Injection of Geothermal CO2 and H2S Gases at the Nesjavellir Site, SW Iceland: A Pre-Injection Overview

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Keywords: Carbfix, carbon mineralization, GECO, CCS, carbon capture and storage

ABSTRACT

ON Power (ON), a subsidiary of Reykjavik Energy, has been disposing CO_2 and H_2S gases emitted from the Hellisheidi Power Plant since 2014. The process involves capturing the gases through their dissolution in water at elevated pressure and injecting the gas-charged fluid directly into basaltic subsurface rocks without depressurization. In the subsurface, the dissolved gases precipitate as minerals for their safe and long-term storage. The method has been developed within the Carbfix project and has been demonstrated to be safe, efficient and cost effective. Plans call for adopting this technology to capture and store the CO_2 and H_2S emitted from the Nesjavellir Power Plant, another geothermal plant owned and operated by ON. Preparation for a pilot injection of ~1000 tons of CO_2 and ~600 tons of H_2S annually is taking place as a part of the EU-funded GECO project. Here we present a general overview of the Nesjavellir injection site, including the subsurface stratigraphy, mineralogy, permeability and chemical composition of the target subsurface aquifer. Results indicate that the Nesjavellir geothermal field is a suitable host for successful carbon and sulfur mineralization due to its geological settings, available infrastructure, and the experience gained from the Carbfix injections at Hellisheidi (e.g. Gunnarsson et al., 2018; Snæbjörnsdóttir et al., 2017, Matter et al. 2016).

1. INTRODUCTION

The reduction of carbon dioxide (CO_2) emissions to the atmosphere is one of the greatest challenges of this century (e.g. Broecker, 2007; Yann et al., 2017; IPCC, 2018). A major contributor to this reduction is the transition to less carbon-intensive and more sustainable energy systems, including more extensive geothermal energy use. Even though geothermal energy plants generally emit far less CO_2 than fossil fuel burning plants of comparable size, emissions of CO_2 and other geothermal gases such as hydrogen sulfide (H_2S), hydrogen, nitrogen, and methane (CH_4) are an inevitable part of geothermal fluids and their treatment needs to be addressed.

The Hellisheidi geothermal plant in SW-Iceland has an installed capacity of 303 MW_e and 133 MW_{th}. The plant currently produces about 37,000 tons of CO_2 and about 9,000 tons of H_2S annually out of the geothermal reservoir. The capture and subsurface mineral storage of these gases has taken place since 2014: Currently about 12,000 tons of the otherwise emitted CO_2 and about 7,000 tons of H_2S are captured by their dissolution in water at elevated pressure and the resulting gas charged water is injected without depressurizing into the basaltic subsurface, where they react with the basaltic bedrock and mineralize for safe and long-term storage (e.g. Sigfússon et al., 2018; Gunnarsson et al., 2018; Clark et al., 2020). The research and development of this method has been carried out as a part of the Carbfix project, which has been led by OR, and since 2020 its subsidiary Carbfix, together with CNRS in Toulouse, the University of Iceland, Columbia University in New York and several other universities and research institutes.

The success of the operations at Hellisheidi has encouraged further applications of the Carbfix method, including capture and injection of CO_2 and H_2S for permanent mineralization at the Nesjavellir geothermal plant – the other geothermal plant operated in the Hengill Volcanic system. The preparations are on-going as a part of a H2020 research and innovation project called GECO (Sigfússon et al., *this issue;* Andersen et al., *this issue*). Here we present a geologic overview of the Nesjavellir injection site, including the subsurface stratigraphy, mineralogy and permeability, and the fluid chemistry at the site.

2. SITE DESCRIPTION

The Nesjavellir geothermal power plant began operations in 1990, with an initial capacity of 100 MW_{th}, which has since been upscaled to 120 MW_e and 300 MW_{th}, through ~20 production wells. Currently, about 15,000 tons of CO_2 and about 8,000 tons of H_2S are emitted by this power plant annually. The plant is a single flash power plant where the geothermal fluid is flashed at the wellhead. The two-phase fluid is then diverted towards the power plant and separated into steam and brine. The steam, which contains most of the geothermal gases, is sent to turbines where it is condensed. The brine is diverted into heat exchangers that heat up cold ground water that is subsequently used for district heating.

