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Model Simulations of the Geothermal Fields in the Hengill Area, South-Western Iceland

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ABSTRACT

The Hengill Area is an important energy source for Reykjavík and surrounding municipalities, both for electricity production and space heating. Two production fields are located in the area, Nesjavellir and Hellisheiði, and two other fields are believed to be suitable for energy production.

We present a numerical simulation of the whole Hengill Area, which was performed using THOUGH2/iTOUGH2 simulation package. Geological survey and monitoring data from the present production fields were used to calibrate the model parameters. The model has been used to predict how production will affect the properties of present fields and for predicting the capacity of potential future production fields in the area.

1. INTRODUCTION

The Hengill Area is located 20 km Southeast of Reykjavík. It consists of the Hengill Central Volcano and a fracture zones Northeast and Southwest of Mt. Hengill. A topological map of the Area is shown in Fig.1. The present production fields are Nesjavellir in the Northwest of the area and Hellisheiði located in the Southwest of the area. The Nesjavellir field has been in use since 1980 and the Hellisheiði field since 2006.

Two potential future fields are in the Hengill Area; the Bitra field and the Hverahlíð field. Three exploration wells have been drilled in each of these fields. Three additional exploration wells are now (June 2009) being drilled in the Hverahlíð field.

A wealth of data is available to simulate the behavior of present production fields. The geology has been studied extensively (Sæmundsson 1967, Sæmundsson and Friðleifsson 2003, Franzson et.al. 2005) and geophysical surface measurements, mainly resistivity measurements, have been used for exploring the distribution of the geothermal activity (Árnason and Magnússon 2001). By using geological survey and surface geophysics only, one has a relatively uncertain knowledge of the distribution of the temperature anomaly.

Numerous wells have been drilled in the current Nesjavellir and Hellisheiði production fields. Direct measurements of temperature and pressure have resulted in a comprehensive picture of the temperature anomaly of the fields. In the other parts of the Hengill area, such as Bitra and Hverahlíð fields, the surface exploration with direct measurements in few exploration wells will have to suffice in order to build a conceptual model of the system.

An existing large scale TOUGH2/iTOUGH2 3D reservoir model has been developed to simulate the effects of production in the geothermal areas in the region (Björnsson et.al. 2006). That model was used to simulate production scenarios in the Nesjavellir and Hellisheiði fields. The model has been recalibrated using production data from Nesjavellir field (Björnsson 2007) and is now considered to accurately predict the behavior of that field.

In recent years, several new wells have been drilled in the Hellisheiði field. Data acquired from down-hole measurements in the new wells has yielded accurate information on formation temperature and initial pressure of the Hellisheiði field.

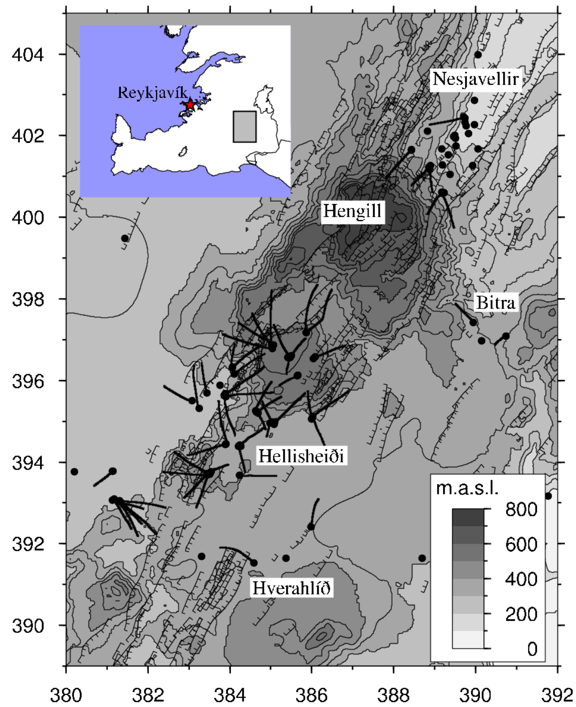

Figure 1: Topological map of the Hengill Area showing the locations of present and potential production fields. Well head are depicted as black dots, directional drilled wells as black lines, and fissures as combed lines. The scale of the map is in the coordinates in the ISNET system. The unit is km. The inset shown the location of the area in SW-Iceland.

The previous conceptual model for Hellisheiði and Nesjavellir had a common heat and mass source for both fields located under Mt. Hengill. New information from down-hole measurements contradict that model. The formation temperature in Hellisheiði decreases in the Northern part of the field, i.e. in the direction of the presumed heat source. Moreover, two new wells in the Southern edge of the Nesjavellir field have a lower formation temperature than wells at the center of the field.

