The EOS1 equation of state module, which describes water in liquid, vapor and two-phase state was used. The module allows for separate tracking of two water components. The numerical grid was generated using the program AMESH, which is based on the Voronoi tessellation method [40]. The grid was refined at the locations of the main feedzones in well HN-17 to allow for accurate calculation of tracer concentration.

The conceptual model developed for this study is a simplified version of the Húsmúli injection site (Fig. 5). A 200 m thick impermeable cap rock is assumed to separate the colder groundwater system from the geothermal system causing very little interaction between the two. The depth and thickness of the cap rock were estimated based on resistivity measurement results [e.g. 41, 42], and alteration mineralogy in well HN-17, which shows the appearance of epidote at 612 mbsl [43]. Injection and production rates for wells considered in our study were supplied by

Reykjavík Energy. As a simplification, only the largest feedzones of each well were used as sources/sinks as shown in Fig. 5.

The central part of the model that lies within the fracture zone was assumed to have higher permeability than the surrounding formation. The model elements were assigned different rock types using the TOUGH2 preprocessor Steinar [44]. All rock types in the model were given an initial porosity value of 10% [45], which has been found to be an adequate estimate for the average active porosity in the reservoir [46]. The initial permeability in the active geothermal system was defined as the permeability of hyaloclastite as chosen by Aradóttir et al. [12], $3x10^{-14}$ m^2.

The tracer test simulations were run in three stages. The first stage was a single water component flow simulation of a period of ~2 yrs before the tracer injection. The initial conditions for this stage were pressure and temperature conditions taken from the Hengill model [46] provided by Reykjavík Energy. The first stage was followed by a 2 hour long tracer injection period, denoted as stage 2. The third and last stage was then a simulation of ~2 yrs where the tracer was transported by the reservoir fluid towards the production wells. Outputs from the third stage simulation at different times were used to monitor the transport and recovery of the tracer in the different production wells. A more detailed description of the model, its boundary and initial conditions, and simulation procedure is provided by Tómasdóttir [47].

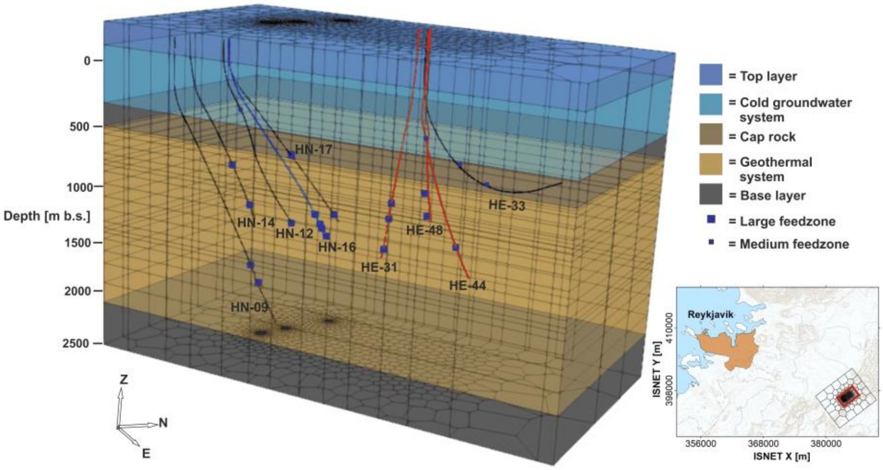

Fig. 5. All wells incorporated in the model, the feedzones that were used as sources/sinks and the general rock-formation distribution in the model. The CarbFix2 injection well, HN-16, and the main monitoring wells, HE-31, HE-48 and HE-44 are shown in blue and red, respectively. The inset shows the location of the grid in SW-Iceland. The part of the model shown in detail is indicated with a red square on the inset figure.