Building on the experience of successful CO_2 and H_2S capture and storage at the Hellisheidi power plant, the same approach is planned to be implemented at the Nesjavellir plant in 2021, starting with a pilot injection of ~1000 tons CO_2/yr and about ~600 tonnes of H_2S/yr. Initial efforts will inject the captured gases into well NJ-18, located in the northern part of the field (Figure 1). The successful mineral storage of geothermal gases and fluids in the Nesjavellir reservoir requires a thorough understanding of the fluid chemistry, and fluid flow at the injection site. This information is essential for: 1) identifying and characterizing the feed-zones and flow-paths in relation to the injection well for successful monitoring of the mineralization of the injected gases within the bedrock; and 2) determining the optimal injection parameters, such as injection rates and gas pressures for successful long-term operation.
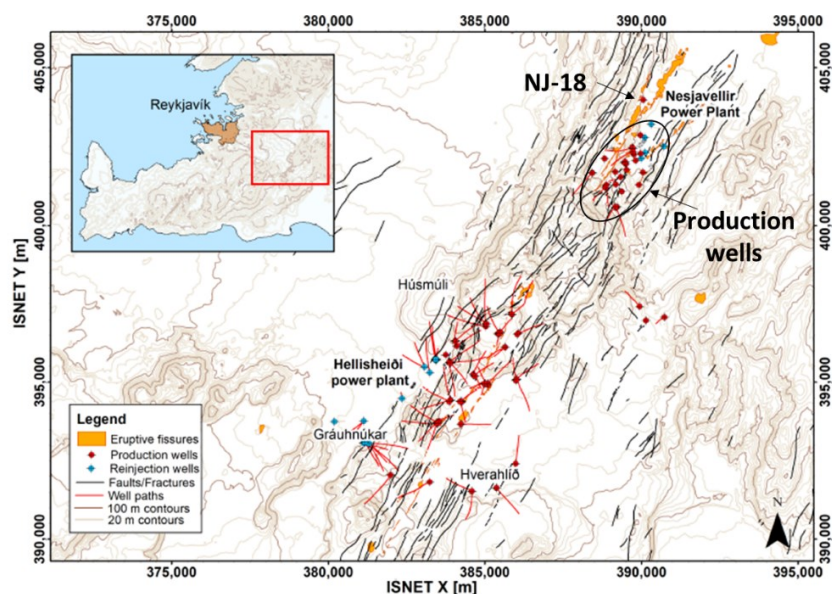
Figure 1. Map of the area near the Nesjavellir power plant showing location of power plants, wells and fissures and fractures (modified from Tomasdottir 2018)

2.1 Geological settings

The Nesjavellir geothermal field (Figure 1) is located in the Northern part of the Hengill central volcano in SW-Iceland. The Hengill volcanic system is located at a triple junction, where the western volcanic zone of Iceland is intersected by the South Iceland Seismic Zone (SISZ). This makes the area very seismically active, with two kinds of tectonic activity dominating; dilutionary rifting, as is evident by a 60-100 km long and 3-5 km wide NE-SW trending fissure swarm with a total throw of over 300 m, and a transform component concentrated in the eastern part of the area related to the SISZ.

The Hengill central volcano is estimated to be about 0.4 million years in age, which puts an upper age limit on the geothermal system (Franzson et al., 2005, 2010). The system was formed by several volcanic cycles during various spreading episodes of the rift zone. Postglacial volcanism at Hengill has been confined to three fissure eruptions, dated at ~10,300 yrs, ~5,700 yrs and ~1.800 yrs ago (Sinton et al., 2005); these have been suggested to have opened new flow paths and to intensify locally the geothermal system (Franzson et al., 2010).