A new conceptual model has been developed and the numerical model has been revised according to available data. The grid of the model has been made denser in the Hellisheiði field, as in the Bitra area and Hverahlíð. The structure of the model has been adapted to the new conceptual model.

Recalibration of the revised model is still on going. The response of the Nesjavellir field to production is well known from production history and the previous version of the model. The behavior of the Hellisheiði field is however not well known. The main focus of this work has been to simulate production scenarios in the Hellisheiði field for decision making in the near future.

2. THE NATURE OF THE GEOTHERMAL SYSTEM

2.1 Surface Exploration.

Extensive geological exploration of the Hengill Area has been undertaken in connection with production there. This work has included making of a bedrock map and mapping of faults/fissures in the area. At higher elevations, the area consist mainly of hyaloclastite and lower flatter parts are covered by lava from recent (Holocene) volcanic craters in the area (Sæmundsson and Friðleifsson 2003).

From a modeling point of view, the fissures and the volcanic craters are the most interesting features. The fissure zones are likely to be permeable and the volcanic craters can indicate a heat source.

Surface hot springs and signatures of older geothermal activity are also useful. Chemical analysis of the geothermal fluid can be used to determine the temperature of deeper parts of the system. Distribution of past and present surface activity hint at the state and development of the heat anomaly (Ívarsson 2009).

Geophysical surface measurements have been used to look under the surface. Transient Electromagnetic Survey (TEM) and Magnetotelluric measurements (MT) have been used to explore resistivity of the formation. High temperature has a distinctive resistivity fingerprint. A higher resistivity core is found to be covered by a low resistivity coat (Árnason and Magnússon 2001).

2.2 Down-Hole Measurements

Collecting the down-hole measurements from wells drilled in the field yields a comprehensive picture of the heat anomaly. Estimated formation temperature at depth of 1 km below sea level is shown in Fig.2.

Higher formation temperatures are limited to relatively narrow areas. In Nesjavellir the temperature anomaly is more or less located in the Nesjavellir Valley. The Northern edge of the anomaly is very steep but the Eastern and Westerns edges are softer. Until recently it was believed that the source of the geothermal activity in Nesjavellir had its source under the highest part of Mt. Hengill. Data from two wells drilled in 2008 however suggest that the formation temperature decreases in that direction.

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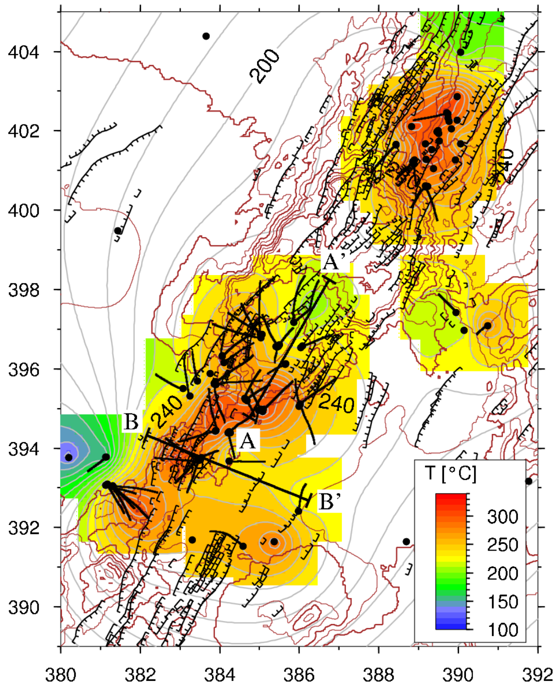

Figure 2: Formation temperature at 1000 m belove sea level. The formation temperature is estimated from down-hole measurements.

