Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

GECO: Geological Properties, Permeability and Porosity of the Nesjavellir High Temperature Area in Relation to the Re-injection of Geothermal CO2 and H2S Gases

Sveinborg H. Gunnarsdottir, Helga M. Helgadottir and Sandra Snaebjornsdottir

Grensásvegur 9, 108 Reykjavik Iceland

Sveinborg.h.gunnarsdottir@isor.is

Keywords: Nesjavellir, GECO, high temperature, CCS, reinjection, porosity, permeability, stratigraphy, alteration

ABSTRACT

GECO (Geothermal Emission Control) is an international research project funded by the EU through the H2020 initiated in 2018. One of the goals of the GECO project is to prepare for re-injection of geothermal CO2 and H2S from the Nesjavellir Power Plant in SW-Iceland. The gases are dissolved in water and injected into the subsurface for permanent storage via mineralization. The success of this procedure requires a thorough understanding of the porosity and the permeability in the system prior to injection. Mapping of the geological factors which affect these properties provides information on the most prominent permeable structures and flow paths of the reservoir.

An assessment of new data from wells in the Nesjavellir high temperature field in SW-Iceland shows that permeability at the production zone is linked to basaltic and intermediate intrusions. This interpretation is strongly supported by previous studies. Furthermore, the new data indicates that faults identified on the surface can be traced to zones of loss circulation at depth experienced during the drilling of production wells.

This paper presents the current knowledge of the reservoir porosity and permeability in the Nesjavellir high temperature field based on new data and results of previous studies. The results will be used as input into both the reservoir and the geochemical simulation of the area prior to CO2 and H2S re-injection to ensure the projected success is attained.

1. INTRODUCTION

The GECO project targets the Nesjavellir geothermal field as the next test site in Iceland for the innovative carbon capture and storage method developed within the Carbfix project. CO2 and H2S will be captured from the emissions from the Nesjavellir power plant and reinjected into the reservoir. The successful reinjection in Hellisheiði showed rapid mineralization of calcite and pyrite within the reservoir. The geological conditions in Hellisheiði are very similar to Nesjavellir, however, it is important to characterize the reservoir properties of each field independently including identifying and correlating aquifers and geology. This will permit a better understanding of the subsurface parameters that will help in modeling the flow in the reservoir and subsequently, simulating in 3D the reactive transport.

2. GEOLOGICAL CONTEXT

The Nesjavellir geothermal field is located on the northern flanks of the Hengill central volcano which is a part of a 60-100 km long NE-SW trending fissure swarm. The Hengill tectonic setting has been described as a triple junction based on the prevailing stress fields. The triple junction is formed by the intersection of trans-tensional rift zone of the Reykjanes peninsula, the Western Rift Zone and the South Iceland Seismic Zone (Figure 1). The Hengill volcanic center is mainly composed of clustered superimposed hyaloclastite ridges of olivine tholeiite with intercalated lava sequences. The most prominent feature of the southernmost segment of the western rift zone is a 3-4 km wide and 40 km long graben trending N25° filled with volcanics at the Hengill volcanic center. Hyaloclastite ridges dominate the landscape while Holocene lavas are found in the lowlands and on valley floors (Saemundsson, 1967, 1995). Postglacial lavas are exposed in Nesjavellir, north of Hengill, and in the Hellisheidi area south of Hengill. Holocene rifting events and associated volcanic fissures date back to around 9000, 5000 and 2000 years BP (Jonsson, 1977, 1975; Saemundsson, 1995). The two younger fissures have been linked to a pronounced geothermal anomaly (Franzson et. al. 2010). The rocks of the Hengill area are generally dominated by olivine tholeiite which is also observed along the RP? and WRZ. There is insignificant petrochemical diversity among the mapped hyaloclastite and lava lithofacies (Saemundsson, 1995) since the few outcrops of intermediate and silicic rocks are very minor. Along the east-margin of the Hengill volcanic system primitive picritic basalts are exposed (Hardardottir, 1983; Hansteen, 1991) while the bulk of the Hengill mountain is composed of MORB-like olivine tholeiites (Trönnes, 1990; Larsson et al., 2002). Few minor outcrops of evolved rocks of rhyolite composition are known within the central Hengill area as well as dykes of evolved composition that emerge in drill cuttings from the area (e.g. Nielsson, 2011, Franzson 1998). The Hengill volcanic system is considered to have reached an early- to intermediate stage in the evolution of a central volcano. It lacks a caldera and despite different geophysical studies no signs of a magma chamber have been found at depth (Arnason et al., 2010). Therefore, the principal heat source of the geothermal activity is assigned to abundant dyke injections beneath the basaltic production anomaly (Foulger & Toomey, 1989; Arnason & Magnusson, 2001; Arnason et al., 2010). Geothermal exploration and extensive drilling within the Hengill center and across the WRZ have revealed rift-zone stratigraphy of unsurpassed quality down to a depth of 2.5-3 km. As evident by the study of drill cuttings, pillow basalt and hyaloclastite dominate the strata down to 800-1000 m b.s.l., while lava sequences are more prominent at depth (Franzson, 2010). Occasional lava sequences are interlaced with the hyaloclastite formations, representing interglacial periods. By counting those lava sequences the age of the strata at 2.5-3 km has been estimated at around 400 000 years (Franzson, 2010). The earliest appearance of evolved rocks within the crustal section marks the embryonic stage of the Hengill volcanic center. Based on chemical analysis of well cuttings this occurred during the Holsteinian interglacial, 200 000 years ago (Níelsson, 2011). At Hrómundartindur east of Hengill a period of enhanced seismicity and uplift was observed from 1994-1998. This activity was the result of magma accumulation beneath the volcanic system. This event illustrates the repeated intrusive activity that is believed to sustain the heat source of the geothermal system above (Clifton et al., 2002; Foulger & Toomey, 1989).

The extensive drilling which has taken place in Nesjavellir in the last decades has provided a wealth of data but only parts of it have been studied in detail. Results from the compilation of data from recent wells shows the same trends as earlier described (Franzson, 1998). Those findings provide the basis for reservoir modeling. Reservoir modelling is important in many aspects but within the GECO project it will be used to predict the fate of the dissolved CO2 and H2S which will be reinjected for permanent mineralogical storage in the reservoir.