The largest part of the Hengill central volcano consists of basaltic rocks, mainly hyaloclastic (glassy) ridges that erupted sub-glacially; these formations dominate the top-most 1000 m of the Hengill area (Franzson, 1998; Franzson et al, 2010; Helgadóttir et al., 2010). The hyaloclastites are highly heterogeneous; they consist of crystalline rocks with minor amounts of volcanic glass, pillow basalts. and formations which almost solely consist of volcanic glass. In the less mountainous parts of the area, the stratigraphy consists of alternating successions of hyaloclastites from the glacial periods and lava sequences formed during interglacial periods. The most prominent basalts originate from a large lava shield, which erupted in the highlands and flowed towards the surrounding lowlands (Franzson et al., 2010). Intrusive rocks dissect the succession below about 800 m depth below sea-level (b. s.) and become dominant below 1700 m b.s. In addition to being a heat source, the intrusive rocks contribute substantially to the permeability in the field and the fracture networks created by their emplacement are a major control on feed-zone permeability below 500 m b.s. The permeability at the reservoir depth is mainly fracture-dominated but in the shallower parts of the wells the aquifers are commonly associated with stratigraphic boundaries (Franzson et al., 2010; 2005).
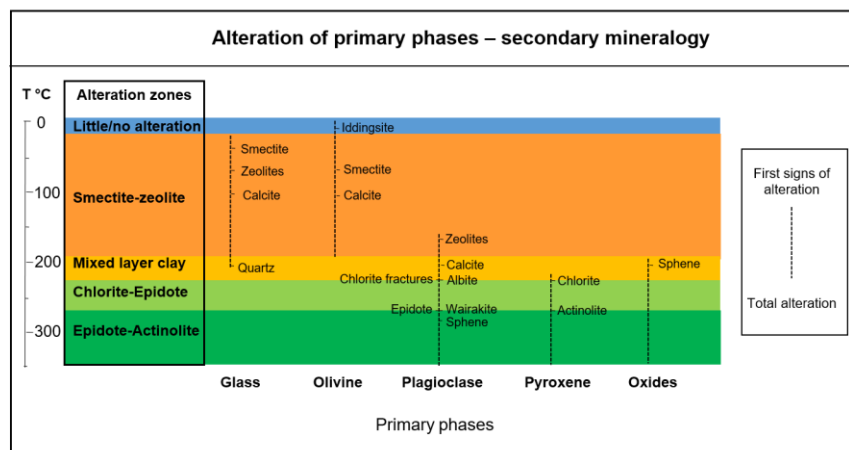

Figure 2. The alteration zones, breakdown of the primary phases and the formation of secondary minerals in the geothermally altered basalts (modified from Snæbjörnsdóttir et al., 2018)

The geothermal alteration in this area has been studied intensively in connection with geothermal utilization, both at Nesjavellir and at Hellisheidi. Secondary alteration minerals form as a consequence of the breakdown of the primary phases, which are unstable at the dominant temperature and pressure conditions (fig. 2). Sequences of alteration minerals with increased depth and temperature are identified as alteration zones, as described in detail by e.g. Kristmannsdóttir. (1978), Franzson. (1998) and Snæbjörnsdóttir et al., (2018). The production wells in the area are usually cased down to the chlorite-epidote zone, indicating temperatures exceeding 230°C.

Calcite and pyrite are among the most common alteration minerals in the geothermal systems of the Hengill central volcano. These minerals reflect the volcanic, magma derived CO_2 and H_2S gas content, and may thus be an indirect measure of the magnitude of intrusive activity in the field (e.g. Gunnarsdóttir, 2012). Calcite is expected to form at temperatures only below 300 °C (e.g. Franzson et al., 1998; Skippen, 1980). It has can be estimated from previous studies in the area (Wiese et al., 2011) that about 5-103 Mt of CO_2 are already bound in calcite within each km^2 of the geothermal field. Sulfides are also quite abundant in the secondary mineral assemblages; mostly pyrite but also pyrrhotite.

2.2 Reservoir fluid chemistry

The main aquifers found in the producing wells of the area are located at 1000-1500 m depth and their temperatures, calculated assuming equilibrium with quartz (Gunnarsson and Arnorsson, 2000) and using a silica geothermometer equation (Fournier and Potter, 1982), range from 260°Cv to 300°C. A long-term production monitoring program revealed a significant pressure drawdown over the geothermal field upon increased production in 2005, but the decrease has slowed down in recent years.

