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Temperature and Pressure Model for the Námafjall Geothermal System in NE-Iceland and Development of a 3-D Numerical Model in 2011

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ABSTRACT

The Námafjall high-temperature geothermal area has a long history of geothermal research going back to the initial geothermal exploration study of the 1960s. For decades the geothermal production in the area remained on a small scale but in the first years of the 21st century Landsvirkjun (National Power Company of Iceland) set up extensive plans for geothermal electricity production in the Námafjall area and therefore a 3-D geothermal reservoir model for the Námafjall area was developed in 2005 to estimate the response of the system to exploitation. Wells B-13, B-14 and B-15 drilled in 2006 and 2008, after the development of the model, show that the pressure drawdown is restricted to the small area of utilisation. The conceptual model of the area was revised between 2009-2010 based on new data from wells B-13, B-14 and B-15, and the numerical model rebuilt in 2011. Formation temperature and initial pressure of the wells reveal that previous production has had a limited effect on reservoir temperatures and pressures. Results of the numerical simulation and volumetric method are consistent for the lower limit of the estimated production capacity, but there are more uncertainties in the upper limit.

1. INTRODUCTION

Námafjall geothermal area is located in NE-Iceland, 10 km SSW of Krafla geothermal area, the site of the first Iceland Deep Drilling well (IDDP-1). Both systems belong to the Kralfa central volcanic system, and results of resistivity surveys show that the systems are possibly connected (Karlsdóttir, 2002). Surface alteration is abundant in the area, with fumaroles and steam vents and the surface of Mt. Námafjall is highly altered (Figure 1). Sulphate alteration is, e.g. abundant, and sulphate was harvested from the Námafjall area centuries ago. The area has a long research history, and both geological and geophysical surveys have been carried out to map the possible extent and properties of the system. A total of 12 geothermal wells had been drilled by 1980 with the purpose of electricity generation, but the well field was restricted to a rather small area west of Mt. Námafjall. Between 2006 and 2008 three new wells were drilled in the well field, extending the proven reservoir.

The first detailed numerical model of the Námafjall geothermal system was developed in 2004-2005 by ÍSOR (Hjartarson et al., 2005). The main results of the production prediction are that the system should be able to sustain 30–60 MW_e electrical production, but 90 MW_e would cause over 50 bar pressure drawdown and result in the drilling of numerous make-up wells. After drilling of three new production wells, B-13, B-14 and B-15, the model was used to predict initial conditions (formation temperature and initial pressure) in the wells (Sæunn Halldórsdóttir et al., 2008). Comparison of predicted pressure and temperature state show that the conceptual model which the model was based on is fully valid. Although at the same time it was clear the numerical model needed to be updated and recalibrated based on new data, pressure data in particular since the observed pressure drawdown was much less than estimated by the previous model.

Between 2009 and 2011, new data was analysed, the conceptual model was revised, and a new numerical model developed. In this paper, the results of the corresponding work are presented as wells as results of production estimates obtained with numerical simulation. The paper is mainly built on results of two ÍSOR reports, by Halldórsdóttir et al. and Gylfadóttir et al. from 2010 and 2011 respectively. The 2011 model was rebuilt two years later by Gylfadóttir (2013) with the purpose of better simulating effects of re-injection and different long term (100-500 years) production strategies. The simulations did not provide a different production estimate since the focus was rather on how to keep the production sustainable over long time periods (Gylfadóttir, 2013). The 2013 model remains the most accurate model of the Námafjall system since it is recalibrated based on recent production data from 2011-2012 with refined mesh size for better location of production (and re-injection). The difference between the two models is described further in section 4. The purpose of the present paper is to describe the development of the new temperature and pressure model and the update of the present conceptual model which both the numerical models are based on.

2. TEMPERATURE AND PRESSURE MODEL OF NÁMAFJALL SYSTEM

Three new wells were drilled in the Námafjall area during 2006-2008, drilling of B-13 was completed in June 2006 while drilling of wells B-14 and B-15 was completed in spring 2008. Results of the drilling have been reported by Gudmundsson et al. (2010). The new wells are all directionally drilled while the older wells, B-1 to B-12, are all vertically drilled. Location and tracks of the wells can be seen in Figure 1. Well B-13 is located on the same drill pad as well B-12 and drilled to northeast below Mt. Námafjall (see figure). Well B-14 is located on the same pad as B-12 and B-13 and drilled to west below Jardbadsholar. Well B-15 is located east of B-9, and directionally drilled to the northwest. Overall the results of the drilling were good, and the step-out wells extended the proven size of the geothermal reservoir.

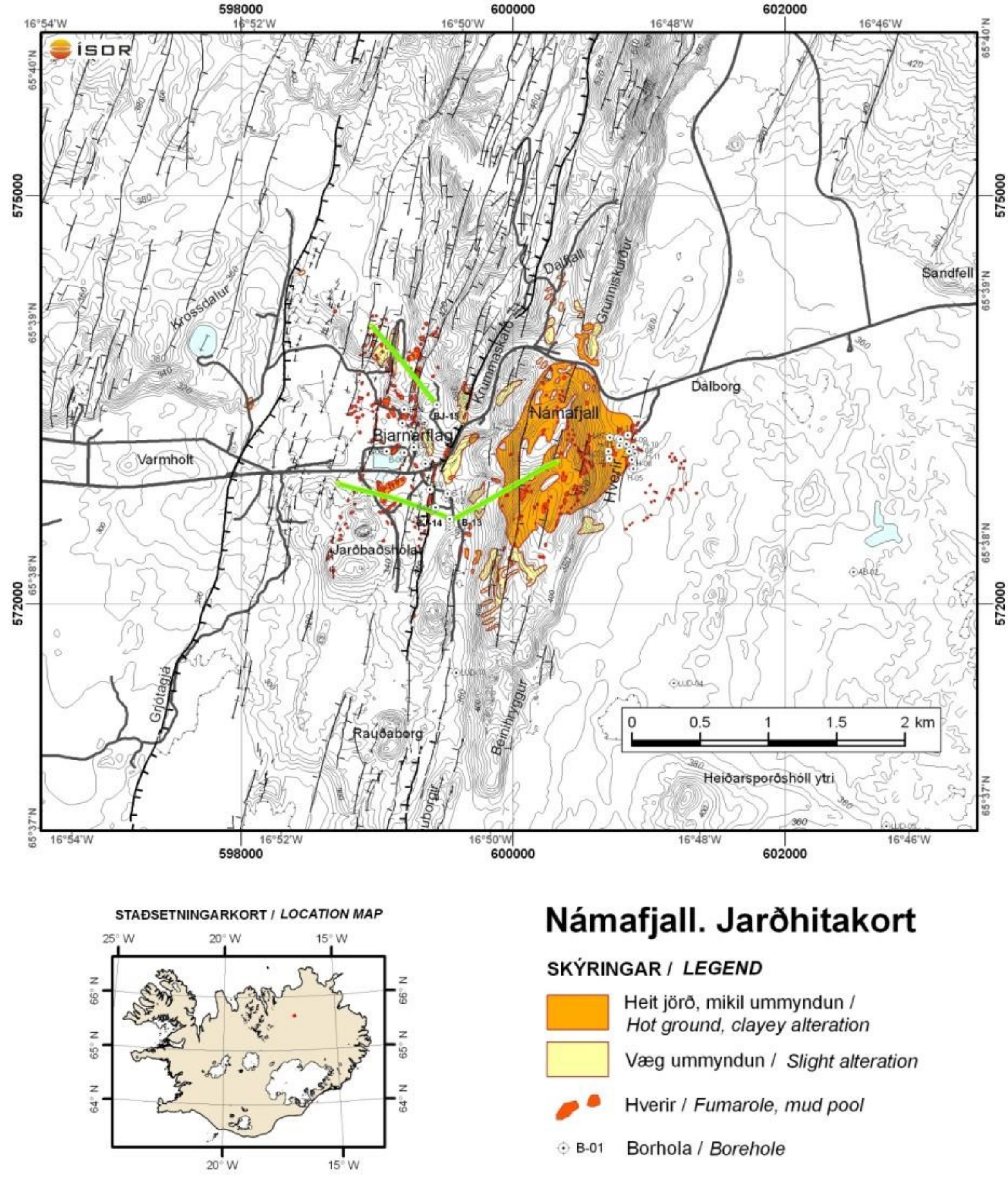

Figure 1: Geothermal map of Námafjall with the most recent wells, B-13, B-14 and B-15, that are directionally drilled shown as green lines.

