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

3D Conceptual Model and Numerical Model Hvíthólar Sub-area at Krafla Geothermal Field, Iceland

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Keywords: Krafla, Hvíthólar, 3D conceptual model

ABSTRACT

This paper reviews the 3D conceptual model for the Hvíthólar sub-area in the southern zone of the Krafla geothermal field. Hvíthólar is one of six sub-areas in south Krafla, located at the intersection of the boundary of Krafla caldera and the NNE-SSW striking fissure swarms of the North Volcanic Zone. Hvíthólar is the only southern sub-area connected to the Krafla power station and has exhibited considerable production decline throughout 1990–2013. According to a lumped parameter model simulation, Hvítholar reservoir follows a two-tank open system with a volume of 6.0 km^3. The enthalpy of Hvíthólar wells today is approximately 1200 kJ/kg; chemically it presents a high concentration of Cl^- and low CO_2. To date, most studies support the hypothesis that Hvíthólar characteristics and behaviour are due to the lack of a heat recharge (cooling intrusion) and that the sub-area is in a phase of waning. An improved understanding of heat source location and permeability variations will provide the basis of future utilisation decisions. This study presents two alternative conceptual models for Hvíthólar to determine the extent of utilisation of the asset. The model developed in this study extends along Vestursvæði, Hvíthólar, and Sandabotnaskarð sub-areas with a combined area of 30 km^2. An update of the geological model was carried out based on data from shallow and deep wells along the southern part of Krafla geothermal field. Data from geothermal surface exploration was integrated with the geological data in Leapfrog Geothermal software to facilitate visualisation as well as a more realistic representation of the geological model in the TOUGH2 permeability structure grid. The two discussed conceptual models locate Hvíthólar sub-are inside (M1) and outside (M2) the Krafla caldera. The study focuses on the location of heat source for this sub-area, and the permeability structure at the south intersection of the caldera boundary and fissure swarm. Each of the conceptual models was validated with TOUGH2 simulations under the premise that a better natural state match will be obtained with the most reasonable permeability structure.

1. INTRODUCTION

A Geothermal Conceptual Model provides a visual depiction of the elements of a geothermal reservoir: location of the heat source, working fluids, permeability structures and fluid paths (Grant, 1983). The conceptual models are important for geothermal field development since the conceptual model provides a good understanding of the multiple process taking place in the study area. When utilisation and expansion plans are discussed, an enriched conceptual model will allow enhancing the outcome of the plans (e.g. location of production or injection wells). Numerical models such as the natural state model aim to provide an initial estimate of reservoir conditions before utilisation (Grant, 1983). The natural state model provides reasonable values of the heat inflow, mass inflow and permeability relations within the study area, which are important when planning development and utilisation of a geothermal field.

Background

The Krafla Geothermal Field is located in the Northeast of Iceland at Skútustaðahreppur municipality (Guðmundsson et al. 1971). The exploration of the Krafla Geothermal area began in the late 1960s, but production drilling started in 1974. The following year, volcanic fissures eruptions started at Krafla " Krafla fires", the outcome of which changed the conditions (mainly chemistry) in the Krafla reservoir and several wells were damaged (Björnsson et al., 1977; Björnsson et al., 1979). The Krafla power plant was commissioned in 1978 and has been supported by subsequent drilling campaigns to increase and sustain production. The current installed capacity of Krafla Geothermal Power plant is 60MW. The Krafla production field is divided into eight sub-areas located inside the Krafla Caldera. For this project, the field is divided into two zones: North and South (Figure 1).

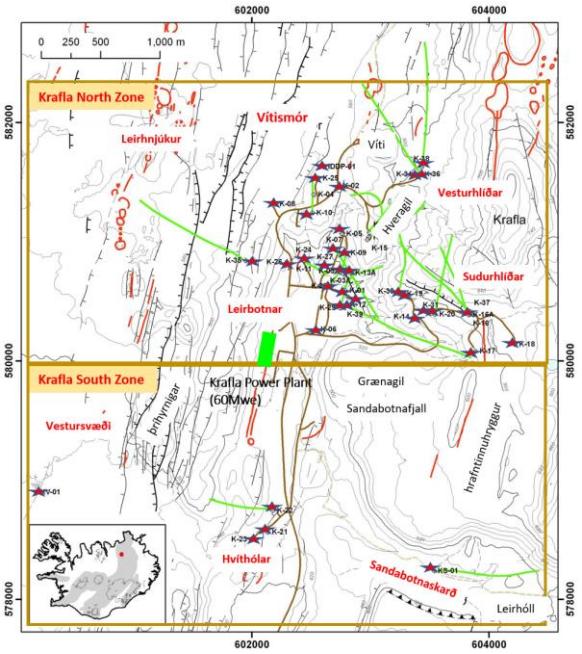

Figure 1: Krafla Geothermal Field. The red lines in the diagram depict major volcanic fissures and craters. The green lines show the deviated well paths. Well locations (45 in total) are shown as red stars. Field sub-areas are in red text (Mortensen et al., 2015) and geographic location areas in black text (Sæmundsson, 2008)

Hvíthólar sub-area is the only southern sub-area connected to Krafla Power Station. The sub-area was first brought online in 1984 and contained three wells, KJ-21, KJ-22 and KJ-23. KJ-22 is directionally drilled to the west. The Hvíthólar wells were drilled in the southern border of the caldera. The field contains hyaloclastites, basaltic lavas, oxidized breccias and scorias as well as basaltic and andesitic intrusions in KJ-21. The wells highest temperature recorded was 260°C. However, all the wells exhibit a temperature reversal below the production deep (around -400 m.b.s.l.). To date, most studies consider that Hvíthólar characteristics and behaviour are due to the lack of heat recharge (controlled by a cooling intrusion), and the waning of heat supply to the sub-area. During production, the sub-area exhibited a 20-21 bar pressure decline throughout 1990-2013 (Weisenberger et al., 2015) before that period well 21 was the most powerful well at Krafla. The wells enthalpy had decreased from 1800 J/kg at the end of the 1980s to 1200 kJ/kg by 2015 (Mortensen et al., 2015) and the reservoir passed from a gas dominated to a liquid dominated resource.