The deep fluid at Nesjavellir is relatively dilute, with chloride (Cl) concentrations ranging from 60-180 ppm and sodium from 90-163 ppm based on 2017 measurements. Initial Cl concentrations were low <10 ppm, however with an increasing use and the accompanying changes in enthalpy, Cl concentrations increased gradually. The potassium concentration is 16-30 ppm whereas calcium is <1 ppm. The deep fluid has a pH ranging from 6.5 to 7.6, and CO_2 and H_2S concentrations of 100-1000 ppm and 76-351 ppm, respectively. The fluid is undersaturated with respect to amorphous silica and supersaturated with respect to calcite. The $\delta^{14}C$ ratio is about 4‰ in CO_2 and -38‰ in CH_4 suggesting a magmatic origin of the gas (Armannsson et al., 1998).

2. PILOT INJECTIONS IN NESJAVELLIR

The initial injection of CO_2 and H_2S from the Nesjavellir Power Plant will take place at the latter part of 2021. The geothermal gases will be diverted from the power plant to a scrubbing tower where the non-condensable gases (CO_2 and H_2S) will be dissolved in condensate water at elevated pressure, and the gas-charged fluid injected without depressurizing it into well NJ-18 (Fig 3).
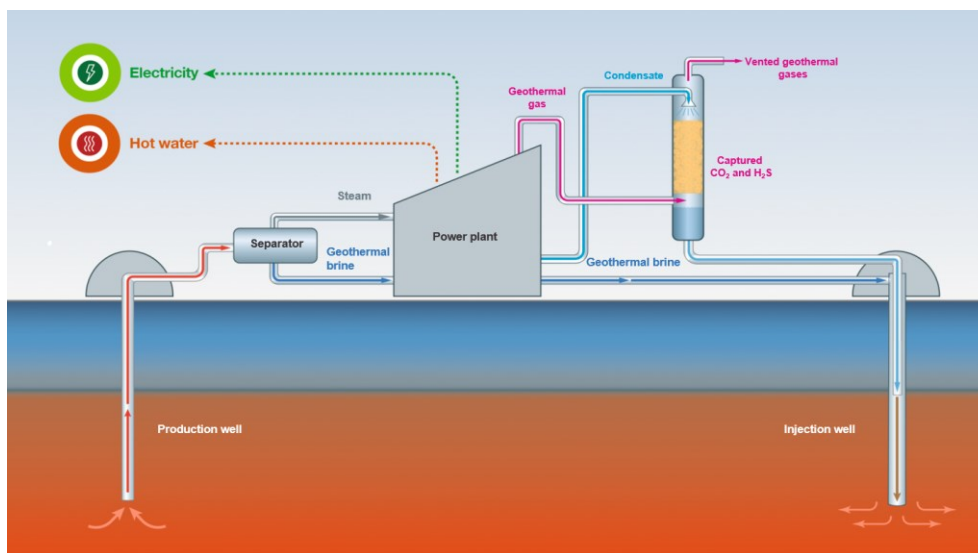

Figure 3. Overview of the geothermal production and the proposed gas capture at Nesjavellir geothermal plant. The non-condensable gases CO_2 and H_2S are dissolved in a scrubbing tower using condensate from the turbines at a pressure above 6 bar-a. Other geothermal gases are vented to the atmosphere. A portion of the condensate (without gases) is currently mixed with the brine prior to re-injection.

The injection well, NJ-18, is located in the northern part of the Nesjavellir geothermal field. The well was drilled as a production well in 1986 but was not considered feasible for production and has never been used as such. In 2018, the well was connected to the plant's water re-injection system and has since then been used for the injection of geothermal brine and condensate from the plant. Currently about 70 l/s of condensate and brine mixture are injected into the well, but about 500 l/s are re-injected in total into re-injection wells in the area. The plan is to inject the CO_2-H_2S charged water below the casing, at depths of about 1000 m.