2.1 Formation Temperature and Initial Pressure in Wells B-13, B-14 and B-15

Formation temperature and initial pressure were interpreted for the three new wells as part of the work presented in this paper. A detailed description is found in Halldorsdottir et al. (2010) on the development of the initial condition estimates for the wells and logs and interpreted profiles are shown in figures A1, A2 and A3 in the appendix. The formation temperature and initial temperature for all the wells drilled in Námafjall system are shown in Figure 2. The formation temperature can be approximated with a boiling point pressure profile in most of the older wells, see a) in the figure, evidence of a colder system is, furthermore, detected, from the surface down to about 200 m a.s.l. (that is in the upper 0-500 m). This cooling seems to extend to greater depths in wells drilled in the southern part of the well field such as B-11 and B-12 and is also quite clear in the latest wells drilled in this part of the field, B-13 and B-14, see c) in the figure.

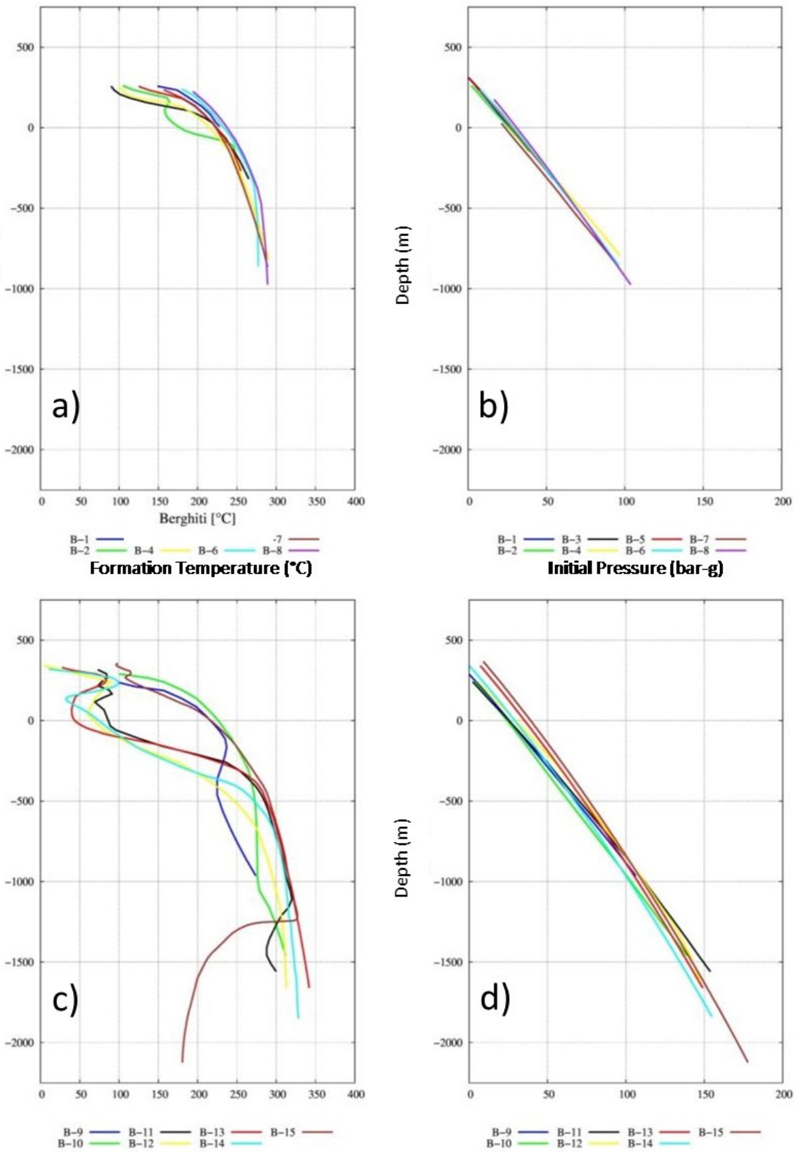

Figure 2. Formation temperature and initial pressure estimated for wells in the Námafjall system.

Well B-13

Drilling of the well was completed at the beginning of June 2006, and there exist two warm-up logs from the well from the end of June and mid-August the same year (Figure A1 in appendix). The pressure pivot-point is estimated at 1370 m with a pressure of 103 bar. The temperature and pressure follow a boiling point curve below 900 m, but above that, the measured temperature is used to estimate the formation temperature. The profiles are shown in Figure 2 c) and d), respectively. The logs from the well prove that the system extents below Mt. Námafjall as the surface alteration indicates.

Well B-14

Drilling of the well was completed in April 2008, and there exist two warm-up measurements from the well from May and June the same year before a short-term production test of the well as well as before and after a three months long production test in 2008-2009 (Figure A2 in appendix). The temperature and pressure follow the boiling point curve between 1000 and 1300 m but above and below the measured temperature is used to estimate the formation temperature. The profiles are shown in Figure 2 c) and d), respectively. The logs from the well prove that the system extents below Jardbadshólar as the surface alteration indicates as well.

Well B-15

Drilling of the well was completed at the beginning of May 2008, and there exist a few warm-up measurements from the well before production testing for four months shortly after and seven months after as well as one measurement during production testing the same year (Figure A3 in appendix). The temperature and pressure follow the boiling point curve between 850 and 1600 m with a temperature of 329°C at 1590–1600 m depth, corresponding to 125 bar pressure that fits with the measured pressure profiles. The pivot point is believed to be in this interwall (1590–1600 m). Above 850 m and below 1600 m, the measured temperature is used to estimate the formation temperature. The profiles are shown in Figure 2 c) and d), respectively. The logs from the well prove that the system extents to NW of the previous well field but also show drastic temperature inversion and cooling below 1600 m.

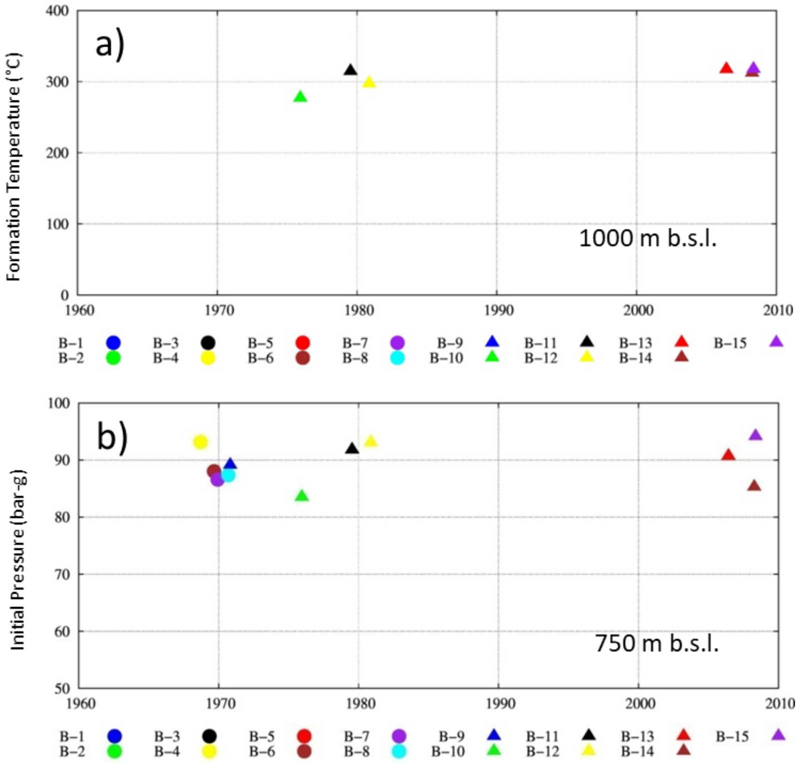

Figure 3. Estimated formation temperature at 1000 m b.s.l. and initial pressure at 750 m b.s.l. for the three most recent wells, B-13, B-14 and B-15, compared with corresponding estimates from older wells.