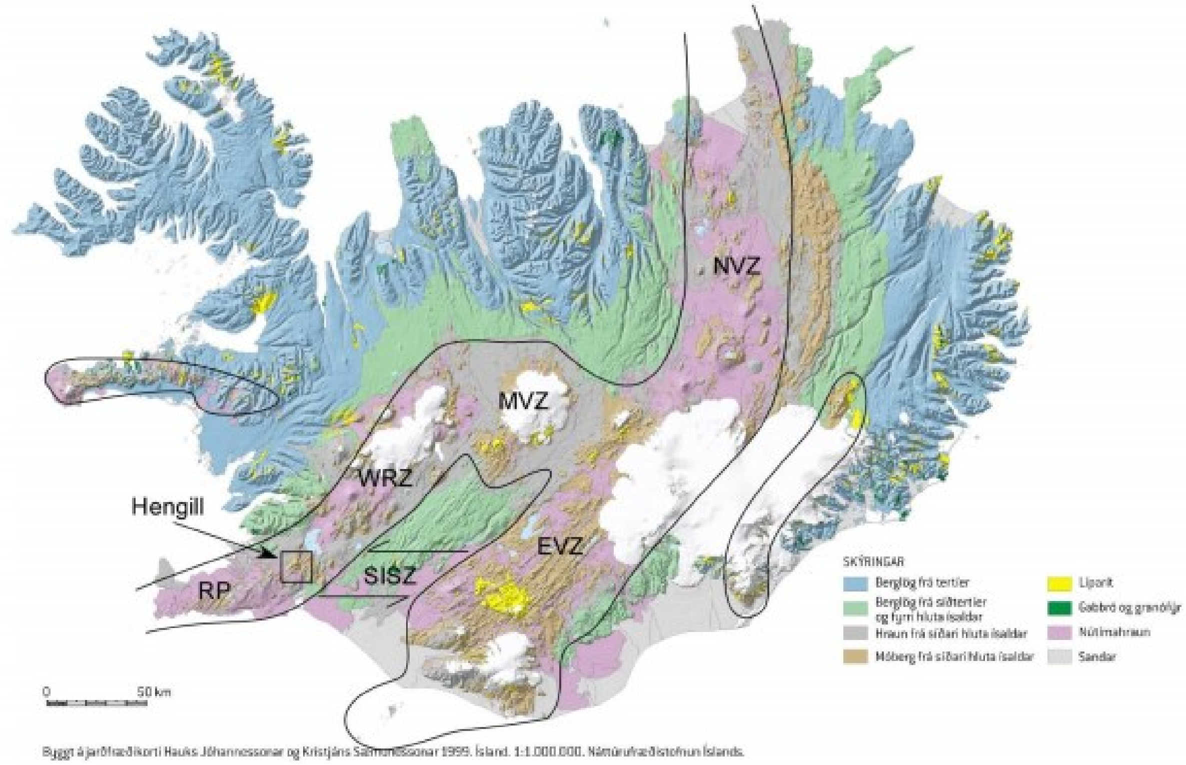

Figure 1: Geological map of Iceland showing the location of the active volcanic zones and transforms. RP=Reykjanes Peninsula, WRZ=Western Rift Zone, SISZ=South Iceland Seismic Zone, EVZ=Eastern Volcanic Zone, MVZ=Mid Iceland Volcanic zone, NVZ=Northern Volcanic Zone (Adapted from Johannesson and Sæmundsson, 1999).

3. CHARACTERIZATION OF NESJAVELLIR RESERVOIR ROCKS

Although permeability is generally considered to be controlled by fractures the porosity of the rock matrix is also important. This is where the bulk of the fluid is stored. The porosity of the rocks and its connectivity define the permeability of the rock matrix itself. To be able to assess these parameters of the reservoir rocks in Nesjavellir lithological logs from the wells are used to categorize different units with different parameters. The lithological logs are based on results from studies of well cuttings which are in good conjunction with the early surface exploration in the area. The alteration of the different units can both play an important role in porosity as well as in chemical reactions with the gas charged fluids.

3.1 Geological and Hydrological Properties of the Nesjavellir Reservoir Rocks

Surface mapping of the Nesjavellir and Hengill area in the early days of exploration revealed the main features of the rocks in Nesjavellir (Sæmundsson, 1995). The composition of the surface rocks is typically basaltic with a subordinate amount of evolved rock. The main characteristics of the subsurface is rather well known after the drilling of 31 deep production wells in the area. Preliminary results from cutting analysis from the wells of the last drilling campaign in Nesjavellir seems to be in a good agreement with the results based on studies of the first 18 wells in Nesjavellir. All this data has now been compiled and can be visualized within the 3-D modelling software Leapfrog. The use of Leapfrog facilitates correlation and interpretation of the data. The software will be used to make the grid for a flow model where the reinjection into the reservoir through well NJ-18 will be simulated. This model will be the basis for a fully coupled reactive transport model of the mixture of dissolved CO2 and H2S. Eventually the goal is to develop such a model on a field scale to be able to simulate the fate of the injected fluid. Properties such as rock type, alteration, porosity and permeability are therefore important. Some of these parameters are relatively well known and easy to constraint whereas others have been less studied.

3.1.1 The Stratigraphy

The stratigraphy of the wells in Nesjavellir is relatively well known. During drilling of the wells cuttings have been sampled every 2 meters. As the preliminary cuttings analyses show the wells intersect different rock formations. A more detailed study of the first 18 wells, including thin section studies of the cuttings, shows the finer details of the subsurface (Hjalti Franzson, 1988). In general, the later preliminary study is in good accordance with the earlier study. The stratigraphy consists of hyaloclastite formations and successions of lava which, at greater depths, are cut by intrusions both of basaltic and evolved compositions. Subsurface mapping shows that the frequency of intrusions in the strata varies with depth and location but between 500 and 1000 m b.s.l. the frequency is generally between 20-40%. At the depth of 1500-2300 m b.s.l. the frequency of the basaltic intrusions rises to 60%. The intrusions seem to form a sheetlike formation with a dip of 20-30° towards the south (Hjalti Franzson, 1988). Above 1200 m b.s.l. most of the intrusions are composed of fresh basaltic rocks and many large feed points are located close to these fresh basaltic intrusions. The frequency of dioritic intrusions increases from the north towards the southern part of the reservoir where the most abundance is found at 1400-1600 m depth. Feed points are frequently associated with these dioritic intrusions.