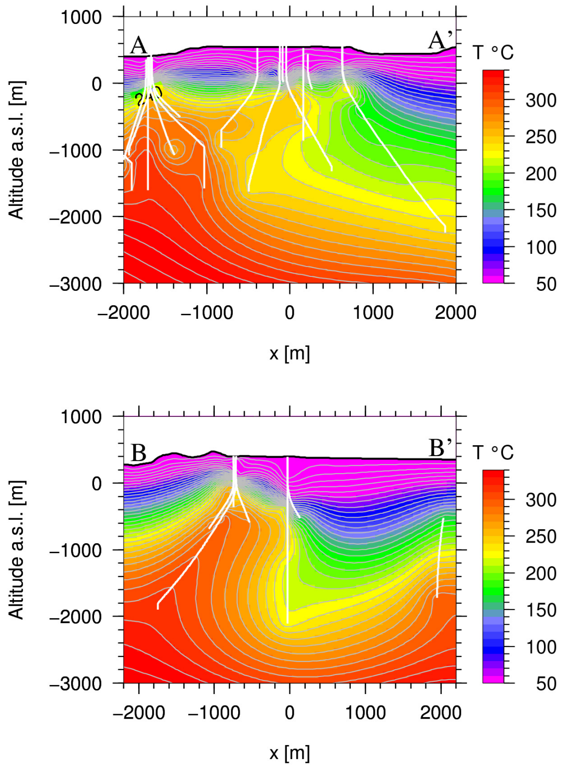

Figure 3: Vertical sections showing formation temperature calculated from down-hole measurements. The white lines show the wells (the data points) used for calculating the temperature. Boundary condition is 5°C surface temperature and temperature of 500°C at 5 km depth. The locations of the sections are shown in Fig. 2.

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In Hellisheiði the hottest formation temperatures are found on a SE-NW belt. The Western edge of the temperature anomaly is steep in Hellisheiði but the Northern and the Eastern edges are softer. The Eastern and Northern edges are characterized by a reversed temperature gradient at the depth of approximately 800-1500 m u.s.l. The reversed temperature gradient can be clearly seen in the cross sections in Fig.3.

With fewer wells, it is difficult to predict what the temperature anomalies in Bitra and Hverahlíð look like. In Bitra, the highest formation temperature was estimated in the Easternmost well. In Hverahlíð, the highest formation temperature was estimated in a well at the center of the field.

3. THE CONCEPTUAL MODEL

The conceptual model of the area is based on geology of the area and formation temperature. For Hellisheiði and Nesjavellir the formation temperature is well know due to numerous wells that have been drilled there. The formation temperature of Bitra and Hverahlíð are not as well known and therefore one has to relay more on geological and geophysical survey.

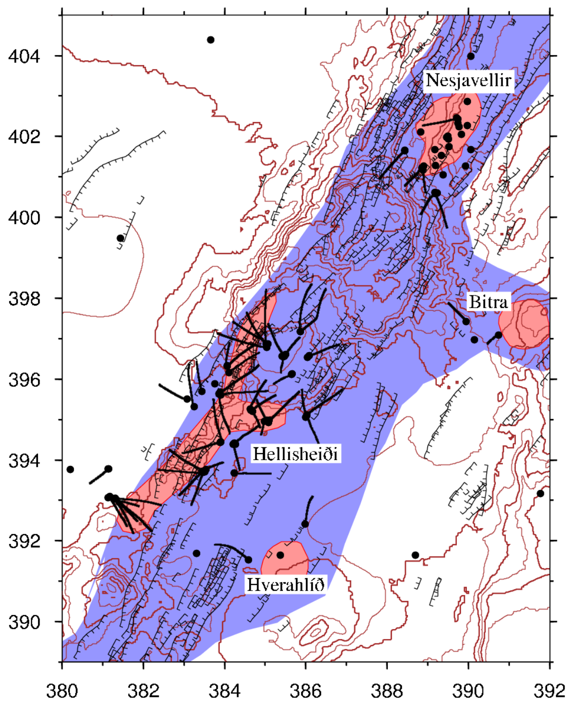

Figure 4: Conceptual model of the Hengill Area. Higher permeability is depicted with blue. That zone is expected to follow more or less the fracture zones. The heat sources are depicted as red.

In building a conceptual model of the area, the most important features are permeability and heat/mass balance. These features are depicted Fig.4. The higher permeability is due do fractures – especially the fractures that are still active.

Four heat sources are expected to be in the area. The heat stems from intrusions in the crust and a magma chamber deeper in the crust. Here it is assumed that hot fluid (low quantity with high enthalpy) is injected into the upper 2.5 km of the system from the bottom of the areas shown in Fig.4. Shallower intrusions are also believed to provide heat to the system as well.

3. NUMERICAL SIMULATION

3.1 Setting up the model

Numerical calculations based on the conceptual model were performed using the TOUGH2/iTOUGH2 software suite. The model consists of 9 layers having 966 elements, i.e. the total number of elements is 8694. The stratification of the model can be seen in Fig.5. The model is a square having size of 100x100 km. The elements of the model at the core of the Hengill Area are shown in Fig.6. The insert in Fig.6 shows the model's location in SW-Iceland.