The sub-area has a fluid composition characterised by a high concentration of Cl^-, and low CO_2. SO_4 concentration is between medium and low, while Ca^+, in general, has average values. Hvíthólar reservoir follows a two-tank open system with a volume of 6 km3 and 0.00004 km3 according to the lumpfit model results published in 2009 (English version: Mortensen et al., 2015). An improved understanding of heat source location and permeability variations is imperative in future decisions regarding the utilisation of Hvíthólar and future exploitation of the Southern Zone of Krafla Geothermal Field.

Data integration from the existent Landsvirkjun Petrel model, geological model, previous geophysical models, and a formation temperature model allows the conceptual model revision. The geological model provides the initial permeability structures. The geophysical surveys also help to locate geothermal reservoirs cap-rock on top of a high resistivity core (reservoir) and heat sources. The geochemistry data allows a better understanding of the connection between the different elements in the reservoirs, such as the heat source and the fluid recharge origin. These elements are essential for the field utilisation. The temperature natural state provides information regarding the thermodynamic condition of the field at drilling time just before utilization and this is important since other methods like resistivity could be showing fossil conditions.

2. CONCEPTUAL MODEL

The first conceptual model of the Krafla geothermal field was developed in 1977 (Stefánsson et al., 1977; Steingrímsson et al., 1978). The increase in information provided by subsequent drilling and numerical simulations concluded the field was a two-phase resource that flows from the west lower reservoir through a fracture near Hveragil where it mixes with the fluids from the eastern part of the reservoir. The discharge of the reservoir is seen as surface springs around Hveragil, and the rest recharges the upper reservoir in the old west part of the field since the conceptual model update in in 1982-1984 (Böðvarsson and Pruess, 1982; Böðvarsson et al.,1984). Revision and upgrade of the conceptual model was done by Grímur Björnsson et al. in 1997. In 2009 the new update of the conceptual model included a volumetric assessment based on a Monte Carlo simulation ensuring Krafla resource capacity of 150MWe for 50 years (Mortensen et al., 2015). Also, interpretation of the MT data and drilling from Vestursvæði, Sandabotnaskarð and Leirhnjúkur sub-areas enriched the field understanding by confirming cooling at Vestursvæði and heat sources (up-flows) at Sandabotnaskarð and Leirhnjúkur sub-areas. In 2015, the Krafla conceptual model update (Weisenberger et al., 2015) included more data from fluid chemistry providing a better understanding of the fluid origin and relations within different sub-areas. Seismic data and update of the geological and alteration models was also improved. The current work is based on the results of a conceptual model update on the Krafla south zone based on well-cutting analysis and revision of all data available.

2.1 Conceptual model elements

In order to understand Hvíthólar sub-area, the project needed to include all the Krafla Southern Zone sub-areas to understand the connection of this sub-areas with the surrounding system. For this reason, an area of 30km^2 enclosing Vestursvæði, Hvíthólar and Sandabotnaskarð sub-areas, and three wells from the Krafla North Zone were selected as sufficient extent for the conceptual model.

This project developed two hypotheses for the location of the caldera fault, given hypothesis are represented in conceptual models CM1 and CM2.

2.1.1 Geology

The stratigraphy for the study area was developed by correlating the surface geology with the existing data from 10 wells in Krafla south area [KS-01, KJ-21, KJ-22, KJ-23, KV-01, AE-10, KH-01, KH-02, KH-05 and KH-06], and, for better correlation, three wells in the Krafla North Zone [KJ-35, KJ-06, KJ-18]. The data came from well cuttings, well cores, reports and previous Petrel model from Landsvirkjun. When developing the stratigraphic classification, the numerical model vertical resolution of 100m was considered, and 13 stratigraphic units were found to represent the model area (Figure 2). It is important to say that some exaggerations were made on the andesitic intrusion on well KJ-21 for Numerical modelling purposes. In addition to the stratigraphy, six faults were selected as the Project area's most relevant structural features [Fissure Swarm, Dal Fires, Hveragil, Dalsel, Leirhóll, and Caldera Faults] (Figure 3).