2.2 The stratigraphy, permeability and geothermal alteration of well NJ-18

Well NJ-18 is 2136 m deep and has a maximum measured temperature prior to any injection of 250°C (Figure 4). The well is cased to 950 m, and below the casing is a perforated liner down to 2033 m depth. The main aquifer is at 1703 m depth. Another significant aquifer is present at 1610 m, and additionally some minor aquifers have been identified at depths of 1050, 1150, 1200, 1320, 1405, 1450-1500, 1895, and 2117 m.

The stratigraphy and alteration stage of the formations intersected in the well were analyzed during and after drilling (e.g. Steingrímsson et al., 1987). Drill cuttings were collected every two meters and analyzed using binocular microscope, and by thin section analysis. X-ray diffraction patterns were made of selected samples. The stratigraphy of the well is similar to other wells in the area; it consists of alternating basaltic hyaloclastites and lava formations. Intrusive rocks, both of basaltic and of intermediate composition, are common below ~1200 m and dominate below ~1500 m. The alteration stage of the rocks below the casing is quite low compared to other wells in the area, but the temperature gradient is relatively steep. Laumontite is first identified at a depth of about 900 m indicating temperature of 120°C, followed by the formation of quartz identified at about 920 m depth indicating temperature of 180°C. The most common alteration minerals below casing at 950 m and down to about 1200 m are quartz, laumontite, and mixed layer clays with smectites dominating chlorite. The chlorite-epidote zone is reached at about 1200 m depth, indicating temperatures exceeding 230°C, but the most common minerals within the zone are epidote, chlorite, prehnite and wairakite. The epidote-actinolite zone is reached at about 1600 m depth and extends down the well, indicating temperatures exceeding 280°C. The most common secondary minerals below 1600 m are chlorite, wairakite, prehnite and epidote.

Secondary minerals are not abundant in the samples analyzed, indicating low permeability in the vicinity of the well. This conclusion is also supported by the secondary mineral assemblage identified in the well samples; even though the alteration is characterized by the distinctive mineral zones (Fig 2.), minerals in disequilibrium with the dominant assemblage are commonly observed. One example of this is the identification of laumontite and smectite (formation temperatures <200°C) together with high temperature alteration minerals such as epidote and prehnite (formation temperatures >240°C) at depths below 1200 m.

The temperatures indicated by alteration minerals compared to the present formation temperature can be used to assess the thermal evolution in the vicinity of the well, as described in detail by e.g. Franzson (1998). The comparison of alteration temperature (temperature inferred from the existence of secondary minerals and the lowest temperatures required for their formation) and formation temperature (direct measurements of in-situ temperature inferred from pressure- temperature and measurements in the well during and after drilling) is shown in Figure 4. The alteration temperature is close to the formation temperature down to about 1000 m, where the high temperature alteration minerals first are observed. Below 1000 m, the alteration mineral assemblage reflects temperatures about 40-60°C higher than present formation temperature. This indicates higher formation temperatures during the formation of the alteration mineralogy than is presently observed, suggesting the cooling of the geothermal field in the vicinity of well NJ-18 prior to any re-injection in the area. Calcite and pyrite are dominant below the casing down to the bottom of the well, suggesting that the conditions in the vicinity of the well currently favour the formation of these minerals.
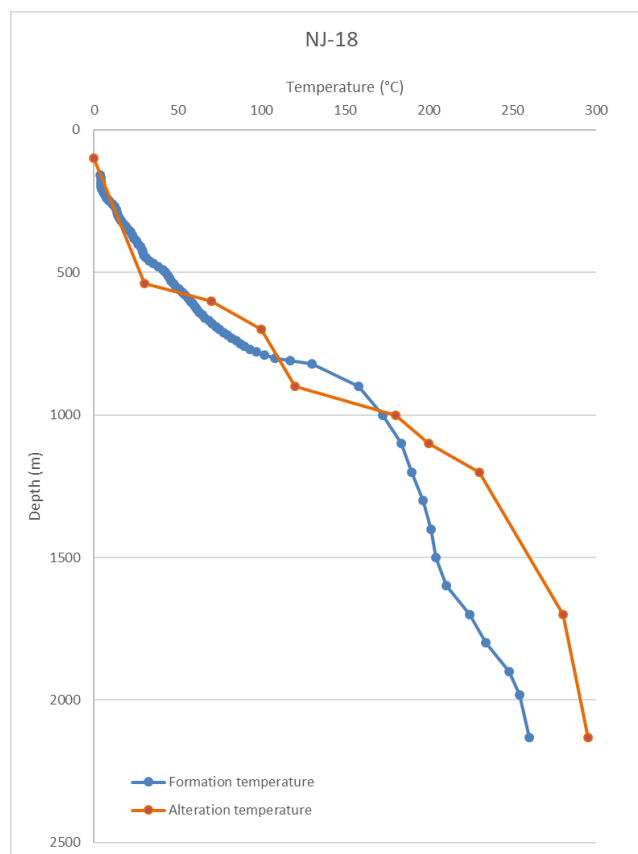

