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Landsvirkjun

Modeling the Námafjall Geothermal System

Numerical Simulation of Response to Production and Reinjection

Report no: LV-2013-116

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Numerical Simulation of Response to Production and Reinjection

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Title: Modeling the Námafjall Geothermal System. Numerical Simulation of Response to Production and Reinjection.

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Co operators:

Abstract: The Námafjall TOUGH2 model has been recalibrated using recent data and run for several reinjection schemes and target power production of 45 and 90 MW_e. Shallow reinjection, effectively an effluent water disposal scheme, is the most feasible option. Having no effect on the enthalpy, it reduces the number of make-up wells needed to maintain the target electric production and only requires relatively inexpensive injection wells. It has, however, no benefits for maintaining pressure in the geothermal system. Reinjection into the production interval provides pressure support but leads to a decline in enthalpy and limits the production potential of the system. To address questions regarding the sustainability of utilization, several long-term forecasts were performed. The simulation results indicate that 45 MW_e production can be considered sustainable while results for 90 MW_e are inconclusive.

Keywords:

Bjarnarflag, Námafjall, model calculation, model prediction, TOUGH2, reinjection, numerical simulation, BJ-11, BJ-12, BJ-13, BJ-14, long-term forecasts, sustainability of utilization

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Project manager´s signature	Reviewed by
Benedikt Steingrímsson	BS, AKM

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1 Introduction

The Námafjall geothermal system has been studied since the 1950's and the first wells were drilled in Bjarnarflag in 1963. Until 1975, a total of 10 wells were drilled, most of which were destroyed during the Krafla fires in 1975–1984. In 1979–1980 wells BJ-11 and BJ-12 were drilled and served as the main production wells until 2005. Due to a planned installation of 90 MW_e power plant, three new exploration wells were drilled in 2006–2008, BJ-13, BJ-14 and BJ-15. Subsequently, the conceptual model of the system was updated and a TOUGH2 reservoir model developed and calibrated based on all data available at the time. The model was finalized in 2011.

During 2011–2012, well BJ-14 was open for discharge for almost a year. It was shut-in in the beginning of March 2012 and its pressure recovery monitored. In addition, several temperature and pressure measurements were done in other wells in the area after the closing of well BJ-14. Additional data on the enthalpy of discharged fluids in producing wells was available from regular measurements included in the management monitoring program. As part of the work reported herein, these data have been incorporated into the calibration of the TOUGH2 model of Námafjall.

In the operation of power plants, reinjection of effluent water from power generation is required. The implementation of reinjection into two-phase reservoirs must be carefully evaluated in order to avoid impairing the production potential of the system through condensation of steam and cooling of the production zone. The Námafjall model lends itself to preliminary investigations into the possible effects of reinjection into the system. To this end, the model has been run for several reinjection schemes and target power production of 45 and 90 MW_e. Additionally, to address questions regarding the sustainability of utilization, several long-term forecasts were performed.

2 Model Update and Fine-Tuning of Calibration

Several numerical models of the Námafjall geothermal system have been developed, the most recent one completed in 2010–2011 (Halldórsdóttir and Gylfadóttir, 2010; Gylfadóttir et al., 2011). The calibration of the model was based on data gathered up to 2010. Since then additional data have been acquired through well logging and wellhead measurements, which provide a basis for the recalibration of the model. The data sets are mainly comprised of temperature and pressure logs from wells as well as measured fluid enthalpy. Regular temperature and pressure logs have been conducted in wells BJ-11 and BJ-12 to observe the temperature and pressure recovery after shut-in in 2007. Well BJ-14 was opened for discharge in February 2011 and closed a year later on 8 March 2012. Following the shut-in, regular monitoring of temperature and pressure has been carried out by well logging in order to observe the recovery of the well. In addition, measurements of the enthalpy of discharged fluid from wells have been added to the calibration dataset. Table 1 lists the data that have been added for model calibration.

Table 1. *New datasets incorporated into the Námafjall model.*

	BN-2	BN-5	BN-9	BJ-11	BJ-12	BJ-13	BJ-14	BJ-15
Drawdown [#measurements]	2	2		2	2		4	2
Enthalpy [years]			2			2	2	
Production [years]			2			2	2	

As the model was revisited, the opportunity to make the following adjustments in the model structure was taken:

- Rock structure in bottom layers was simplified
- “Heat plate” at the bottom was removed
- Permeability in the second layer was reduced in order to minimize the disappearance of fluid in the (inactive) top layer.
- Permeability in the western part (outside the main production area) was increased with respect to the eastern part in order to capture better that the outflow is to the west.

Following these adjustments, fine-tuning of the model calibration was done and a final set of model parameters obtained. The fit to measured data is presented in Figures 1–3.

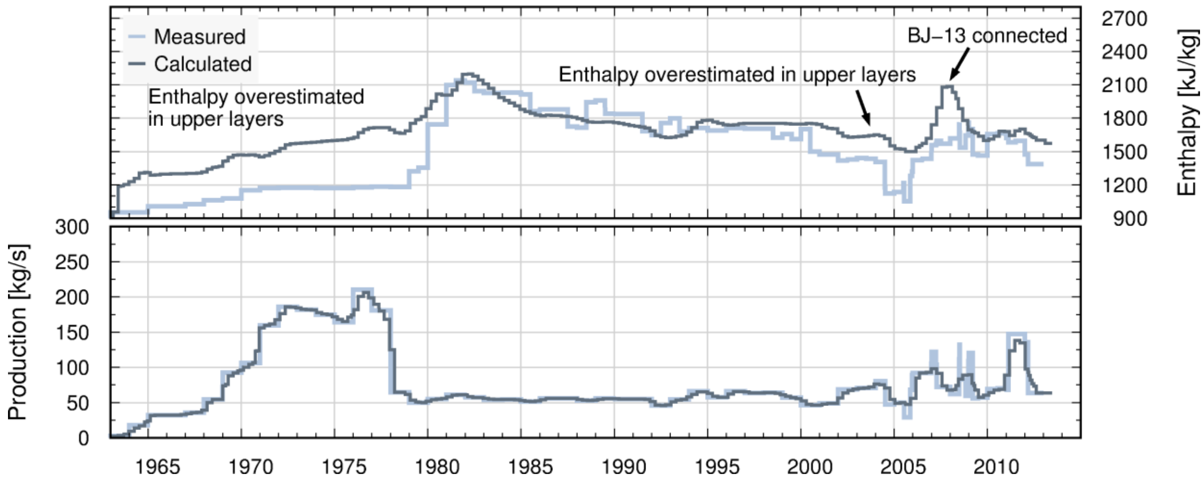

Figure 1. *Comparison of measured and model calculated average enthalpy and production for wells in Bjarnarflag.*

The recalibration resulted in an improvement of the fit to formation temperature and pressure for most wells. Some improvement in the fit to drawdown data was obtained, although for well BJ-12 the fit worsened in the period from 1980 to 2005 but the pressure recovery in the last decade is better captured. New drawdown data from wells BJ-14 and BJ-15 are very well simulated by the recalibrated model. The fit to enthalpy data has in most cases remained adequate. The worst case is for well BJ-13, which has a higher enthalpy in the model calculation than measured.

The main points of future improvement in the fit are listed for future reference.

- The fluid enthalpy for older wells is generally too high, typically around 1300–1400 kJ/kg, but was most likely around 1100–1200 kJ/kg, based on the few measurements that exist[1].
- Enthalpy in shallow wells increases too much during discharge. The longest enthalpy data series from wells BJ-11 and BJ-12 are, however, reasonably well captured by the model. Related to this is the worsened fit of the enthalpy in well BJ-13.

[1] Three measurements of enthalpy are available. Well fluid from BN-4 had an enthalpy of 1085 kJ/kg at the end of July 1969, for BN-7 in May 1977 it was 1200 kJ/kg and in well BN-9 in 1984 the enthalpy measured 1220 kJ/kg.

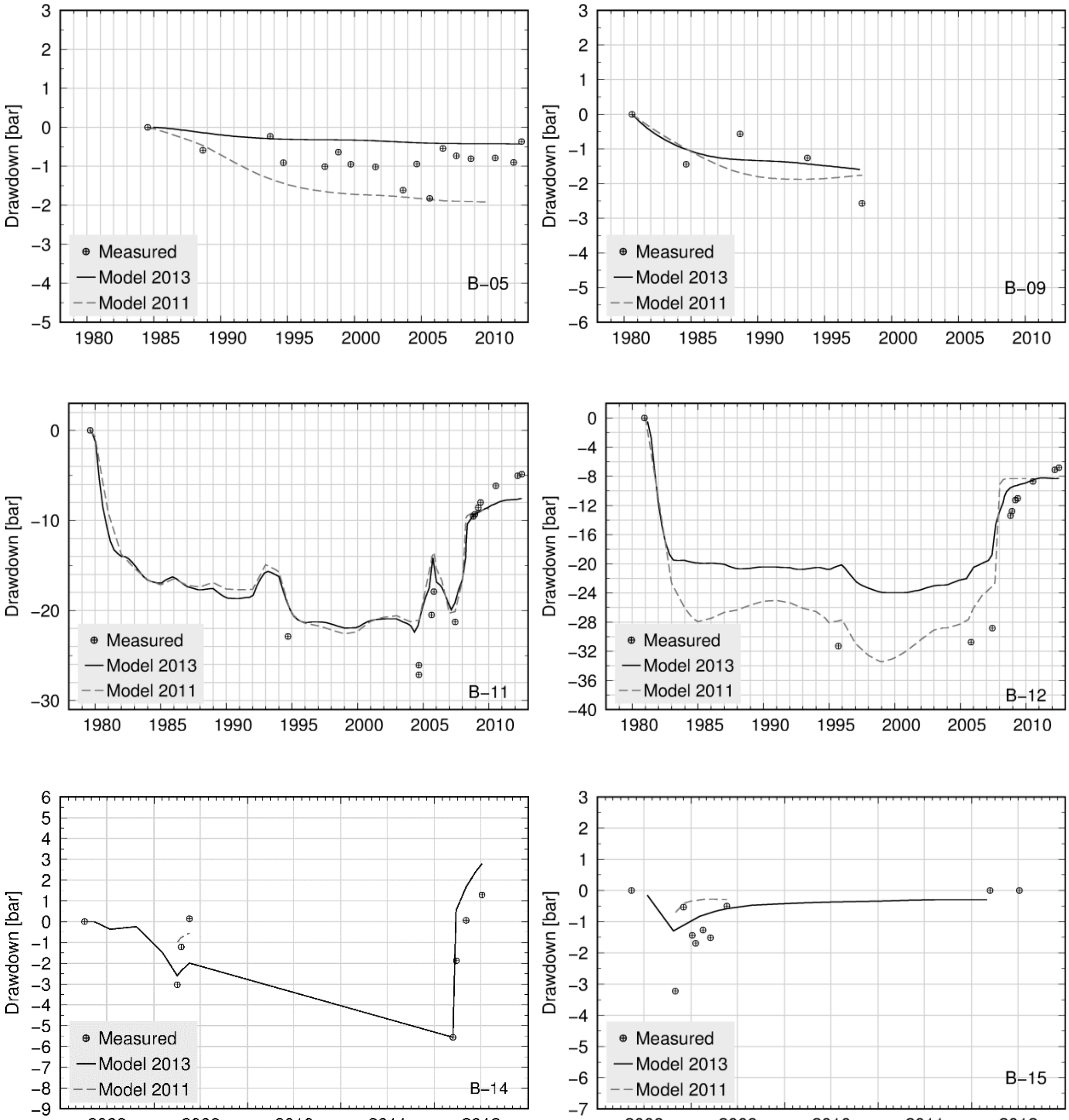

Figure 2. *Comparison of measured and model calculated drawdown for wells BN-5, BN-9, BJ-11, BJ-12, BJ-14 and BJ-15.*

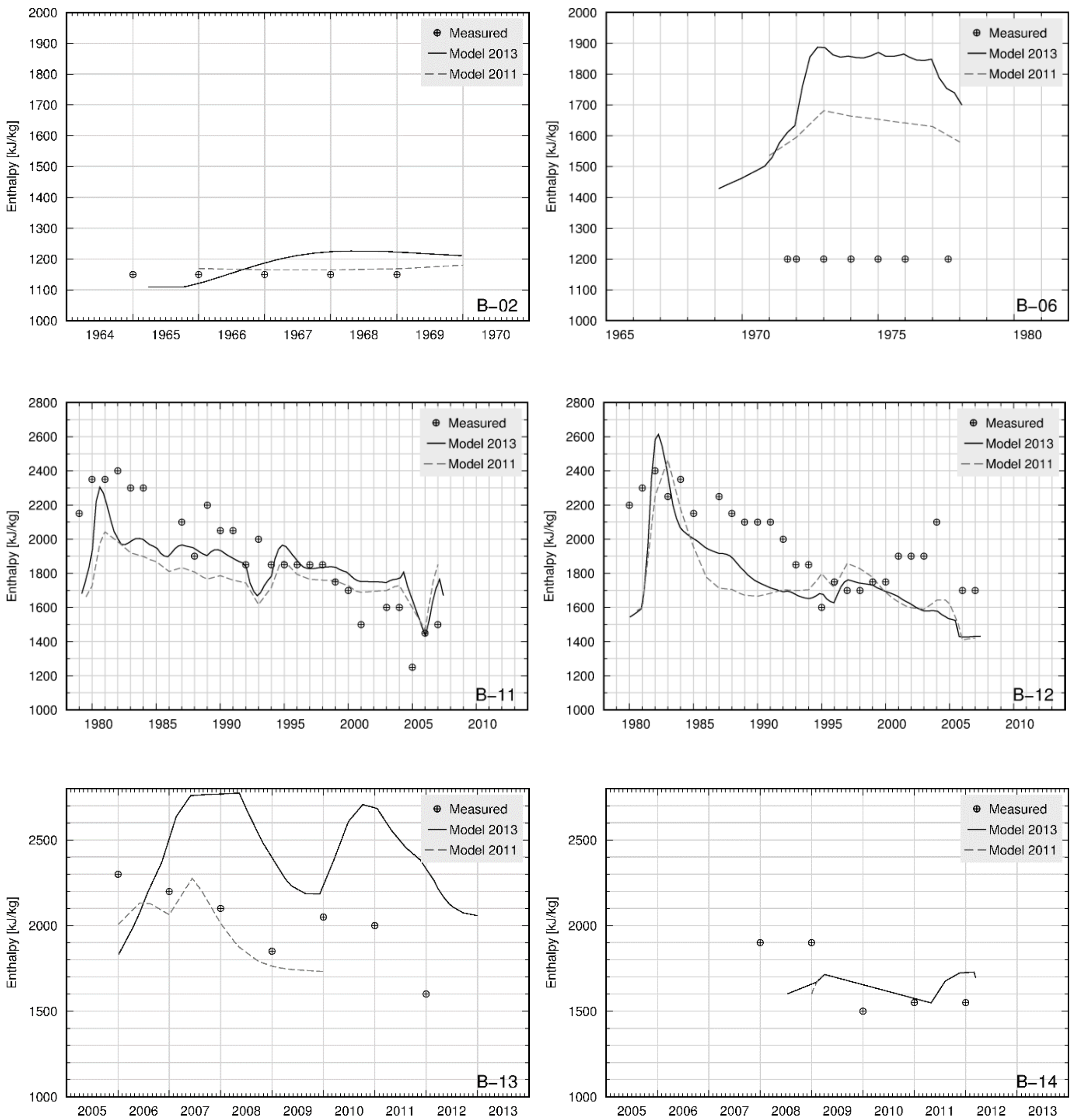

Figure 3. *Comparison of measured and model calculated enthalpy for wells BN-2, BN-6 and BJ-11 to BJ-14.*

3 Wellbore Simulation

In numerical models of geothermal systems, representation of producing wells is usually simplified, their geometry is ignored and no attempt is made to model the two-phase flow within the wellbore. During the operation of production wells, the pressure gradient from the main feed zones to the wellhead responds to changes in reservoir pressure and enthalpy. To accurately model well behaviour in reservoir models, it is important to take this into account. There are essentially two ways to simulate producing wells in TOUGH2:

- As a fixed mass flow sink discharging at a constant or time-dependent rate.
- As a deliverability sink where the productivity index is specified and the amount of mass flowing into the well depends on the difference between reservoir pressure outside the well and the pressure inside the well at the feed zone depth.

For the latter method of incorporating a well in a TOUGH2 model, the default option is to specify a fixed bottomhole pressure. In geothermal power plant operations, however, the production wells are more often operated at a constant wellhead pressure. To simulate this setup in TOUGH2, a table of bottomhole pressure for a range of mass flow and enthalpy values must be provided. The table is used in an interpolation scheme where the flow rate and bottomhole pressure are obtained through an iterative solution (Pruess et al., 1999). The table is created by performing wellbore simulations for a fixed wellhead pressure (to match the specifications of the power plant operation) and varying the enthalpy and mass flow from the reservoir. This method of representing wells provides a more accurate picture of the evolution of well productivity during model simulations.

There are six available production wells in Bjarnarflag, BN-9 and BJ-11 through BJ-15. Only 4 were used in the simulations. Well BJ-15 was discarded since temperature measurements reveal significant cooling below 1600 m depth (TVD). Well BN-9 is primarily used as a source of hot water for the Jarðböðin Spa and will likely be replaced by effluent water from the power production once the plant comes online. Wellbore simulation was performed for the remaining four wells. The resulting input-tables for TOUGH2 are illustrated in Figure 4. Useful information on the four wells (BJ-11 to BJ-14) used in the wellbore simulation is provided in the next Sections.

BJ-11

Well BJ-11 was drilled in 1979 after the Krafla Fires had destroyed most of the wells in Bjarnarflag. A 9⅝" production casing down to 620 m depth is followed by a 7⅝" slotted liner down to 1915 m (Guðmundsson et al., 1989). The well was logged regularly during temperature recovery and after discharge it produced up to 2007, with a break in 2004–2005. Data collected during regular discharge measurements (Russel-James) are available. During the early years until 1985 it was very powerful, discharging about 25 kg/s of a high enthalpy fluid (2300–2400 kJ/kg). Between 1987–1988 the total mass flow measured 18–20 kg/s and the enthalpy had dropped to 2000 kJ/kg at a WHP of 19 bar-a (Guðmundsson et al., 1989). Between 2000–2004 the enthalpy had decreased to 1500–1700 kJ/kg and the total flow was 25–30 kg/s. The last measurement from April 2007 reveals a mass flow of 33 kg/s and an enthalpy at approximately 1500 kJ/kg.

Temperature logs from 2004–2012 reveal that just below the production casing shoe cold water (150°C) flows into the well, mixes with hotter water inflow at 1300–1400 m depth and flows out near the bottom of the well (Hjartarson and Ásmundsson, 2005; Gylfadóttir, 2012a, b). This probably began when the reservoir pressure had fallen sufficiently due to production. The cold inflow causes difficulties in initiating discharge and the well has been closed since 2007 (Hjartarson, 2005).

There exist three temperature and pressure logs during discharge for well BJ-11, from 20 August 1987, 27 March 2007 and 10 April 2007. The last log was used to estimate the productivity index of the well, resulting in a value of

$$PI = \frac{Q}{\beta(P_0 - P_{wb})} = 6.29 \times 10^{-13}\ \mathrm{m}^3$$

where

$$\beta = \frac{k_{rl}\rho_l}{\mu_l} + \frac{k_{rv}\rho_v}{\mu_v}$$

BJ-12

Drilling of well BJ-12 began in the autumn of 1979 and the well was completed towards the end of 1980. The 9⅝" production casing reaches a depth of 686 m and the production section is lined with a 7" slotted liner from 634–1957 m. The well is 1999 m deep (Guðmundsson et al., 1989).

Similar to well BJ-11, cold inflow below the casing shoe causes difficulties in initiating discharge. The well has been closed since 2007 and regular temperature and pressure logs taken to monitor the recovery of the well.

Flow measurement and a pressure log taken during discharge on 28 March 2007 was used to estimate the productivity index of the well resulting in $PI = 6.74 \times 10^{-13}$ m^3.

BJ-13

Well BJ-13 was the first exploration well drilled for the planned expansion of the Bjarnarflag power production. It was drilled in 2006 from the same drill pad as well BJ-12 and directed under the Námafjall ridge. The 9⅝" production casing reaches to a depth of 861 m and a 7" perforated liner is installed from 816–2135 m (Þórarinsson et al., 2006). There are two temperature recovery measurements available, from 25 and 75 days after drilling. The well was connected shortly after the second temperature recovery logging and has been producing without interruptions ever since. No temperature and pressure profiles have been logged during discharge. Most of the time, the well has discharged 35 kg/s of fluid with enthalpy 2200 kJ/kg. From mid-2011 the wellhead pressure and enthalpy have declined and today the enthalpy measures around 1660 kJ/kg and the discharge is 37 kg/s. By performing a wellbore simulation to estimate the bottomhole pressure using the well design and the latest wellhead measurements, the productivity index was estimated $PI = 1.35 \times 10^{-12}$ kg/s/bar (similar results are obtained by using measurements from 2008). In order to obtain a good fit between measured discharge and that calculated by the TOUGH2 model, the *PI* had to be raised to 4.0×10^{-12} m^3.

BJ-14

Well BJ-14 was drilled in 2008 to continue the exploration of the Námafjall system. The 9⅝" production casing shoe is located at 840 m and a 7" perforated liner is installed from 801.7 to 2479 m (TVD 2218 m) (Mortensen, et al., 2008). The well was injection tested after drilling, and the interpretation of the test gave a permeability thickness of $kh = 6.9 \times 10^{-12}$ m³ and a skin factor of $s = 3$. This can be used to calculate the productivity index of the well (Pruess et al., 1999), resulting in a value of 4.4×10^{-12} m³.

$$PI = \frac{2\pi kh}{\ln\frac{r_e}{r_w} + s - \frac{1}{2}}$$

A value of 2.5×10^{-12} kg/s/bar, however, is used in the model, in order to get a better fit with the measured discharge.