2.2 Temperature and Pressure Model

Formation temperature and initial pressure for wells B-1 to B-12 in the Námafjall geothermal field is shown in Figure 2 along with the new estimates for wells B-13, B-14 and B-15 that were done as part of the present study. The formation temperature can be approximated with a boiling point pressure profile in most of the wells, see a) and b) in the figure, evidence for a colder system is detected, from the surface down to about 200 m b.s.l. (that is in the upper 0-500 m). This cooling seems to extend to greater depths in wells drilled in the southern part of the well-field to about 400 m b.s.l. (B-11, B-12, B-13 and B-14) as is clear from the temperature cross-section through the system shown in Figure 4.

There is a clear inversion in temperature below 1200 m b.s.l. in well B-15 to the northwest of the centre of the well field. At the boundaries of the geothermal system, it can be assumed that temperature-depth gradient is 110-120°C and accordingly the temperature on the boundaries of the system should be around 220–240°C at 2000 m depth. Therefore, this inversion is more than can be explained with the well being directed out of the geothermal field (away from the upflow). Above 1850–1900 m depth in the well high-temperature alteration minerals are evident, but below this depth, calcite is observed which could indicate cooling at this depth in the system (Blischke et al., 2009). Above this depth, the well is clearly within the system and the temperature is above 329°C at 1600 m depth. Therefore, the possibility that the well intersects a fissure swarm with colder water can't be ruled out. No other wells show indications of this type of extensive cooling, so it is difficult to speculate whether the cooling is strictly localised or not, and this will only be determined with additional step-out drilling.

The initial pressure in wells B-13 and B-15 is much higher than in the other wells in the field (Figure 2d). Comparison of the estimated initial pressures shows that drawdown because of production is not extensive as is also shown in Figure 3b) were the initial pressure at 750 m depth is compared. Pressure in well B-14 is around 30 bar which is similar to what was found in the older wells. Well B-13 is drilled below Mt. Námafjall, east of the well field and the elevated pressure and temperature observed supports the present conceptual model that the main upflow to the system is located below the mountain.

Figure 3a) shows the estimated formation temperature at 1000 m b.s.l. as a function of the time when the wells were drilled. Formation temperature in well B-11 and B-12 that are drilled close to 1980 is about 300°C and in wells B-13 to B-15, drilled between 2006-2008 is the same.

A cross-section of temperature and pressure through the south part of the system is shown in Figure 4, where the elevated temperature with depth below Mt. Námafjall is quite clear. Also, there is an increase in temperature with depth below Jardbadsholar, difficult to explain without the existence of a small upflow below that location. This is also shown in the horizontal view at 800 m b.s.l. through the geothermal system, shown in Figure 5.

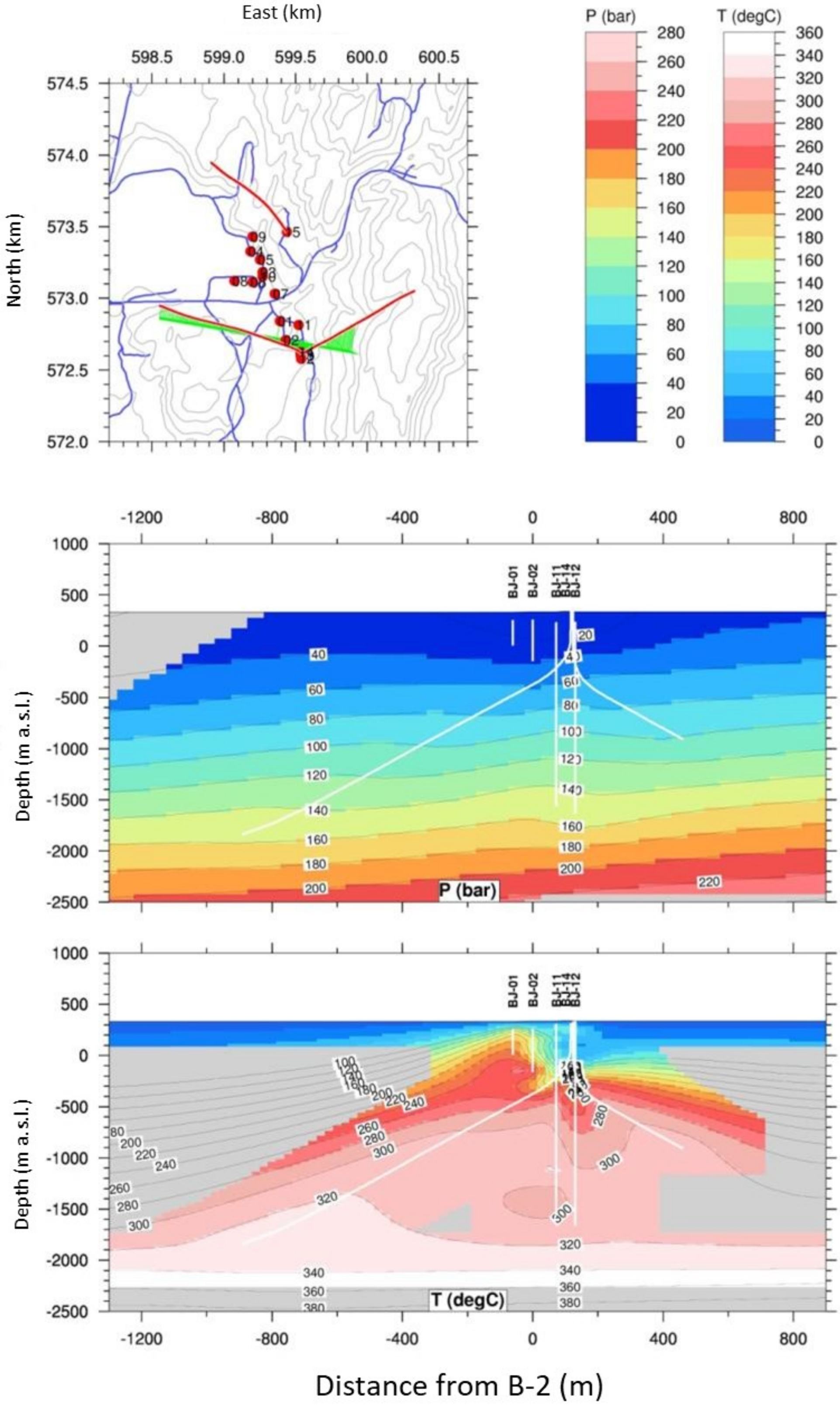

Figure 4: Temperature and pressure cross-section through the Námafjall geothermal system. The location of the section is shown in the upper left corner. Data located within 200 m from the section are projected onto the cross-section (shown in green).