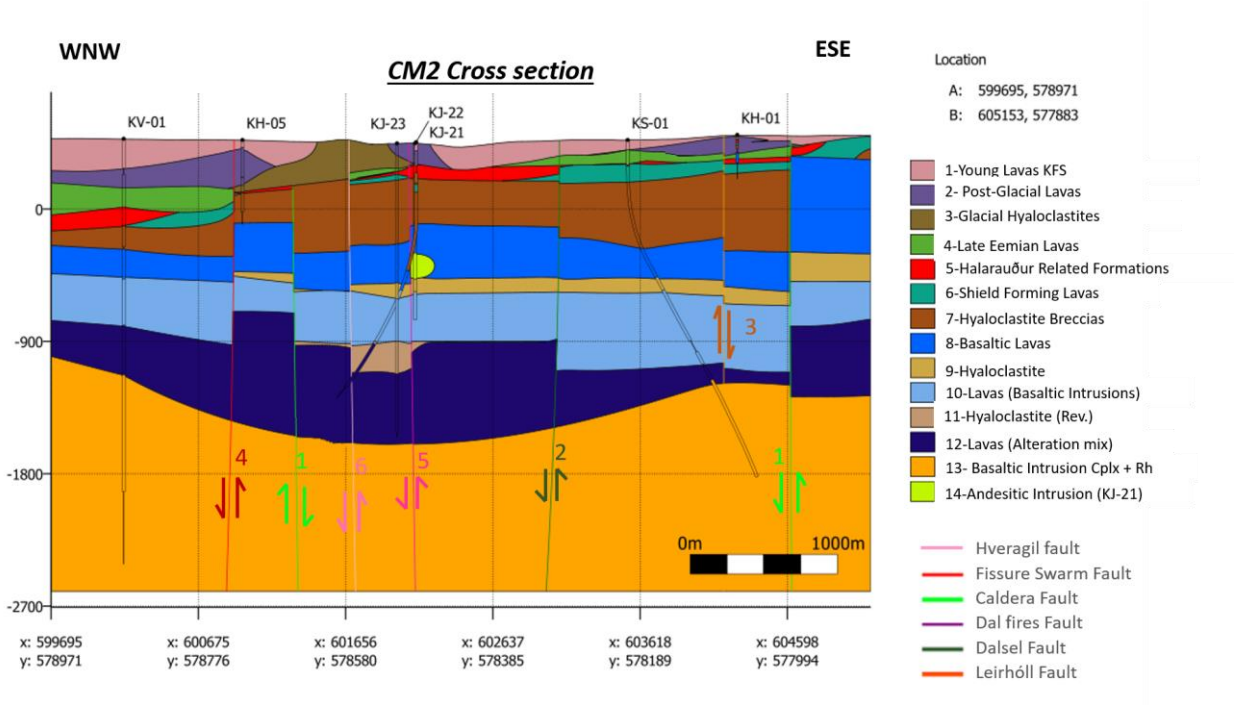

Figure 2: Krafla South Zone Geological model cross section

A portion of the Krafla caldera in the Southern border has been said to be buried in the southern boundary (Mortensen, 2015). This study hypothesises two possible locations for the Krafla caldera fault. Since at Krafla geothermal resource faults are the main system driver addition of faults such as Hveragil extension to the south boundary of Krafla can be done. Concluded that the most critical drivers for the Krafla Geothermal System are faults (Stefánsson and Steingrímsson, 1980). Thus, the six faults selected from the Project Area Fault Models have also been treated as permeability domains in the conceptual model. Therefore, the location or addition of faults is determining at the time of defining the conceptual model of Hvíthólar. This project uses Hveragil and the caldera faults as a possible heat driver.

2.1.2 Geophysics

In terms of deep heat sources (outside of the study area), resistivity data showed two peaks of low resistivity located at Mt. Krafla and Sandabotna affecting the North and east boundaries of the study models respectively. The eastern peak is linked to the heat source underneath Leirhóll fault and Sandaboskarð sub-area. Within the study area at shallow deeps (< -2000 m.b.s.l) it was possible to see a low resistivity area at the centre of the zone to the north-east the Hvíthólar sub-area at -1000m.b.s.l. (Þoresteinsdóttir, 2017). This area shows a pattern of low resistivity cap on top of a high resistivity core indicating the possible presence of a geothermal reservoir at that location. The results from the geophysical data provided the heat source from the North and East of the project area. Also, two possible geothermal systems a shallow system (less than -1000 m.a.s.l.) at Hvíthólar, and a deeper resistive core at -1000 m.a.s.l. at Sandaboskarð.

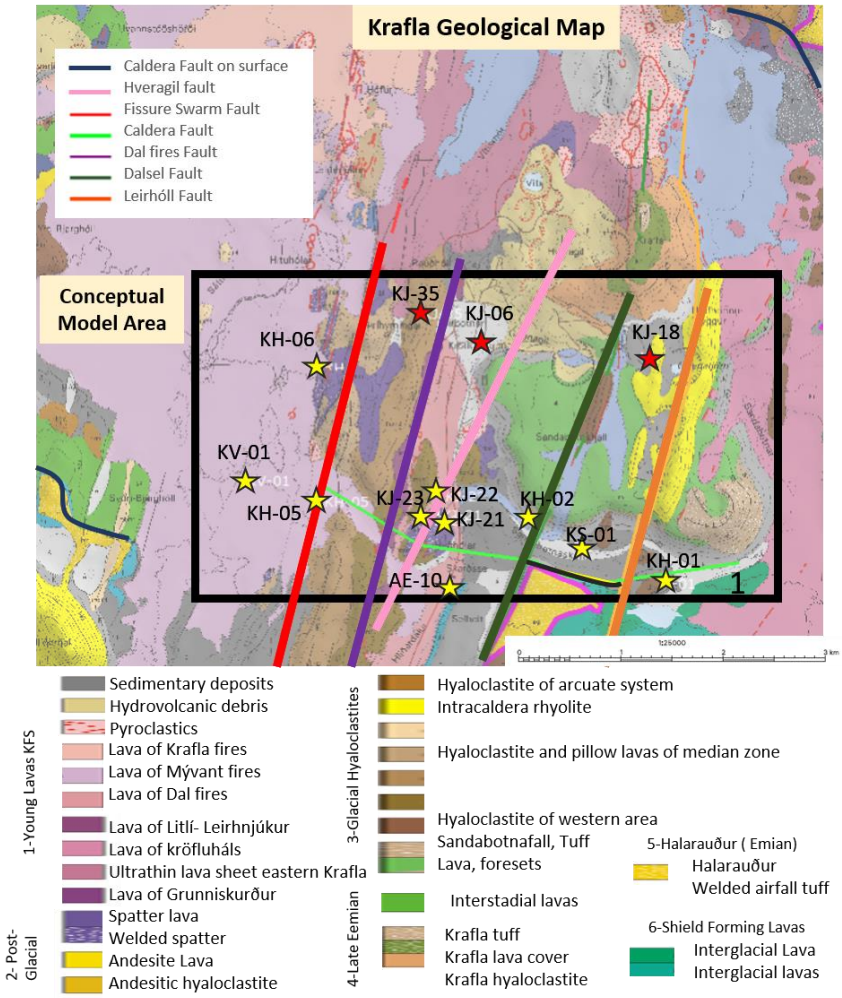

Figure 3: Krafla South Zone model faults. Geological model taken from (Sæmundsson, 2008) Legend numbers allow to correlate the surface geological units with the conceptual model stratigraphic units. Yellow stars represent the Krafla south Zone wells and red stars the Krafla North Zone wells used in this study.