Boundary conditions of the model are assigned so that the top and bottom layers are maintained at constant pressure and temperature (referred to as “inactive”). The volume of the outermost elements is large compared to active part of the model, effectively making them “inactive”.

Temperature of the top layer is fixed at 15°C and the pressure at 10 bar. Temperature of the bottom layer in vicinity of existing wells was estimated from the down-hole measurements. Elsewhere it was set to 265°C assuming a temperature gradient of 100°C/km and temperature of 15°C in the top layer.

Net mass flow under natural conditions is only through the top and bottom. The bottom layer has low permeability. It is however high enough to allow limited amount of fluid to flow in and out, thus simulating flow of fluid from, and to, lower parts of the system.

Inactive upper layer simulates precipitation and interaction of the geothermal system to the cold ground water system. Hot water can enter the ground water where it is washed away and ground water can flow into the geothermal system. The cap rock of the hot geothermal system has however a very low permeability, which limits flow between the ground water and the geothermal system.

Knowledge about lower parts of the system is very limited. The bottom of the deepest well is at ~3000 m under sea level. Most of the wells are significantly shallower, extending to ~2000 m below sea level or higher. Due to limited knowledge and the fact that the software used in the simulations (TOUGH2/iTOUGH2) cannot handle superheated water, the depth range of the model is not greater.

Interaction of the model with deeper parts of the system is simulated through a fixed bottom temperature and heat sources in the H-layer (the second deepest layer). Both heat and hot fluid is injected into the H-layer in areas shown in Fig.6. The injected heat is to simulate heat from cooling intrusions. The injected hot fluid has high enthalpy and is to simulate the fluid that comes from lower parts of the system.

Another possibility for simulating the interaction of the model to the part below its range, is do assign higher permeabilities to the subregions of the assumed heat and mass sources in the bottom layer. Pressure difference will drive the flow from and to the bottom layer, thus simulating the interaction of the upper geothermal system to its deeper roots.

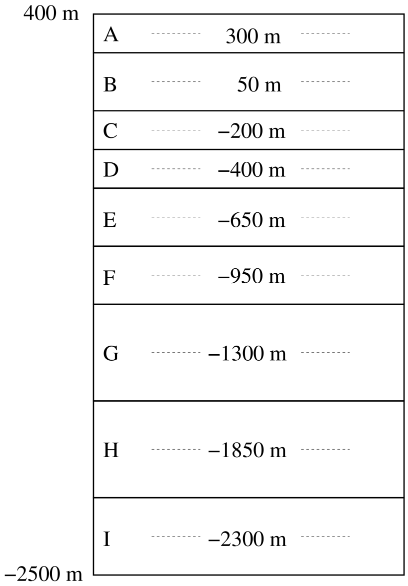

Figure 5: The stratification of the model. The top of the model is 400 m above sea level and the bottom at 2500 m belove sea level.

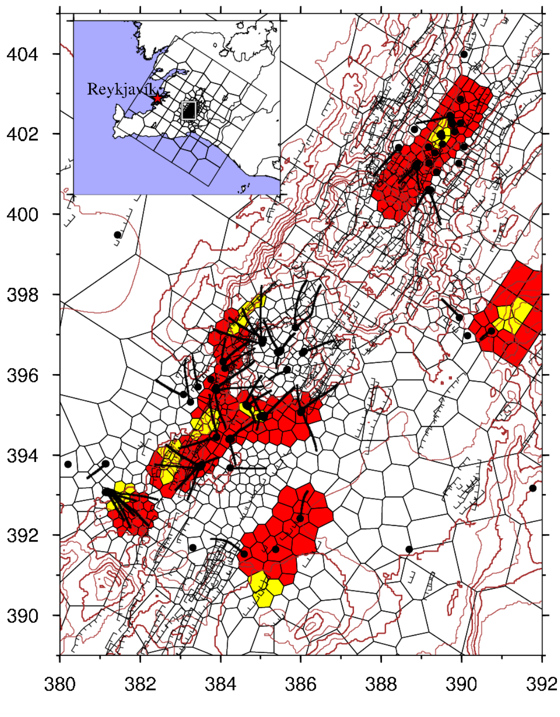

Figure 6: The elements in each layer in the center of the model. The colored areas show the elements where heat is introduced into the bottom of the model. The yellow elements are where hot fluid is introduced into the H-layer of the system. The inset how the whole model is located in SW-Iceland.

This method of having permeable bottom areas has also been tested with the model. So far it has not given as encouraging results as the method of injecting hot fluid and heat at fixed rate into the system.