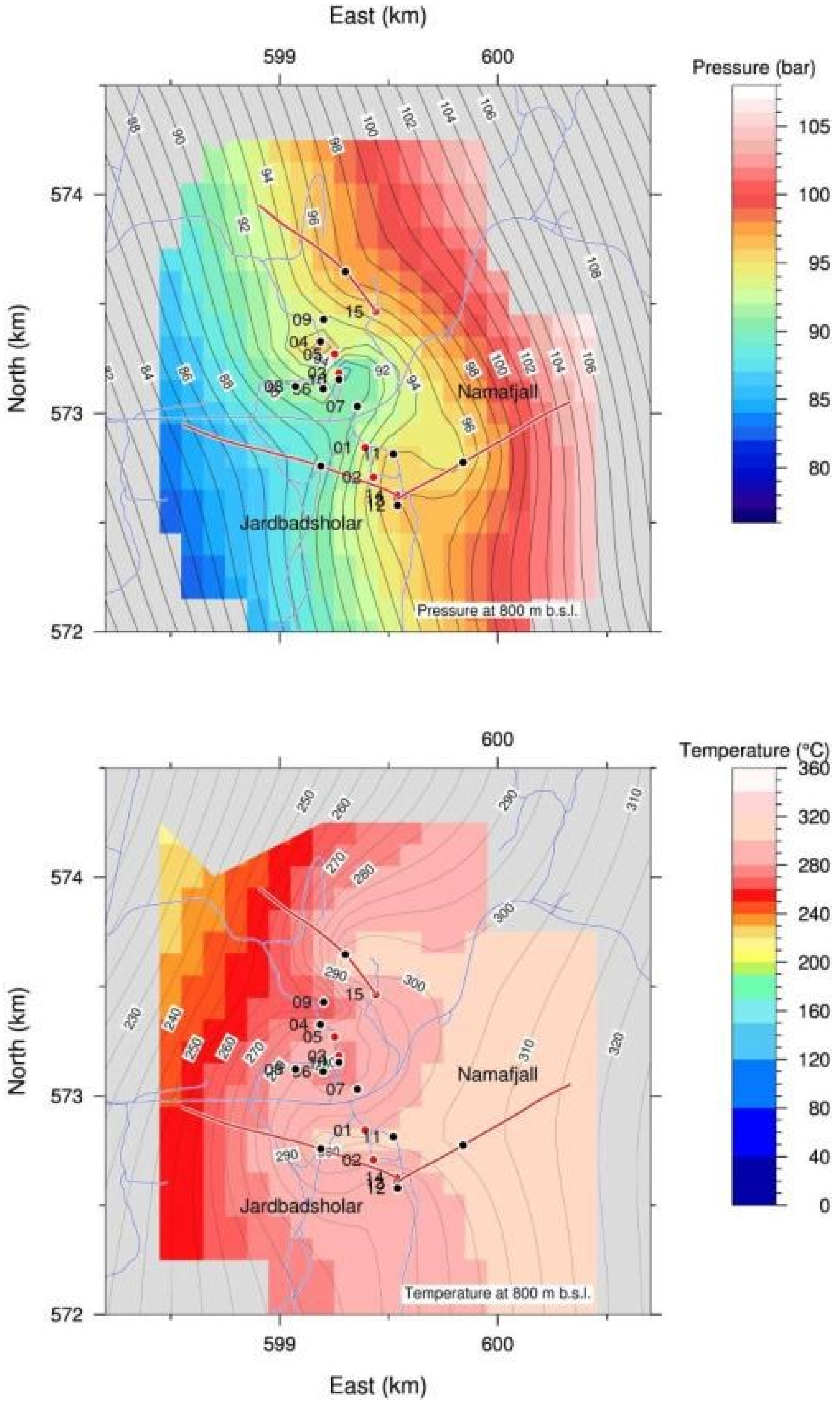

Figure 5: Pressure and temperature at 800 m b.s.l. in the Námafjall well field. Temperature is shown below the pressure. The data used to draw the section is shown with black dots, wellheads and well tracks with red dots and lines, respectively.

3. NUMERICAL MODEL OF THE NÁMAFJALL GEOTHERMAL SYSTEM

3.1 Updated Conceptual Model

Measurements from the new wells, B-13, B-14 and B-15, show that temperature and pressure changed little over the four decades of production from the field since the drilling of B-11 and B-12 (Halldórsdóttir o.fl., 2010) and Figure 3. This is apart cooling in the uppermost part of the system that has been explained by opening of fractures and cooling from above due to the Krafla tectonic and eruptive episode between 1975 and 1984 (Gudmundsson et al., 1989). In the previous conceptual model, which the numerical model of Hjartarson et al. from 2005 is based on, the main upflow to the system is believed to be located below Mt. Námafjall. The logged temperature and pressure in B-13 supports this idea. Logs from B-14 also show an increase in temperature and pressure to the southwest of the well field towards the direction of Jardbadshólar (Figure 4) which indicates another upflow likely to be located there, smaller than the one beneath Námafjall.

A thorough description of the conceptual model, and how it was developed, can be found in Halldórsdóttir et al. (2010). It largely agrees with the conceptual model presented by Hjartarson et al. (2005) except that a small additional upflow is assumed in the later, as supported by the B-14 data, and already mentioned. The main elements of the conceptual model are the following:

- The system is believed to be independent of the Krafla system with its main upflow, connected to a heat source below Mt. Námafjall.
- The NNE-SSW fissure swarm between Grjótagjá-fault in west and Krummaskard-fault affects permeability in the system. As detected by the permeability in wells B-14 and B-15. The two faults are shown with black lines through the geothermal area in Figure 6 (the part showing the inner grid of the numerical model).
- The inflow of fluid to the system is mostly from the south through the main fissure swarm, but also from the Krafla highlands in the north. East of Námafjall rock formations are less permeable, as detected in the bottom-most part of B-13 (Thórarinsson et al., 2006), and there is limited inflow to the system from the east.
- Shallow outflow from the system is clearly to the west towards lake Mývatn.
- Main fluid pathways within the system are controlled by faults and fissures and location of sills and dykes, but they are not known in detail (i.e. the fluid pathways).
- Permeability is less below Mt. Námafjall and east of Krummaskard-fault than within the NNE-SSW trending fissure swarm. This is why there is so much pressure drawdown close to wells B-11 and B-12 when they are producing.
- Colder fluid infiltrates the system from the surface through fissures and causes cooling in the top layers of the system. This cooling is evident down to about 500 m depth in the Námafjall wells and is believed to be a result of the 1975-1984Krafla episode.
- The temperature inversion in well B-15 below 1200 m b.s.l. is greater than can be expected from the well being drilled out of the system; a more likely explanation is that the well cuts a fault system transporting cold water. This cooling, evident in well B-15, is believed to be localised since there is no other evidence of it in other wells.

The cooling in the uppermost 500 m of the system previously mentioned is not considered to be part of the systems natural state conditions and therefore is not incorporated/simulated in the numerical model (see below). Also, the drastic inversion evident in B-15 is not modelled with a cold source of some kind, the well rather marks the boundary of the system at this location. Whether or not this constitutes major cooling of some kind, will only be revealed with further step-out drilling.