2.1.3 Geochemistry

Geochemistry shows that Hvíthólar fluids are composed of mixed water that recharge from meteoric cold water form the west and hotter recharge from the North. Isotopic composition of the east with low deuterium values show mixing with old waters that are hypothesized to come from Vatnajökull glacier. Sandabotnaskarð in the east has the most depleted waters implying an old origin (deep reservoir) suggesting the contribution from the east to the Hvíthólar sub-area (Ármannsson et al., 2015).

2.1.4 Mineral Alteration vs Temperature models

The mineral alteration interpolation model was compared with the well's formation temperature model and the position of the project faults. A considerable difference in the mineral alteration temperature was observed and the measured temperature in the western part of the Fissure swarm of the Krafla South Zone showing cooling of Vesturs væði. The alteration minerals supported the contact between Caldera fault and Leirhóll fault in the south-east, as well as, the Caldera fault and Hveragil fault to be the area with highest temperatures at the planar maps of 0 m.b.s.l. and 600 m.b.s.l. In the case of Hvíthólar, even though was correlation between temperature model and the alteration, the formation temperatures were lower than the alteration temperatures.

2.2 Conceptual models

Figure 2 shows the east-west cross-section of conceptual model CM2, with the up-flow zone located in the east at Leirhóll fault and lateral flow towards Hvíthólar along Lavas 8, and Hyaloclastite 7 represent the cap-rock. Since the resolution of the temperature model interpolation higher than the distance between wells, it is assumed that the temperature anomaly can be controlling flow and temperature along the caldera fault to the Hvíthólar sub-area (white line on Figure 2).

Figures 4a and 4b show the 3D conceptual models proposed by this study. The red lines represent heat sources; the yellow lines represent the hot fluid path and blue represent recharge of colder fluids. The star in CM1 represents the cooling dike at Hvítholar sub-area.

2.2.1 Conceptual model 1

The Conceptual Model 1 (CM1) Considered Hvítholar area is outside the Krafla caldera (Figure 4a). This concept is based on the premise of only observing Halarauður formation outside the Krafla caldera and explaining the stratigraphic offset as been

originated from the rifting subsidence. Based on the Resistivity surveys, the Krafla South Zone has two heat sources. Heat source one is located in the north boundary of the area and mainly transporting the fluid through faults such as Leirhóll and Dalsel-Hólseldar. The temperature model showed cooling on the south-west sub-area of Vestursvæði. This temperature drop is implying high permeability in the west part of the reservoir till the project Fissure Swarm Fault that denotes the western flank of the glacial fissure eruptions (median zone Figure 3). On the other hand, due to the strong temperature reversal at Hvíthólar. The low temperature of well KJ-22 provides the assumption that there is a temperature barrier on the eastern flank of the rift median zone fissure eruptions that is represented by Dal fires (Figure 3). Heat source two is located on the east boundary of the study area. The up-flow zone is located at the intersection between Leirhóll and the Caldera fault. Additionally, CM1 also assume that the principal heat source for Hvíthólar sub-area is a non-renewable heat source around the andesitic intrusion at 700 m.b.s.l.

2.2.2 Conceptual Model 2

The conceptual model 2 (CM2) considered Hvítholar sub-area inside the Krafla caldera and addition of Hveragil fault to be crossing the field from the northeast of the project area till the south passing through the Hvíthólar sub-area (Figure 4b). Regarding stratigraphy, the addition of Hveragil fault best match the stratigraphic units off-set observe from the well correlation (especially around Hvíthólar sub-area). Based on the resistivity surveys, CM2 maintain the two heat sources from CM1, but given the fact that Hveragil is connecting the North heat source with the southeast heat source, it allows easy transport of the heat over the faults. This CM2 model maintains and reinforces the mixing of water between both the north and southeast. Regarding the south-west subarea of Vestursvæði, it maintains the same characteristics as CM1 and CM2, which is maintained. This temperature drop is implying high permeability in the west part of the reservoir till the project Fissure Swarm Fault that denotes the western flank of the median zone fissure eruptions. On the other hand, due to the strong temperature reversal at Hvíthólar, the low temperature of well KJ-22 provides the assumption that there is a temperature barrier on the eastern flank of the Wechelian fissure eruptions that is represented by Dal fires. A particularity of CM2 is that the Caldera fault does not extend to surface, but instead, it remains buried where surface evidence is not seen. All the other project faults extend to surface from the bottom of the model.