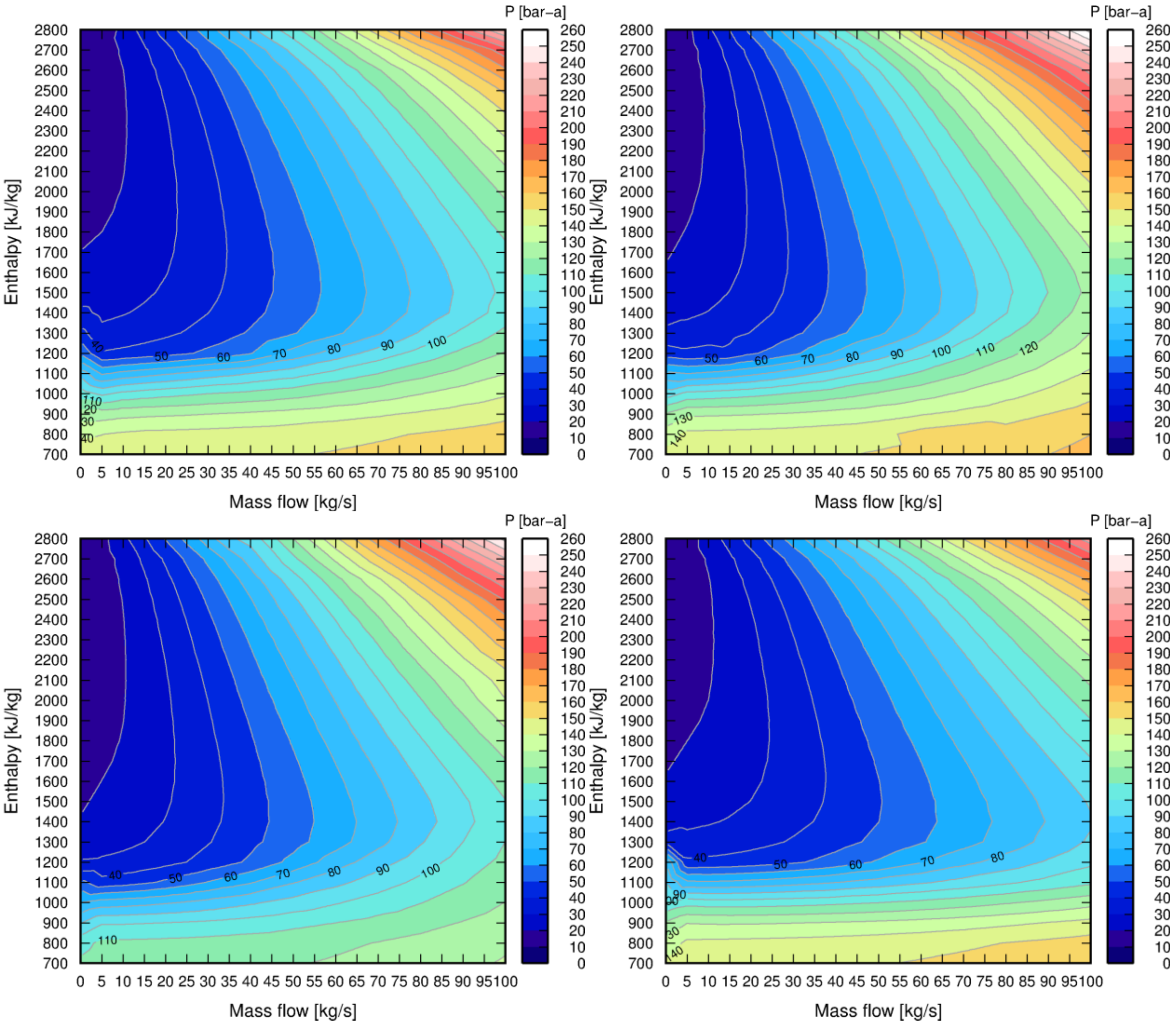

Figure 4. *Variation of wellbottom pressure with mass flow and enthalpy, obtained through wellbore simulation of the four main production wells in Bjarnarflag: BJ-11 (top left), BJ-12 (top right), BJ-13 (bottom left) and BJ-14 (bottom right).*

4 Future Production Wells

The location of production wells needed to obtain and maintain the 45 and 90 MW_e production scenarios for 30 years is shown in Figure 5. Well BJ-16 is needed to start the 45 MW_e power plant and BJ-17 and BJ-18 are inserted as make-up wells (the latter is only necessary for one reinjection scenario, infield reinjection into the production layer). Wells BJ-16 through BJ-20 are needed to start the 90 MW_e power plant and wells BJ-21 through BJ-26 are inserted as make-up wells (the last one is only necessary for infield reinjection into the production layer).

For simulations of the response of the 100 years of 45 MW_e and 90 MW_e production, the production wells needed are shown in Figure 6. For a 45 MW_e plant, wells BJ-17 through BJ-23 are needed as make-up wells and for 90 MW_e generation, wells BJ-21 through BJ-60 are needed as make-up wells.

The well locations actually refer to the main feedzone of wells, not the wellheads, and are assumed to be reached through directional drilling from planned drill pads (shown in the figures). The main production layer of the model is layer F (1350–1700 m depth), from which roughly 80% of the extracted mass originates. The remaining 20% are extracted from layer E (1000–1350 m depth).

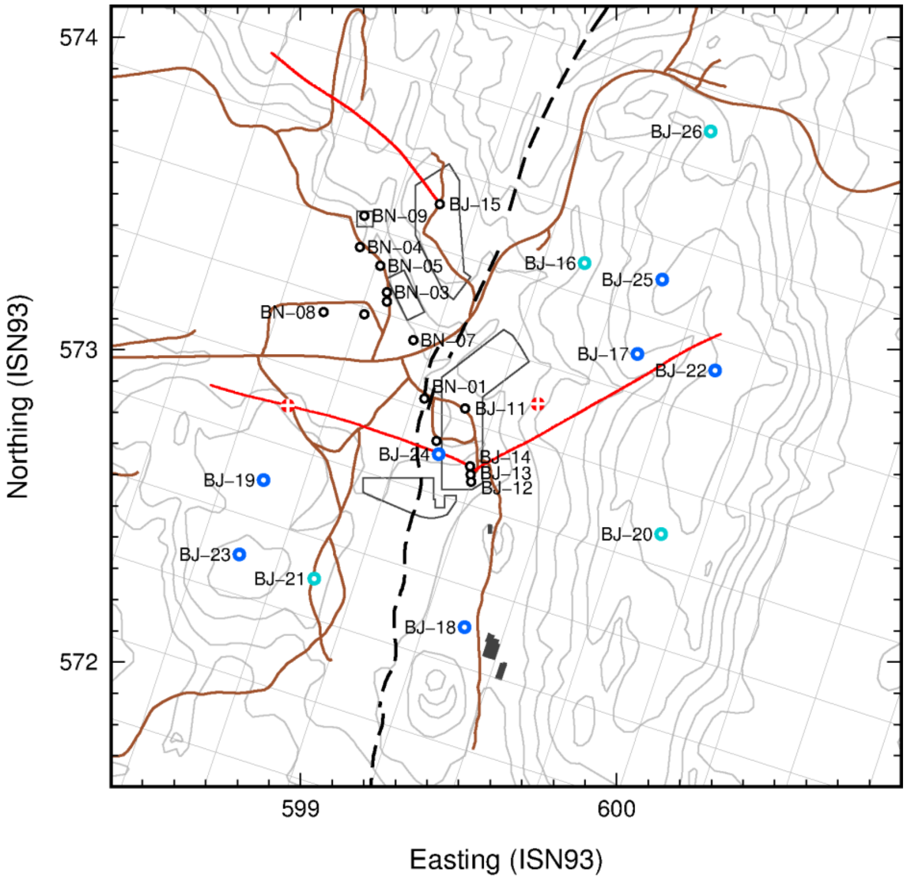

Figure 5. *Location of future production wells in Bjarnarflag for simulations of response to 30 years of production. For 45 MW_e, wells BJ-11 to BJ-14 and BJ-16 to BJ-18 are used. For 90 MW_e, wells BJ-11 to BJ-14 and BJ-16 to BJ-26 are used. Cyan denotes feed zones in layer E and blue dots denote feed zones in layer F. Red circles with white crosses denote location of feed zones in the model for wells BJ-13 and BJ-14.*

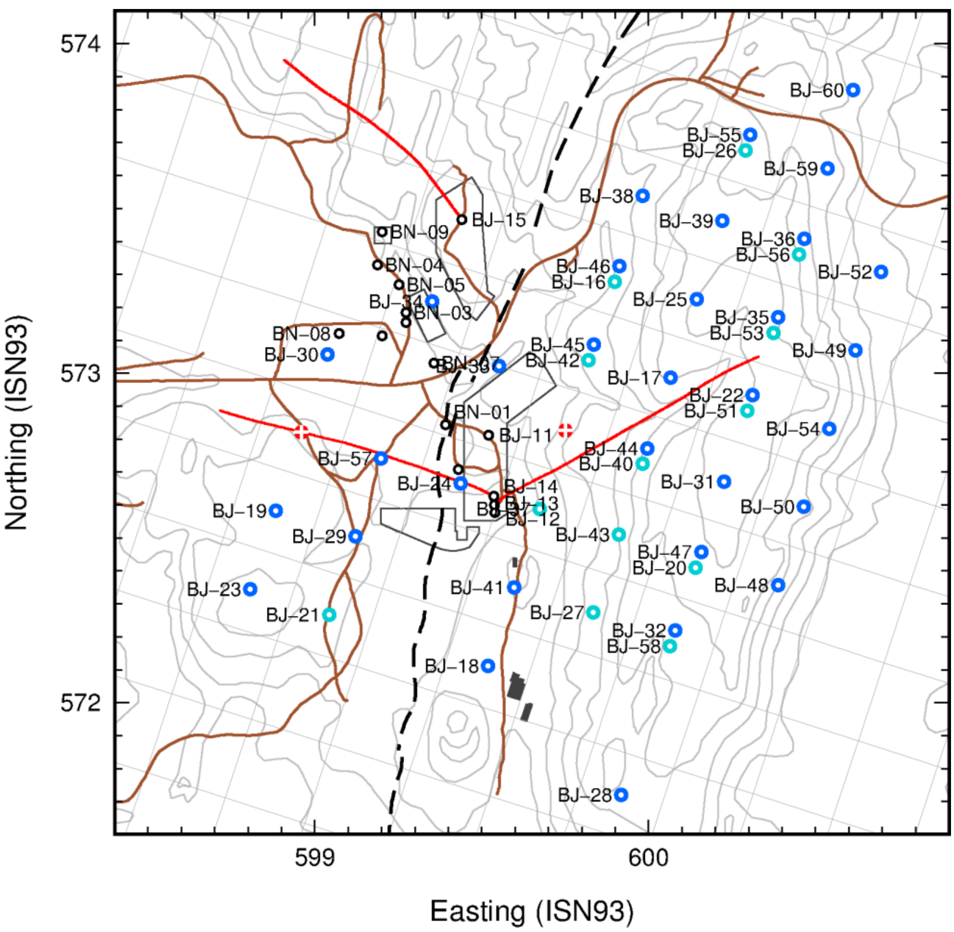

Figure 6. *Location of future production wells in Bjarnarflag for simulations of long-term response when production is maintained for 100 years.*

5 Reinjection Targets

Reinjection sites were located according to the specifications provided by Landsvirkjun:

A. Two to three 300 m deep wells between Jarðbaðshólar and drilling area B6.
B. Well B-15 and one to two similar wells close-by.
C. Two to three 2000 m deep wells, approx. 1 km west of drilling area B5.
D. Two to three 2000 m deep wells, approx. 1 km southeast of drilling area B5.
E. Two to three wells located by ÍSOR specialists, to maximize the benefit of reinjection.

Figures 7 and 8 show the injection areas for the 45 MW_e and 90 MW_e production scenarios, respectively. Several strategies were tested for scenario E, deep infield reinjection (purple stars), outfield reinjection to the northwest, etc. In the end, a combination scenario was chosen to utilize the benefits of different reinjection schemes. This is shown with circles in Figures 7 and 8.

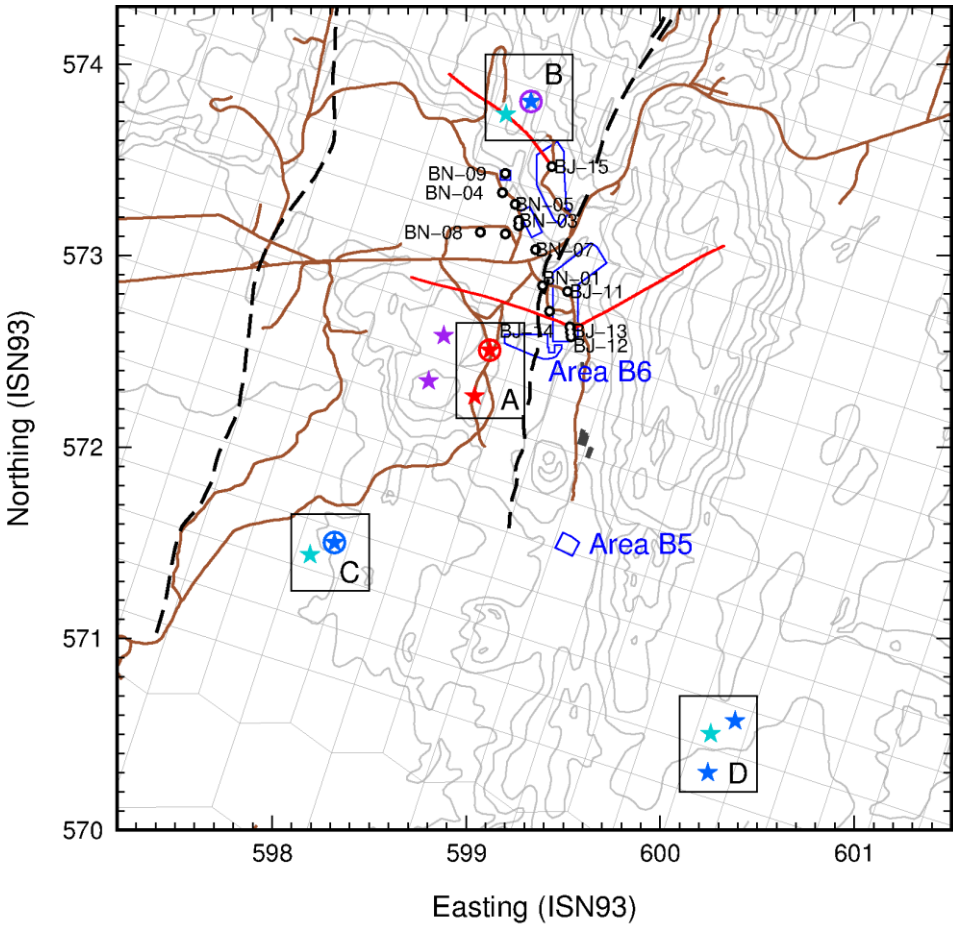

Figure 7. *Location of injection sites for the 45 MWₑ scenario. Red denotes sinks in layer B (200 m), turquoise in layer E (1175 m), blue in layer F (1525 m) and purple in layer G (1925 m). The circles indicate sites used for the distributed reinjection scenario. Letters refer to different reinjection strategies.*

The amount of brine and condensate available for reinjection was calculated based on the following specifications:

- The amount of brine was calculated based on a separation pressure of 9.5 bar-a (177.7°C).
- The amount of condensate was calculated by assuming a pressure of 0.1 bar-a (45.8°C, given by the schematic diagram of the brine cycle provided by Landsvirkjun) for the condenser where steam from the turbines is condensed.
- Condensate was mixed with brine to bring the temperature below 110°C. If there was not enough condensate to do so, all the condensate was mixed (i.e. 100% reinjection). In most cases, the amount of condensate was not sufficient to reduce the temperature below 110°C , meaning that there was 100% reinjection.

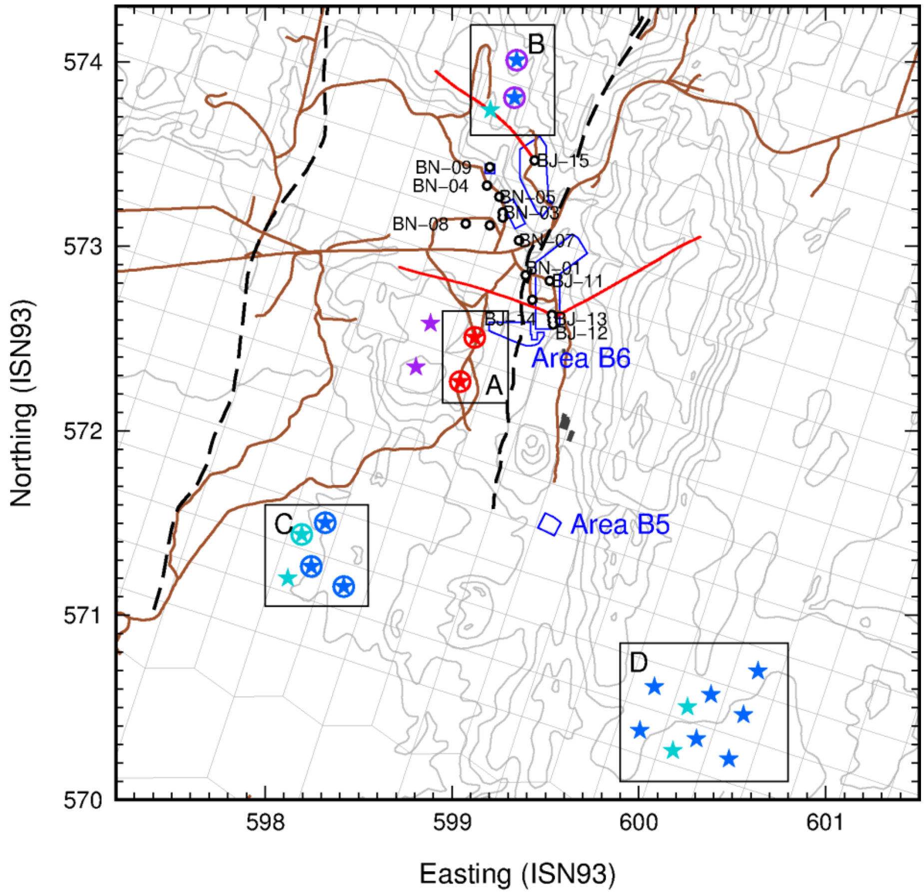

Figure 8. *Location of injection sites for the 90 MWₑ scenario. Red denotes layer B (200 m), turquoise denotes layer E (1175 m), blue denotes layer F (1525 m) and purple denotes layer G (1925 m). The circles indicate sites used for the distributed reinjection scenario. Letters refer to different reinjection strategies.*

6 Simulation Results

6.1 Reinjection Scenarios A-D

Four scenarios were considered: A, B, C and D (see Chapter 5 for an overview of reinjection sites). For scenario A (shallow infield reinjection) the reinjection was placed in layer B of the model, whereas for the other scenarios it was placed in the main production layers and roughly divided according to the production from each layer, i.e. 20% into layer E and 80% into layer F. Figures 9 and 10 show the total well output and average well fluid enthalpy for the different reinjection scenarios for a production target of 45 MW_e and 90 MW_e, respectively. Also shown are the simulation results obtained for no reinjection. Shallow reinjection has a limited effect on the production from the system, except for a slight reduction in enthalpy accompanied by a slight increase in mass extraction. The enthalpy rises during the first years of production but levels off and remains relatively stable at 1900–2000 kJ/kg (2200 kJ/kg for 90 MW_e) throughout the period. The production behaves similarly and is stable at around 150 kg/s (220 kg/s for 90 MW_e) for most of the period. Infield reinjection into well BJ-15 causes a pronounced cooling and the enthalpy of produced fluid decreases by 300–400 kJ/kg, from around 1800 kJ/kg to 1400 kJ/kg. Due to this, the mass extraction needed to maintain the power production increases steadily throughout the period from 200 to 275 kg/s (350 to 550 kg/s for 90 MW_e). Moving the reinjection 1 km to the Southwest of the main production area shows little improvement, the reason being the high permeability modeled within the rift zone west of the Námafjall ridge. The enthalpy of the produced fluid drops by almost 400 kJ/kg in a similar fashion as for the in-field reinjection site. This is mainly due to the system being two-phase. Reinjection leads to increased pressure, which in turn leads to condensation of steam and lowering of the fluid enthalpy. Siting the reinjection to the Southeast has the effect of reducing the enthalpy drop since the area has low permeability and the effects of reinjection travel more slowly.