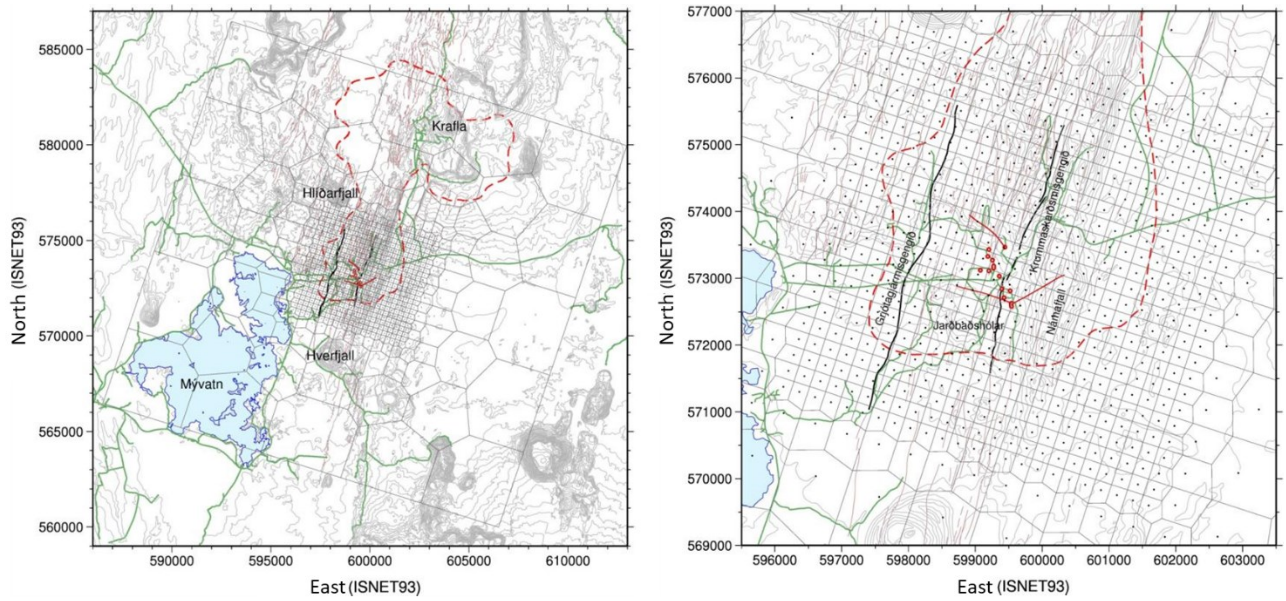

Figure 6: The outer and inner grid of the numerical model of Námafjall from 2011. Roads are shown with a green line; boreholes are shown with red circles and paths of directionally drilled wells with red lines. The outlines of the low resistivity cap at 500 m b.s.l. is shown with a red dotted line. Faults are shown with black lines and other lineaments with brown lines.

3.2 Implementation of the Conceptual Model and Development of the Numerical Model

The numerical model is a technical implementation of the conceptual model described in section 3.1 above. The 2011 model was developed with the TOUGH2 code (Pruess at al., 2002) and first tuning of the natural state was carried out manually using forward runs. Fine calibration of the model was done using the iTOUGH2 code (Finsterle,1999) with the results described in the next section. The inner and outer grid of the model is shown in Figure 6. In the centre, there is a dense, regular 250 m x 250 m grid, oriented in the same direction as the NNE-SSW trending fissure swarm believed to be controlling the permeability of the system. The mesh size increases away from the centre of the grid, and it covers 21 km x 21 km. The main purpose of the outermost grid cells is to keep properties fixed at the boundaries.

The model has a depth range of little over 3000 m and consists of 10 layers. The bottom and the top layers being inactive with almost no permeability and constant temperature and pressure of 6,9°C and 1,47 bar, and 356,9°C and 268 bar, for the top and bottom layer respectively. These values correspond to a regional temperature gradient of 112°C/km believed to exist away from the geothermal system. The boundaries of the model are kept at this fixed temperature gradient by keeping the heat capacity of the outermost grid cells high. In the first active layers from the top and bottom respectively are located sinks and sources to simulate the upflows and outflows of the system. These are shown as blue circles and yellow stars, respectively for sinks and sources, with a black background in Figure 7.

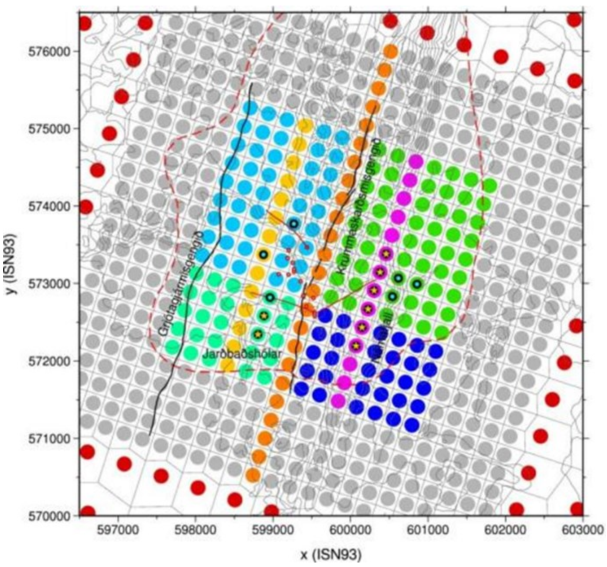

Figure 7: Centre mesh of the 2011 Námafjall model with rock properties, locations of sinks representing fumaroles and steam vents in the top active layer and sources representing upflow of hot fluid in the bottom active layer. Sinks and sources are shown as blue circles on a black background and yellow stars with black background respectively.

The centre mesh of the numerical model developed in 2011 is shown in Figure 7. This is a dense 250 m x 250 m grid oriented in the same direction as the NNE-SSW trending fissure swarm believed to be controlling the permeability of the system. The different colours of the grid block represent different rock properties, most importantly, different permeability. The yellow, orange and pink lines that run throughout the centre mesh, represent the three faults believed to act as fluid pathways for the system and are detected by location of feed zones in the three most recent wells (Mortensen et al., 2008; 2009; Thorarinsson et al., 2006).

3.3 Calibration of the Numerical Model

To calculate the initial state of the model, that refers to the state of the reservoir before the onset of production, initial pressure and formation temperature profiles from all the 15 wells in the Námafjall, shown in Figure 2, are used for calibration. To study how well the parameters are simulated, calculated values are shown as functions of measured values in Figure 8. For a complete fit between the values, they would fall exactly on a straight line. The figure shows that the model from 2011 simulates the pressure quite well both in shallow and deeper layers but the previous model from 2005 had difficulties in simulating the pressure in the deeper layers correctly The main reason was believed to be the closeness of the bottom layers to the sources representing the upflow of the system (Hjartarson et al., 2005). The later model has more layers and extended depth range, and therefore the sources are located well below the bottoms of the wells. There is also rather good fit between the temperature values as shown in Figure 8, although the present model tends to overestimate the temperature. The previous model from 2005 also had a similar fit between the calculated and measured values (Hjartarson et al., 2005).

The calculated initial temperature in layer D is shown in Figure 9; the centre of the layer is at 825 m depth. The figure also shows the low resistivity cap at 500 m b.s.l. (800-850 m depth) believed to represent the boundaries of the geothermal system. The elevated temperature, compared to regional gradients outside the system, is distributed over the area delineated by the low resistivity.

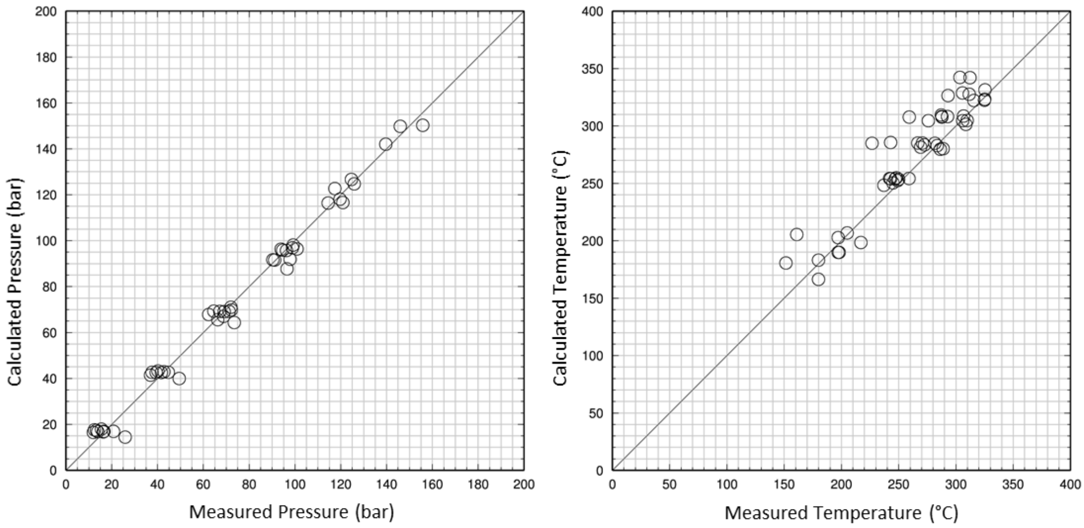

Figure 8: Calculated pressure and temperature as functions of measured pressure and temperature, respectively.