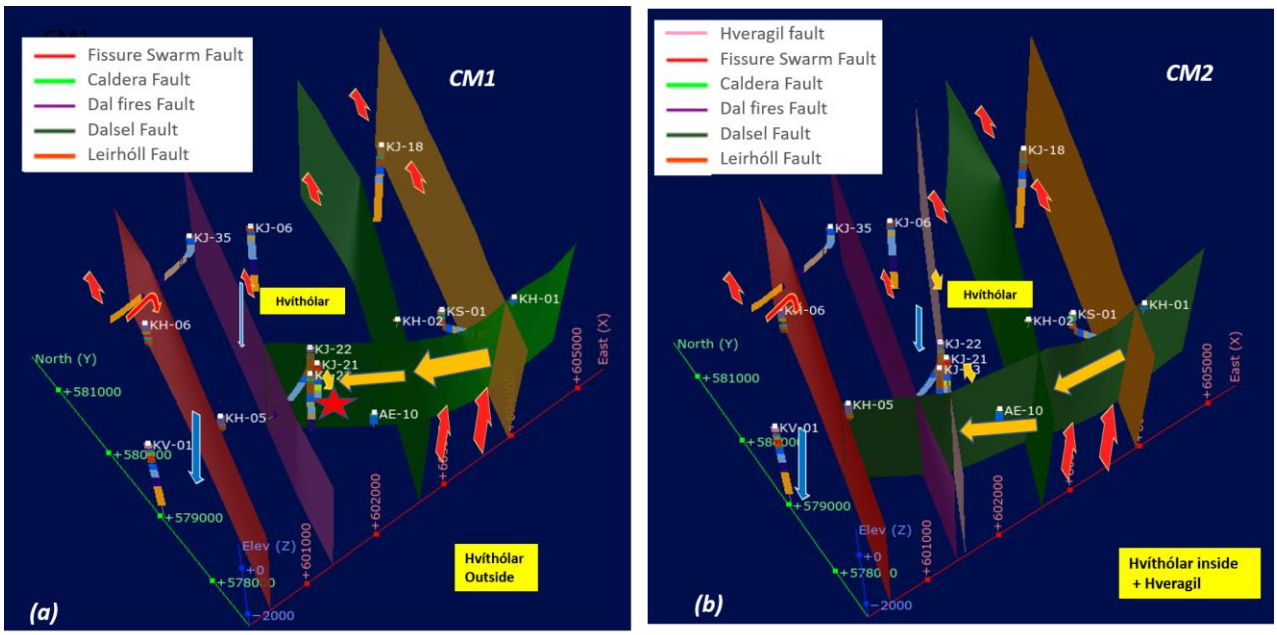

Figure 4: Conceptual Models for Krafla South Zone. (a) Conceptual model CM1 where the starts represent a cooling intrusion. (b) Conceptual models CM2 includes Hveragil fault.

3. NUMERICAL MODEL

Two numerical models (NM1, NM2) are used to provide an approach to the project area of the natural state. To ensure that the simulations were providing a reasonable natural state representation of the area, the simulation outputs of this project were compared against the well formation temperatures of the Krafla South Zone. The numerical models in this project are said to test the conceptual models by assuming that the permeability structure can be the basis of achieving a better match to the subsurface natural stated temperature at the wells. The geological structure of the conceptual model (CM1, CM2) provides the permeability domains (i.e. The permeability structure), and the model's calibration process involves adjusting the permeability value for each domain to obtain a better match between the well formation temperatures and the numerical model temperature output. Adjustments were also made to location and amount of heat and mass generators. Multiple simulations were needed in order to achieve a reasonable match. The main objective is to find which of the two conceptual models calibrated permeability structure best fits the Krafla South Zone data.

3.1 Model Set up

3.1.1 Grid

The model has an unstructured grid created with a PyTOUGH, with the high of the surface blocks adjusted to the groundwater table. With 20,269 blocks the grid covers an area of 400 km^2 (20 X 20 km) with a depth of 3200 m divided into 18 layers. The layer structure is finer at the top through the first 800 m in order to be able to incorporate the detail of the stratigraphic permeability

domains. The model contains one large atmospheric block at the top. The layers thickness varies from 100 m in the top of the model to 500 m at the base. A rectangular grid was used for the XY plane, with grid block widths ranging from 200 to 3000 m in each direction. The finest grid blocks were located around the Hvíthólar sub-area. Due to the orientation of the rift at Krafla geothermal field; the model is rotated 8° from North in direction to the main permeability trend, based on the average field permeability direction previously used on the field operator Petrel Krafla model .

3.1.2 Boundaries

The numerical model has been constructed assuming closed side boundary conditions. In order to approximate unconstrained flow at project zone side boundaries (The conceptual model extent is 6 km x 5 km), the numerical model boundaries were extended laterally to 20 km x 20 km (significantly larger than the Project area).

The top boundary is defined as one big atmospheric block above the Krafla water table. The block has a pressure of 1bar and a temperature of 5°C. This layer allows cold influx at the model top. Trough the simulation at this atmospheric block initial condition does not change due to the large volume of the block. The bottom layer contains specified heat and mass generators selected to match the conceptual models. The heat generators are distributed mainly over the centre of the magmatic activity located through the geophysical data. A background heat flow of 100 mW/m^2 was used to cover all the area outside the Krafla South Zone in order to represent the regional heat flow in rift conditions better. This approach to heat generation was because the Krafla geothermal field and surrounding area is located on a thermal anomaly related to the tectonic rifting. Specific to Krafla South Zone, a heat generator of 200 mW/m^2 was chosen to be the base heat flux into the Project zone from depth. The selection of the heat generator for Krafla South Zone is consistent with existing models along the Icelandic ridge geothermal areas which have been set as 210 mW/m^2 [58].

All the bottom boundaries of the model are based on the geophysical data such as the resistivity peaks found at the bottom of the field model. The bottom temperature of the model (-2600 m.a.s.l.) is driven by magma chambers and the bottom "shallow" 3600 m.b.s.l. ductile-brittle boundary (500°C +-100) which assumes a thermal gradient of 100 °C/km. The influence of the magma chambers was delineated as concentric zones of 500 mW/m^2, 400 mW/m^2 and 300 mW/m^2 with the highest heat flow in the central zones. The shape of each heat generator domain was created with the plane view of the geophysics peaks at the same depth as the base of the model extents, as well as the data of the location of the magmatic chambers provided by seismic S wave (Árnadóttir et al., 1998 ; Weisenberger, 2015). Heat generators at the bottom boundary are the same in all numerical models.

The mass generators are located where deep source evidence is suggested in the conceptual models. Generators were located coming from Leirhnjúkur, and Mt. Krafla in the north, as well as Sandabotnaskarð in the south-east. Since Leirhnjúkur sub-area was outside the conceptual model boundary two groups of generators to simulate the Northwest boundary. In both models, mass generators are in the same position, however, on NM2 additional generators were incorporated underneath the Hveragil Fault to provide the fault transport property. Regarding mass input at the model bottoms, the main difference is the magnitude of the generators in the north where mass generation was increased from 3.5 kg/s to 5 kg/s. Only sources at Leirhóll were considered to have a liquid saturation enthalpy of 1760 kJ/kg the remaining mass generators were assumed to have 1590 kJ/kg.

3.1.3 Permeability

Each model (NM1, NM2) have a different distribution of the rock types, depending on the conceptual model settings. Each of the stratigraphic units represents a permeability domain of the Krafla South Zone and every fault and intersection of fault has its own permeability domain. To ensure the numerical models preserve the conceptual model work therefore the grid was populated in three steps.