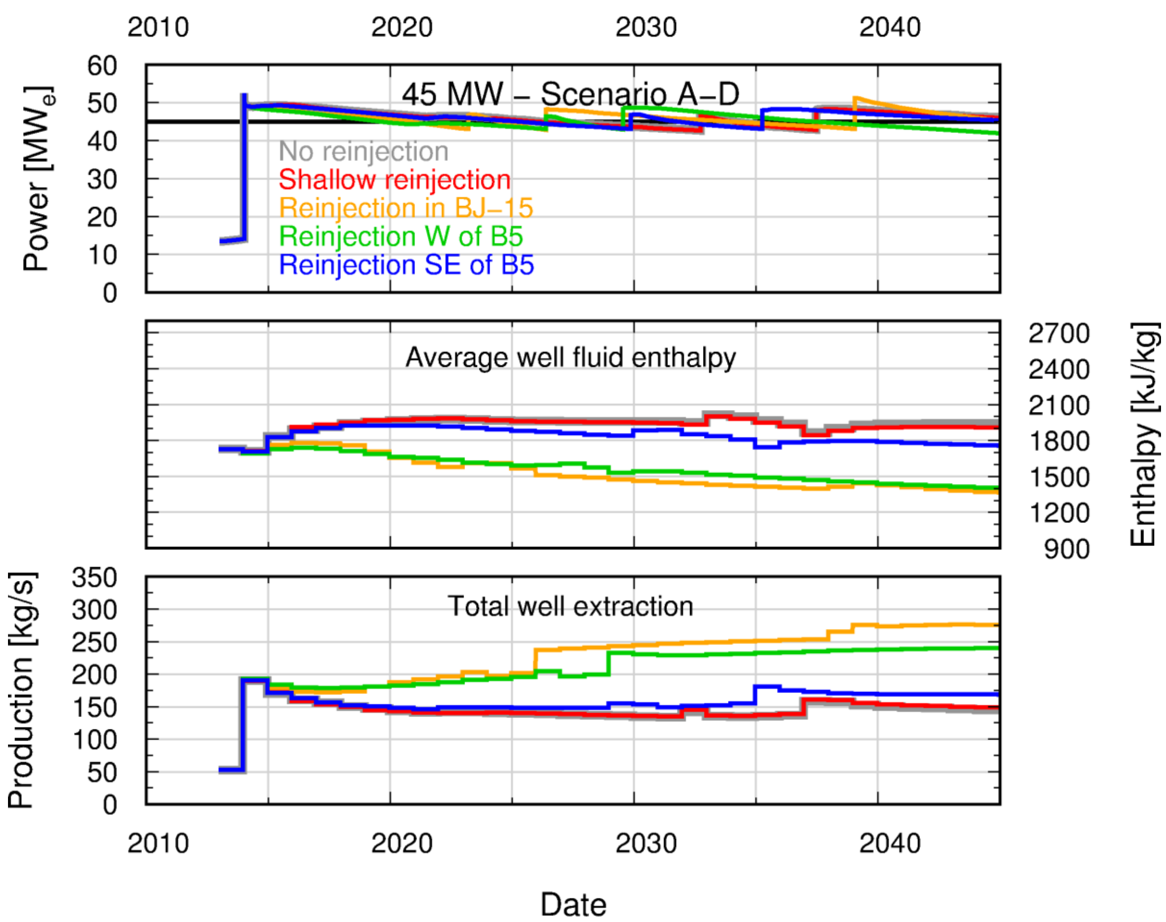

Figure 9. *Simulation results for reinjection scenarios A-D and 45 MW_e production for 30 years.*

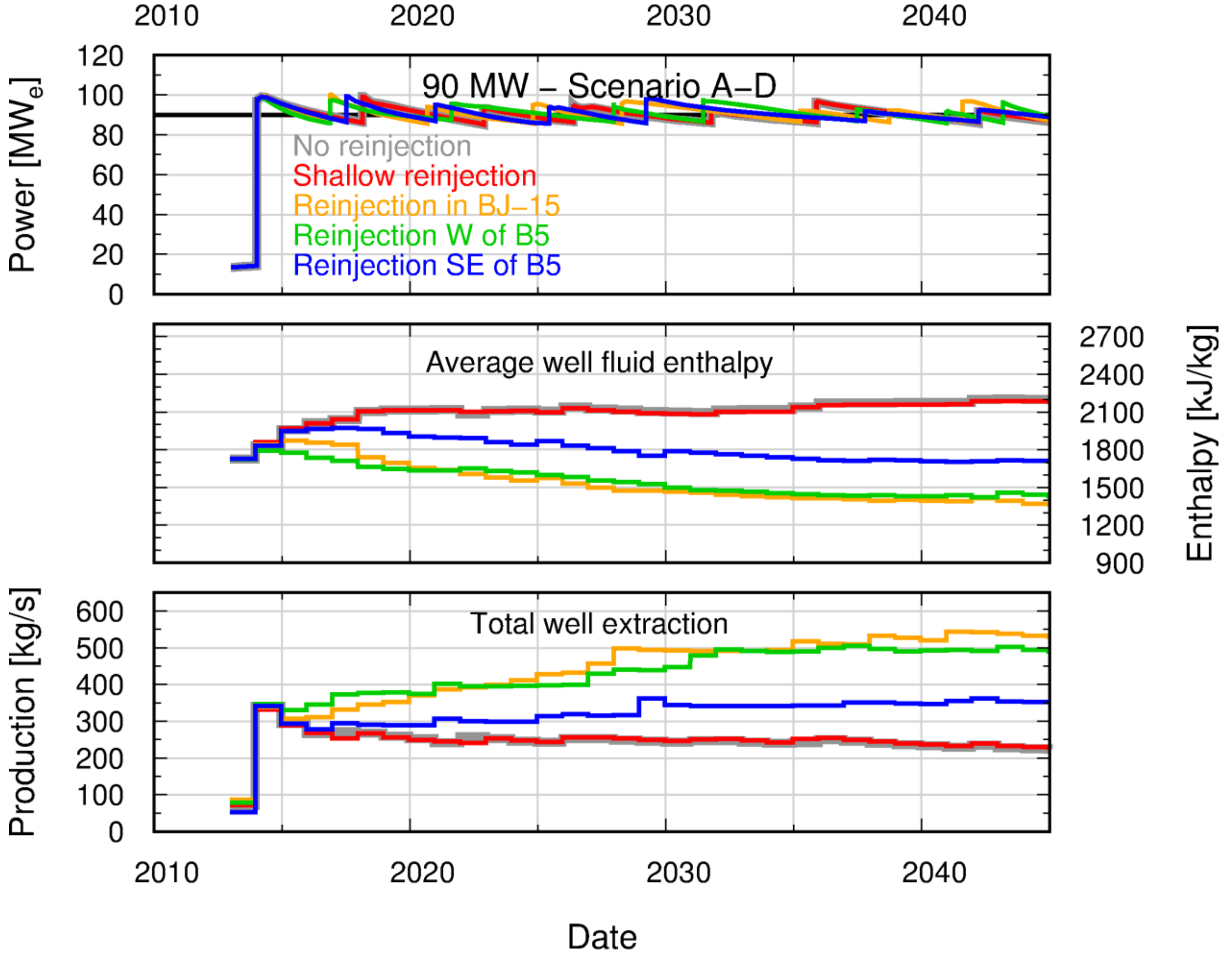

Figure 10. *Simulation results for reinjection scenarios A-D and 90 MW$_e$ production for 30 years.*

Figures 11 and 12 show the simulated system response to 45 MW$_e$ and 90 MW$_e$ production, respectively, for the different reinjection scenarios. Shallow reinjection (scenario A) clearly has a very limited effect on the reservoir and can therefore be considered as waste water disposal only. During the utilization period, the reservoir pressure and temperature fall by close to 20 bar and 15°C, respectively, (35 bar and 25°C for 90 MW$_e$) similar to the results for no reinjection. Reinjection into well BJ-15 (scenario B), assuming that most of the fluid enters the production feed zones, causes significant cooling of the system. Since the fluid is injected directly into the system, the pressure support is significant and immediate. Over the 30 year period the pressure only falls by around 5 bar (10 bar for 90 MW$_e$). However, the reinjection causes the temperature to fall by almost 30°C (45°C for 90 MW$_e$). Placing the reinjection site 1 km Southwest of the main production area (scenario C), within the permeable fault structure, reduces the cooling of the system significantly while at the same time providing adequate pressure support. The temperature falls by about 7°C (18°C for 90 MW$_e$) and the pressure drawdown over the 30 year period is around 8 bar (18 bar for 90 MW$_e$). By siting the reinjection to the Southeast of the production area (scenario D) the benefits of reinjection are limited due to lower connectivity between the reinjection and production zones. The pressure drop is reduced by less than 5 bar compared to no reinjection and the temperature drop is reduced to less than 5°C.

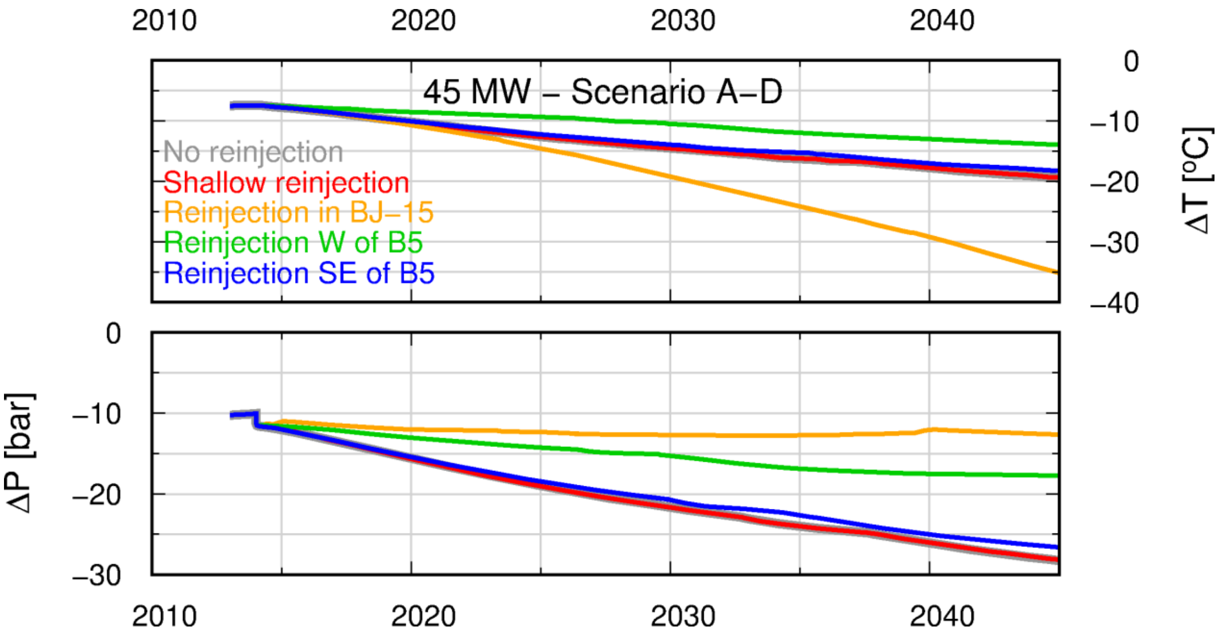

Figure 11. *Simulation of system response to 45 MW$_e$ production under reinjection scenarios A-D.*

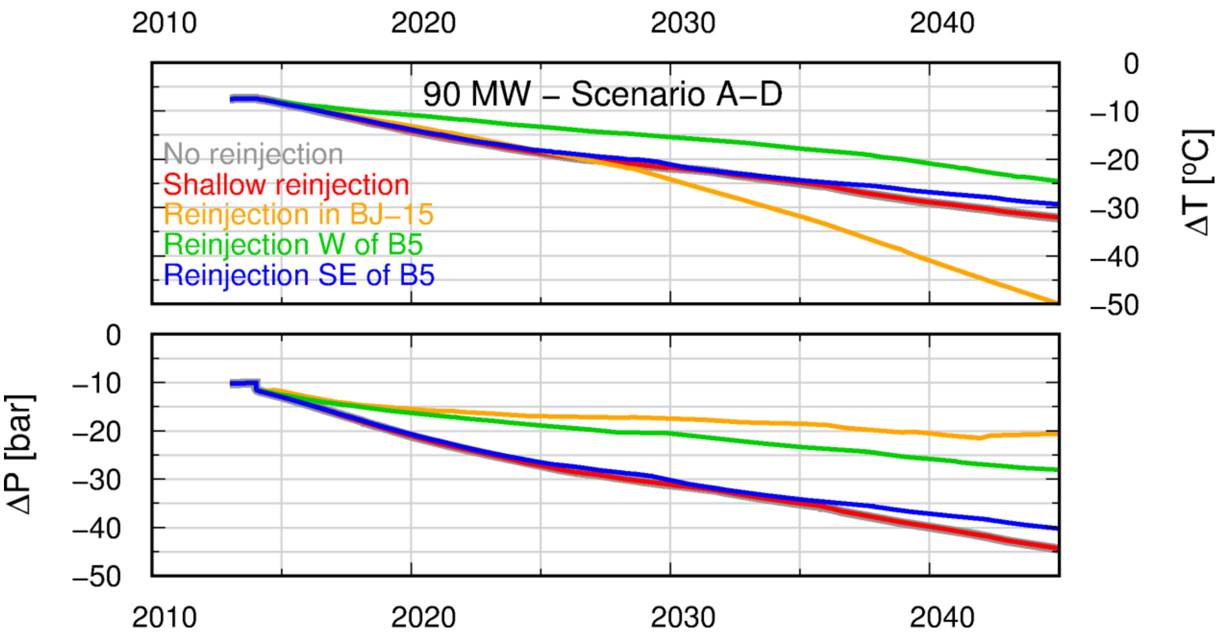

Figure 12. *Simulation of system response to 90 MW$_e$ production under reinjection scenarios A-D.*

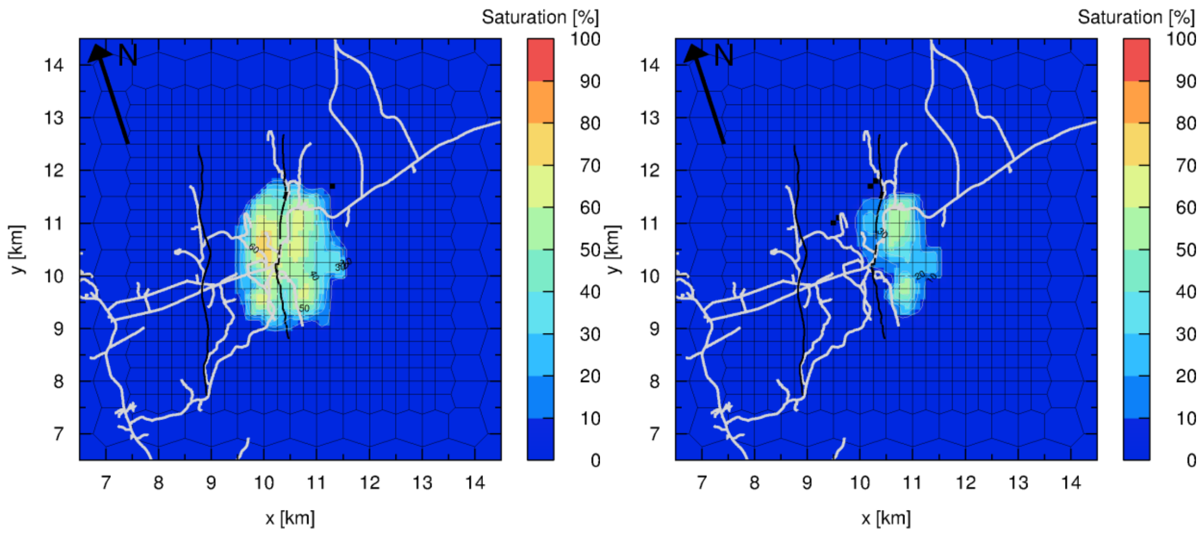

Figure 13. *Steam saturation in the main production layer (F) after 30 years of 45 MW$_e$ power production. Left panel shows results for no reinjection and the right panel shows results for reinjection into 2 wells 1 km west of drilling area B5 (scenario C).*

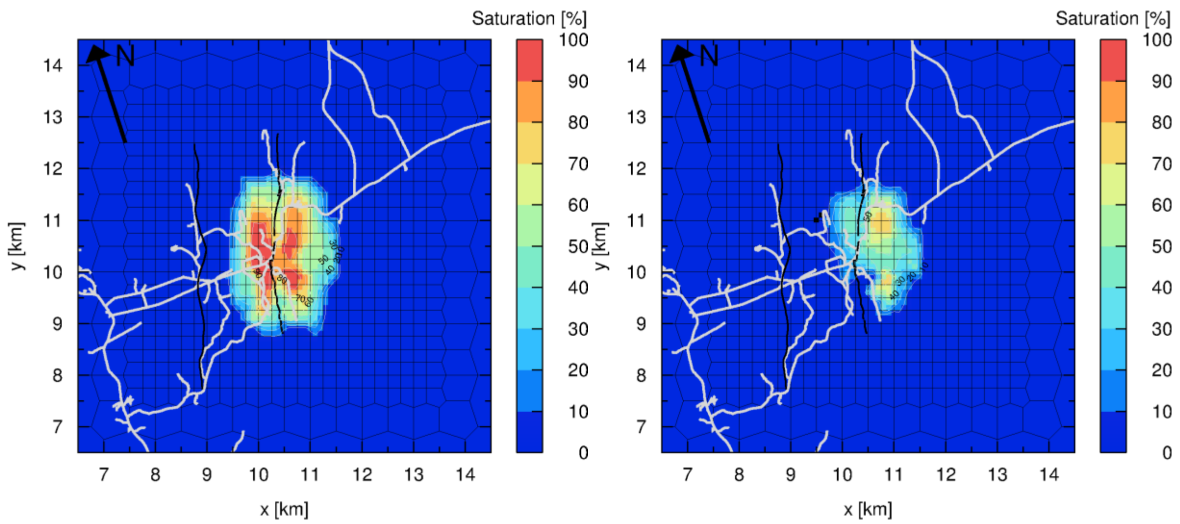

Figure 14. *Steam saturation in the main production layer after 30 years of 90 MW$_e$ power production. Left panel shows results for no reinjection and the right panel shows results for reinjection into 2 wells 1 km west of drilling area B5 (scenario C).*

Figures 13 and 14 show a comparison of the steam saturation in the main production layer (layer F) after the 30 year generation of 45 and 90 MW, respectively, for reinjection 1 km southwest of the production area. For comparison, the results for no reinjection are shown on the left panel of the figures. The pressure support from reinjection causes extensive condensation of steam in the production area and consequently a lowering of the produced fluid enthalpy.

A few other reinjection sites were tested by simulation without significant change in results.

6.2 Deep in-field Reinjection (E)

As evident by the results presented in the previous section, reinjection into the main production layers causes significant reduction in fluid enthalpy, thus increasing the need for make-up wells. By moving the reinjection below the main production interval the pressure support is reduced, which leads to a smaller decrease in the fluid enthalpy. Three cases were examined: reinjection into BJ-15 after deepening the casing to approximately 1800 m, and reinjection into wells drilled in the Jarðbaðshólar area cased to approximately 1800 m and 2200 m. Figure 15 shows the well power generation, average well fluid enthalpy and mass extraction for the 45 MW_e case. The results are largely insensitive to the location of reinjection wells within the production field and primarily dependent on depth. For the three scenarios, the enthalpy remains relatively stable at around 1600 to 1800 kJ/kg throughout the production period and the mass extraction varies between 150 and 200 kg/s.

Figure 16 shows the calculated reservoir response. As expected, the deeper the reinjection is targeted, the smaller the effect on the reservoir pressure. Compared to the results for no reinjection, the pressure drawdown is 5 bar less when the reinjection is targeted just below the production interval and only half that when it is located deeper in the system. The reduced pressure drawdown results in reduced cooling of the two-phase system.

Although the results for 90 MW_e production are not shown, the same conclusions apply.

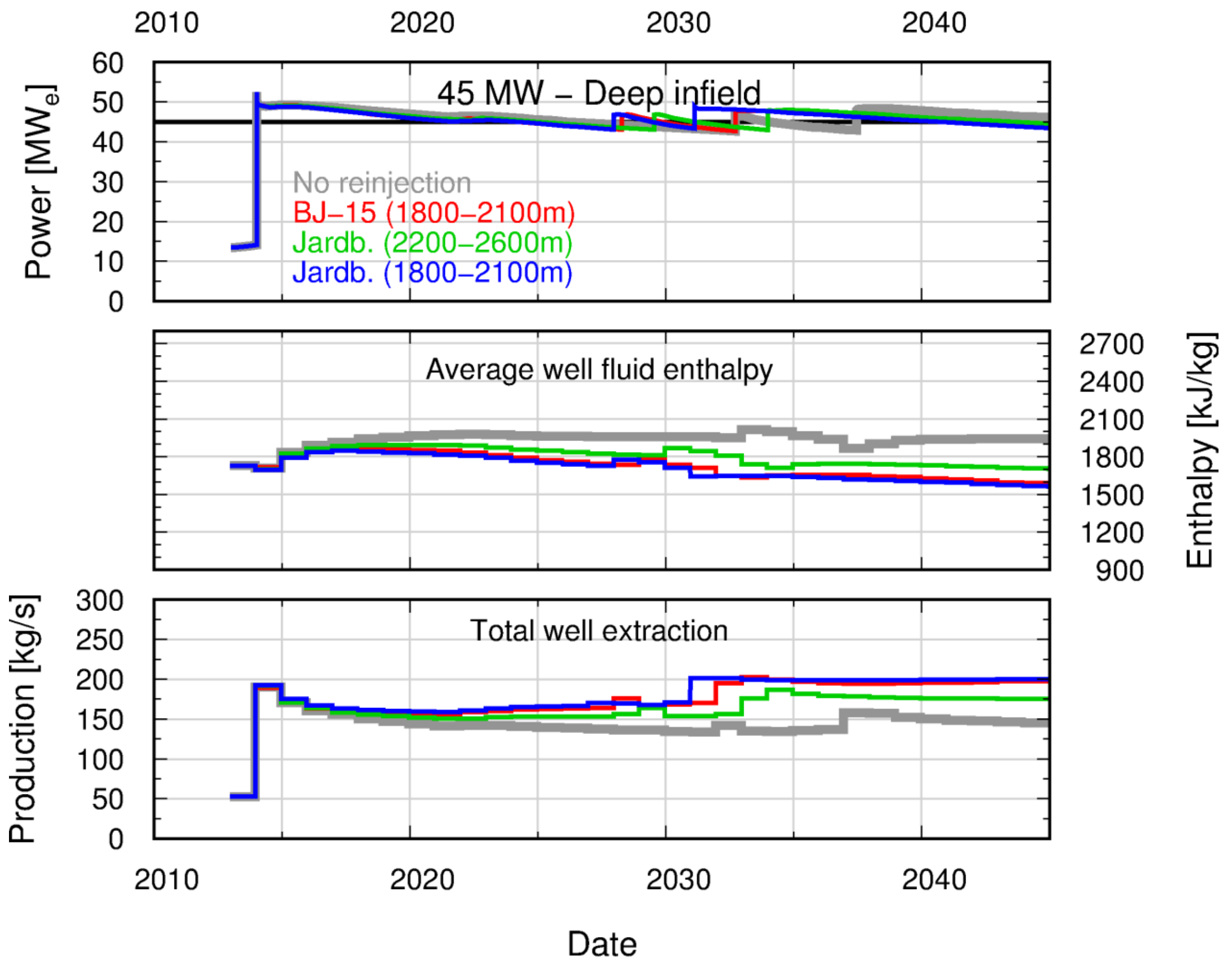

Figure 15. *Simulation results for deep in-field reinjection and 45 MW_e production for 30 years.*

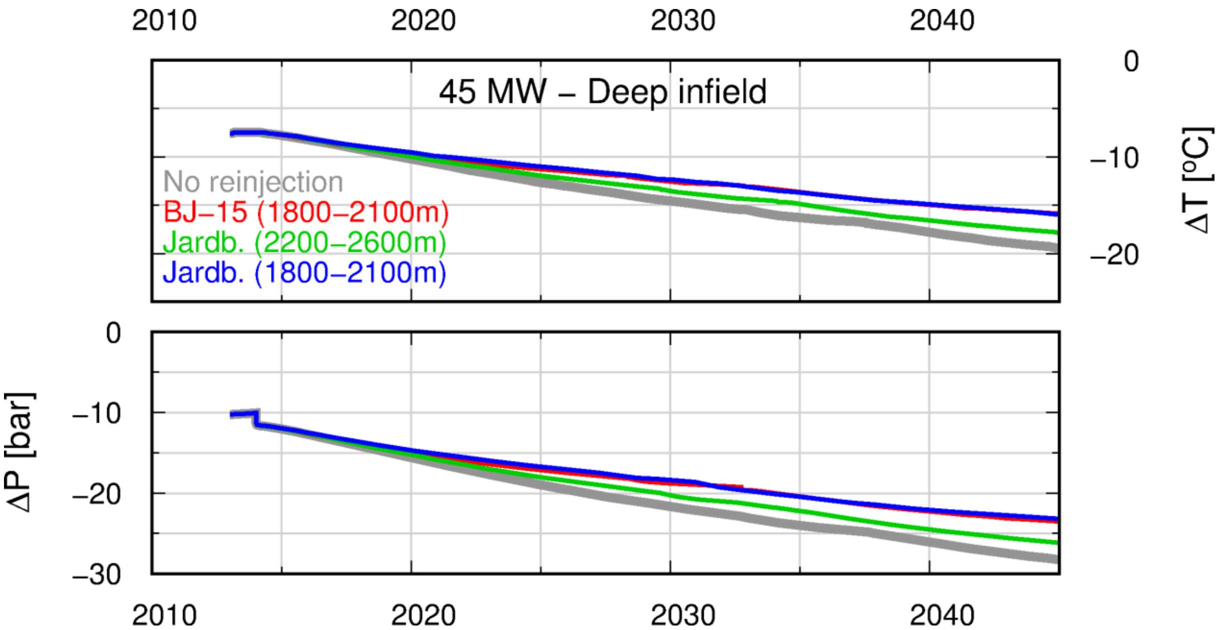

Figure 16. *Simulation of system response to 45 MW_e production with deep in-field reinjection.*

The benefit of moving the reinjection below the main production interval is in increased steam saturation, as shown in Figure 17. Injection into well BJ-15 almost quenches the steam production but by moving it to deeper layers the steam saturation is maintained reasonably well.