Key data for the calibration of the model are those that best describe the response of the system to production. Such data, available for the Námafjall field, are the pressure measured in closed wells during production breaks. This can be used to estimate the pressure drawdown, i.e. the pressure difference between the pressure measured after the onset of production and estimated initial pressure. Changes in pressure travel rather fast in the reservoir and should, therefore, give a good representation of the reservoir state at a given time. Comparison of calculated and measured pressure drawdown is shown in Figure 10.

Measurements of the enthalpy of the fluid produced from the wells are also available for modelling of the production response and were simulated by the model. Those measurements, however, have larger uncertainties and can show very localised effects, e.g. because of boiling into the formation in a well that causes the measured enthalpy to be much higher than the actual enthalpy of the fluid in the reservoir.

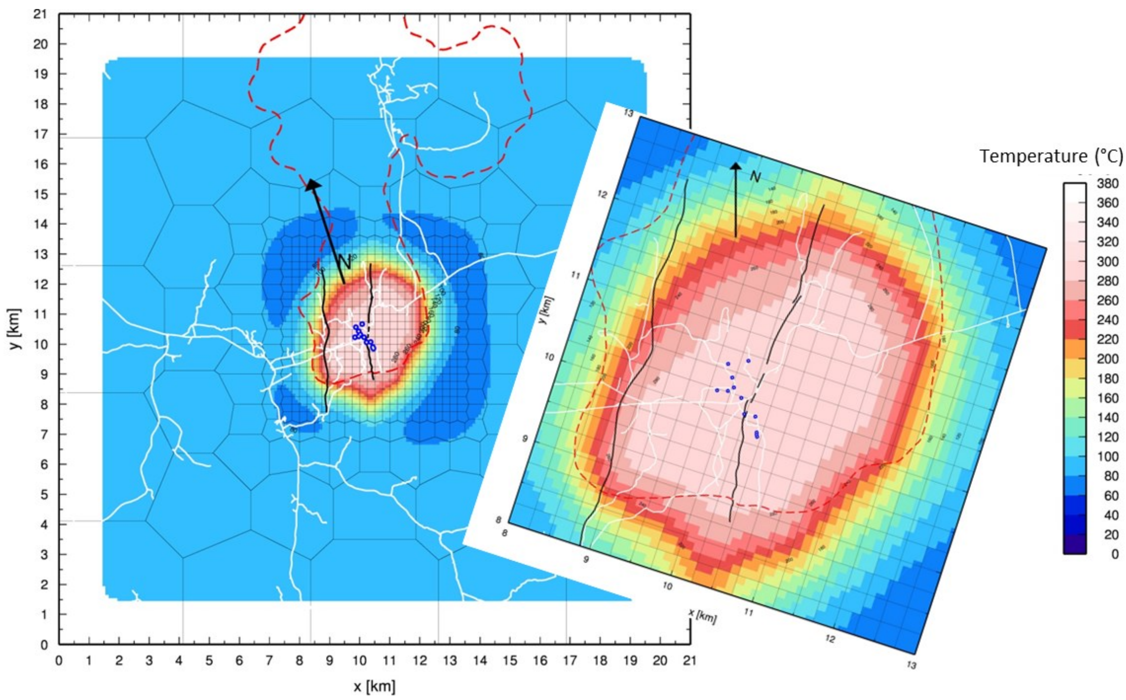

Figure 9: Initial temperature in layer D, with centre at 825 m depth, in the Námafjall model. The broken red line shows the extent of the core part of the geothermal system, according to resistivity surveying.

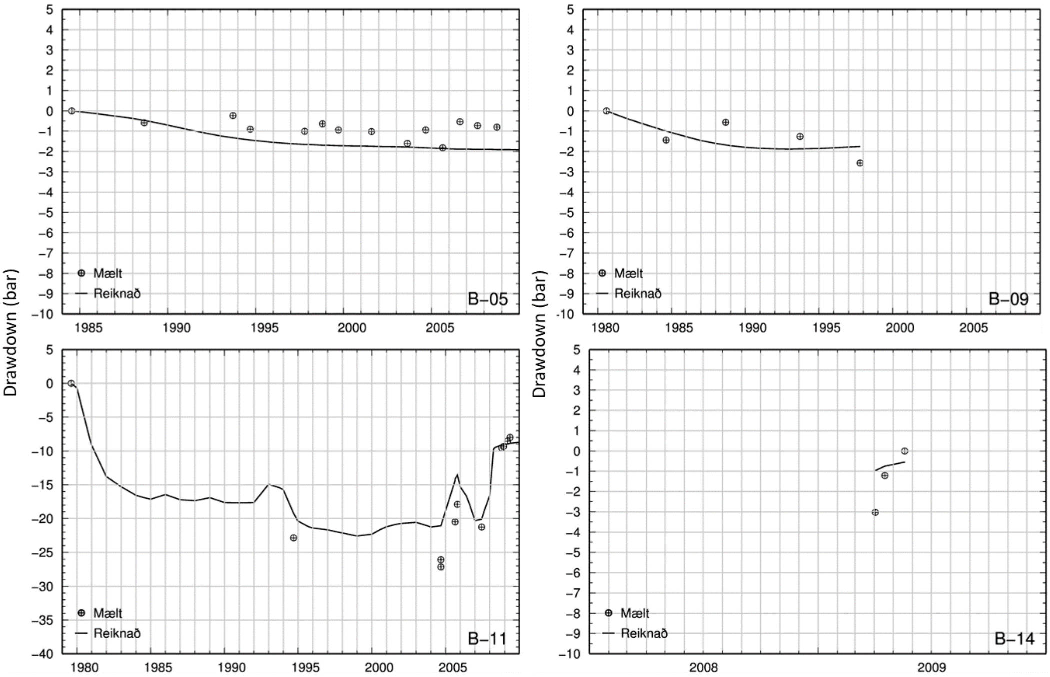

Figure 10: Calculated and measured pressure drawdown in selected wells in the Námafjall model.

3.4 Production Forecasts

Two scenarios were considered for production forecasts: a) 45 MW_e electrical power from 2013 and b) 90 MW_e electrical power in two steps, first 45 MW_e in 2013 and then 45 MW_e in 2016, Figure 11. Both production scenarios were modelled with and without re-injection of the effluent water.

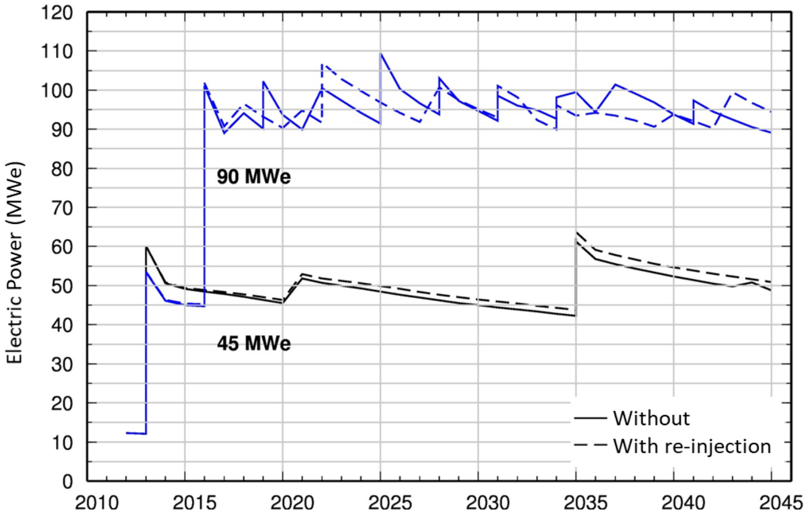

Figure 11: Two scenarios for the production forecast, 45 MWe and 90 MWe electric power until 2045.