1) The Leapfrog conceptual model's permeability domain output (6 x 5 km^2) was used to populate the grid with rock types. However, this rock type assignation for the blocks was only done within the conceptual model extends. In order to populate the remaining grid. 2) The Leapfrog grid output was extended to the numerical model boundaries (remaining 20x20 km^2). The corner blocks of the grid have a considerable bigger horizontal size compare to the block at the conceptual model area (e.g. $6x10^6$ m^2 vs $4x10^4$ m^2), it is vital to minimise the flux impact of the big blocks towards the smaller blocks in the central part of the model (Conceptual model boundaries). Therefore, 3) the rock types outside the Krafla South Zone needed modification. Each rock type outside the project area had one third (1/3) of the original rock type permeability estimates.

3.2 Numerical models Results

The following is a general description of the main calibration domains permeabilities results. The cold temperatures on the shallow domains (1-Young Lavas KFS and 2- Post-Glacial Lavas) were considered to have high permeability in order on ten mDa in all the numerical models. These formations are interpreted as the upper aquifer. Low permeability formations within the permeability domain 4-Late Eemian Lava flows as an impermeable supported by core samples test done by Escobedo et al.(Escobedo et al, 2018) Stratigraphic units 5 Halarauður Related Formation and 6 Shield Forming Lavas are said to be very permeable since these formations were most affected by the caldera collapse event. However, Shield Forming Lavas is said to be anisotropic with values in the 10 of mDa in the X Y components and low permeability in the Z component. A low resistivity cap is assigned to domain 7-Hyaloclastite Breccias, supported by the low resistivity showed around 0 m.r.s.l as well as the alteration mineral correlation at and the formation temperatures found at Hvíthólar. At Hvíthólar, this is the domain that has been selected as the reservoir cap rock. Followed by the reservoir domain 8-Basaltic Lavas formation that at Hvíthólar area contains a considerable number on intrusion from which one of the most important is a group of Andesitic intrusions that are denoted as domain 14-Andesitic Intrusion (KJ-21). Both domains have a high permeability. However, based on the Lupfit assessment [17], it was known the permeability difference between the two tanks that have been derived to represent the Hvítholar reservoir. Therefore, the difference between domain 8 and 14 was assumed to be always (48.1 mD) And the difference between domain 8 and 9 4.9 mD. These values change through the calibration process, but proportions remain. Table 3.2.1 contains a summary of the final input parameters for the project models.

The main stratigraphic domains conserve values in a similar order of magnitude. However, due to the different location of the caldera fault, substantial difference area seen between NM1 and NM2. The results of each numerical model section are presented as sub-areas temperature profiles, comparing the model calculated "natural state temperature" and the formation wells temperature data. In order to facilitate the comparison between the models the following notation will be used: T_{1n} for Model NM1 and T_{2n} were n=1,2,3: => well KJ-21, 2KJ-22 and 3 KJ-23.

3.2.1 Numerical Model 1 (NM1)

NM1 is characterized for locating the Hvíthólar sub-area outside the Krafla caldera. In the current conceptual model, a non-renewable heat source is located between 400-500 m.b.s.l. In order to simulate the given source, a heat generator was in place, but no natural state was reached in the simulation. Consequently, it was decided to use the caldera fault as the primary heat source for the Hvíthólar sub-area. Results on Figures 5 and 6 were obtained by using no heat source at Hvíthólar location for CM1.

At Hvíthólar sub-area is possible to see low temperatures starting bottom the bottom of the model where higher temperatures are needed. Figure 5 shows the simulation temperature against the formation temperatures. Well KJ-22 that is closer to the caldera fault seems to be showing a more corresponding temperature with 40°C difference at the highest temperature. However, the BHT is 26°C colder than required. Wells KJ-21 and KJ-23 have a similar temperature anomaly shape, but the temperature difference around 56°C in the upper 1500 m and almost 95°C in the bottom (Figure 5).

3.2.2 Numerical Model 2 (NM2)

NM2 locates Hvíthólar sub-area inside the collapse Caldera. The CM2 particularity of having the caldera fault buried and constrain to the Halarauður stratigraphic unit seemed to improve the temperature distribution at both Hvíthólar sub-area and along the Caldera fault. Also, it considers the Krafla south caldera boundary connected to the north heat source system through Hveragil fault. This extra connection improves the models allowing to bring more heat south towards Hvíthólar sub-area. The permeability structure used for this model is presented in CM2. Dues to the addition of Hveragil a modification had to be done on the amount and distribution of the mass generators in the north boundary of the fault. KS-01 shows a higher temperature in the top layers. KV-01 is still not showing the shallow temperature reversal.

At Hvíthólar sub-area the top layers show a reasonable match in all three wells been KJ-23 the best. Figure 5 shows the well simulation temperature against the formation temperatures. Well KJ-23 that is closer to the caldera fault seems to be showing a more corresponding temperature. Wells KJ-21 and KJ-22 have a similar temperature anomaly shape, but the temperature difference ranges in 5°-26°C in the upper 1500m and almost 80°C in the bottom (Figure 5).