4.2. Model calibration and results

Different approaches were used to calibrate the model against the observed tracer recovery from well HN-17 (Fig. 6). The first approach tested whether the tracer recovery curves could be reproduced by a homogeneous model. This homogeneous model assumed that flow occurred solely as a consequence of the pressure gradient created by the injection and production rates in a homogeneous rock of a fixed permeability. The second approach "single channel model" tested whether the inclusion of a more permeable flow channel extending over the horizontal and vertical extent of the main feedzones in wells HN-17, HE-31, HE-48, HE-44 and HE-33, would result in a more realistic recovery. The third approach "multi-channel model" tested a system with two narrower flow channels directly connecting the individual feedzones in the wells. The flow channels were not meant to represent specific fractures but rather a fractured zone that the fluid could quickly travel through. The idea behind the channel approach is that fault zones that are parallel to the direction of flow in a system can act as flow conduits but also as barriers to flow perpendicular to the fault zone [48, 34].

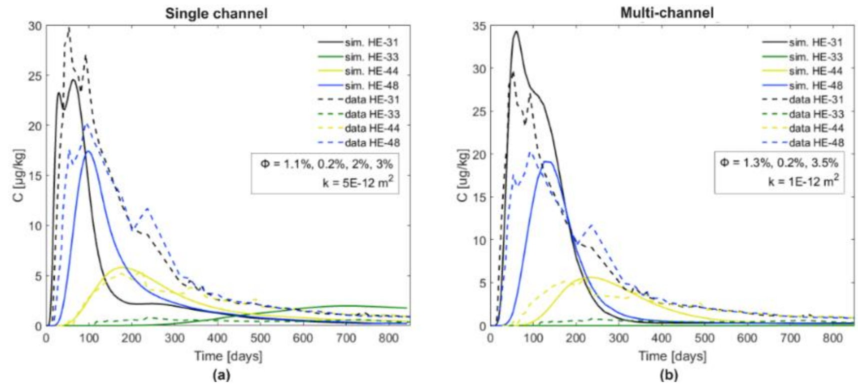

Fig. 6. Simulated (solid lines) and observed (dashed lines) tracer recovery for (a) the single channel approach (b) the multi-channel approach. Modified from Tómasdóttir [46].

The results showed that the fast recovery of the tracer injected into HN-17 in Húsmúli could not be simulated with a homogeneous approach; the tracer recovery was both too late and too limited. More realistic results for both the tracer arrival times and concentration peaks were obtained using the single and multiple flow channel approaches. The parameters that gave the best fit for the single channel were permeability of $5x10^{-12}$ m^2 and porosities ranging from 0.2%-3% in the different channel sections. For the multi-channel model they were $1x10^{-12}$ m^2 and 0.2%-3.5%, respectively. This low porosity represents the active pore volume within the channel bounds, i.e. the volume of the permeable fractures. The channels therefore make for an abstract representation of fractured zones within the medium.

All approaches showed a strong density effect in the tracer flow, where the tracer sank at the beginning due to the higher density of the colder injected fluid and then rose as it heated along the flow path at greater depth. This lengthened the flow path of the tracer and resulted in contact with a greater volume of rock. Fig. 7 shows the tracer distribution in the system with time using the single channel calibration approach.

Temperature changes in the model were monitored to evaluate and compare the different calibration approaches as little to no cooling has been observed in the production wells in reality. The cooling front in the model was more than an order of magnitude slower than that of the observed and simulated tracer, showing clearly the predictive power of tracer tests. Greater cooling was seen with the single-channel modelling approach than with the multiple narrower channel approach, which hardly showed any cooling in the production elements during the simulation time. This indicates that the flow paths are more likely multiple channels consisting of fracture networks.