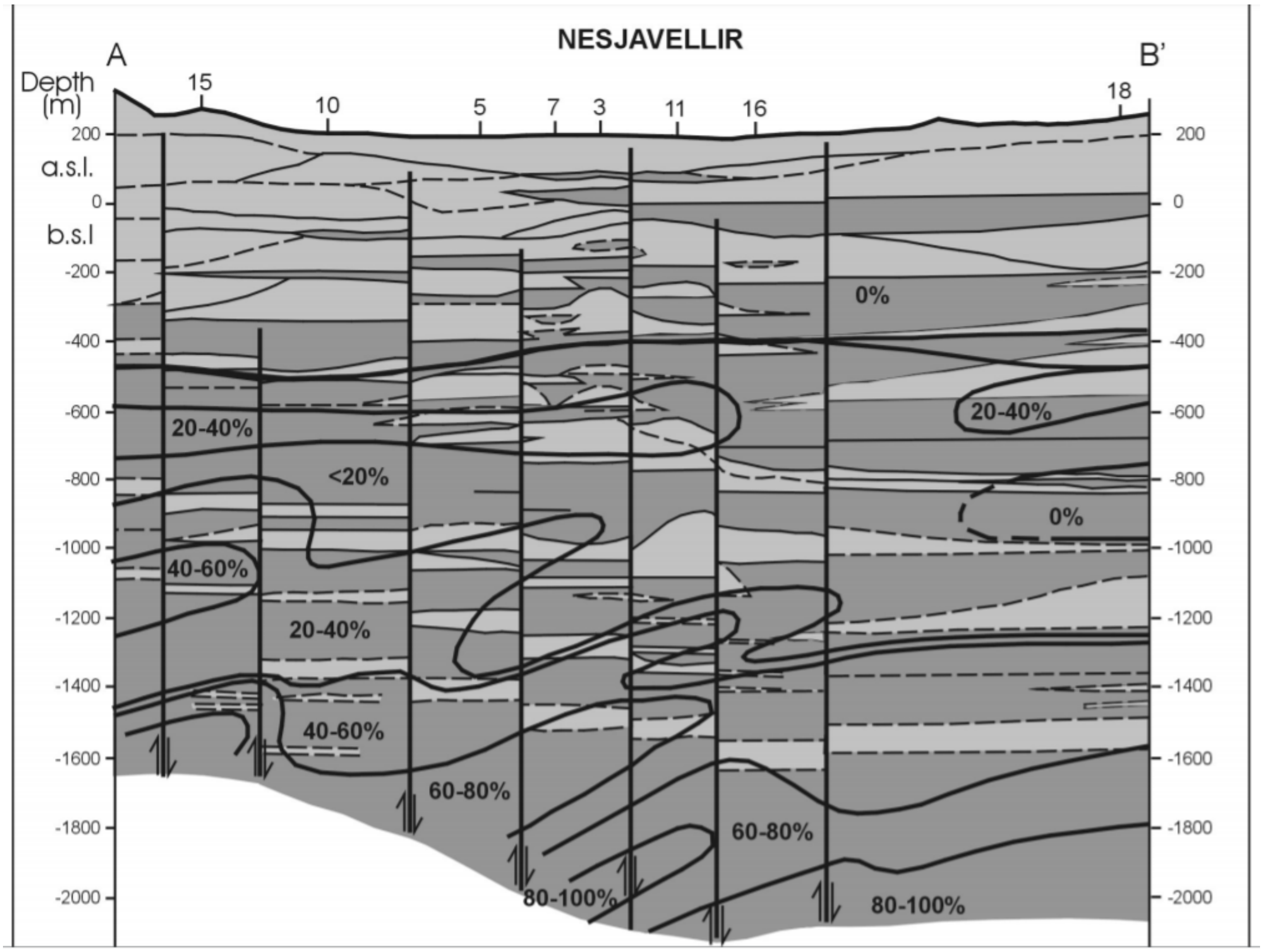

Figure 2: S-N cross section from Nesjavellir geothermal field based on studies from drill cuttings show hyaloclastite prevailing in the upper 400-500 m with intercalated lava sequences which deeper down dominate the strata (Franzson, 1998). The isolines indicate the amount of intrusions. The well numbers are shown above the surface. Reinjection of dissolved CO2 and H2S will take place in well NJ-18.

3.1.2. Alteration of the Strata

The Nesjavellir reservoir rocks show the well-known trends of alteration zonation within high temperature geothermal fields. The top tens or hundred meters are fresh rocks, followed by a layer of cap rock where the alteration mainly consists of smectite clay and zeolites. Below the alteration is characterized by mixed layer clay which further down is substituted by chlorite. Usually a bit deeper epidote is found with the chlorite clays and even deeper the alteration is additionally characterized by the presence of amphibole. With alteration of the rocks, different and often more voluminous minerals form which changes the porosity of the rock formations. Within the smectite alteration zone, hydrous and more voluminous minerals have formed which clog can clog primary pores of the rocks. The results are a less permeable zone, which in geothermal respect is often referred to as cap rock.

Alteration plays an important role when assigning permeability values for rock types since fresh basaltic rocks have open pore spaces whereas pores in altered basalts are likely to have filled up. Different alteration minerals are associated with each alteration zone, which will influence the chemical reactions that take place during the reinjection of CO_2 and H_2S.

3.2 Permeability and Porosity

The most important parameter controlling fluid distribution in reservoirs is permeability which is pressure dependent. Results of experiments and modeling, as well as observations, confirm that permeability of basalts is highly heterogenous and anisotropic (Fisher, 1998). Field scale studies of the Carbfix site on the south side of the Hengill, reported horizontal and vertical absolute permeabilties (kh and kv) of 3.0 x 10-13 and 1.7 x 10-2 respectively (Aradóttir et al., 2012). These results are in some agreement with results from a 3D X-ray microcomputer tomography study of core samples from the same reservoir, which reported horizontal and vertical permeability of 5.10 x 10-11 m2 and 2.07 x 10-10 m2 respectively (Callow et al., 2018). Porosity plays a role but the connectivity of the pores is also really important parameter which is still elusive. Porosity of basalt also varies a lot between different formations. Unaltered hyaloclastites have been measured to have a porosity of 15-60 % (Frolova et al., 2005). Initial porosity of basalt lava flows has been determined to be in the range of 5-40 % (Franzson et al., 2008). Fresh rocks have empty pores but as alteration proceeds they will consequently be filled up (Figure 3). With alteration of the basalts, these volumes decrease down to ~1-10% (Sigurdsson and Stefansson, 1994). Rocks with less than 15% primary porosity will have variable degree of infilling while rocks that exceed 15% primary porosity are likelier to have the pore space nearly completely filled (Franzson et al., 2008). This indicates a non-linear relationship between porosity and permeability.

For the purpose of modeling the reservoir of the Helliheidi geothermal field an average porosity value of 10 % was assumed (Gunnarsson et al. 2011). As a first assumption the permeabilty of the Nesjavellir reservoir is regarded as fracture dominated, but as first results of modeling of the Húsmúli reservoir showed it was necessary to take into an account the different rock formations with different permeabilty and porosity, to be able to simulate the flow of tracers in the reservoir (Ratouis, 2019).