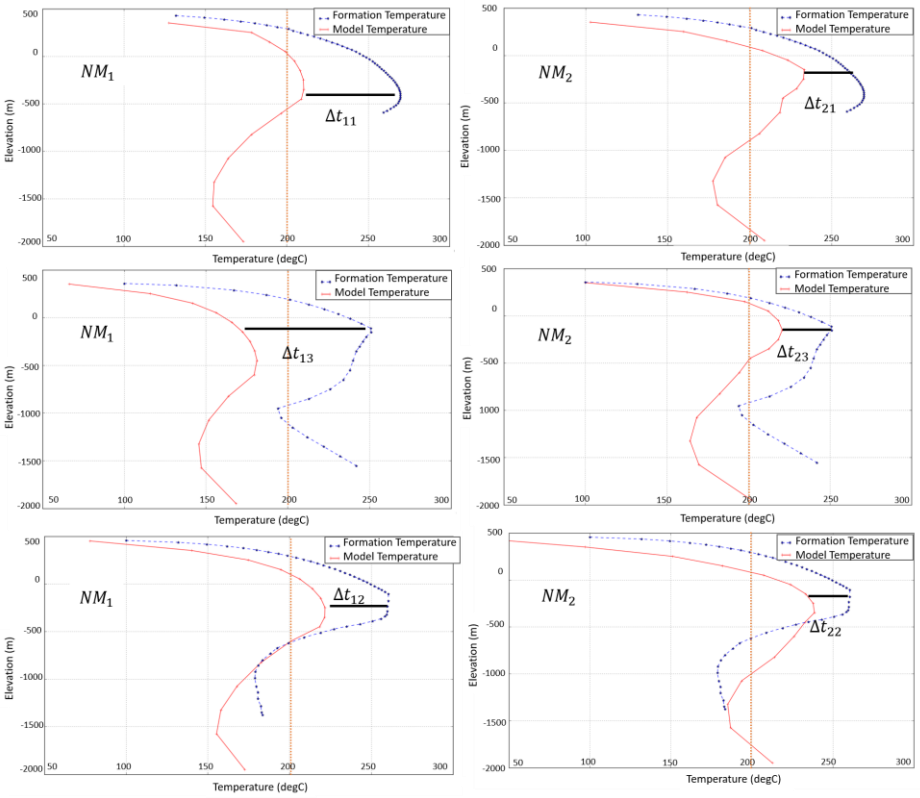

Figure 5: Hvíthólar sub-area wells temperature match for each model.

4. DISCUSSION

The conceptual model seems to fit better numerical model NM2 (from the intersection of the faults and the upflows surface thermal alteration, the explanation at Hvíthólar stratigraphy, the thickness of different formations)

The numerical model proved model conceptual model CM2 to match better the natural state temperature in the bottom is possible to see that the strong temperature reversal is possible if the source (relatively distant) and that the strength of the mass generators influence how big the convection will be driven. In both model 1 and 2, the well closer to the fault intersection seems to have a better fit. This showing that is having the well locates on the fault on proximity is representative of the natural state pattern. Also, it is possible that due to the grid refitment at the wells did not allow enough heat to be correctly transported from the north.

The temperature in the wells of will imply the caldera fault is affecting closer well KJ-22 more than KJ-21 which does not seem correct since it is KJ-21 the well that presents the most important permeability (However, it is known due to tracer test that 22 and 21 are very connected and injection at 22 can affect production at 21. The bottom hole temperature of well-KJ-23 has also been improved. It is to say the adding a very subtle generator might help to war up to the bottom of the model. However, since the heat source must be cooling this option was not tested. (we want to be loyal to the conceptual model to be tested) (Figure 6)

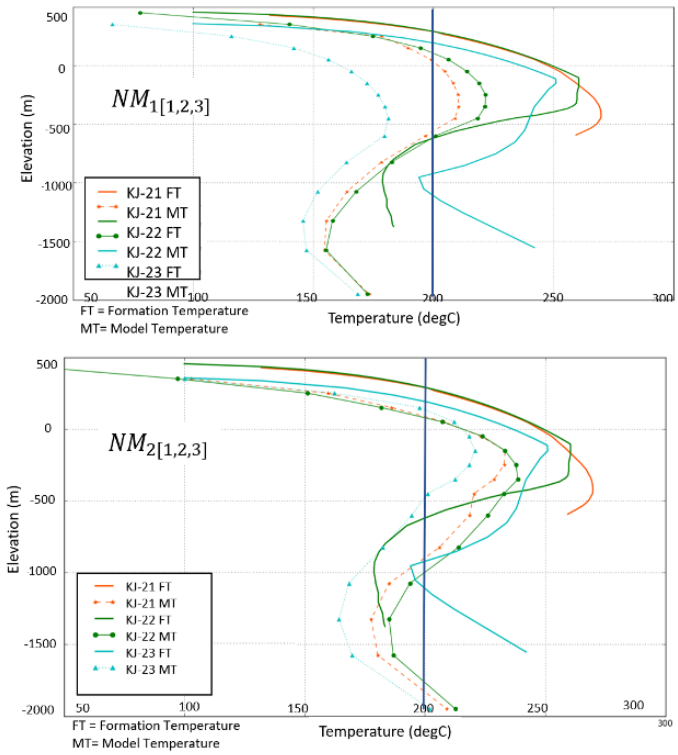

Figure 6: Hvíthólar Wells temperatures comparison

5. CONCLUSION

Result proved conceptual model CM2 to be the best representation of the Krafla South Zone. Conceptual model CM2 correlates strongly with data from wells, geochronological field development, and provides a physical structure that supports the most visible thermal manifestations seen on the surface. Numerical model NM2 provides a reasonable representation of the Krafla South Zone and validates conceptual model CM2 in general. Further refinement of the Numerical Model is required to achieve a better fit with the Hvíthólar sub-area. Re-delineation of the blocks that are at the intersections between the caldera fault with the Hveragil and Dal Fires faults will help the model an improved fit for Hvíthólar. Krafla South Zone conceptual model has between the Sandabotnaskarð and Leirhóll sub-areas, a deep heat source that has been observed in the geophysical data and supported by the formation temperature. On the west side of the project area at Vestursvæði sub-are cooling is confirmed by data from drilling, resistivity, mineral alteration and consistency with the Numerical model simulations. The Fissure swarm ridge is interpreted as a permeability barrier. Towards the west of the ridge (þríhyrnigar mountains), a shallow outflow zone of geothermal water coming from the Leirhnjúkur sub-area flowing south has been identified, however, no important flow of cold fluid is moving towards Hvítholar.