The main conclusions from the simulation results for the reinjection strategies discussed above are the following.

- Shallow reinjection is effectively an effluent water disposal scheme with limited effect on the geothermal system. It provides no pressure support but in turn causes almost no cooling or condensation in the system, which is beneficial in the long run.
- In-field reinjection into the production part provides significant pressure support but causes excessive cooling and quenches boiling in the two-phase reservoir.
- Peripheral reinjection in the permeable fault system (scenario C) provides adequate pressure support and less cooling than in-field reinjection. There is, however, a significant reduction in discharged enthalpy. By moving the reinjection out of the fissure swarm to the less permeable area southeast of the production area (scenario D), the pressure support decreases while the enthalpy remains stable. The effects of this reinjection scheme are similar to those of shallow reinjection, which is a more cost-effective alternative.
- Moving the in-field reinjection deeper reduces the decrease in enthalpy and temperature while providing moderate pressure support.

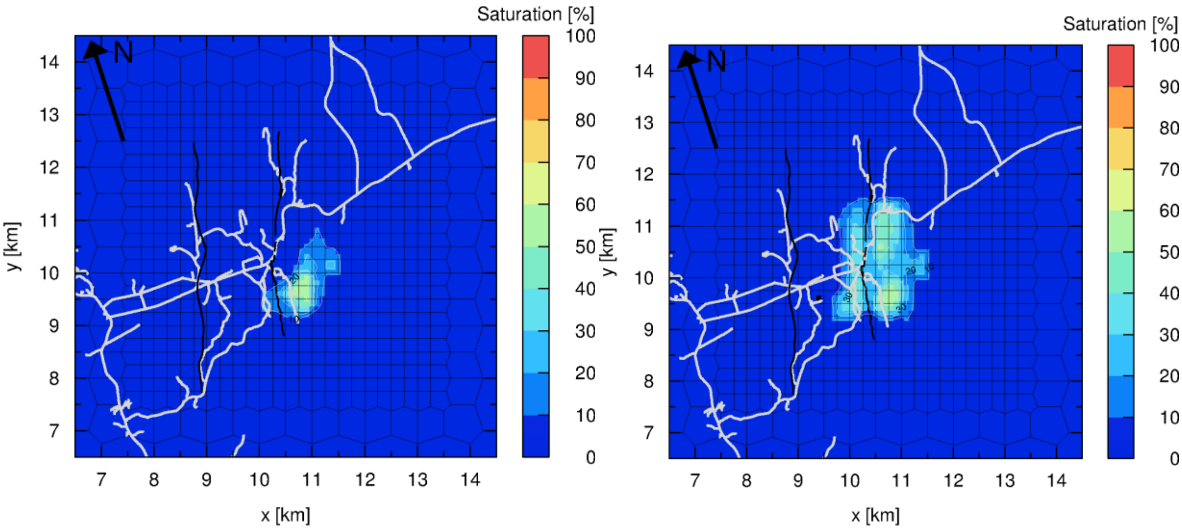

Figure 17. *Steam saturation in the main production layer (F) for reinjection into production part of well BJ-15 (left) vs. deeper reinjection into the same well (right).*

From an economic standpoint, the shallow reinjection scheme appears to be the most feasible option. Having no effect on the enthalpy of produced fluid (as compared to not injecting at all), it reduces the number of make-up wells needed to maintain the target electric production and only requires relatively inexpensive injection wells. It has, of course, no benefits for maintaining pressure in the geothermal system, which has little limiting effect in the model simulation. It must, however, be kept in mind that the main limiting factor for well productivity in the model is pressure drawdown and no operational issues such as scaling are taken into account. This gives a somewhat optimistic view of well performance. Another point to keep in mind is that the wellbore simulation, discussed in Chapter 3, which was performed to construct wellbottom pressure tables, is based on limited data. The results control well performance in the model, thus there is a significant uncertainty in the evolution of well output in the forecasts.

6.3 Distributed Reinjection

As an alternative to the shallow reinjection strategy, to obtain some pressure support without affecting the production potential too greatly, a distributed reinjection scenario was constructed. In this, 60% of the brine and condensate is injected into wells 1 km West of drilling platform B5 (scheme C), 20% is disposed of in shallow in-field wells (scheme A) and 20% is injected deep into well BJ-15, which is assumed to be cased down below the main production layer (approx. to 1800 m). The simulation results are shown in Figures 18 and 19 along with the base scenarios for comparison. This scenario combines:

- Good pressure support from out-field reinjection into the production layer.
- Limited cooling and enthalpy reduction due to deep in-field reinjection while still decreasing the pressure drawdown.
- 20% of fluids are disposed of through shallow reinjection.

Table 2 presents a comparison of the energy extraction and number of wells needed for the main reinjection scenarios. The extraction of thermal energy is the lowest for shallow reinjection and greatest for in-field reinjection into well BJ-15 for similar average power generation. In the latter case an extra make-up well is needed to drive the production for 30 years. For other cases the number of make-up wells is the same, but drilling can be delayed longer for the shallow reinjection scheme.

Table 2. *Comparison of energy extraction and drilled wells for different reinjection strategies and 45 MW$_e$ power production for 30 years. For detailed information on well productivity consult Appendices E and F.*

Reinjection	E_{th} (PJ)	E_{el} (PJ)	P_{avg} (MW$_e$)	Start-up wells	Make-up wells
None	276.4	45.1	47.6	5	1
Shallow (A)	276.7	45.1	47.6	5	1
BJ-15 (B)	339.5	45.5	48.1	5	2
West (C)	322.8	44.5	47.0	5	1
Southeast (D)	287.3	45.3	47.8	5	1
BJ-15 Deep	299.7	45.1	47.6	5	1
Combination	307.2	44.7	47.2	5	1

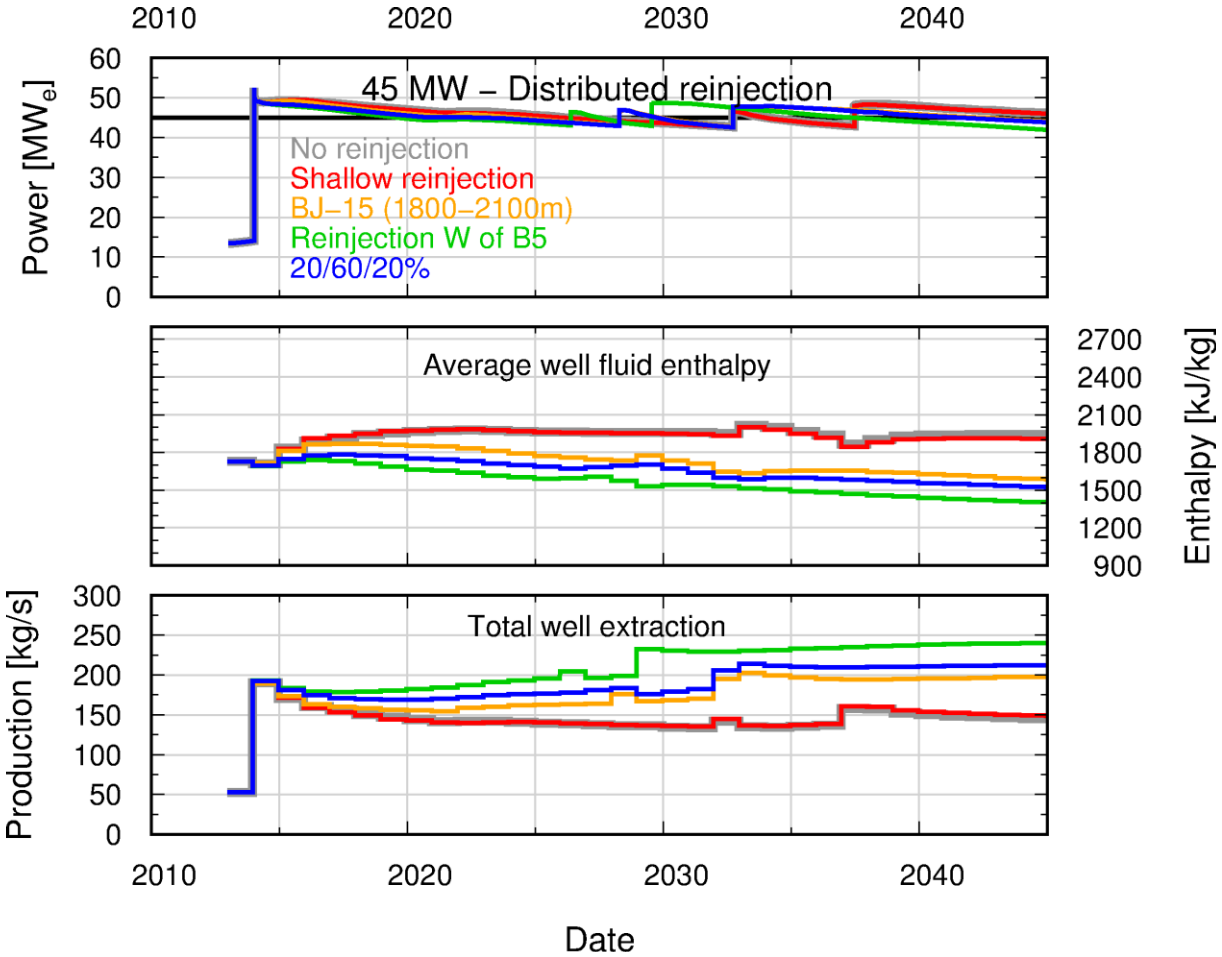

Figure 18. *Simulation results for 45 MW$_e$ production with distributed reinjection.*

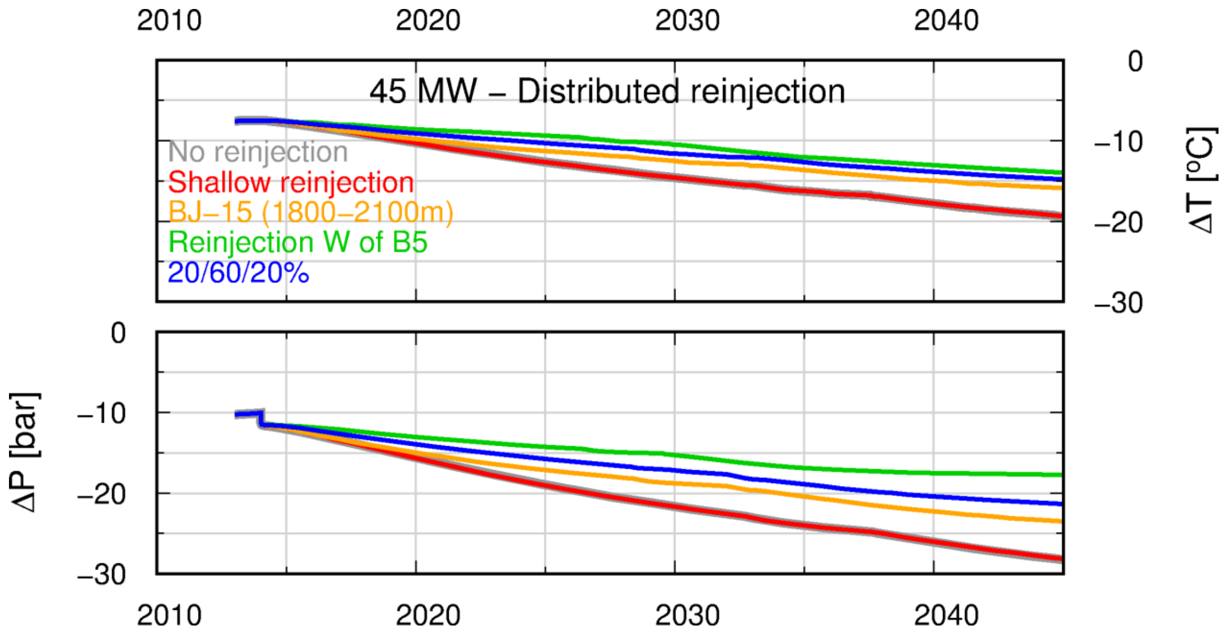

Figure 19. *Simulation results for 45 MW$_e$ production with distributed reinjection.*

The temperature and pressure change in the main production layer for shallow and distributed reinjection is shown in Figures 20 and 21 for 45 MW$_e$ and 90 MW$_e$, respectively. Comparing the two reinjection schemes, for shallow reinjection the pressure drawdown in the production area is greater, leading to increased boiling (see Figures 22 and 23) and lower temperature. When the reinjection is partly in the main production interval, the cooling effect of the injected fluid is pronounced around the reinjection site and travels towards the production area through fractures simulated in the model. During the 30 year simulation, a breakthrough impeding power production does not occur for the 45 MW$_e$ case. In the 90 MW$_e$ case cold injection fluid has reached the Jarðbaðshólar area after the 30 year period. Whether this holds true in reality is subject to significant uncertainty and careful monitoring would be essential to avoid reducing the production potential of the system.

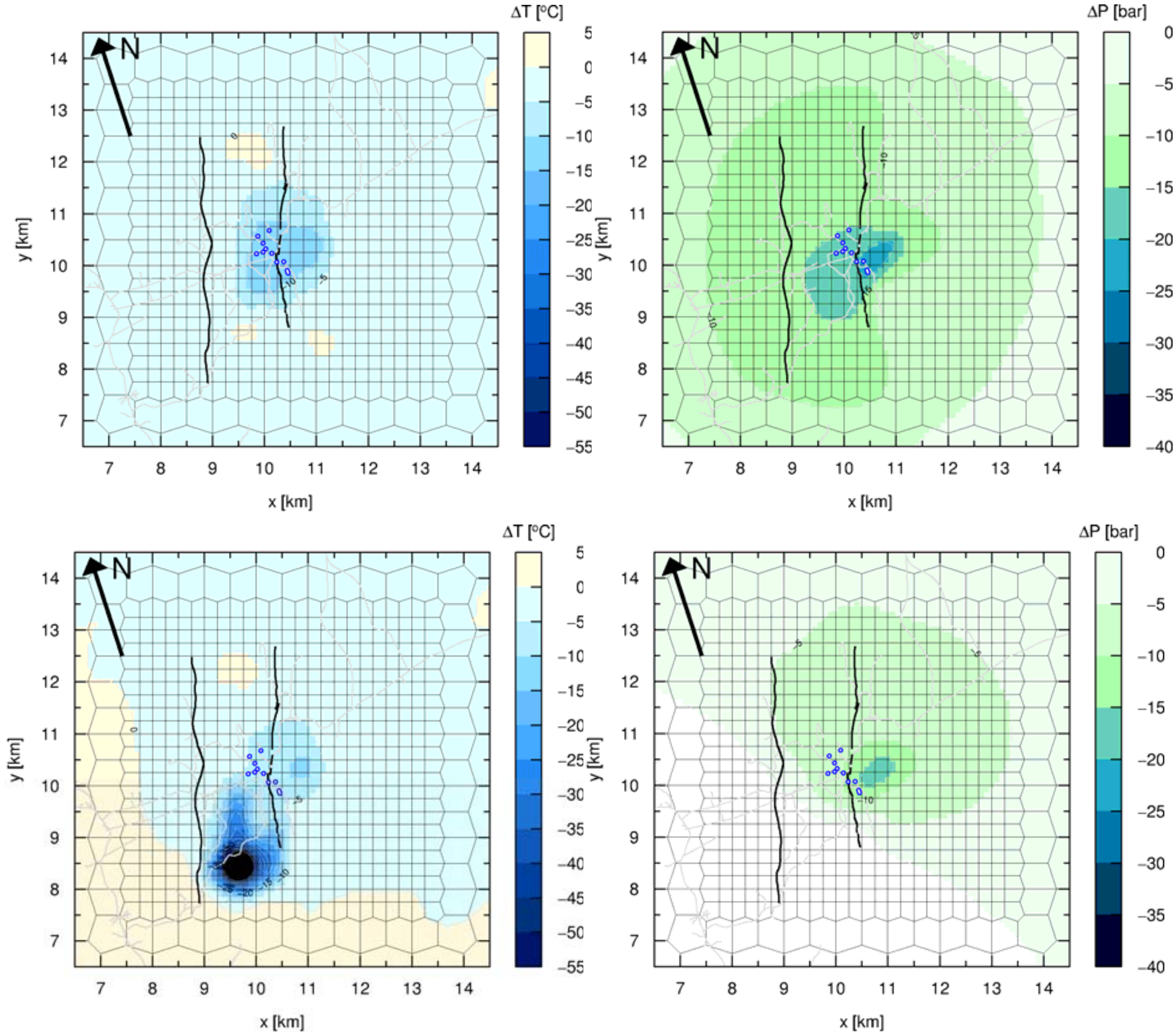

Figure 20. *Simulation results for 30 years of 45 MW_e power production. Upper panel shows the temperature change (left) and pressure drawdown (right) in the main production layer (F) at the end of the period for shallow reinjection. Lower panel shows the same for distributed reinjection.*

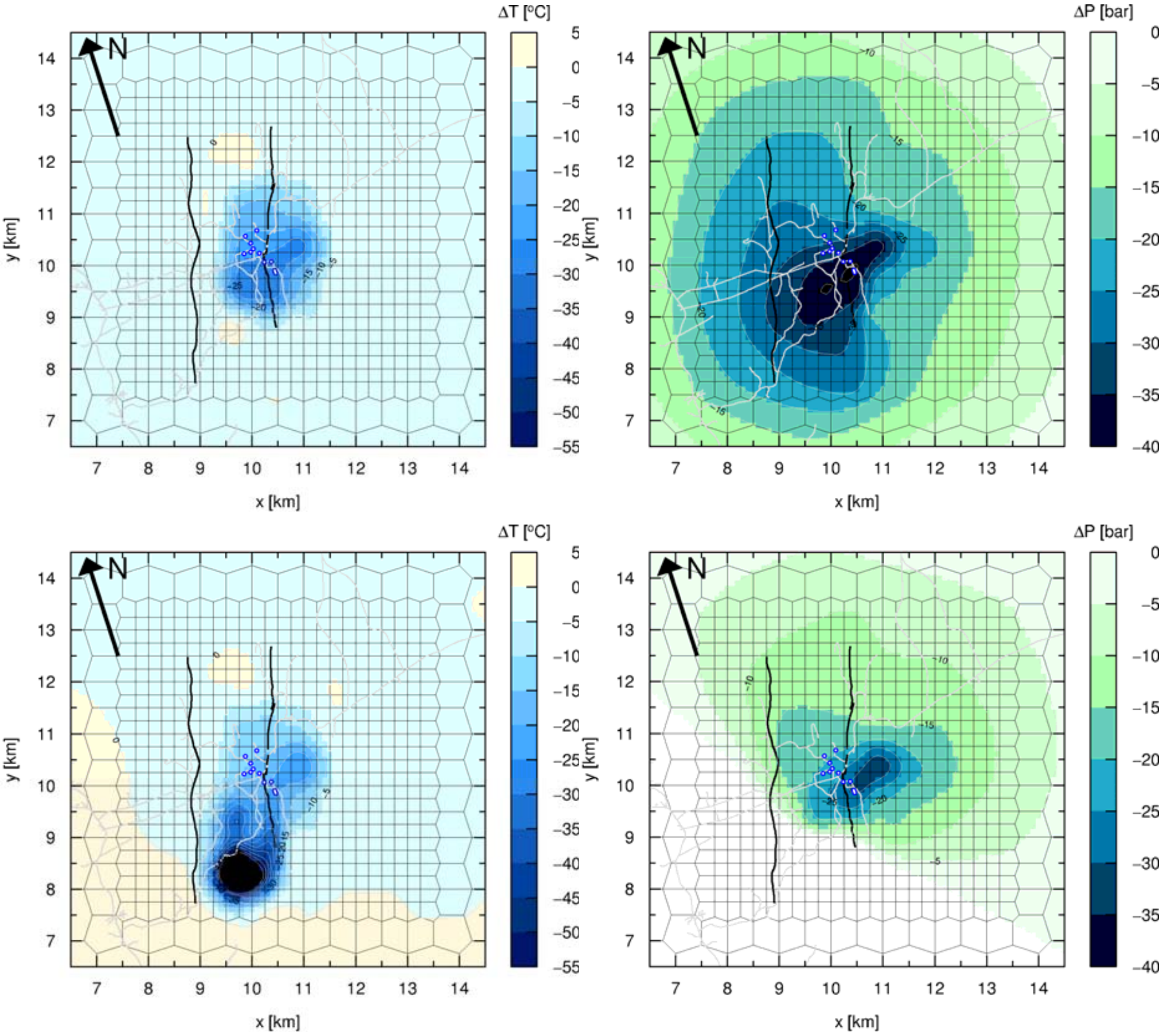

Figure 21. *Simulation results for 30 years of 90 MW$_e$ power production. Upper panel shows the temperature (left) and pressure drawdown (right) in the main production layer (F) at the end of the period for shallow reinjection. Lower panel shows the same for distributed reinjection.*

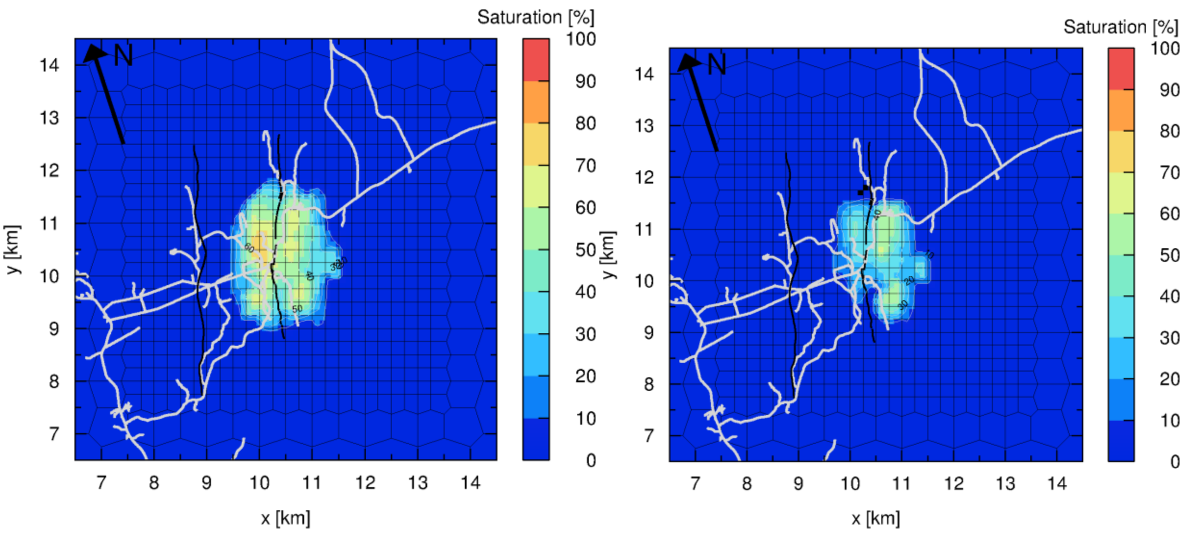

Figure 22. *Simulation results for 30 years of 45 MW$_e$ power production. Steam saturation in the main production layer (F) for shallow reinjection (left) and distributed reinjection (right) at the end of the period.*