3.2 Natural State

The natural state of the model is defined as the steady state with no production. In order to reach a steady state the whole model is given a temperature gradient of 100°C/km and a fixed pressure and temperature in the top and bottom layers. The heat- and mass sources in the second deepest layer (the H-layer) then drive the system until it has reached an equilibrium.

The rule of thumb used in these calculations is that the model is taken to be in a steady state when the time step of each iteration exceeds 10'000 years. One can however argue that 10'000 years is a very long time in the life of a geothermal system.

There are technical reasons for choosing this long stability time. When optimizing the parameters of the model, repeatability and stability are necessary. One has to be able to distinguish between variations in results due to changes in parameters and oscillations in the system that has not reached stability. It should be noted that the model does not always reach this stability, i.e. time step of 10'000 years. It often happens that the primary variables of the model oscillate.

3.3 Calibrating the parameters

Permeability of the inner part of the system, i.e. the part colored blue in Fig.4, is set high in layers E F G and H. The uppermost layers of the system (B and C) are assigned low permeability, so are the top and bottom layers of the entire model. The areas surrounding the core of the system are given low permeability.

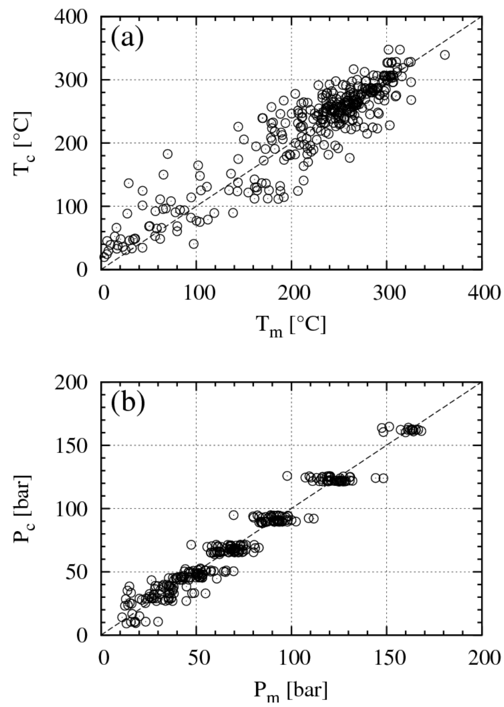

Figure 7: Comparison of measured and calculated variables. In (a) the calculated temperature (T_c) is plotted as function of measured temperature (T_m). In (b) calculated pressure (P_c). is compared with measured pressure (P_m).

Injection of heat into the H-layer is set to a relatively low value. Mass of the injected fluid is set to ~1 L/s per element and the enthalpy is set to ~1500 kJ/kg. The steady state of this initial guess is then compared to measured values of formation temperature and initial pressure.

The inversion software iTOUGH2 was used to optimize the model parameters. More subregions of elements having different permeability were introduce during the process of calibrating the model in order to simulate finer structure in the formation temperature and initial pressure. The aim was to obtain a good fit to the natural state of the model for the formation temperature and initial pressure using as simple model as possible.

In Fig.7 calculated temperature (T_c) and pressure (P_c) are compared with formation temperature (measured temperature) (T_m) and initial (measured) pressure (P_m). The T_m and P_m are taken to be estimated values of formation temperature and initial pressure at the depth of the center of each layer in each well (excluded are layers A and I). These values are compared with calculated values in the elements which have their center closest to the well in the corresponding layer.

The dots in both graphs in Fig.6 are concentrated on the y=x line. The temperature values are somewhat scattered, especially for the intermediate values. The pressure values are more concentrated on the x=y line than the temperature values. The pressure values for each layer do not vary much within a layer in the calculations as can be seen in Fig.6(b).

Some work might still be done on the model in order to improve the accordance between measured and calculated values. The correlation is however relatively good. The correlation coefficient for temperature and pressure are 0.93 and 0.98, respectively.

The model was further calibrated using production data. A production history of Nesjavellir goes back to the 80's. Due to this long production history the model can be well calibrated there. The production history in Hellisheiði goes back to 2006. This is a short production history, making it difficult to improve the calibration significantly. The parameters of interest when calibrating the model using production data are mainly enthalpy of the fluid and drawdown. The drawdown depends on porosity and permeability and can be used to calibrate these parameters.

It is more challenging to simulate the enthalpy of the fluid. The enthalpy depends on the nature of the wells. First, one has to simulate the pressure drop around the well, which can be complicated in a fractured reservoir. Secondly, the behavior of the well itself can be difficult to simulate (Pruess 1999).