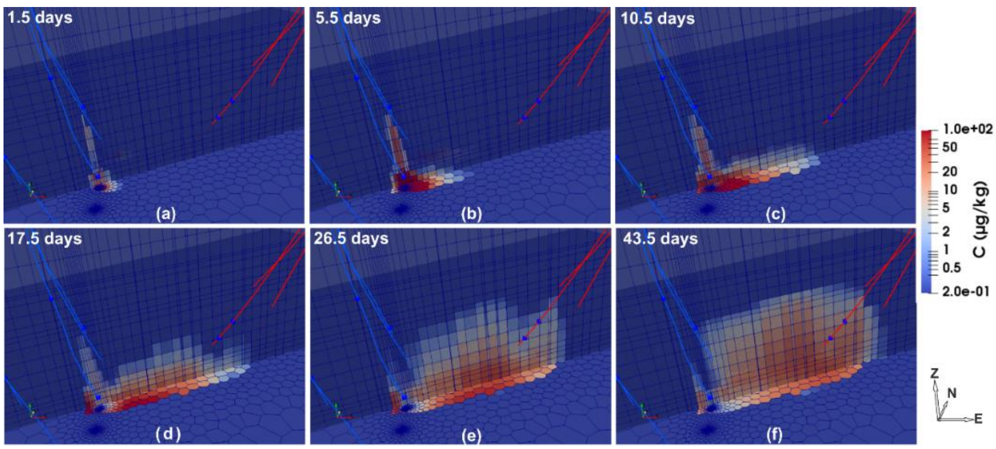

Fig. 7. Tracer distribution over time shown horizontally at a depth of 1565 mbsl and vertically in a cross section along the center of the single channel. Injection wells are shown in blue and production wells in red. Feedzones are shown with blue squares. Channel permeability is $5x10^{-12}$ m^2 and porosity is 1.1%, 0.2%, 2% and 3% in the different channel sections. Note that the view is slightly tilted (see orientation axis). The times are (a) 1.5 days, (b) 5.5 days (c) 10.5 days (d) 17.5 days (e) 26.5 days and (f) 43.5 days. Modified from Tómasdóttir [47].

5. General conclusions and implications

The CarbFix2 injection site at Hengill is highly permeable, as evident from the several large feedzones (Fig. 2) and the high injectivity indices of the CarbFix2 wells. These high injectivities are above the average index values of wells in the area [34]. This is an important factor for the injection of CO_2 and CO_2-H_2S-gas mixtures, due to the water demand for fully dissolving the gases, and the rapid mineralization rates, especially those for the S-bearing minerals. The main difference between the subsurface rocks of the CarbFix2 site compared to the CarbFix1 site where the pilot injections took place [e.g. 3, 6, 7, 12] is the high alteration state of the CarbFix2 reservoir. The presence of sulfides and calcite within the reservoir, with the latter further quantified by Wiese et al. [9], confirms that the conditions are favorable for the formation of C- and S-bearing minerals. The sources of cations within the reservoir, to combine with the injected gases for the formation of carbonates or sulfides, must be further studied. These could be intrusive rocks, since these rocks are usually not as altered as their host rocks, and/or secondary phases such as epidote and chlorite [49].

Reservoir modelling was carried out to model the fast tracer recovery at the site. The calibration process required substantial permeability structure modifications. Since these modifications were adopted on a local scale, and directly in connection with the permeable structures in the wells, the specific results for the hydrological parameters are very dependent on these wells and their location. The modelling, therefore, does not provide quantitative information about the heterogeneous structure of the system away from the localized channels connecting the injection and production wells involved in this experiment. It does, however, indicate the level of detail needed to derive realistic permeability and porosity values for the whole system and confirms the heterogeneity of the permeability structure of this system. The modelling also shows that the flow paths are substantially lengthened by sinking of the relatively cool injected fluid, which results in its contact with a greater rock surface area. This is important for the site's mineralization potential of the injected gases.

It must, however, be kept in mind that the permeability structures and flow paths in Húsmúli are not static. Thermal expansion/contraction resulting from the injection of colder fluid into hot rock causes mechanical changes in the permeability [e.g. 36]. Even without that effect, increased cooling of the reservoir rock close to the injection wells with time means that the fluid needs to continuously travel to greater depths to find warm enough surroundings to enable density driven rising. An advance of colder rock and/or permeable structures, as well as mineralization and/or dissolution due to the injection of gases, could with time change the flow paths in the system. This would result in new surfaces of the host rock being exposed for reactions with the injected gas-charged fluid. Results from upcoming tracer tests at the CarbFix2 site will give further valuable information on the extent of such changes. To get a more complete picture of the flow paths in Húsmúli, further modelling studies will be conducted including a better representation of the fractured medium, provision for determining the fluid compositions, and mineral reactions over the flow path.

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