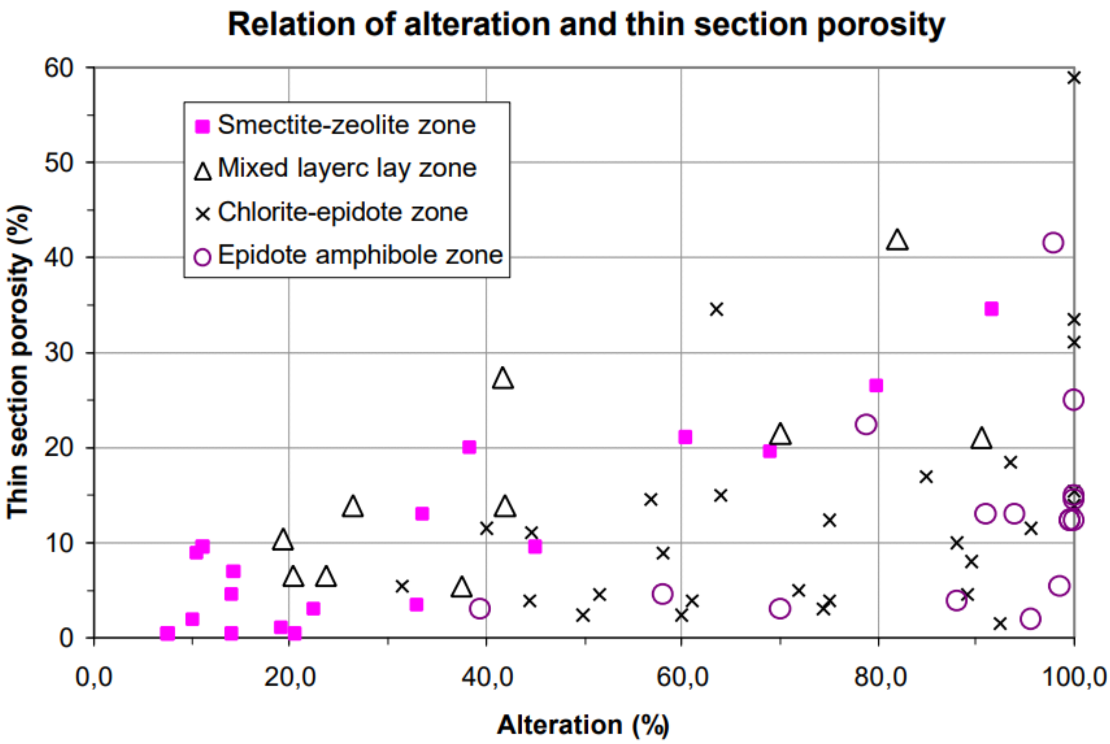

Figure 3. Porosity determined by a thin section analysis of basalt lavas and its relationship with alteration. A distinction is made between samples of different alteration zones (Franzson et al. 2001).

Permeability in both Hellisheiði and Nesjavellir reservoirs has long been linked to lithological boundaries, both stratigraphic boundaries or boundaries of intrusion and the host rock (Hjalti Franzson, 1998). The importance of faults to the permeability has become apparent with more drilling. Results of tracer tests and modeling of the Carbfix site implies that the flow in the reservoir in Húsmúli is largely dictated by fractures (Ratouis, 2019). The status of the mapping of the area has remained more or less the same for the last decades. The regional map of Hengill is the latest publication including mapped faults (Sæmundsson, 1995). Some mapping has been done on small areas within the reservoir with regards to well siting. The general understanding is that the big NNE trending structures of Nesjavellir play a major role in permeability. These are extensional faults which are particularly obvious on both sides of the Nesjavellir graben. Some N-S structures have also been identified. Where these N-S faults intersect NNE extensional faults the vertical permeability is high and upflow seems to occur (Hjalti Franzson, 1998). These faults are generally regarded as more or less vertical structures. Horizontal permeability is mostly related to lithological boundaries and boundaries to intrusions (Hjalti Franzson, 1998). Intrusive rocks have pores and are rather impermeable, but they tend to be fractured as well as their host rock.

4. AQUIFERS OF THE NESJAVELLIR RESERVOIR

Aquifers in the production wells of Nesjavellir have been mapped by analysis of different data sets e.g. circulation losses during drilling, temperature logs during drilling, heating up and monitoring as well as lithological logs. This data will be used to refine the layering of the flow model grid. This set of data will also be of use for the subsequent reservoir model of the Nesjavellir field. The aquifers were given a relative size of 1-3 and the correlation to geology was also noted if apparent (Figures 4 and 5). Three different categories exist for the geological correlation but in most cases the correlation was unknown. In some cases, the aquifers were located at lithological boundaries and in other cases the existence of an intrusion had been noted. During the drilling of the last few wells the relation of faults and aquifers have been more in focus, however, the control structures have on permeability has not been studied in detail. Tracer tests have until now not been successful, but tracers were injected into NJ-18 early July 2019. Hopefully results of these tests will indicate where flow paths are located. A study of the Húsmúli area showed how the flow of fluids reinjected into the reservoir is confined to large extensional and strike slip faults (Ratouis et al, 2019).