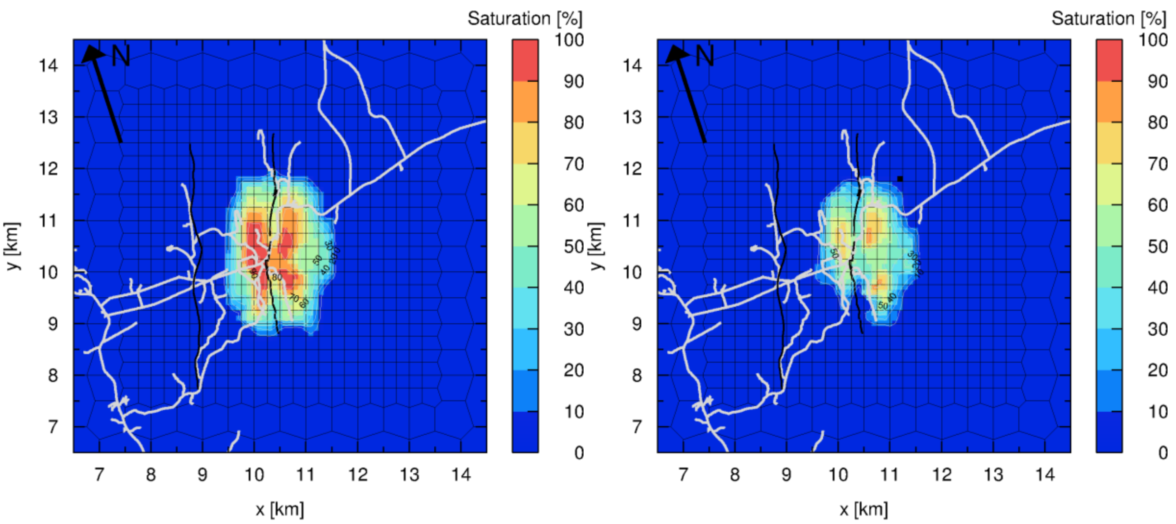

Figure 23. *Simulation results for 30 years of 90 MW$_e$ power production. Steam saturation in the main production layer (F) for shallow reinjection (left) and distributed reinjection (right) at the end of the period.*

Table 3. *Comparison of energy extraction and drilled wells for different reinjection strategies and 90 MW$_e$ power production. For detailed information on well productivity consult Appendices E and F.*

Reinjection	E_{th} (TJ)	E_{el} (TJ)	P_{avg} (MW$_e$)	Start-up wells	Make-up wells
None	519	89.2	94.2	9	5
Shallow (A)	519.4	89.2	94.2	9	5
BJ-15 (B)	665.7	89.3	94.3	9	6
West (C)	656.9	89.6	94.6	9	6
Southeast (D)	575.8	89.6	94.6	9	5
Combination	605.2	89.4	94.4	9	5

7 Long-term Response to Production

To assess the long-term response of the system to production, the model was run for 100–500 years for the following three cases:

- Production stopped after 30 years and recovery calculated for 500 years.
- Drilling of make-up wells stopped after 30 years and production allowed to decline for 500 years.
- Production maintained at 45 and 90 MW_e for 100 years in total.

During the runs, wells are turned off if they fall below a certain limit, i.e. if the wellbottom pressure becomes higher than the reservoir pressure, or if they fall below approximately 1 MW_e in capacity.

7.1 Production Maintained for 100 Years

When the production is maintained at 45 MW_e for 100 years, the enthalpy appears to reach a semi-equilibrium and remains around 1400 kJ/kg for distributed reinjection and 2000–2100 kJ/kg for shallow reinjection, as shown in Figure 24. As a consequence, the mass extraction is on average stable around 250–270 kg/s for distributed reinjection and 130–150 kg/s for shallow reinjection. A total of 6 make-up wells are needed to maintain the production for distributed reinjection in contrast to only 4 wells for shallow reinjection. Figure 25 shows the simulation results for a production of 90 MW_e. The enthalpy and mass extraction are stable for the distributed reinjection scheme, whereas for shallow reinjection the pressure drawdown results in increased boiling in the reservoir and thus a higher average enthalpy of the well discharge. This in turn leads to reduced mass extraction. A total of 40 make-up wells are needed to maintain the production for distributed reinjection but only 27 wells if the reinjection is shallow.

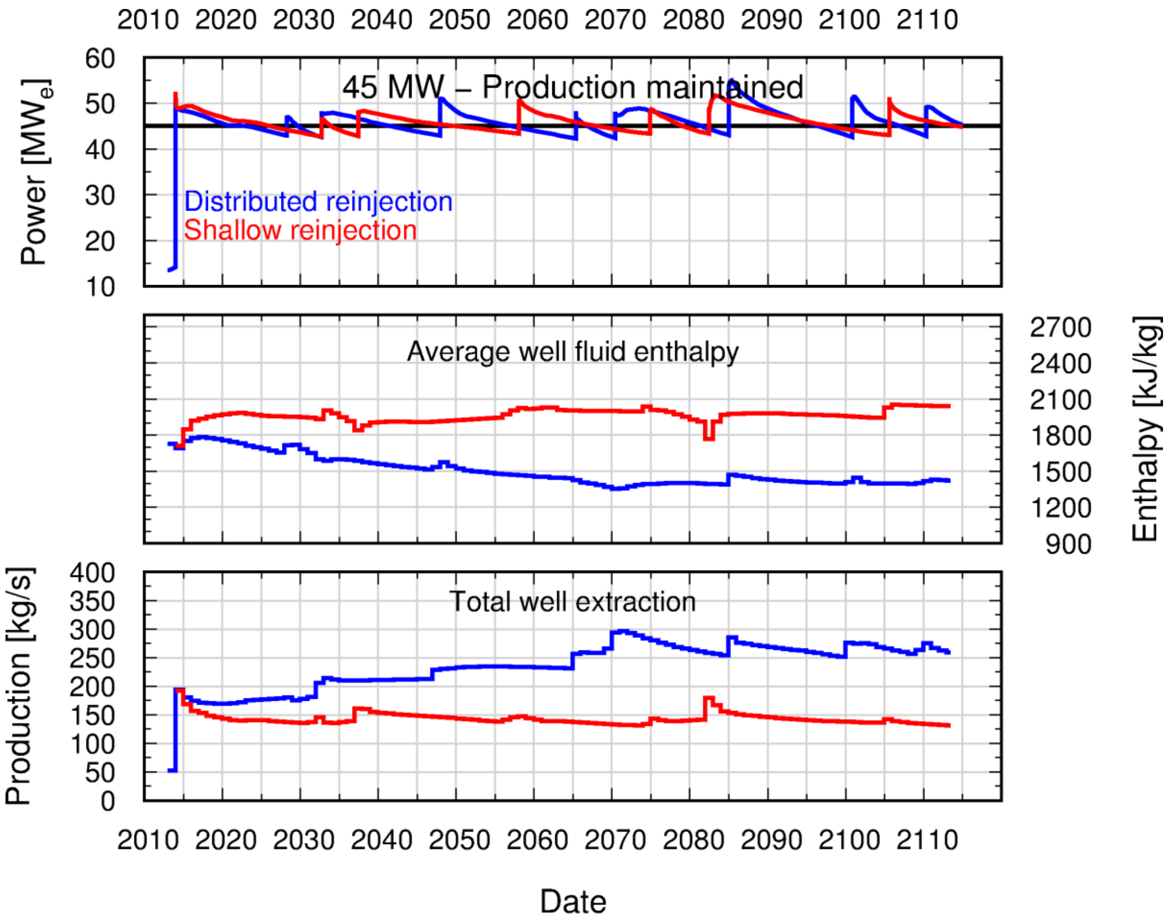

Figure 24. *Simulation results of 45 MWₑ production from the Námafjall system for 100 years.*

Figures 26 and 27 show the temperature and pressure decrease over the forecasting period for 45 MW_e and 90 MW_e production, respectively. The pressure support of reinjection into the production layer is clear from the figure, as the pressure reaches stability for the last 30 years of the simulation, whereas it continues to decrease when the reinjection is shallow and is unable to return the brine to the geothermal system. Signs of thermal breakthrough for distributed reinjection are visible in evolution of the temperatures it continues to fall after the pressure has reached a stable value. For shallow reinjection, the pressure and temperature fall continuously throughout the forecasting period. This is a consequence of the structure of the model, which has effectively closed boundaries. The extraction due to production is well above the natural inflow of mass and heat in the model and as a result, the pressure (and temperature) falls almost linearly with time. The pressure drawdown is extreme in the case of 90 MW_e production, as it has reached over 80 bar at the end of the 100 year forecasting period. The record drawdown observed worldwide today is around 50 bar.

Table 4. *Comparison of energy extraction and drilled wells for shallow and distributed reinjection schemes and 45 and 90 MW_e power production maintained for 100 years.*

	E_{th} (TJ)	E_{el} (TJ)	P_{avg} (MW_e)	Start-up wells	Make-up wells
45 MW_e, shallow, 100yrs	892.9	147.2	46.6	5	4
45 MW_e, distributed, 100yrs	1120.0	147.5	46.7	5	6
90 MW_e, shallow, 100yrs	1622.3	287.9	91.2	9	27
90 MW_e, distributed, 100yrs	2046.8	289.8	91.8	9	40

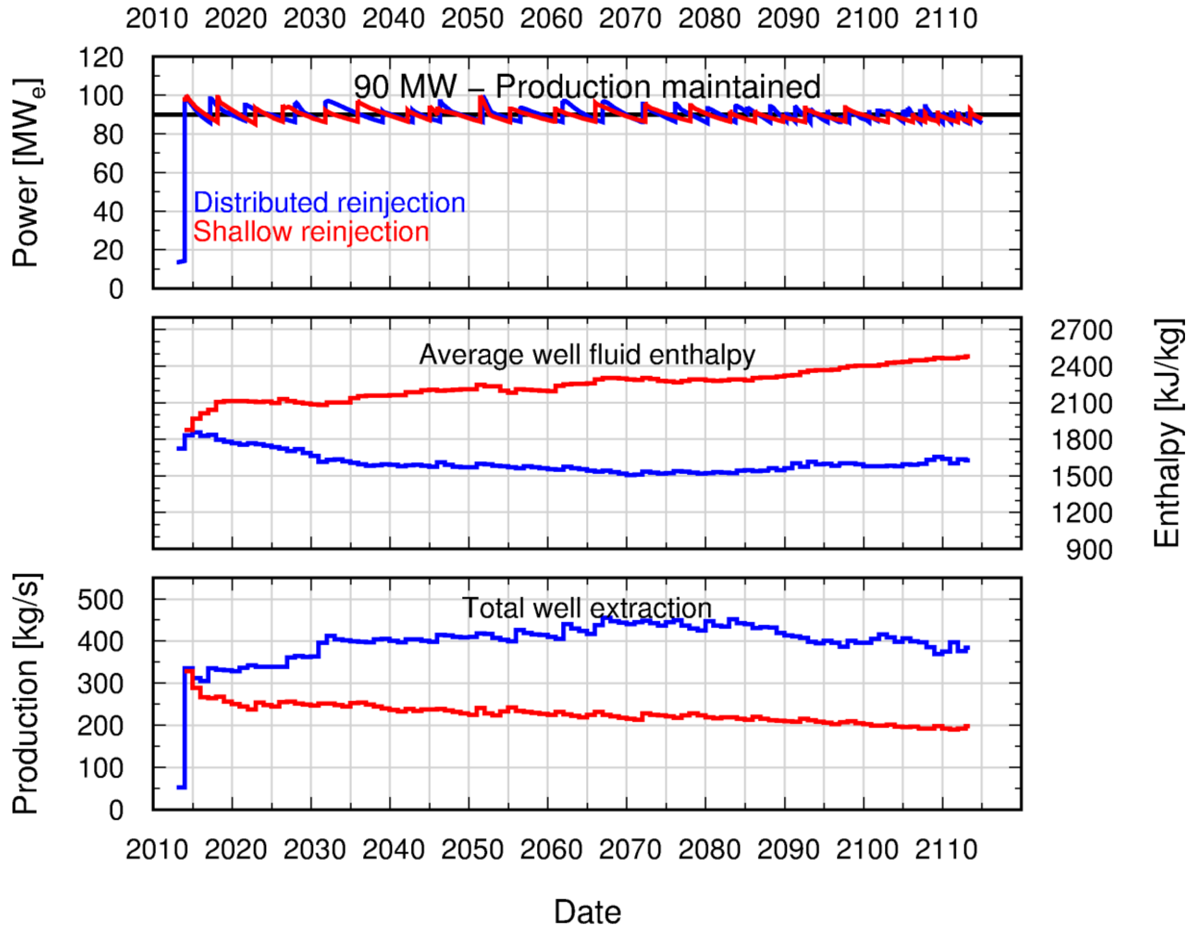

Figure 25. *Simulation results of 90 MWₑ production from the Námafjall system for 100 years.*

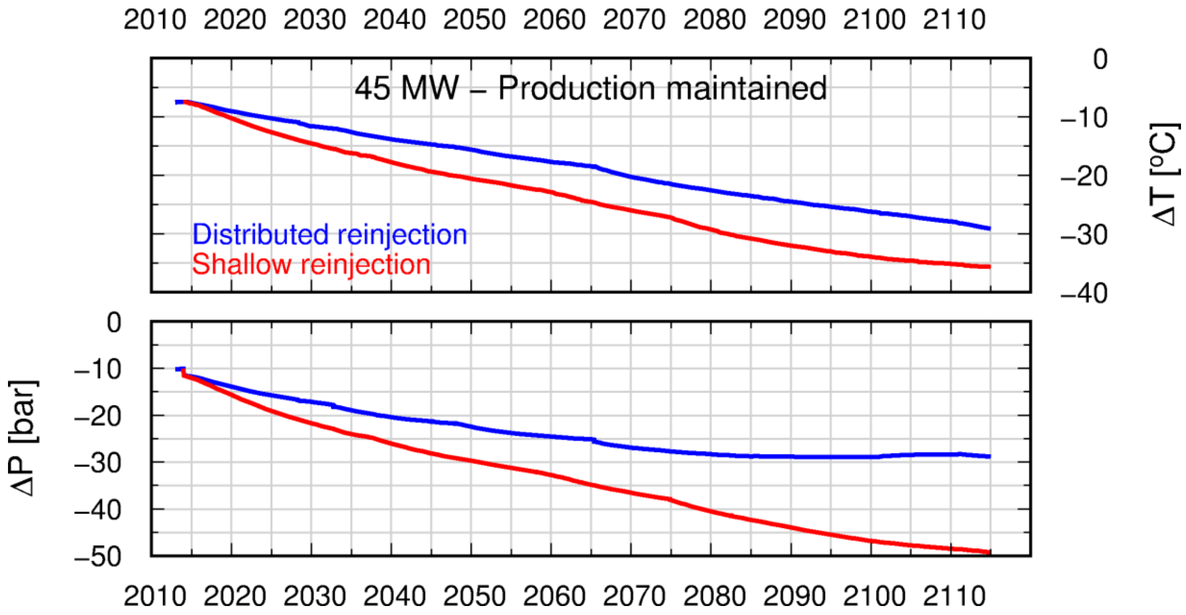

Figure 26. *Long-term response of the Námafjall system to 45 MWₑ power production for 100 years.*

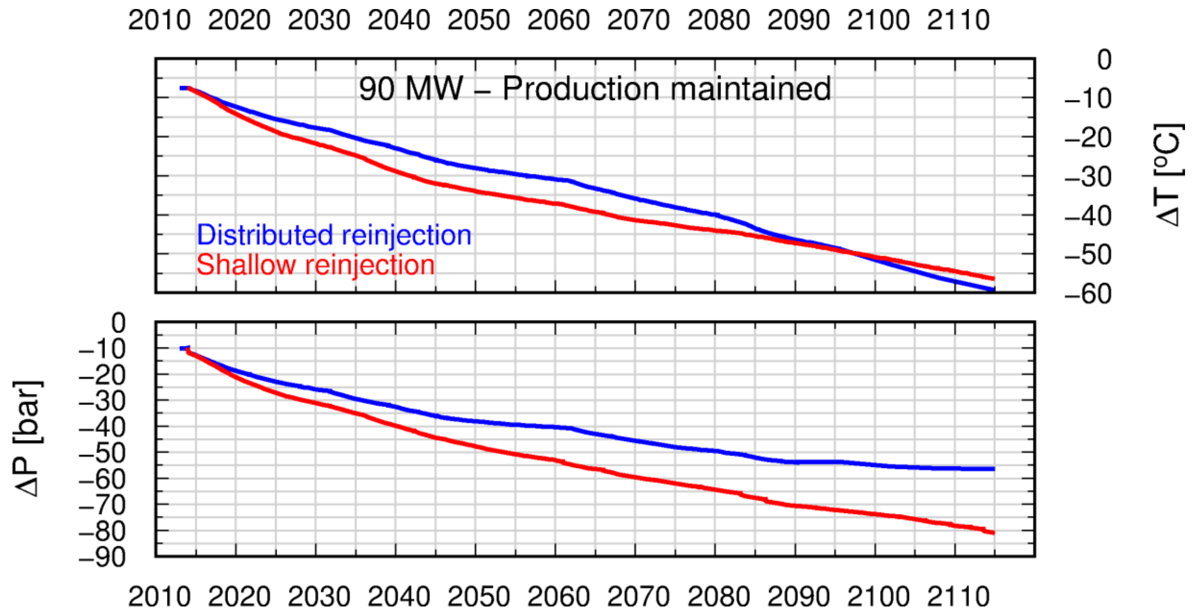

Figure 27. *Long-term response of the Námafjall system to 90 MW_e power production for 100 years.*

7.2 Make-up Drilling Stopped after 30 Years

Figures 28 and 29 show the enthalpy and mass extraction if drilling of make-up wells is stopped after a 30 year production period. The mass extraction declines in response to pressure drawdown and/or declining enthalpy. At the end of a 500 year forecasting simulation, the power production has leveled off at 13 MW_e for both reinjection schemes and a production target of 45 MW_e. For a 90 MW_e power production, the results are qualitatively similar in the case of distributed reinjection, with a production of 15 MW_e at the end of the simulation, but for shallow reinjection the wells are eventually choked due to the drastic pressure drawdown and the production declines in steps to below 5 MW_e.

In the case of distributed reinjection, the pressure drawdown reaches a minimum about 50 years after drilling efforts are abandoned, see Figures 30 and 31. After that it rises continuously throughout the period. The pressure recovery is understandable, as about 80% of the produced fluid is reinjected into the system and additional mass is gained through inflow from the heat source at the bottom of the model. In the case of 45 MW_e production, the pressure drawdown continues throughout the period for shallow reinjection due to the depletion of mass. The wells respond to the drawdown through decreased output, but the response is not fast enough to level out the pressure. As discussed above, for a 90 MW_e production the excessive pressure drawdown in the system eventually causes choking of production wells. At the same time, boiling in the remaining wells is evident. As a result, the pressure begins to recover during the last 150 years of the simulation.