On the south, the conceptual model CM2 supports the hypothesis concerning the location of the Caldera fault to be south of Hvíthólar sub-area. Differently than the previous Hvíthólar sub-area conceptual understanding, this study concluded that Hvíthólar is crossed by Hveragil fault in an NNE-SSW direction. The inclusion of Hveragil fault provides higher temperatures coming from the north boundary into Hvíthólar wells on numerical model NM2. Also, the intersection of Hveragil fault and the Caldera fault provides a physical structure explanation for the surface thermal manifestations around Hvíthólar area in the conceptual model.

The results of the study also differ from the current view that a cooling intrusion is the main driver for the heat source of Hvíthólar sub-area. Instead, CM2 assumes all the heat is transported from the east through the caldera fault and north through Hveragil fault. The Hvíthólar chemistry under CM2 assumptions is explained as a mix of old waters that come from Sandabotnaskarð through the Caldera and local groundwaters that come from the North though Hveragil fault.

The results of this study indicate that Krafla South Zone has the potential for further exploitation. The most prospective areas are in the South-East of the Krafla South Zone at the Sandabotna and Leirhóll sub-areas, which is evidenced by the presence of an up-

flow as a consequence of the deep heat source suggested by the geophysical data. There is some indication that resource at the Hvíthólar sub-area is not exhausted, albeit that production is declining. This notion supported by the structures interpreted from the geophysical data located to the east of Well KJ-21. Also, the numerical model indicates that Hvíthólar wells are surrounded by heat transport structures (Caldera fault and Hveragil fault). The combination of finding in this area supports the hypothesis that Well KJ-21 is located at the western edge of the Hvíthólar reservoir. However, more research is necessary to validate this hypothesis. Drilling of more wells at the Krafla South Zone will allow confirming the conceptual model CM2.

REFERENCES

Ármannsson, H., Fridriksson, Th., Benjamínsson, J. and Hauksson, T. (2015). History of chemical composition of geothermal fluids in Krafla, northeast Iceland, with special emphasis on the liquid phase. *World Geothermal Congress 2015*.

Árnadóttir, T., Sigmundsson, F., Delaney, P.T.: Sources of crustal deformation associated with the Krafla, Iceland, eruption of September 1984. Geophyisics. Res. Lett. **25**, (1998) 1043–1046.

Björnsson, Saemundsson, K., Einarsson, P., Eysteinn, T. and Grönvold, K.: Tertiary volcanism in Iceland, *Nature*, **266**, (1977), 318–323.

Björnsson, Jhonsen, G., Saemundsson, K., Sigurdsson, S., Thorbergsson, G. and Eysteinn, T.: "Rifting of the plate boundary in north Iceland", 1975–1978, *Journal of Geophysical Research, Solid Earth*, **266**, (1979), 318–323.

Böðvarsson, G. and Pruess, K.: The Krafla geothermal field. Final report on modelling studies, *Landsvirkjun*, Háaleitisbraut 68, Reykjavik (1982)

Böðvarsson, G., Pruess, K., Stefansson, V., and Eliasson, E.: The Krafla Geothermal Field, Iceland 2. The Natural State of the System, *Water Resources Research*, **20**, (1984), 1531–1544.

U. Þoresteinsdóttir, G. Hersir, H. Helgadóttir, and A. Blichke, "3D Geological Static Field Model of the Krafla Geothermal Area, NE-Iceland : Constructing a Workflow", IMAGE (Integrated Methods for Advanced Geothermal Exploration), ÍSOR-2017/059 (2017)

Grant M.: **Review no.1** Geothermal reservoir modelling, *Geothermics*, **12**, (1983), 251–263. DOI: https://doi.org/10.1016/0375-6505(83)90001-9

Guðmundsson, G. , Pálmason, G., Grönvold, K., Ragnars, K., Sæmundsson, K., and Arnórsson, S.: Námafjall-Krafla. Áfangaskýrsla um rannsókn jarðhitasvæðanna. Orkurannsóknir, Háaleitisbraut 68, Reykjavik (1971)

K. Arnason, "Conceptual model of krafla geothermal System, NE Iceland", In proceedings, 2018.

K. Sæmundsson, "Krafla. Jarðfræðikort, 1:25.000", Landsvirkjun, Háaleitisbraut 68, Reykjavik, Geological map, 2008.

Mortensen, A., Guðmundsson, Á., Steingrímsson, B., Sigmundsson, F., Axelsson, G., Ármannsson, H., Björnsson, H., Ágústsson, K., Sæmundsson, K., Ólafsson, M., Karlsdóttir, R., Halldórsdóttir, S., Hauksson, T., and Jónsdóttir, H.: The Krafla Geothermal System Research summary and conceptual model revision Translation of report LV-2009/111, Landsvirkjun, Háaleitisbraut 68, Reykjavik. *LV-2015-098*, Oct. (2015)

Stefánsson, V., Kristmannsdóttir, H., and Gíslason, G.: Holubréf nr. 7, Orkustofnun Jarðhhitadelid, Háaleitisbraut 68, Reykjavik, (1977).

Steingrímsson, B., and Stefánsson, V.: Holubréf nr. 9, Orkustofnun Jarðhhitadelid, Háaleitisbraut 68, Reykjavik, (1978)

Valgarður Stefánsson and Benedikt Steingrímsson. "Production characteristics of wells tapping two-phase reservoirs at Krafla and Námafjall. Í: Ramey, H. J. and Kruger, P. (ritstj.), *Proceedings of the Sixth Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, USA, (1980), 49–50.

Weisenberger, T. , Axelsson, G., Arnaldsson, A., Blischke, A., Óskarsson, F., Ármannsson, H., Blanck, H., Helga, H., Berthet, J., Árnason, K., Ágústsson, K., Gylfadóttir, S., and Guðmundsdóttir, V.: Revision of the Conceptual Model of the Krafla Geothermal System, Prepared by Iceland GeoSurvey (ÍSOR) for Landsvirkjun. Vatnaskil, Háaleitisbraut 68, Reykjavik, *LV-2015-040*, Oct. (2015)