Figure 4. The formation temperature (blue) of well NJ-18 compared to the alteration temperature (orange) as indicated by the formation of secondary minerals identified in drill cuttings from the well.

2.2 Field site characterization

Several activities are planned to further characterize the injection site and the subsurface flow paths in the area. The permeability of the geothermal reservoir is, as previously mentioned, mainly fracture dominated.

A tracer test was started during the summer of 2019, when three tracers were injected into well NJ-18: 2.7 NS, PFC and krypton gas. The aim of the tracer test is to study the flow paths between the injection well and nearby production wells, which will be used for monitoring the chemical evolution of the injected fluid. The findings of this tracer test will establish residence times of the fluid in the reservoir enabling prediction of the mineralization progress. The results will be used for reservoir modelling and designing the monitoring program before and during gas injection.

Surface gas flux measurements have been performed to identify potential diffused soil gas anomalies, focusing mainly on CO_2 in the vicinity of the injection site. The main purpose of this survey is to identify subsurface fractures or permeable zones in the field. The results will also establish the background CO_2 fluxes enabling identification of possible CO_2 leaks towards the surface after the water-charged gas-injection has been started.

Finally, a high-resolution structural mapping combined with high-resolution drone imagery is being carried out in a project led by a research group from the University College London, with the aim to map out the predominant structures within the area, as further described by Stanton-Yonge et al. (this issue).

3 FINAL REMARKS AND DISCUSSION

The capture and subsurface storage of CO_2 and H_2S from the Nesjavellir geothermal power plant will begin in the latter half of 2021, when a pilot study of ~1000 tons of CO_2 and ~600 tons of H_2S will be injected into well NJ-18, the northernmost well of the field. The approach adopted will build on the success of the CCS operations at the Hellisheidi power plant, which have taken place since 2014.

The stratigraphy, alteration mineralogy and permeability of well NJ-18 has been characterized, based on well logs (Steingrímsson et al., 1987). The stratigraphy consists of basaltic lavas and hyaloclastites with basaltic and intermediate intrusions dominating below 1500 m. Comparison of formation temperatures and alteration temperatures indicates cooling of the geothermal system in the vicinity of the well, with the current temperatures up to 250°C. Pyrite and calcite are identified in samples below casing at a depth of about 950 m and down to the bottom of the well at 2136 m.

The primary permeability of the well is low, as indicated by low abundance of alteration minerals, and the co-existence of minerals formed at different temperatures. However, several aquifers are intersected in the wells, most likely fracture dominated. The high injectivity of the well has been supported by the re-injection of 70 l/s of geothermal brine and condensate. The re-injection has been ongoing since November 2018 without complications. These findings suggest that the well should be suitable for re-injection of water-dissolved CO_2 and H_2S.

The state prior to gas-charge water injection will be established via 1) results from tracer injections into well NJ-18 to map the flow paths of the well and its connection to the production wells at the site; 2) mapping of the CO_2 surface fluxes in the vicinity of the planned injection to identify subsurface fractures or permeable zones in the field; 3) mapping of surface structures to further constrain fracture characteristics and their relation to flow paths in the vicinity of the injection; 4) geochemical modelling of the injected and formation fluids. The results of these activities will be used to optimize the injection activities at Nesjavellir field by e.g. further model the injection site, including a building of a reservoir model, and to design the injection and monitoring program prior to and during the gas-charged water injection.

ACKNOWLEDGEMENTS

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