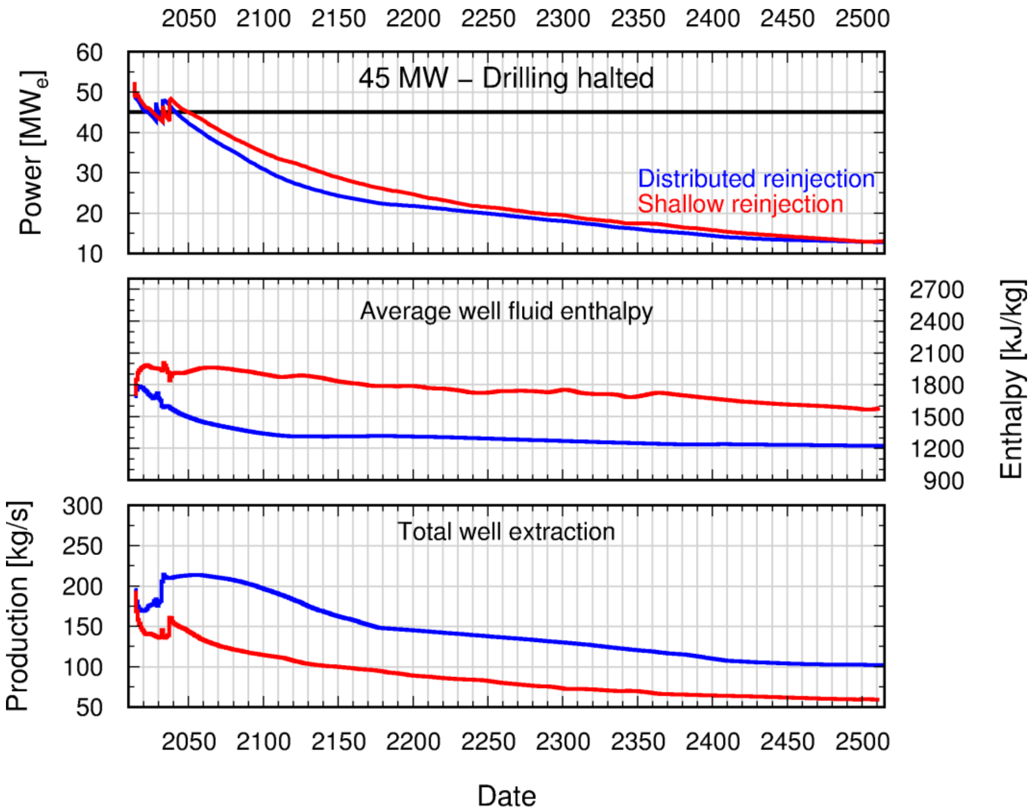

Figure 28. *Simulation of the long-term response of the Námafjall system to 45 MWₑ power production for 30 years and subsequent halt in drilling of make-up wells.*

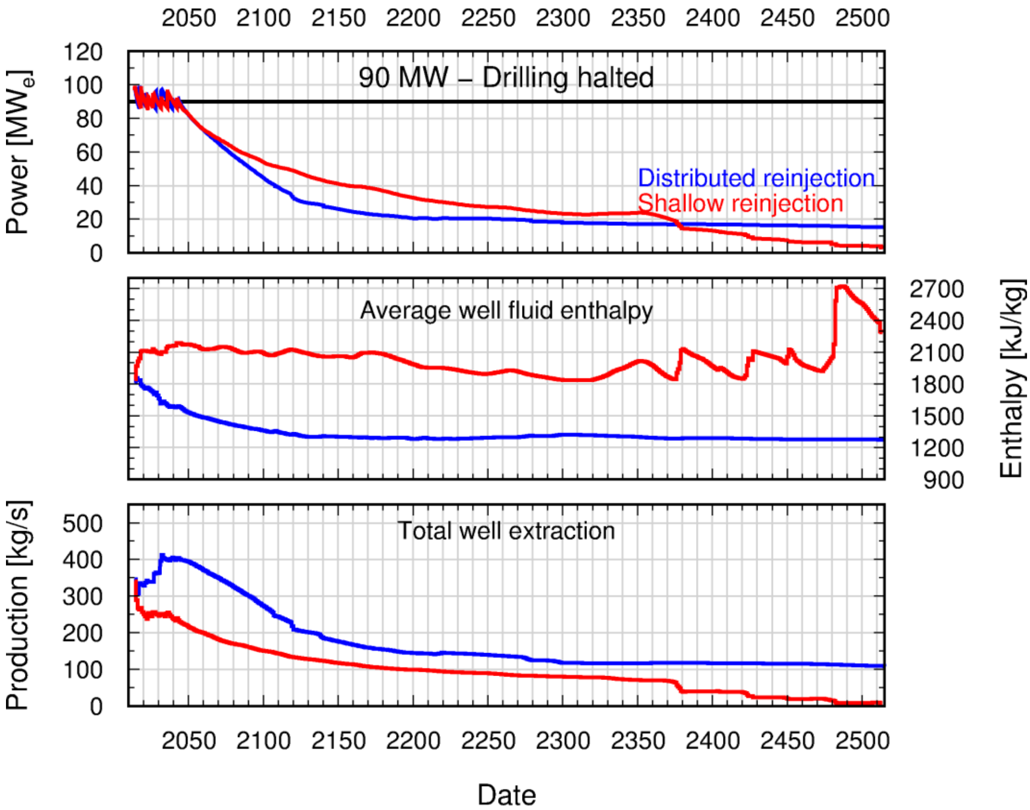

Figure 29. *Simulation of the long-term response of the Námafjall system to 90 MWₑ power production for 30 years and subsequent halt in drilling of make-up wells.*

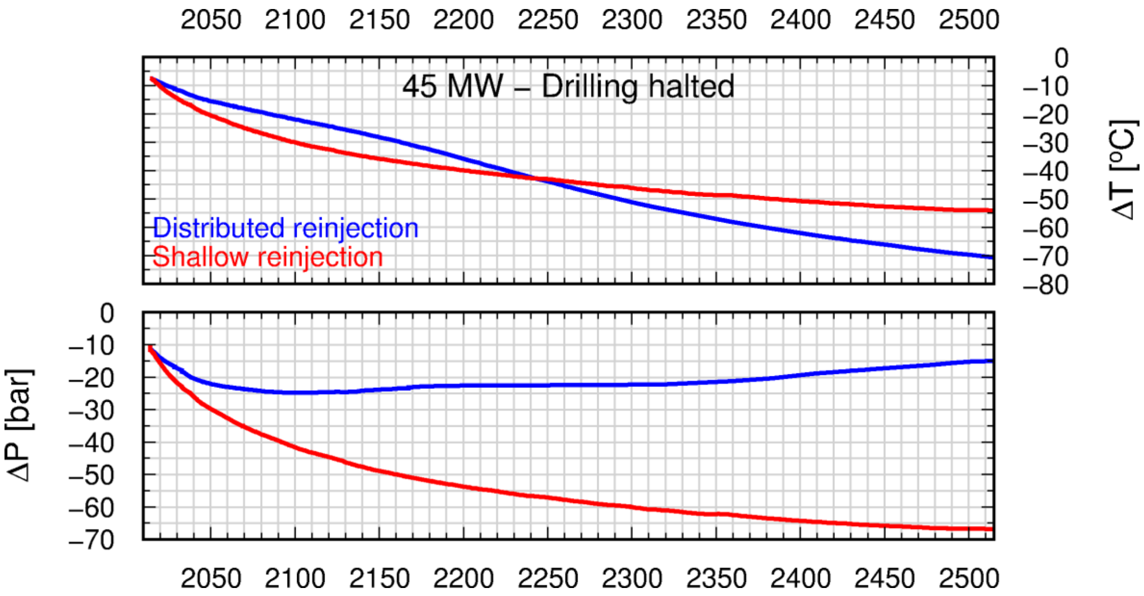

Figure 30. *Simulation of the long-term response of the Námafjall system to 45 MWₑ power production for 30 years and subsequent halt in drilling of make-up wells.*

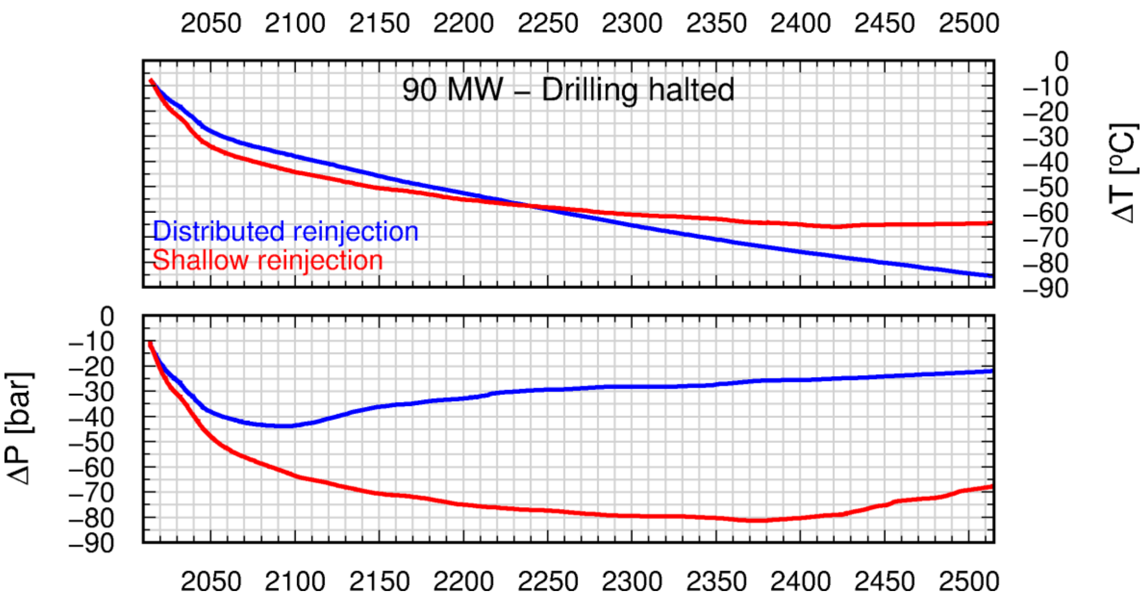

Figure 31. *Simulation of the long-term response of the Námafjall system to 90 MWₑ power production for 30 years and subsequent halt in drilling of make-up wells.*

Table 5. *Comparison of energy extraction and drilled wells for shallow and distributed reinjection schemes and 45 and 90 MWₑ power production when drilling is halted after 30 years. Only production from the remaining 470 years is included in the estimates.*

	E_{th} (TJ)	E_{el} (TJ)	P_{avg} (MW_e)	Start-up wells	Make-up wells
45 MW_e, shallow, 470yrs	2186.4	336.4	22.7	5	1
45 MW_e, distributed, 470yrs	2700.9	304.7	20.5	5	1
90 MW_e, shallow, 470yrs	2548.7	428.2	28.9	9	5
90 MW_e, distributed, 470yrs	3204.1	374.3	25.2	9	5

7.3 Production Stopped after 30 Years

If production (and reinjection) is stopped after 30 years, the pressure recovers and for 45 MW_e production it has reached pre-utilization levels after just over 50 years for distributed reinjection, although it takes significantly longer for the case of shallow reinjection due to the greater drawdown. For 90 MW_e production it takes about 85 years to reach pre-utilization levels in the case of distributed reinjection and 350 years for shallow reinjection. The temperature recovery is much slower and is not complete at the end of the 500 year forecasting period. These results are sensitive to boundary conditions in the model. As discussed earlier, the model has very impermeable boundaries, which leads to a slow recovery as the heat source at the bottom of the model provides the only mass inflow to the system.

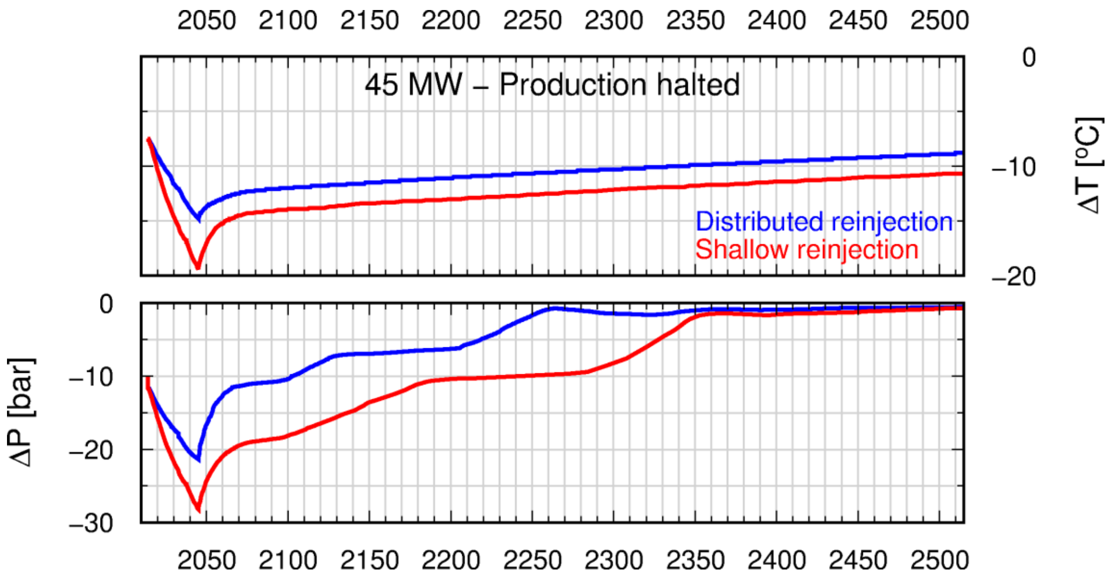

Figure 32. *Long-term response of the Námafjall system showing recovery after 30 years of 45 MW_e power production.*

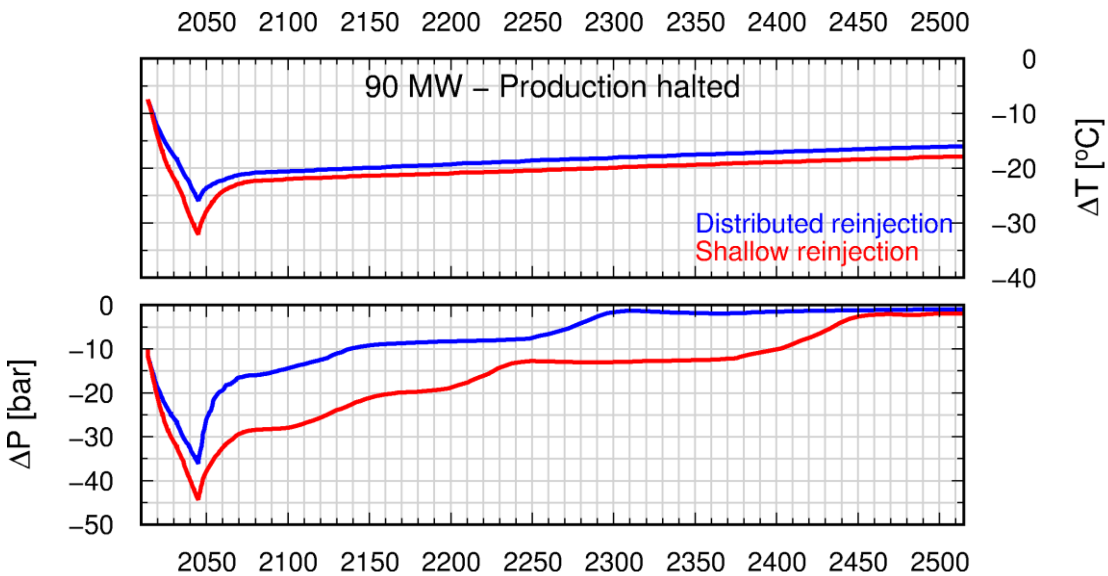

Figure 33. *Long-term response of the Námafjall system showing recovery after 30 years of 90 MW_e power production.*

8 Discussion

8.1 Sustainability of Utilization

The model simulations of the long-term response of the Námafjall geothermal system can be used to assess the sustainability of electric production from the resource. Sustainable utilization of a geothermal resource takes into account the three main pillars of sustainable development: social, economic and environmental (Axelsson et al., 2010). Here we only focus on one aspect, the *sustainable yield*, defined through the following statement:

> *The term sustainable yield refers to the contention that for each geothermal system there should be a certain level of maximum energy production (E_0), for each mode of production, below which it will be possible to maintain constant energy production from the system for at least 100 years. (Ketilsson et al., 2010).*

The exact value of the maximum energy production depends e.g. on the nature of the system in question and the mode of utilization. It can change with advances in technology and improved knowledge through research and monitoring of systems during utilization. The definition does not address the question of acceptable recovery time scale after production is halted.

Several numerical model studies of geothermal systems indicate that pressure recovery after utilization is on a time scale similar to the utilization time whereas temperature recovery is significantly slower (Axelsson et al., 2010, O´Sullivan et al., 2010). The studies here confirm this although the time needed for pressure recovery depends on the severity of pressure drawdown in the system. The temperature recovery is slow, as expected, and the temperature has not reached pre-production values at the end of the simulations.

When drilling of make-up wells is stopped after 30 years of utilization, the production slowly declines. Whether the system and production reach a steady state depends on the mode of reinjection. When reinjection is partly into the production layer, the pressure support prolongs the life of wells and the production can become stable at around 13 MW_e for the 45 MW_e scenario and 15 MW_e for the 90 MW_e case. Shallow reinjection on the other hand has no effect on the reservoir and the pressure declines continually with time. Once it has fallen by about 80 bar, the wells begin to choke. This only happens when the production level is initially at 90 MW_e.

When production is maintained for 100 years, the produced fluid enthalpy and mass flow remain fairly stable for the last decades of the simulation, the enthalpy increasing slightly towards the end for a 90 MW_e production. When the reinjection is partly in the production interval, the pressure levels off towards the end of the forecasting period. Shallow reinjection has limited effect on the pressure in the reservoir, which continues to decline during the entire simulation. The temperature declines steadily throughout the period, in the case of shallow reinjection the decline is due to the pressure drop whereas for distributed reinjection it is mainly due to cooling by thermal breakthrough of injected brine. In light of the definition of sustainable yield on a time scale of 100 years, the simulation results indicate that 45 MW_e production can be considered sustainable but 90 MW_e at the limit of being unsustainable. At the end of the simulation period for shallow reinjection, the pressure drawdown is around 80 bar, which is the limit at which wells begin to get choked. For distributed reinjection, the pressure remains stable but the cooling and condensation caused by reinjection leads to increased need for make-up wells, a total of 40, which is probably economically unfeasible. Whether a 90 MW_e production can be considered sustainable is uncertain. The Námafjall model is designed to be conservative and this affects the simulation of the long-term response to production. Firstly, the model boundaries are effectively closed. This means that the model underestimates the increased inflow from surrounding areas when production causes a pressure decline within the system. By doing a baseline gravity and GPS survey before large-scale production commences and repeated surveys after the power plant comes online, an estimate of the natural recharge to the system can be made. A survey was done in 2012 in Námafjall, but to distinguish natural changes from production induced, a second survey before production commences is recommended. Once an estimate of the natural recharge is available, the model can be adjusted and recalibrated to reflect this. Secondly, the magnitude of the model heat source is calibrated to explain in a minimal sense the temperature anomaly associated with the system, interpreted through the logging of drilled wells. A comparison with 3D interpreted MT data (Ragna Karlsdóttir et al., 2012) shows that the heat anomaly has at some point in time been larger than that of the model, see Appendix B. More detailed data on the natural heat outflow from the area would be useful to quantify this and update the calibration of the model. While these data are missing, an option would be to calibrate an optimistic version of the model with open boundaries. This could provide an upper bound on the long-term behaviour of the system during utilization.

As a final note, although the production history of the Námafjall system is among the longest available in Iceland, as the system has been constantly utilized since the 1960's, the production has been limited to the equivalent of 10–15 MW_e for most of that period. This is probably not far from the natural recharge to the system, which means that the calibration of the model is not capturing the behaviour of the system during utilization that exceeds significantly the natural recharge. This limits the reliability of long-term predictions of the reservoir response.

8.2 Comments on Reinjection

Reinjection into two-phase reservoirs requires careful testing and monitoring to maximize the benefits without impairing the production potential of the system through decline in enthalpy and rapid thermal breakthrough of injected fluid. The reinjection increases the pressure, which leads to condensation of steam within fractures and therefore lowering of fluid enthalpy (for an overview see Bodvarsson and Stefansson (1989) and references therein). Numerical simulations of the Wairakei geothermal system in New Zealand have demonstrated the reduction in production potential due to infield reinjection (Mannington et at., 2004; Kaya et al., 2011). The increased liquid saturation due to condensation leads to an increase in the mobility of the liquid phase, which manifests in higher liquid flow rates while the steam flow remains constant (Bodvarsson and Stefansson, 1988). Rapid migration of cold injection fluids is an issue in fractured geothermal systems, although the effect can be reversed rapidly by halting the reinjection (Pruess and Bodvarsson, 1984). If deep reinjection into the production interval of a two-phase system is to be considered, it is of utmost importance to employ tracer testing to determine flow paths between the reinjection and the production zones and to assess the danger of thermal breakthrough. Injection tests lasting at least several months are also recommended along with careful monitoring of production enthalpies and fluid chemistry so as to monitor any adverse effects on the production potential of the system.

From an economic standpoint, the shallow reinjection scheme appears to be the most feasible option. Having no effect on the enthalpy of produced fluid, it reduces the number of make-up wells needed to maintain the target electric production and only requires relatively inexpensive injection wells. It has, of course, no benefits for maintaining pressure in the geothermal system, which has little limiting effect in the model simulation except on large time scales. It must, however, be kept in mind that the main limiting factor for well productivity in the model is pressure drawdown and no operational issues such as scaling are taken into account. This gives a somewhat optimistic view of well performance. Also, the wellbore simulations performed to construct wellbottom pressure tables are based on limited data. The tables are a key factor in determining well behaviour in the model and this introduces a significant uncertainty in long-term predictions.