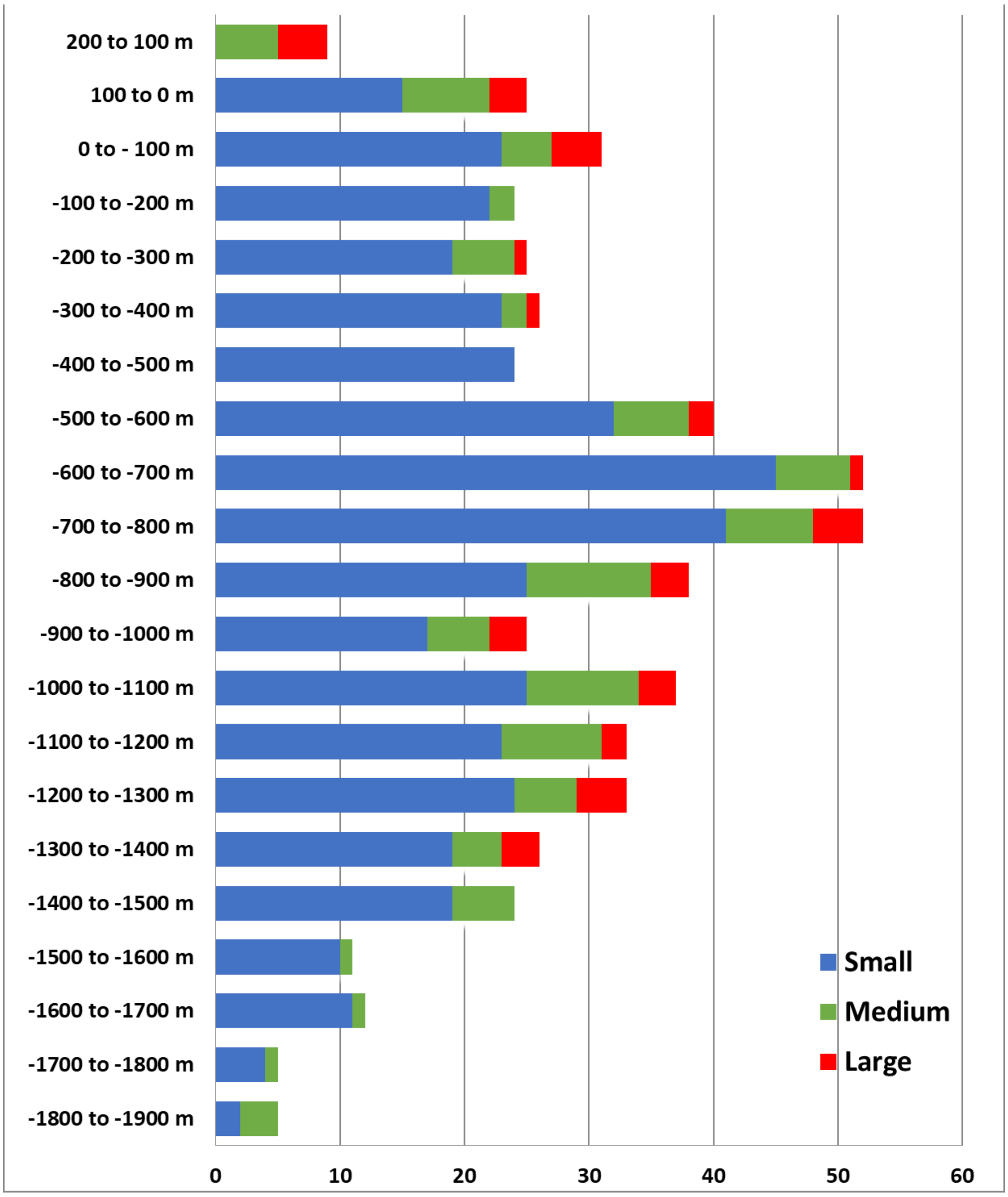

Figure 4: Aquifers in all deep wells in Nesjavellir.

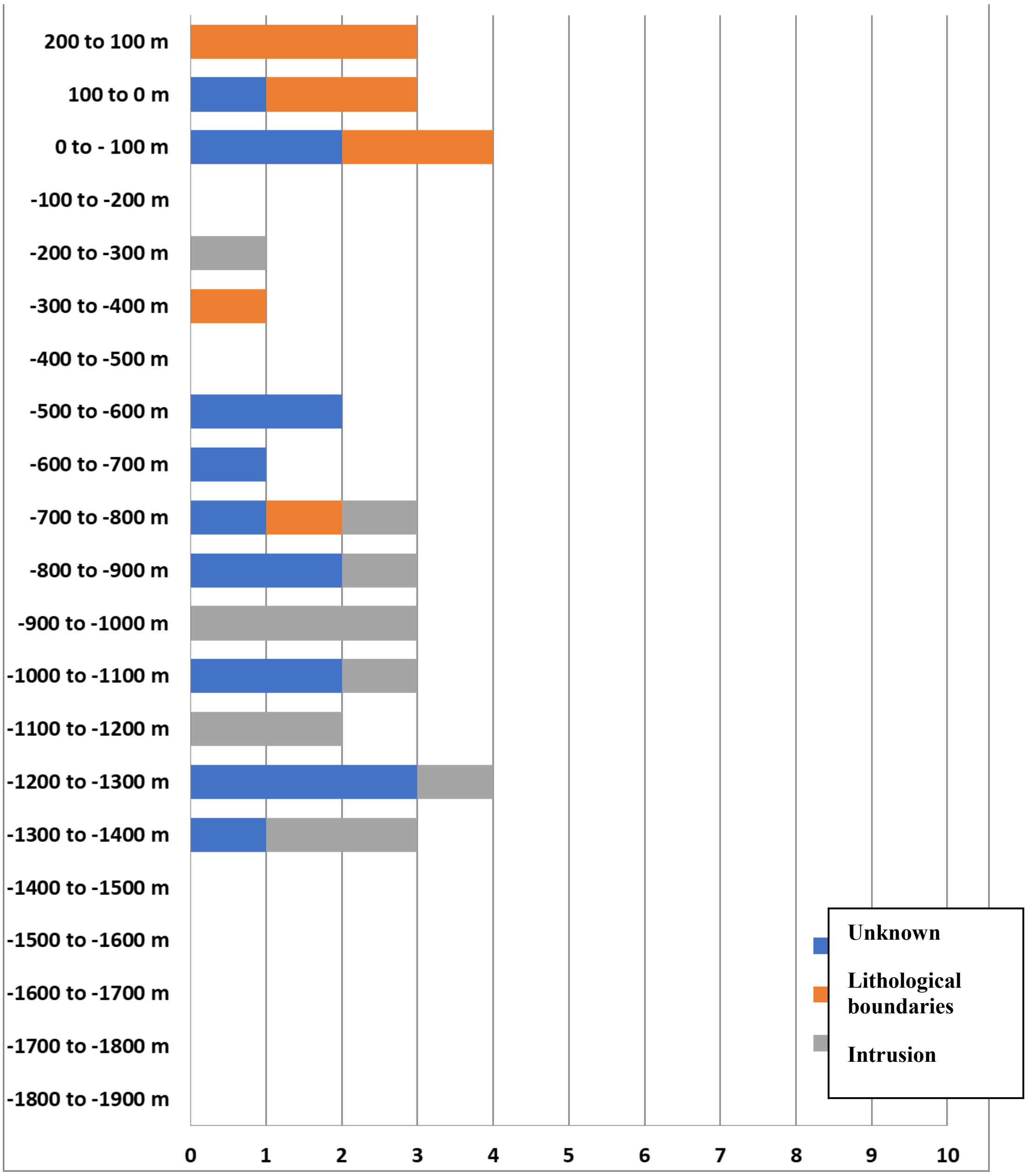

Figure 5: Aquifers in all deep wells in Nesjavellir and their relation to geology. Blue=unknown, Brown=lithological boundaries, grey=intrusions.

4. WELL NJ-18

Well NJ-18 is located on the volcanic fissure with the same NNE strike as the nearby extensional faults. Since it is a near vertical well and these faults are more or less vertical it is difficult to predict if any nearby faults intersect it. It is assumed that the well intersects the roots of the volcanic fissure with its intrusions, which involve permeable zones. This is evident from wells that intersect the same volcanic fissure further south.

The stratigraphy of the well is composed of hyaloclastites and lava sequences similar as in most wells in Nesjavellir. Noticeable is the prominent lava sequence of tholeiitic composition at the depth of 781-1046 m (measured depth).

According to the latest correlation of various data the following alteration zones in NJ-18, in order of increasing alteration grade, are observed: Smectite-zeolite zone (500 to 1060 m b.s.l.), mixed layer clay zone (1060 to 1180 m b.s.l.), chlorite-epidote zone (1180 to 1640 m b.s.l.) and epidote-actinolite zone (1640-2136 m b.s.l.).

Twenty-four feedpoints have been mapped in NJ-18. Most of them are small but a medium size aquifer was found at 1621 m and the largest at 1705 m (Figure 6). The location of the medium and large feedpoints was in a relation to an intrusion.