In current work the pressure drop in the vicinity of the well has been simulated using two concentric cylinders around the feed zone. The properties of the cylinders are often the same as the surrounding rock. If a well is highly productive, the rock in the cylinders are given higher permeability values.

The production of each well is also difficult to simulate. The rate of production of a real well depends on the formation temperature and the pressure difference between the well and the surrounding bedrock. The pressure in the well is dependent on the enthalpy of the fluid, depth, production rate, and well-head pressure, which can be controlled to some extent. These parameters are more or less correlated making it complicated to simulate them precisely. There are few ways to simplify the problem. The method used in present work was to control the production rate.

3.4 The Calculated Natural State

The formation temperature measured in each well does give a limited picture of the distribution of the temperature anomaly. The temperature between the wells is calculated using an interpolation scheme. The temperature shown in Fig.2 and in the sections in Fig.3 is obtained using GMT's surface routine (Wessel and Smith 2006) and appropriate boundary conditions. It is always a matter of discussion what is an appropriate boundary condition and interpolation method.

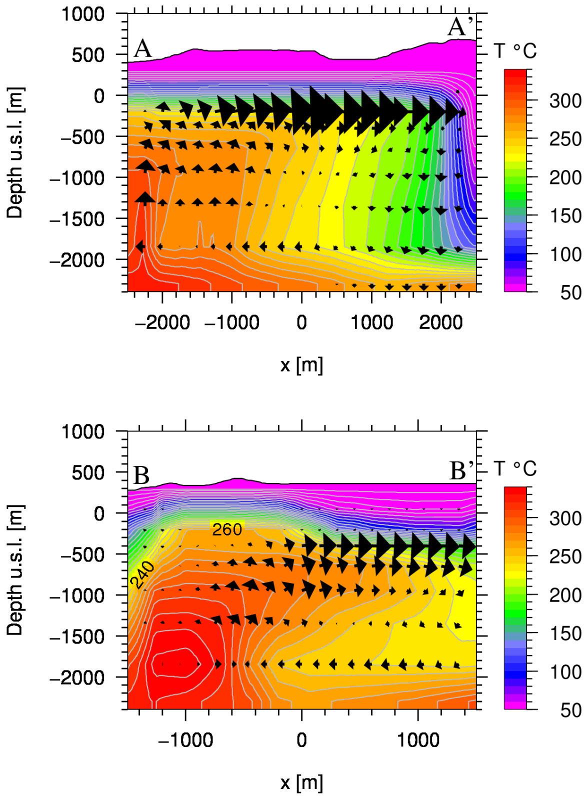

Figure 8: Formation temperature and flow in natural state as calculated by the model. The locations of the sections are shown in Fig.2.

In Fig.8 the calculated formation temperature in the same cross sections as in Fig.2 and Fig.3 is shown. The calculated fluid flow is also depicted in Fig.8. Both the AA' cross section from the North of the Hellisheiði Field and the BB' section in the Southern part of that field have reversed temperature gradient at a depth interval belove ~1000 m b.s.l. This reversed temperature gradient is most likely due to convection of the fluid in the formation.

A schematic of the convection can be set up by investigating the estimated formation temperature from down-hole measurements as is done in Fig.3. A simulation calibrated by using the down-hole data gives a much broader picture of the temperature anomaly, in particular the shape of the convection cells and the flow therein. Using the simulation it is also possible to predict to some extent how the temperature anomaly looks like in the vicinity of the drilling field. Such predictions are helpful when deciding upon future exploration.

The shape of the temperature anomaly in the Southern part of the Hellisheiði field is in particular interesting (see Fig.8 section BB'). The most powerful Wells are drilled near the western edge of the temperature anomaly. The Western edge is very steep. These wells are drilled in mostly hyaloclastite bedrock which has relatively high porosity but very low matrix permeability. The hyaloclastite formation has however numerous fractures, that govern its permeability. The formation is extremely hot and the wells drilled Therein yield a high enthalpy fluid.

East of the high temperature in the hyaloclatite formation is a more permeable formation. The temperature there is lower and the wells drilled there have lower enthalpy and a reversed temperature gradient is observed.

From the simulation it is evident that the reversed temperature gradient East of the hot heat source is due to convection. The simulation also predicts that a hot resource could be found at shallower depths east of the present drilling field. The policy in recent years has been to drill always deeper wells and these wells have often gone though a hot formation into a cooler one. Drilling shallower wells into the hot shallow resource, without drilling through it, might result in higher enthalpy of the fluid. It will in any case result in a less drilling cost.