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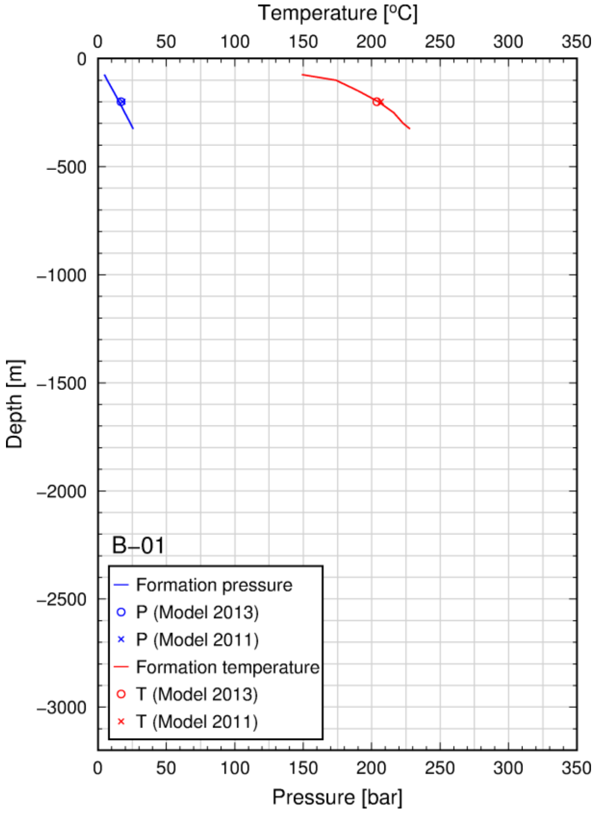
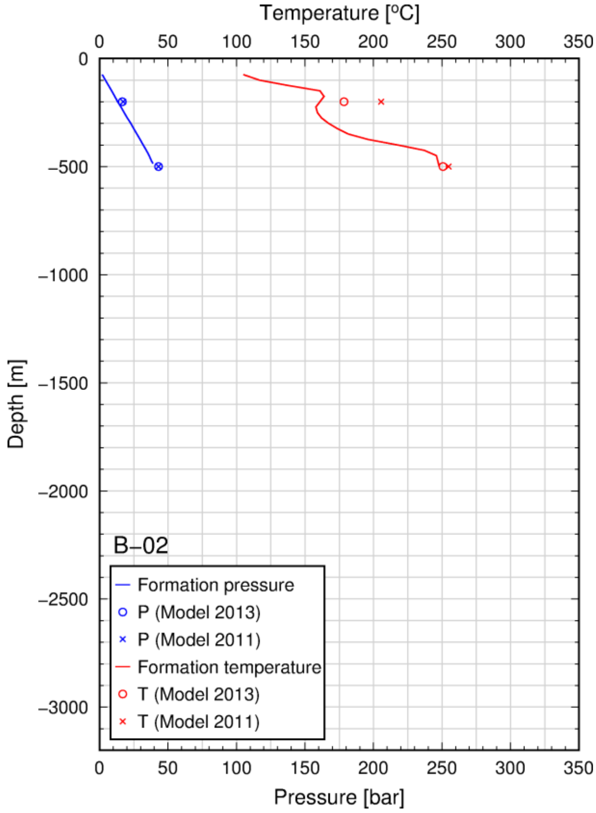
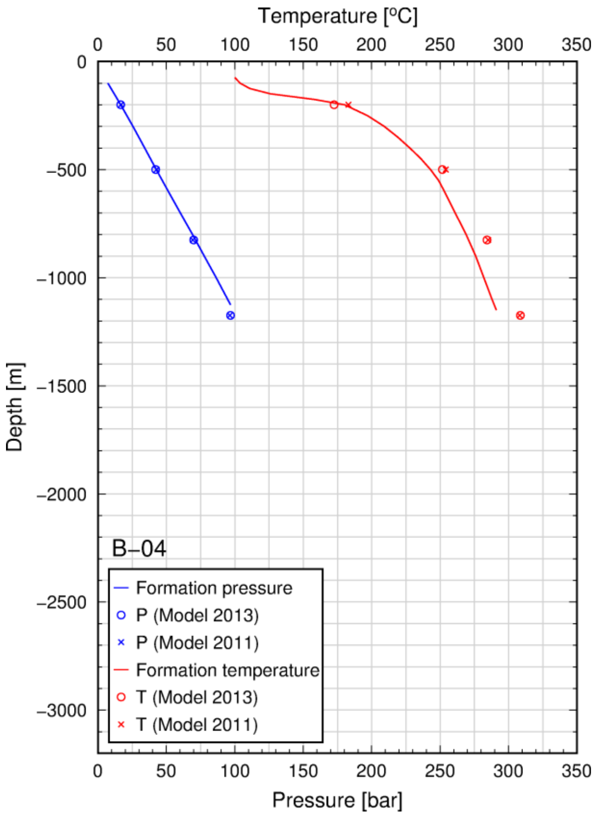
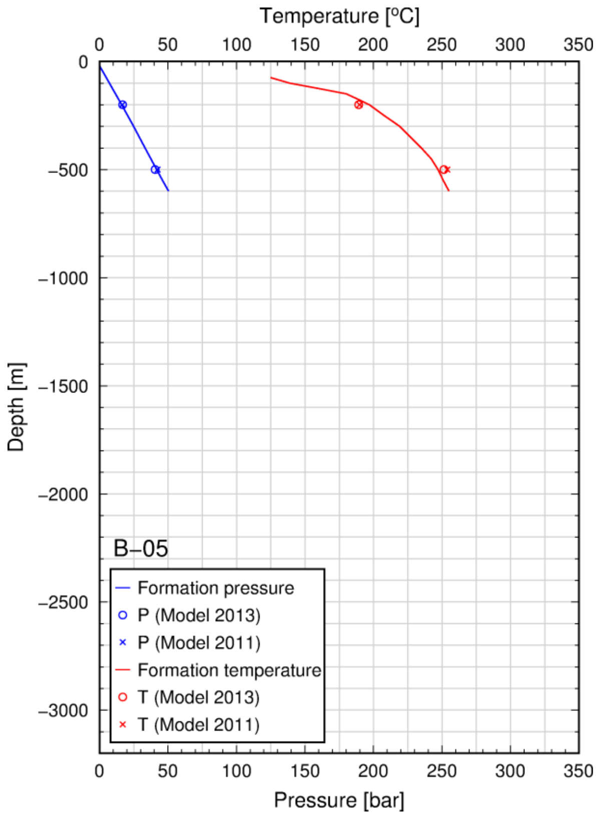
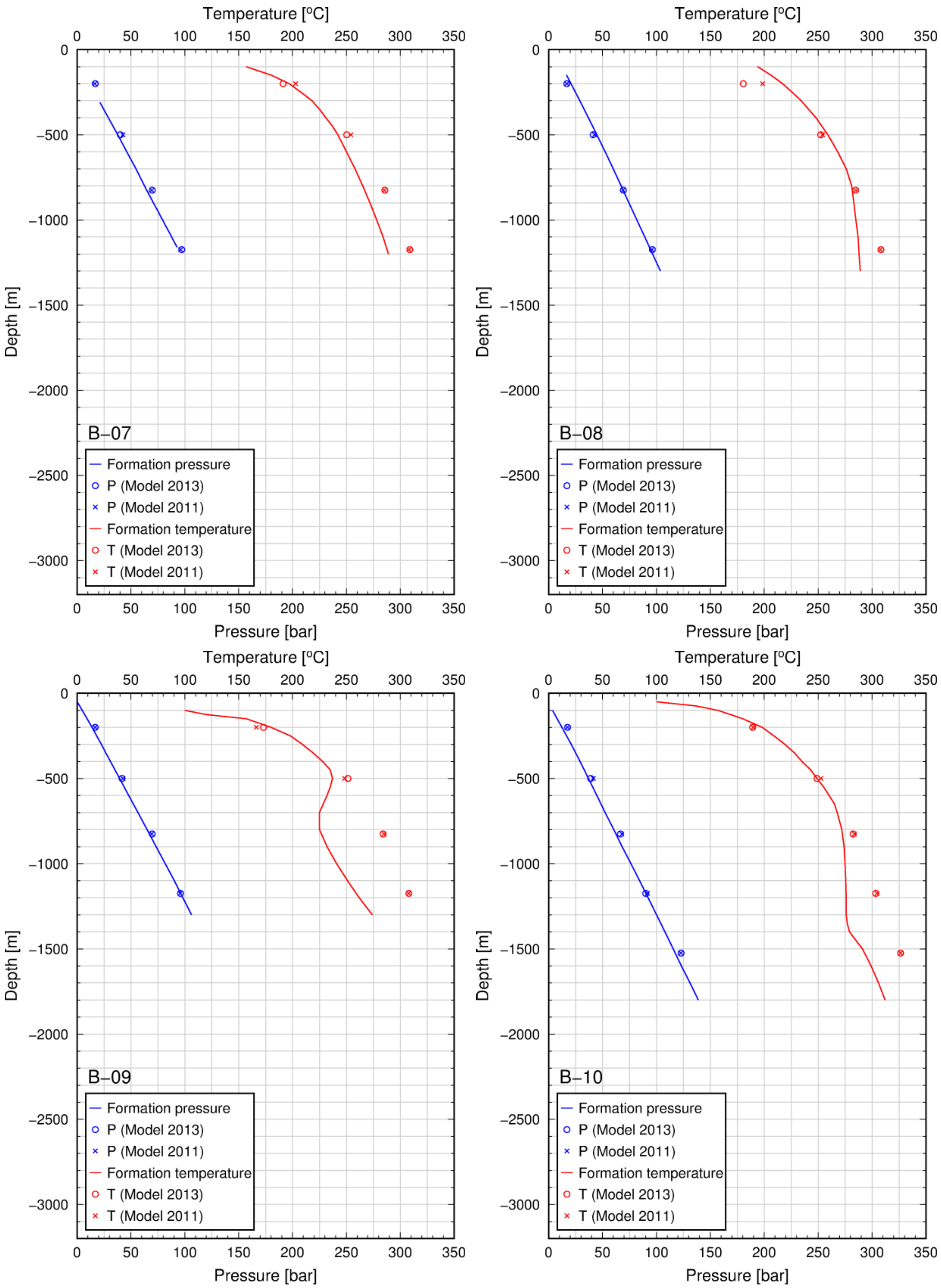
Appendix A: Formation Temperature and Pressure

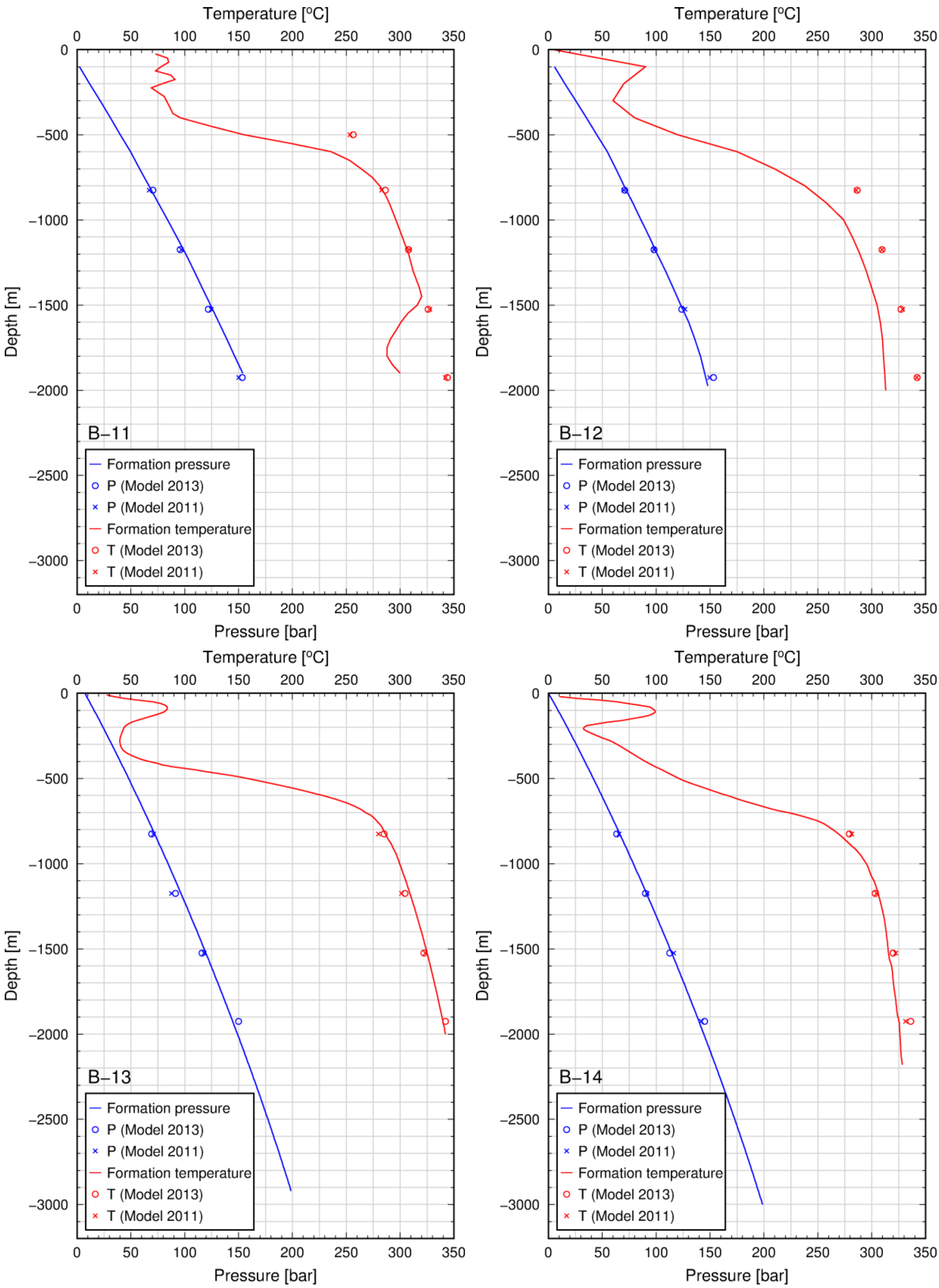


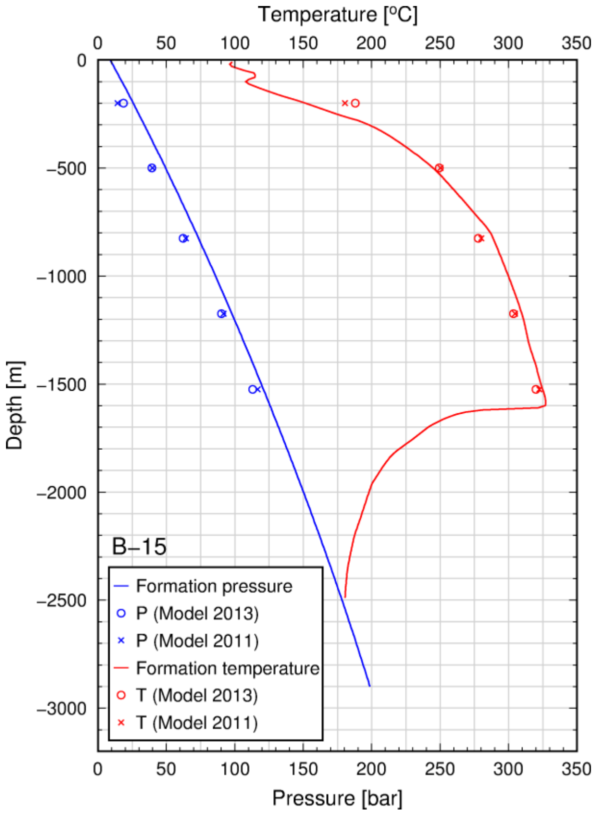






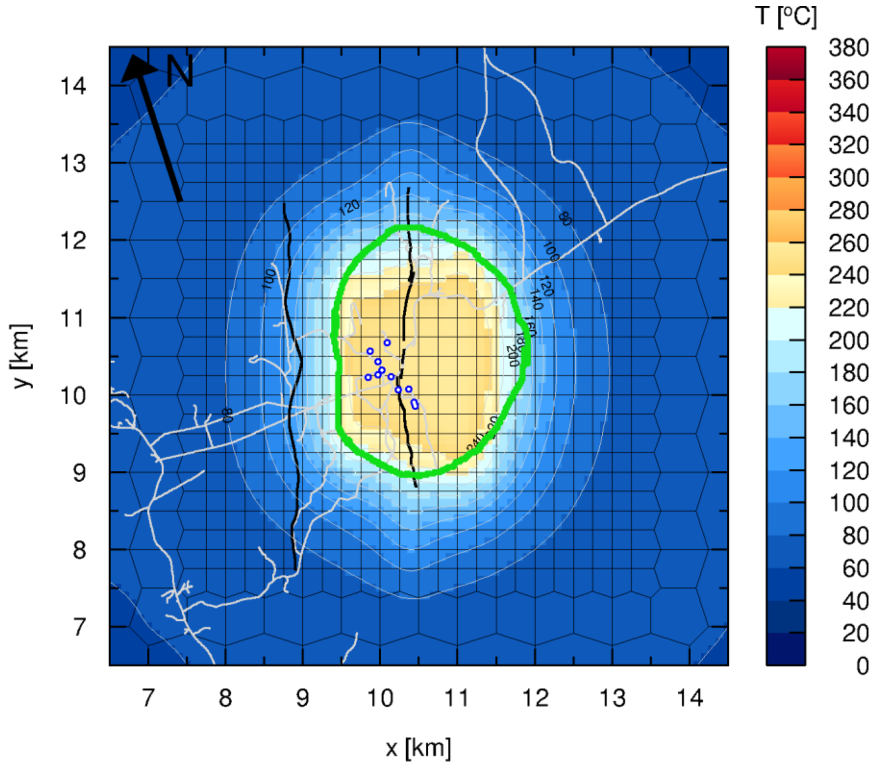

Temperature [°C]
Depth [m]
Pressure [bar]
0 50 100 150 200 250 300 350
0 −500 −1000 −1500 −2000 −2500 −3000
B−07
B−08
B−09
B−10
Formation pressure
P (Model 2013)
P (Model 2011)
Formation temperature
T (Model 2013)
T (Model 2011)

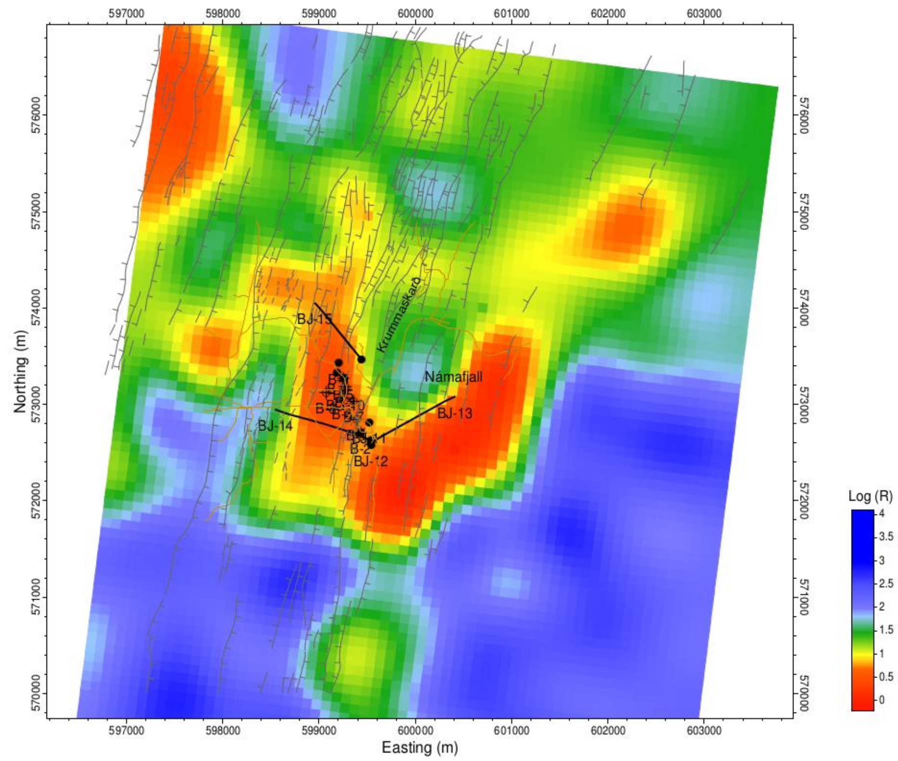

B−11
B−12
B−13
B−14
Temperature [°C]
Depth [m]
Pressure [bar]
Formation pressure
P (Model 2013)
P (Model 2011)
Formation temperature
T (Model 2013)
T (Model 2011)


Temperature [°C]
0
50
100
150
200
250
300
350
0
−500
−1000
−1500
−2000
−2500
−3000
Depth [m]
B−15
Formation pressure
P (Model 2013)
P (Model 2011)
Formation temperature
T (Model 2013)
T (Model 2011)
Pressure [bar]

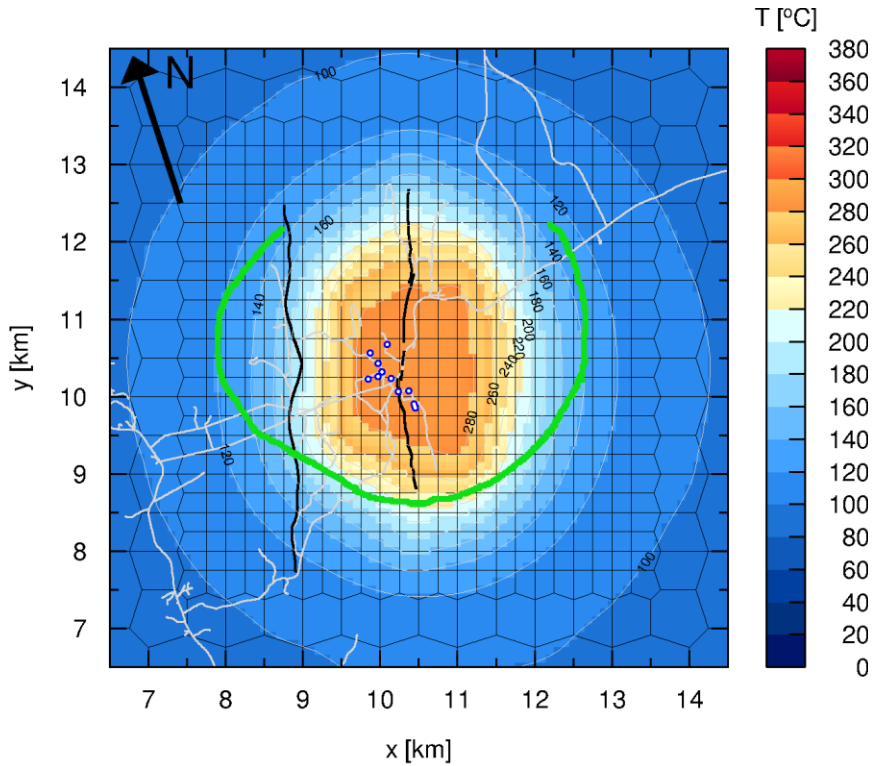
Appendix B: MT Data and Formation Temperature

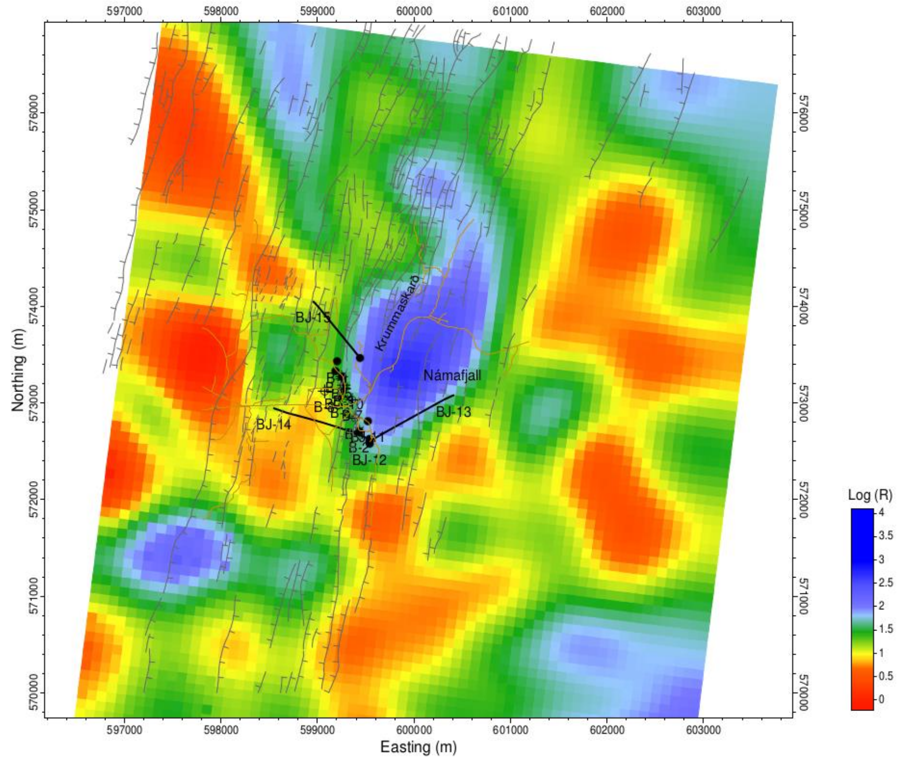
At 160 m b.s.l.



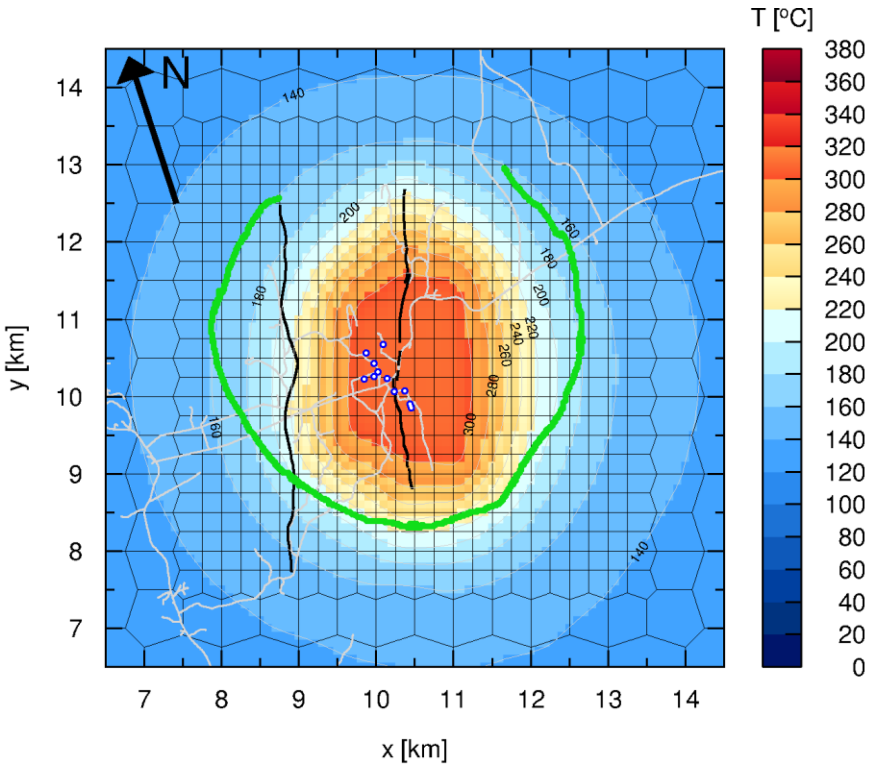


At 485 m b.s.l.