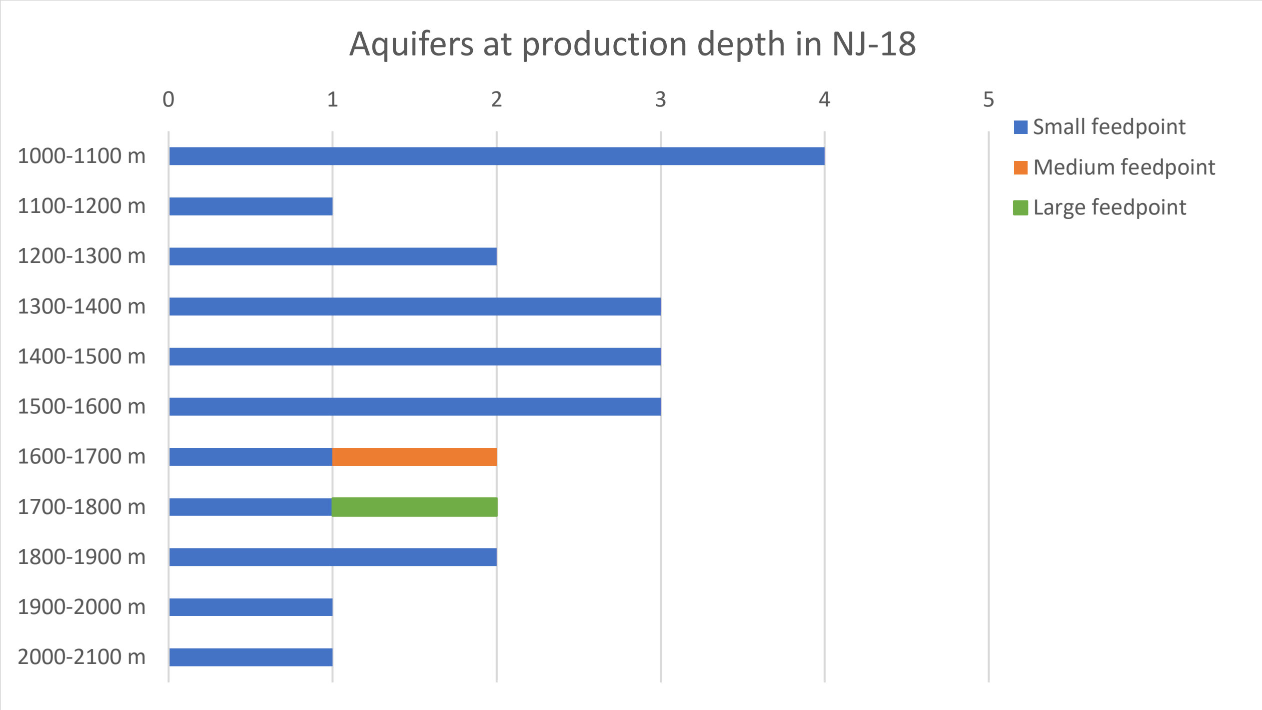

Figure 6: Aquifers at 100 m depth intervals below the production casing in well NJ-18 in Nesjavellir and their relative size (1-3).

As a first proximate for a new three-dimensional flow model for the reinjection at Nesjavellir the vicinity of NJ-18 is being modelled with a single porosity approach. The rock units surrounding NJ-18 are assigned porosity and permeability values using similar criteria as in a study on the Húsmúli area at the SW side of Hengill (Ratouis, 2019) where a distinction was made between basalt, hyaloclastite, intrusions and clay cap. Furthermore, it was defined if the rock units were altered or fresh.

Porosity and permeability are affected by the rock type and the alteration of the rock. For the purpose of modeling the flow and chemistry in the reservoir, all these parameters have been taking into an account, combined and simplified. The results are formations which have been named permeability formations. These formations have been assigned different relative permeability (low, medium and high). The permeability formations in NJ-18 are shown in table 1. This simplification of the formations is not straight forward. Intrusive rocks are generally regarded dense, with low porosity and permeability. However, intrusive rocks are formed by magma intruding into the country rock where it slowly cools down and can form cooling fractures. Theoretically intrusions follow orientation of the least principal stress. This orientation can vary with time and depth. It can be vertical, similar to most surface fractures and faults . It can also be subvertical, resulting in the formation of sills. This results in permeable formations, within and around intrusions, which is evident from the fact that feedpoints in wells can often be correlated with intrusions (Franzson, 1988). The stratigraphy, alteration zones, feedpoints and the derived permeability formations are shown on Figure 7. The same procedure was followed for wells within the study area and the results are shown on Figure 8A and B.

Table 2: Rock formations in NJ-18 and their different permeability categories and relative permeability. The permeability is regarded isotropic in the (x,y) space.

Depth from (m MD)	Depth to (m MD)	Permeability category	Relative permeability
0	500	Fresh rocks	High
500	1060	Clay cap	Low
1060	1262	Altered basalt	Rather low
1262	1316	Intrusions	Low and high
1316	1440	Altered hyaloclastite	Medium
1440	2136	Intrusions	Low and high

Before the modeling of the flow from injecting into NJ-18 started, an area of interest was defined (Figure 6). No tracer data or other direct evidence for the direction of the flow in the Nesjavellir reservoir exists. Thus, some general assumptions had to be made on the direction of flow. The groundwater flow is in general towards the Þingvallavatn lake but at reservoir level it is assumed that the flow is towards the centre of the production, where the main upflow has been regarded to be located. The main flow is regarded to be along the volcanic fissure which NJ-18 is located on. A secondary flow channel, of much smaller influence and evidenced by borehole cuttings data, is assumed to have a N-S direction and intersect the NNA trending volcanic fissure. Within the area of interest there are a number of production wells. For the purpose of flow modeling, simplified permeability formations have been defined in wells NJ-11, NJ-16, NJ-18, NJ-19, NJ-24 and NJ-25b. These formations have been simulated for the whole study area along with the permeable NNE volcanic fissure and the N-S fault (Figure 6).