For the 45 MW scenario, 17 bar drawdown in the centre well field at a depth of the main production (layer F) is predicted for a production period of 30 years and the 90 MW scenario, 33 bar drawdown is predicted, as shown in Figure 12. Enthalpy of the produced fluid increases throughout the production period: by 400-500 kJ/kg for the 45 MW scenario and by 700 kJ/kg for the 90 MW scenario. Because of increased boiling due to production from the system, the temperature will decrease: 12°C in the centre well field for the 45 MW scenario and 25°C for the 90 MW at a depth of the main production (layer F).

For the 45 MW_e, the model predicts that a total of 7 wells are needed (2 make up wells). To start the 45 MW_e production in 2013 wells B-11, B-12 and B-14 are connected in addition to wells B-9 and B-13 already in production and then two make-up wells are added during the 30 years production period. For the 90 MW_e, the model predicts that a total of 16-17 wells are needed (7-8 make up wells). To increase the production to 90 MW_e in 2016, 2-3 wells are needed in addition to the wells already drilled and utilised, i.e. wells B-9, B-11, B-12, B-13, B-14, B-15 and two new wells in 2016.

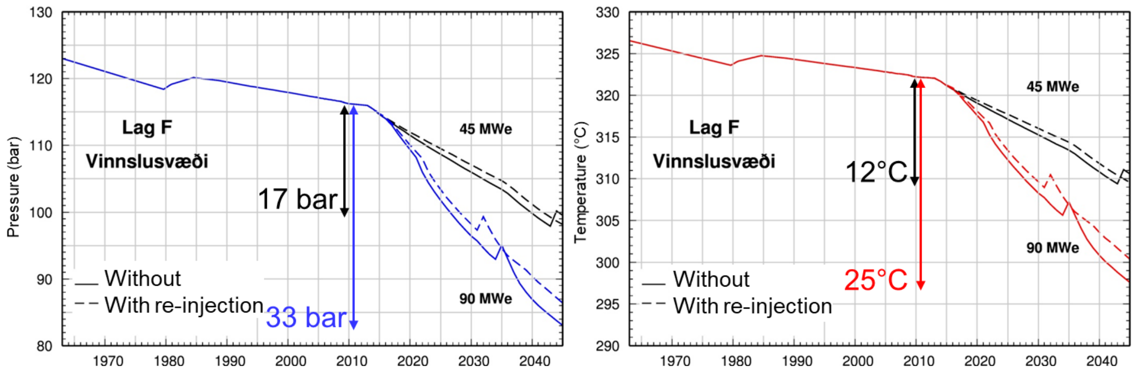

Figure 12: Calculated pressure and temperature in the main production layer in the centre of the Námafjall well field for the 30-year production period. The temperature will decrease because of increased boiling due to production increase.

4. PRODUCTION CAPACITY ESTIMATE FOR THE NÁMAFJALL GEOTMERMAL SYSTEM

The results of the numerical simulations done with the model from 2011 are that the Námafjall geothermal system should easily sustain a production scenario of 45 MW_e and probably the 90 MW_e scenario as well. The size of the geothermal system in this model expands the assumed size in the previous model from 2005, which is the main reason for why the present model predicts less pressure drawdown. In the previous model, the reservoir was restricted to the proven reservoir represented by the small well field at the time. The newly drilled wells have extended the proven reservoir, but on top of that, in the later model, the reservoir is assumed to extend into the area within the low resistivity cap at about 500 m b.s.l. as shown by the TEM resistivity measurements. The size of this area is about 20 km^2. In addition, the pressure drawdown data obtained during production testing of the new wells provide more accuracy to the calibration of the 2011 model.

Results of a Monte Carlo volumetric assessment done by Halldórsdóttir and Björnsson in 2009 are that the production capacity of the Námafjall system is in the range of 50–170 MW_e (90% confidence interval). Results of numerical simulations and volumetric method are therefore consistent for the lower limit of the estimated production capacity. The upper limit for the production capacity estimated with the volumetric method is mostly dependent on the size of the reservoir which was assumed to be 20 km^2 as indicated by the TEM resistivity results (Karlsdóttir, 2002). Result of MT studies indicates that the area of the system is at least the same or larger than TEM resistivity results indicated (Karlsdóttir et al., 2012).

The Námafjall model was once again rebuilt in 2013 with the purpose of better simulating effects of the re-injection of effluent water into the reservoir than the 2011 model had done. The centre mesh was expanded over a larger surface area, and the mesh density was increased (Gylfadóttir, 2013) to locate production and re-injection with more accuracy. The model was based on the same conceptual model as the previous model (described in the present paper), but simulation consisted of a detailed long term (100-500 years) modelling of different production and re-injection strategies. Including haltering of production periodically and re-injection at different locations and depths. The simulations were done for 45 and 90 MW_e production scenarios and did not provide a different production estimate as such. The focus was rather on how to keep the production sustainable over long time periods (Gylfadóttir, 2013).

From these three studies mentioned above, it can be concluded that the production capacity of the Námafjall geothermal system is at least 50 MW_e. There are more uncertainties in the upper limit, and the results of the latest simulation from 2013 show that on a time scale of 100 years, the 45 MWe production can be considered sustainable but 90 MW_e at the limit of being unsustainable (Gylfadóttir, 2013). Both the 2011 and the 2013 numerical models are designed to be conservative, and this affects the simulation of the long-term response to production. Although long production history exists for Námafjall geothermal field, the main production has only been between 10–15 MW_e over most of the production period. Response to increased production is unknown and therefore poorly calibrated in both models.

5. CONCLUSIONS

The conceptual model of the Námafjall geothermal system was revised between 2009-2010 based on data from three new wells drilled in 2006 and 2008 and the numerical model rebuilt in 2011. Formation temperature and initial pressure of the wells reveal that the past production has had limited effects on the reservoir temperatures and pressures. Previously drilled wells, B-1 to B-12, are restricted to a small surface area west of Mt. Námafjall. With the drilling of the new wells, B-13, B-14 and B-15, the proven reservoir has expanded since they are all directionally drilled, away from the centre of the well field. This increases the likeliness of a reservoir with the same size as results of TEM measurements from 2002 indicate. The upper limit for the production capacity of the system arrived with volumetric calculations in 2009 is mostly dependent on the size of the reservoir which was assumed to be 20 km^2 as indicated by the TEM (Karlsdóttir, 2002). The volume of the productive part of the numerical model from 2011 is also calibrated with the size of this area. Result of recent MT studies indicates that the area of the system is at least the same or larger than TEM resistivity results previously indicated (Karlsdóttir et al., 2012).

The conceptual model described in the present paper is consistent with the previous model derived by Hjartarson et al. in 2005 except that in addition to the upflow assumed to be located below Mt. Námafjall another, smaller is assumed to be located below Jardbadshólar. The existence of those two upflows are supported by data from well B-13 and B-14, for Námafjall and Jardbadshólar respectively. Results of 3D resistivity modelling presented since have further supported the existence of both these upflows (Karlsdóttir et al., 2012; 2015).

Results of numerical simulations carried out with the 2011 model and recalibrated model presented by Gylfadóttir in 2013 are consistent with results of volumetric method calculations done in 2009 for the lower limit of 50 MW_e for the estimated production capacity of the Námafjall geothermal system. There are more uncertainties in the upper limit for the production capacity, but the numerical simulations indicate that the system can sustain up-to 90 MW_e.