3.5 Model Prediction

The main emphasis of the revision work for the Hengill Area model has been on Hellisheiði. The Nesjavellir Field is already well calibrated in the older version of the model, due to the long production history of the field. The conceptual model, on which it is based, is however not entirely correct as mentioned earlier. Limited information was available on the formation temperature of the Hellisheiði Field when the older version of the model was calibrated. The soundness of earlier assumptions has been called into question.

The present production at the Hellisheiði Field is 210 MW_e (4 x 45 MW_e high pressure units and a 30 MW_e low pressure unit). 330 kg/s of steam at 9 bar-a are needed to drive the high pressure units. By flashing water from the steam-water separators from 9 bar-a to 2 bar-a, steam is obtained for the low pressure unit.

In the simulations presented here the aim was to extract mass from the system, which yielded 330 kg/s of the high pressure steam. The water from the separators was enough to obtain the necessary amount of low pressure steam. It is not always possible to obtain enough water for the low pressure steam production. This is mostly due to practical reasons. The capacity of the current pipelines from the most productive parts of the field is still limited, which makes it preferable to use them to carry steam from wells that yield high enthalpy fluid in order to maintain energy throughput. The powerplant and the pipeline system are still under construction and therefore it was assumed here that the transport of fluid is not an obstacle.

Reinjection of waste water was also simulated in the model. Total amound of 430 L/s is injected into the Southern and the Western edges of the field. The enthalpy of the injected water was set to be 504 kJ/kg.

In order to maintain constant enthalpy and minimize the drawdown, new wells were introduced during the production time. The feed zones for most of the new wells were placed relatively shallow or in layers D and E. Because the temperature is close to boiling point in the center of the production field, one can expect higher proportion of steam in the upper layers when the pressure drops. Thus producing from the shallower layers yields higher enthalpy.

Fig.9 shows the number of wells used during the production time. During the simulations 22 existing wells were used and 18 wells were introduced. On average the new wells yielded 18 L/s. The average enthalpy of the extracted fluid is shown in Fig.10. The total flow from the system, along with the amount of high pressure steam (9 bar-a) and low pressure steam (2 bar-a) are plotted vs. time in Fig.10. The enthalpy of the fluid increases in the beginning of the production. It is assumed to reach a maximum in the year 2012 and after that it begins to decreases. By introducing new wells with higher enthalpy as discussed above the average enthalpy can be kept around 1500 kJ/kg.

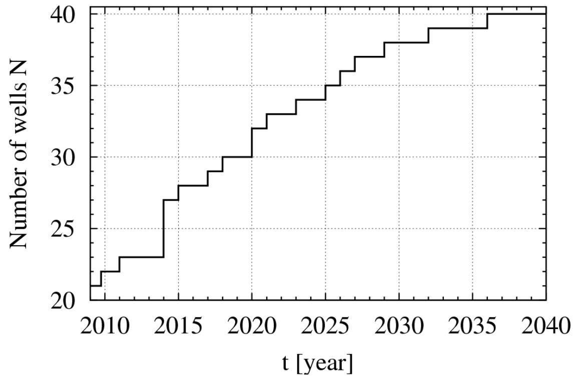

Figure 9: Number of well used during the production time.

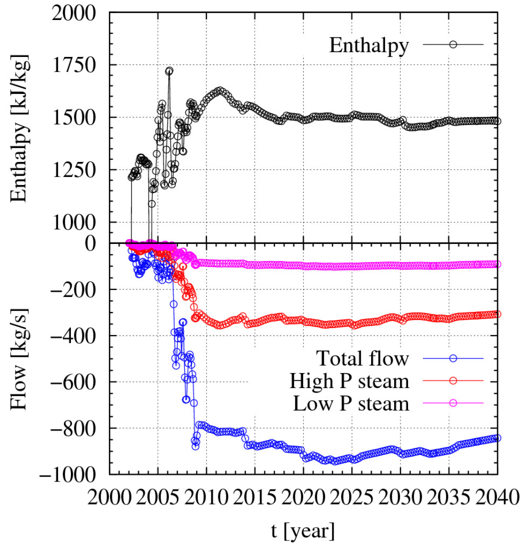

Figure 10: Enthalpy and production in the during the production time.

There is a significant drawdown in the field due to the production. In Fig.11 the drawdown in layer E (the layer where most wells have their feed zones) is shown. The pressure has dropped by more than 20 bar in the active area of the field.