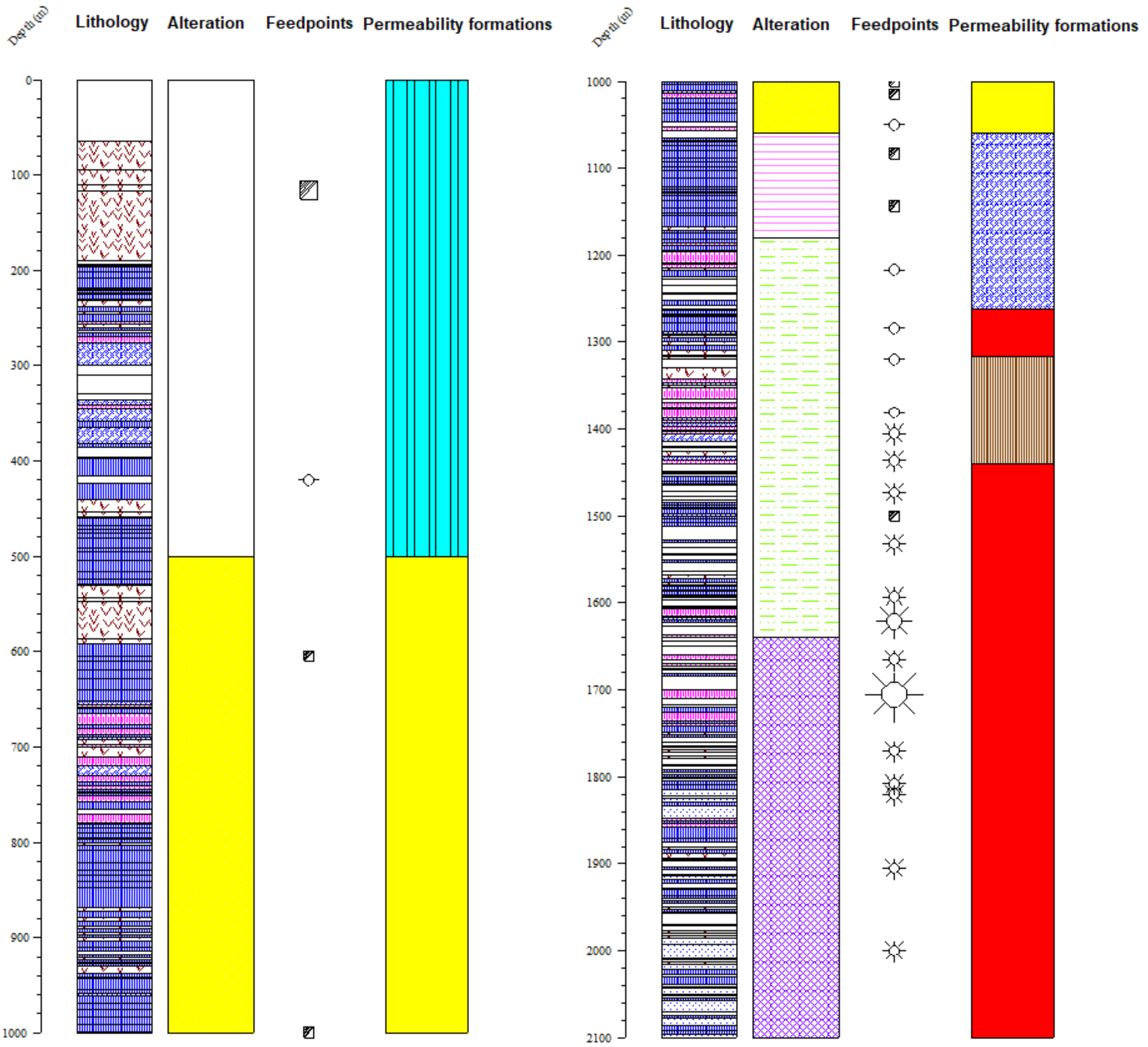

Figure 7: The stratigraphy (blue=fine grained basalt, pink and brown=different hyaloclastites), alteration zones (white=fresh, yellow=smectite-zeolite zone, pink= MLC zone, green lines=chlorite-epidote, purple=amphibolite), feedpoints (3 relative sizes, different symbols indicate relations with geology), simplified permeable formations (as described in table 1) in NJ-18.

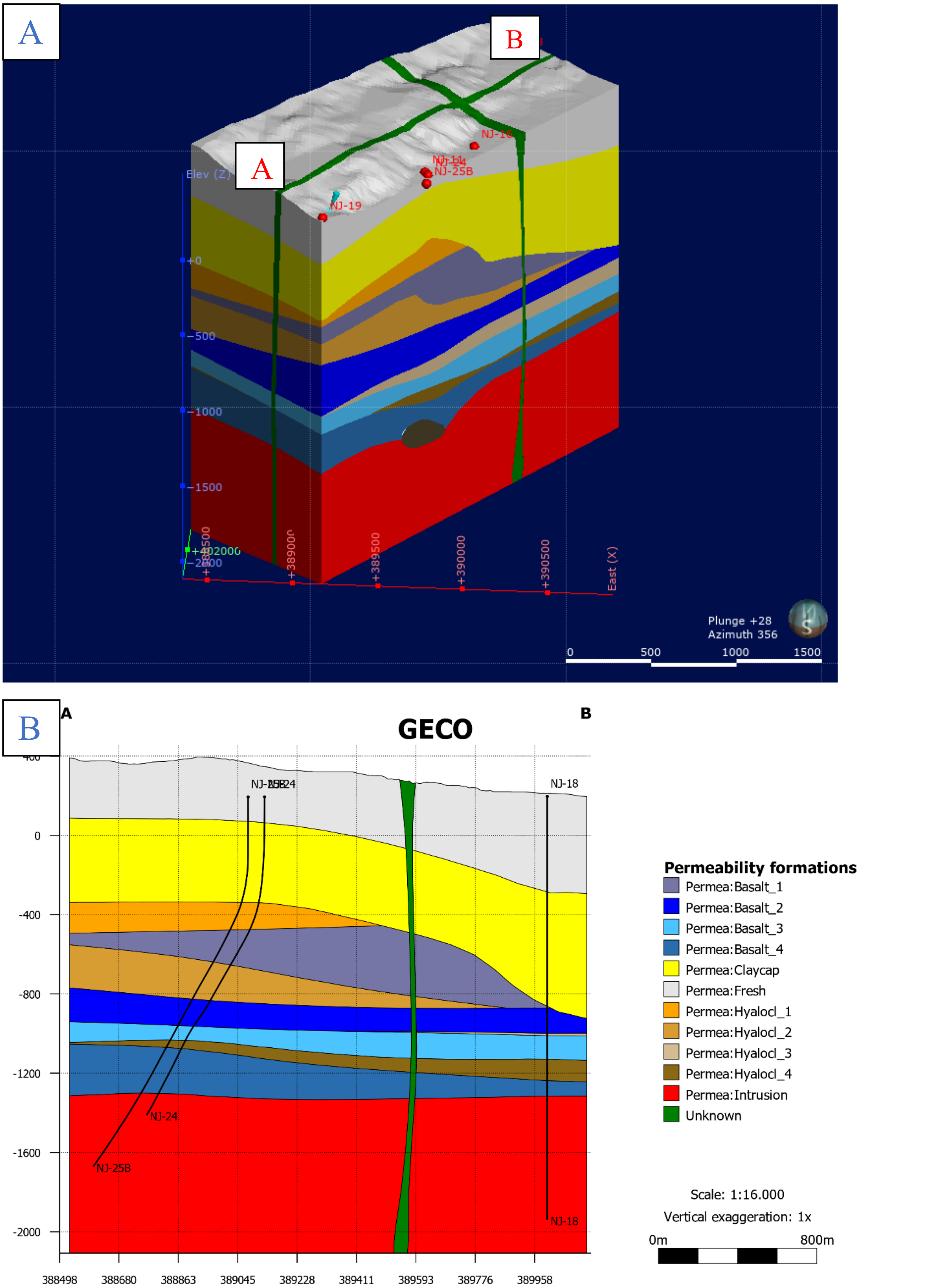

Figure 8: A simplified model of a part of the Nesjavellir geothermal area, showing different formations that have been distinguished to have different permeability based on rock type and alteration. A) A view of the study area from the south and the reservoir down to 2000 m below sea level. B) A cross section (A to B) of the same model. White=fresh, Yellow=clay cap, brownish=altered hyaloclastite, blue/gray=altered basalt, red=intrusions