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APPENDIX: T&P logs from wells B-13, B-14 and B-15 and interpretation of formation temperature and initial pressure.

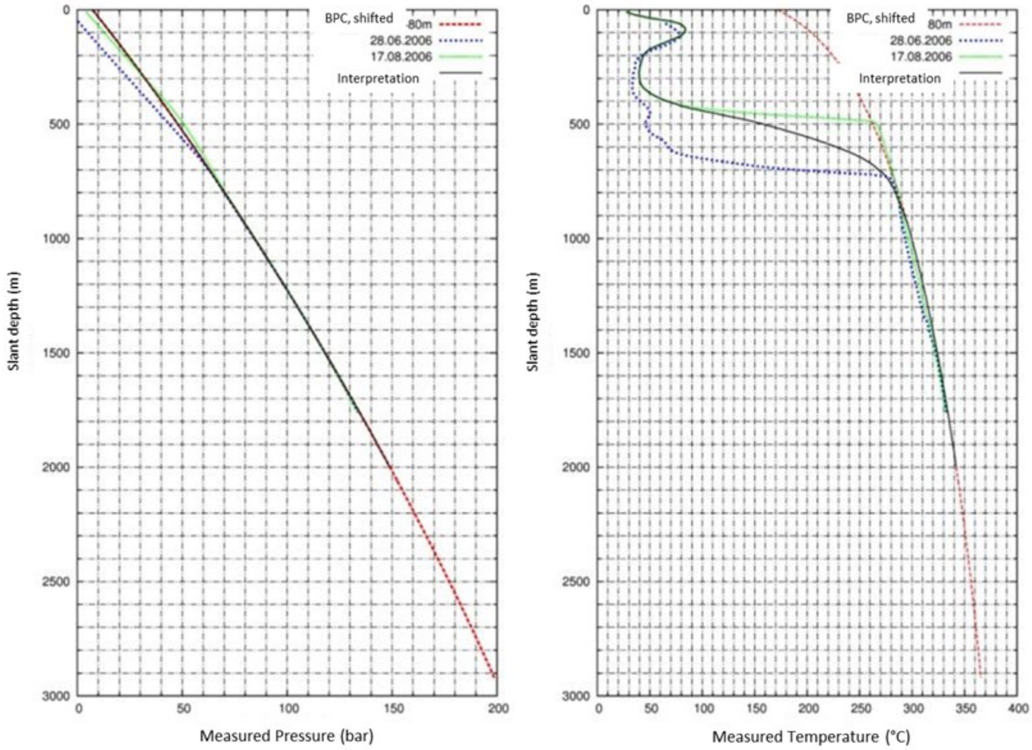

Figure A1: Measured pressure and temperature in well B-13 in and estimated formation temperature and initial pressure.

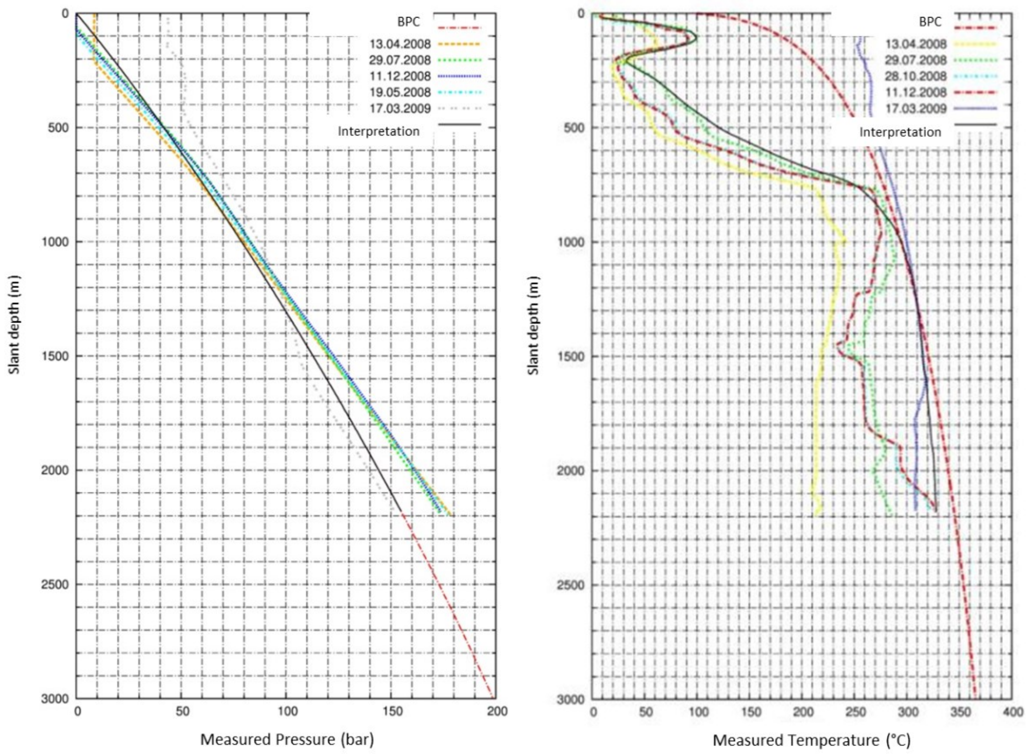

Figure A2: Measured pressure and temperature in well B-14 in and estimated formation temperature and initial pressure.

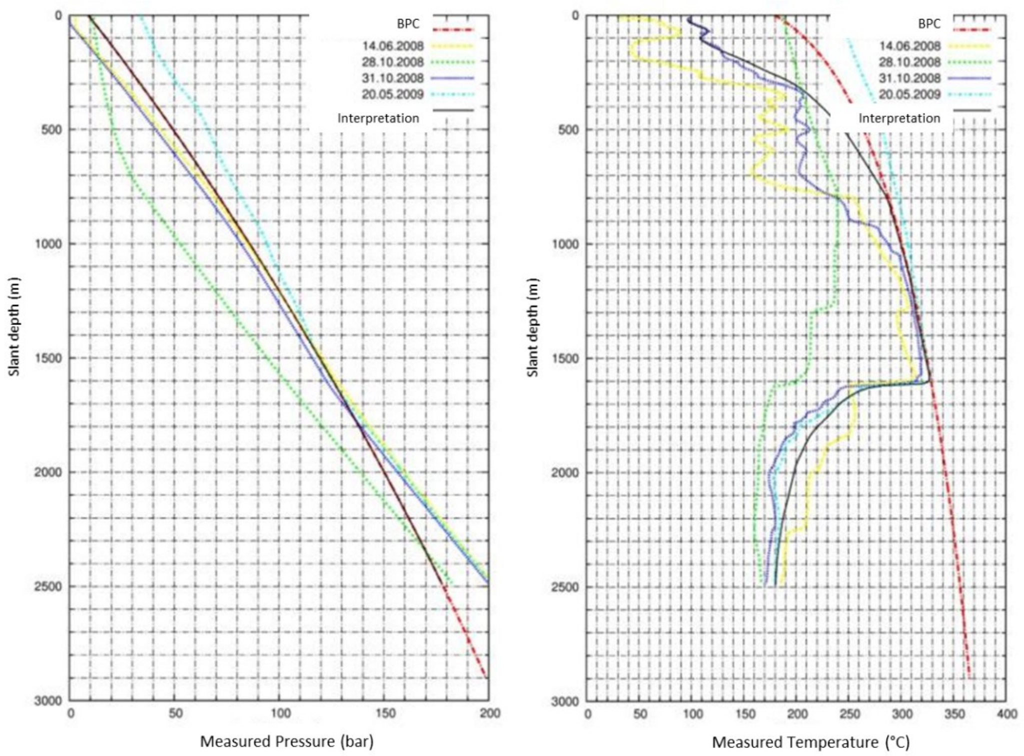

Figure A3: Measured pressure and temperature in well B-15 in and estimated formation temperature and initial pressure.