In Fig.12 the temperature change in layer E in year 2040 is shown. The temperature has decreased by more than 20°C in the active area of the field. As mentioned earlier the formation temperature in the central part of the production field is close to boiling point. The pressure drop during production causes the fluid to boil and thus lowers the temperature of the formation. Flow from the edges of the system due to pressure drop and reinjection do also cool of the system.

The drawdown and the cooling of the system will have a significant effect on the productivity of the system by year 2040.

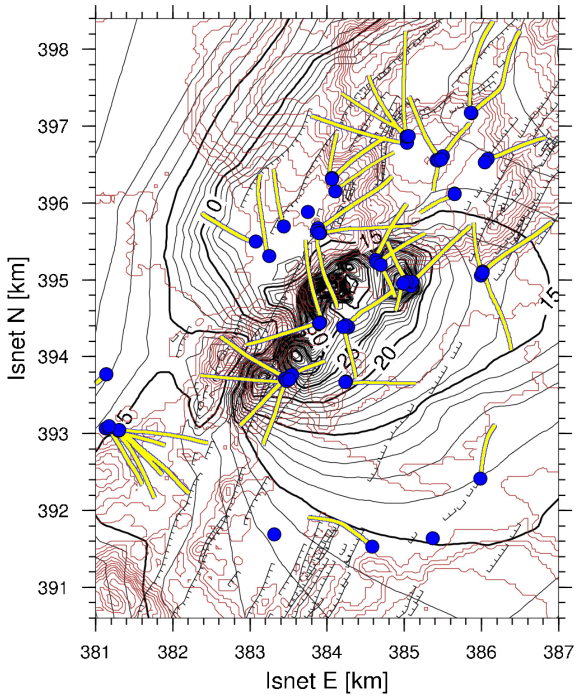

Figure 11: Drawdown in layer E in year 2040.

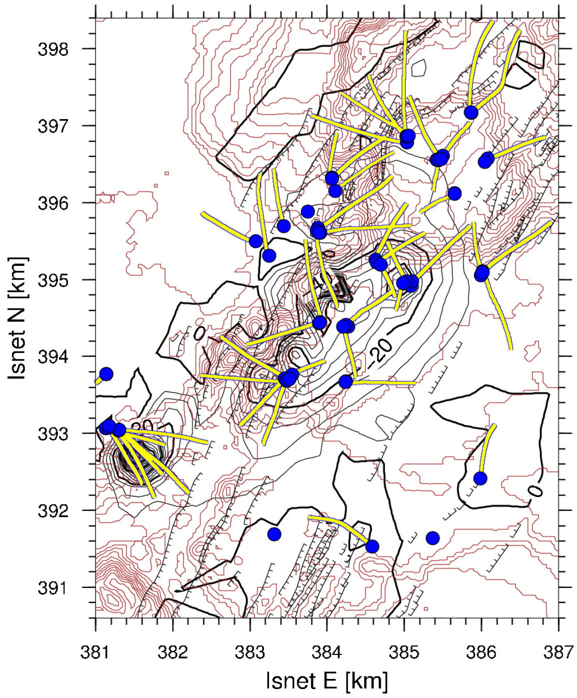

Figure 12: Temperature change of layer E in 2040.

2. CONCLUSION

In recent years numerous new wells have been drilled in the Hengill Area, SW-Iceland. Most of the wells have been drilled in the Hellisheiði field. In light of recently acquired data from the new wells, a previously proposed conceptual model had to be revised.

A work has been undertaken to build a new conceptual model and consequently update the previously existing numerical model. In the new conceptual model, the geothermal fields in the Hengill Area are driven by separate heat sources located below the system, rather than a common heat source as previously assumed.

The revised model has been calibrated according to data from production histories and down-hole measurements. The aim was to restructure and simplify the model. Presently the model simulates fairly well the formation temperature and the initial pressure of the area.

Most emphasis has been on estimating the production capacity and sustainability of the present power production in Hellisheiði. According to the calculations presented, the Hellisheiði field can sustain a production of 330 kg/s of high pressure stream till 2040. By then the drawdown and cooling of the field will have be considered in the operation plan for the powerplant.

These calculations are an ongoing project. The next steps will be to investigate more production, and recovery, scenarios in the Hellisheiði Field and. The model also has to be recalibrated according to the production data from Nesjavellir.

Two potential production fields, i.e. Hverahlíð and Bitra are in the model. A provisional model prediction for the Hverahlíð field will soon have to be made due to present interest in building a new powerplant there.

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