5. CONCLUSIONS

A thorough understanding and knowledge of the geology of the subsurface is important when undertaking a big project like the reinjection of CO2 charged fluids for mineralogical storage. For the reinjection to be successful the precipitation of minerals like calcite will have to occur. When lithological units surrounding the reinjection well have been mapped they can be assigned with the appropriate porosity and permeability values, based on the best knowledge. Feedzones which have been located in wells give indication on the most important flow paths in the reservoir. In previous studies of the Nesjavellir geothermal area have concluded that lithological boundaries are important for the flow but preliminary mapping and clues from drilling of the latest production wells in Nesjavellir indicate that faults might play an even bigger role in the flow of the area. Based on this knowledge a grid for a numerical simulation of a part of the Nesjavellir reservoir will be built. Based on this model a reactive transport model can be built which will allow for predictions on the precipitation of alteration minerals depending on the fluid flow and composition as well as the composition of the rocks.

REFERENCES

Aradóttir, E.S.P., Sonnenthal, E.L., Björnsson, G., Jónsson, H.: Multidimensional reactive transport modeling of CO2 mineral sequestration in basalts at the Hellisheidi geothermal field, Iceland. *International Journal of Greenhouse Gas Control*, 9, (2012) 24–40.

Arnason, K., Eysteinsson, H. and Hersir, G.P.: Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. *Geothermics*, 39, (2010), 13- 34.

Callow, B., Falcon-Suarez, I., Ahmed, S., Matter, J.: Assessing the carbon sequestration potential of basalt using X-ray micro CT and rock mechanics. *International Journal of Greenhouse Gas Control*, 70, (2018), 146-156.

Clifton, A.E., Sigmundsson, F., Feigl, K., Gudmundsson, G. and Arnadóttir, Th.: Surface effects of faulting and deformation resulting from magma accumulation at the Hengill triple junction. *Journal of Volcanology and Geothermal Research*, 115, (2002), 233-255.

Foulger, G.R. og Toomey, D.R.: Structure and evolution of the Hengill-Grensdalur Volcanic complex, Iceland: Geology, Geophysics, and seismic tomography. *Journal of Geophysical Research*, 94, (1989), 511-522.

Franzson, H., Gunnlaugsson, E., Arnason, K., Saemundsson, K., Steingrimsson, B. and Hardarson, B.S.: The Hengill geothermal system, conceptual model and thermal evolution. *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia (2010).

Franzson, H., Gudfinnsson, G.H., Frolova, J., Helgadóttir, H.M., Pauly, B., Mortensen, A.K., Jakobsson, S.P.: Icelandic Hyaloclastite Tuffs, Petrophysical Properties, Alteration and Geochemical Mobility. Report prepared for National Energy Authority and Reykjavík Energy. Iceland (2011). ISOR, Reykjavik; ÍSOR-2011/064

Franzson, H., Gudlaugsson, S.P. and Fridleifsson, G.O.: Petrophysical properties of Icelandic rocks. Proceedings of the 6th Nordic Symposium on Petrophysics, Tronheim, Norway. In: Knut Backe & Ton Loermans (ed), The Norwegian University of Science and Technology (2001). Trondheim, Norway.

Franzson, H.: Reservoir geology of the Nesjavellir high-temperature field in SW Iceland. *Proceedings of the 19th Annual PNOC-EDC Geothermal Conference*, Manila, Philippines, (1998), 13-20.

Franzson, H.: Nesjavellir – Borholujarðfræði, vatnsgengd í jarðhitageymi., Report prepared for National Energy Authority and Reykjavík Energy. (1988). Orkustofnun, Reykjavík; OS-88045/JHD-09.

Franzson, H., Zierenberg, R., Schiffman, P.: Chemical transport in geothermal systems in Iceland. *Journal of Volcanology and Geothermal Research*, 173, (2008), 217–229.

Hansteen, T. H.: Multi-stage evolution of the picritic Maelifell rocks, SW Iceland: constraints from mineralogy and inclusions of glass and fluid in olivine. *Contribution to Mineralogical Petrology*, 109, (1991), 225-239.

Hardardottir, V.: The petrology of the Hengill volcanic system, South Iceland (MS thesis) (1983). McGill University, Montreal, Canada.

Johannesson, H. and Saemundsson, K.: Geological map of Iceland, 1: 1 000 000, (1999). Icelandic institute of natural history.

Nielsson, S.: Jarðfræði og ummyndun í jarðhitakerfinu við Hverahlíð á Hellisheiði (MS thesis) (2010). University of Iceland.

Ratouis, T., Snæbjörnsdóttir, S.O., Gunnarsson, G., Gunnarsson, I., Kristjánsson, B.R., and Aradóttir, E.S.P.: Modelling the Complex Structural Features Controlling Fluid Flow at the CarbFix2 Reinjection Site, Hellisheiði Geothermal Power Plant, SW-Iceland. *Proceedings*, 44st Workshop on Geothermal Reservoir Engineering, Stanford, California (2019).

Saemundsson, K.: Hengill - geological map (bedrock) 1:50.000, Energy Authorities of Iceland, Reykjavik Energy and National Land Survey of Iceland, Reykjavík (1995).

Snæbjörnsdóttir S.Ó., Tómasdóttir S., Sigfússon B., Aradóttir E.A., Gunnarsson G., Niemi A., Basirat F., Dessirier B., Gislason S.R., Oelkers E.H., Franzson H.: The geology and hydrology of the CarbFix2 site, SW-Iceland. *Energy Procedia*, Volume 146, (2018) 146-157.

Steingrímsson, B., Sverrisdóttir, G., Eysteinsson, H., Sigurðsson, Ó., Franzson, H. and Hermannson, G.: Nesjavellir, Hola NJ-18. Borun, rannsóknir og vinnslueiginleikar, (1987). OS-87029.

Thien, B.M.J., Kosakowski, G. & Kulik, D.A. Differential alteration of basaltic lava flows and hyaloclastites in Icelandic hydrothermal systems. *Geotherm Energy* (2015) 3: 11.

Trönnes, R.: Basaltic melt evolution of the Hengill volcanic system, SW Iceland and evidence for clinopyroxene assimilation of primitive tholeiitic magmas. *Journal of geophysical research,* 95 (B10), (1995) 15893-15910.