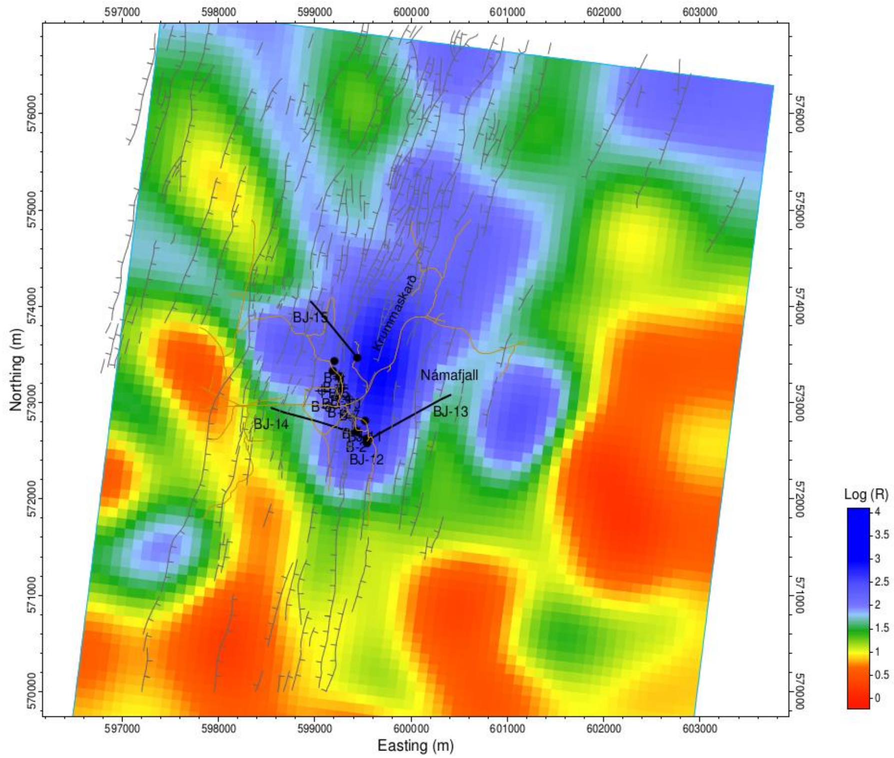

N
T [ºC]
x [km]
y [km]


Krummaskarð
Námafjall
BJ-15
BJ-14
BJ-13
BJ-12
Northing (m)
Easting (m)
Log (R)

At 825 m b.s.l.

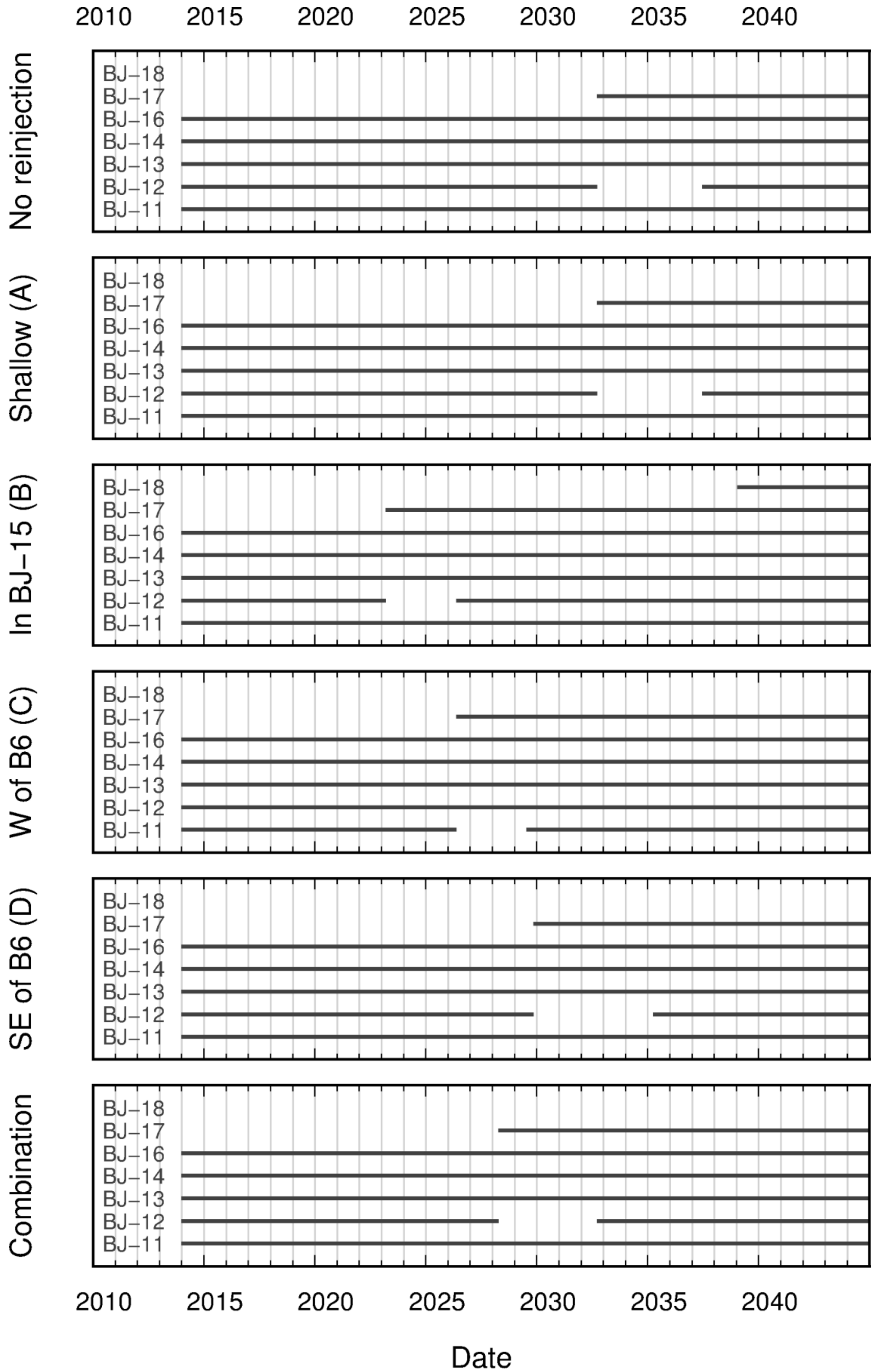


N
T [ºC]
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
y [km]
x [km]

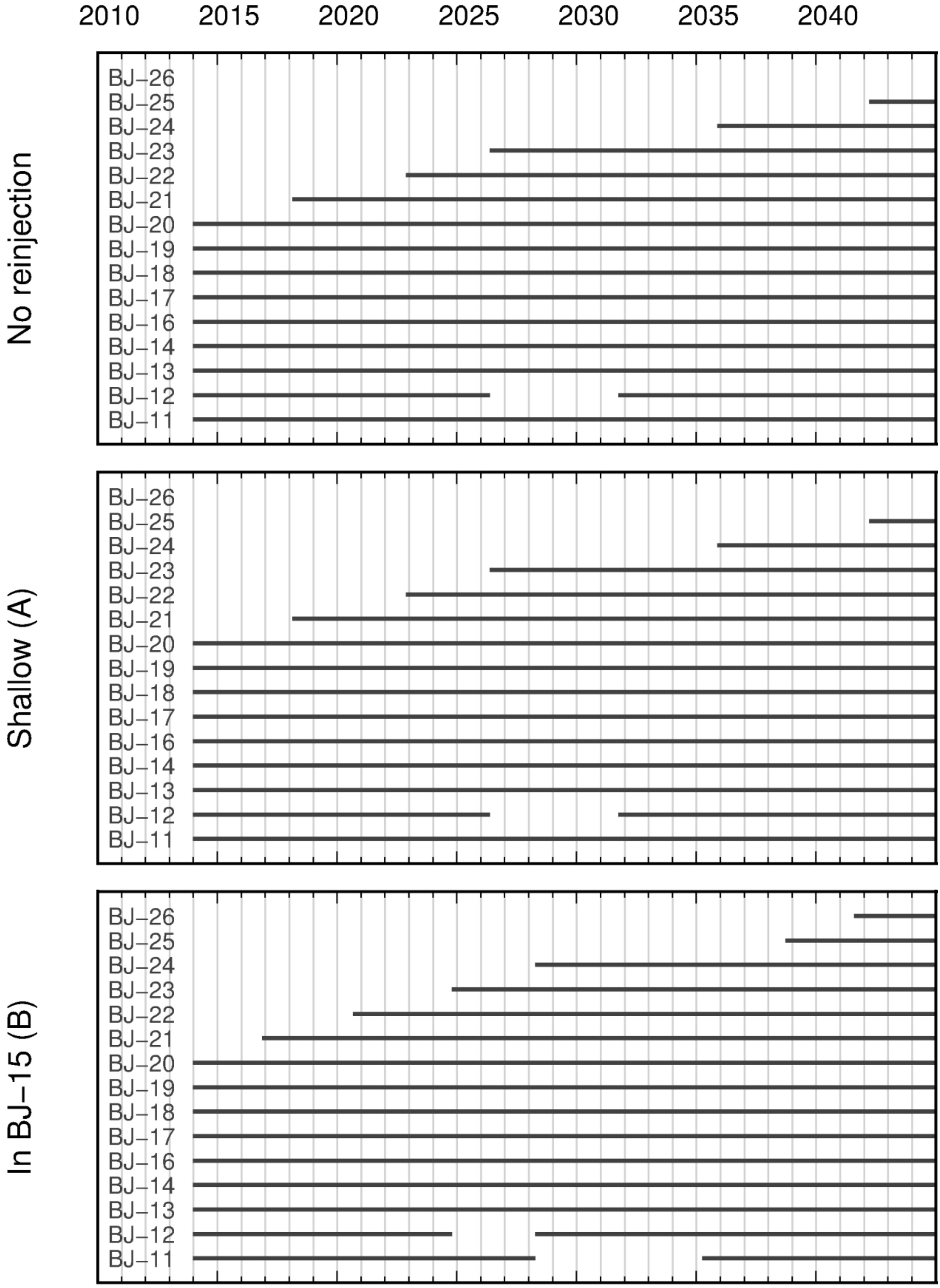


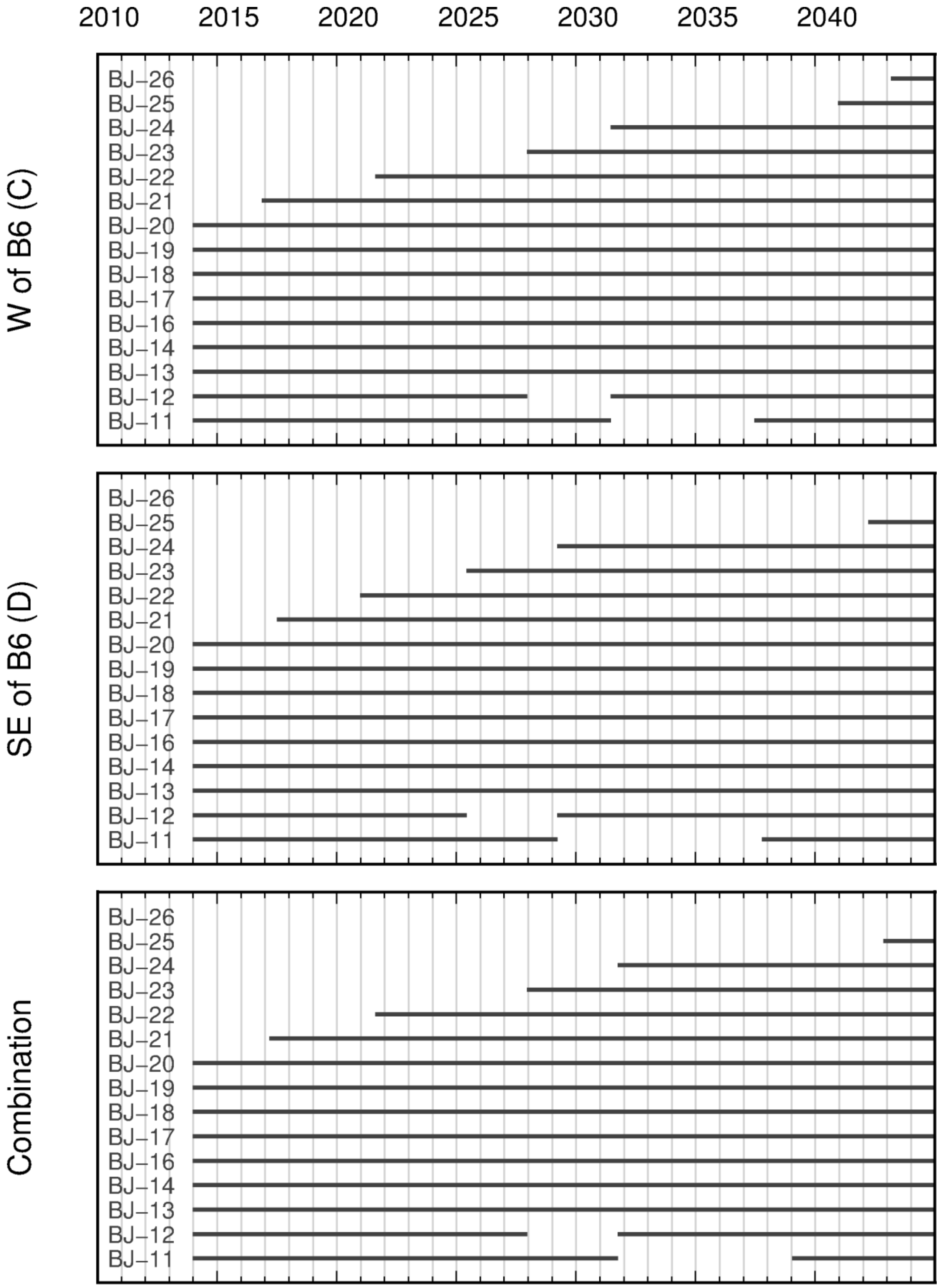
BJ-15
BJ-14
BJ-13
BJ-12
Námafjall
Krummaskarð
Northing (m)
Easting (m)
Log (R)

Appendix C: Well History 45 MW$_e$

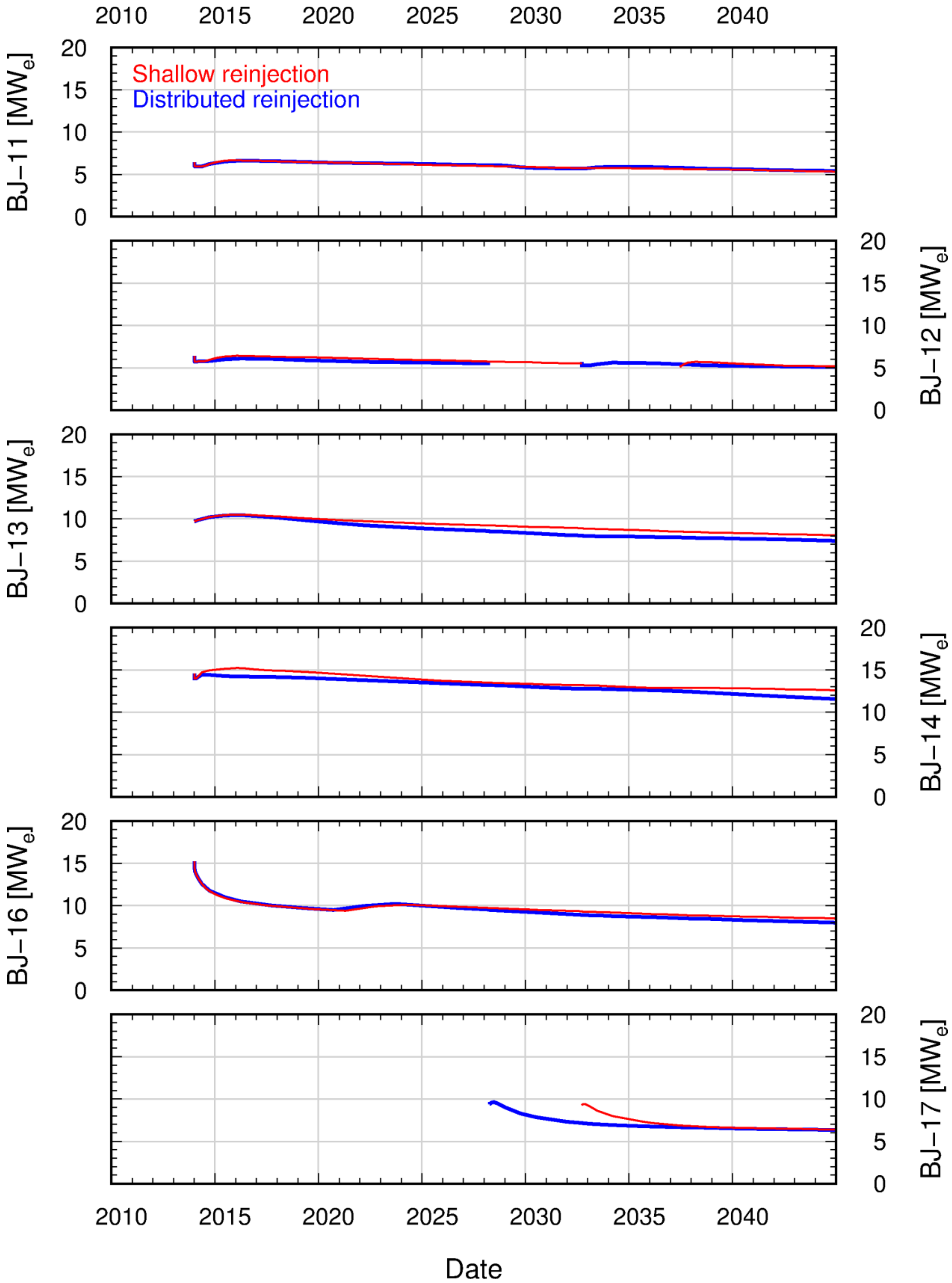


Appendix D: Well History 90 MWₑ

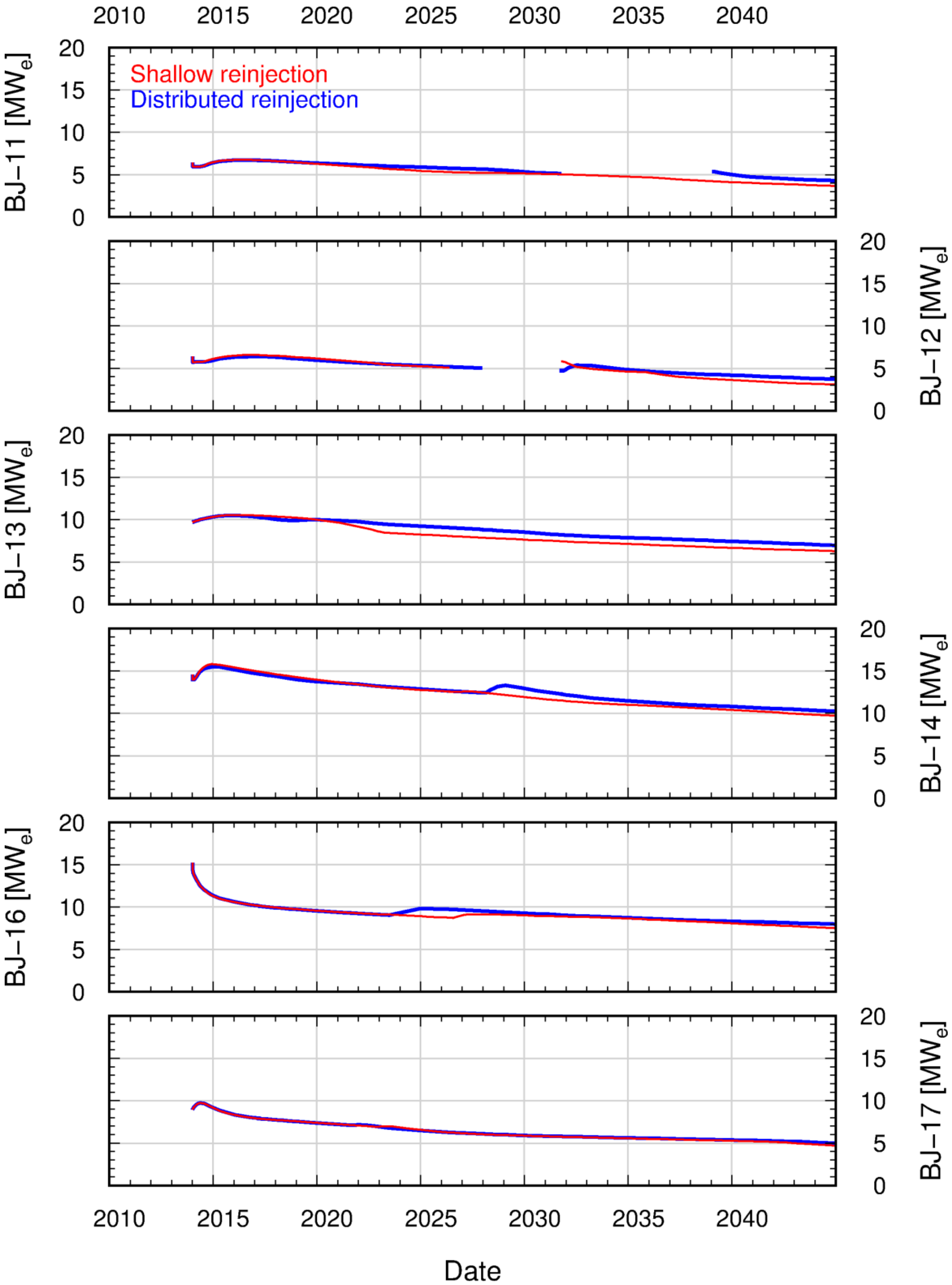


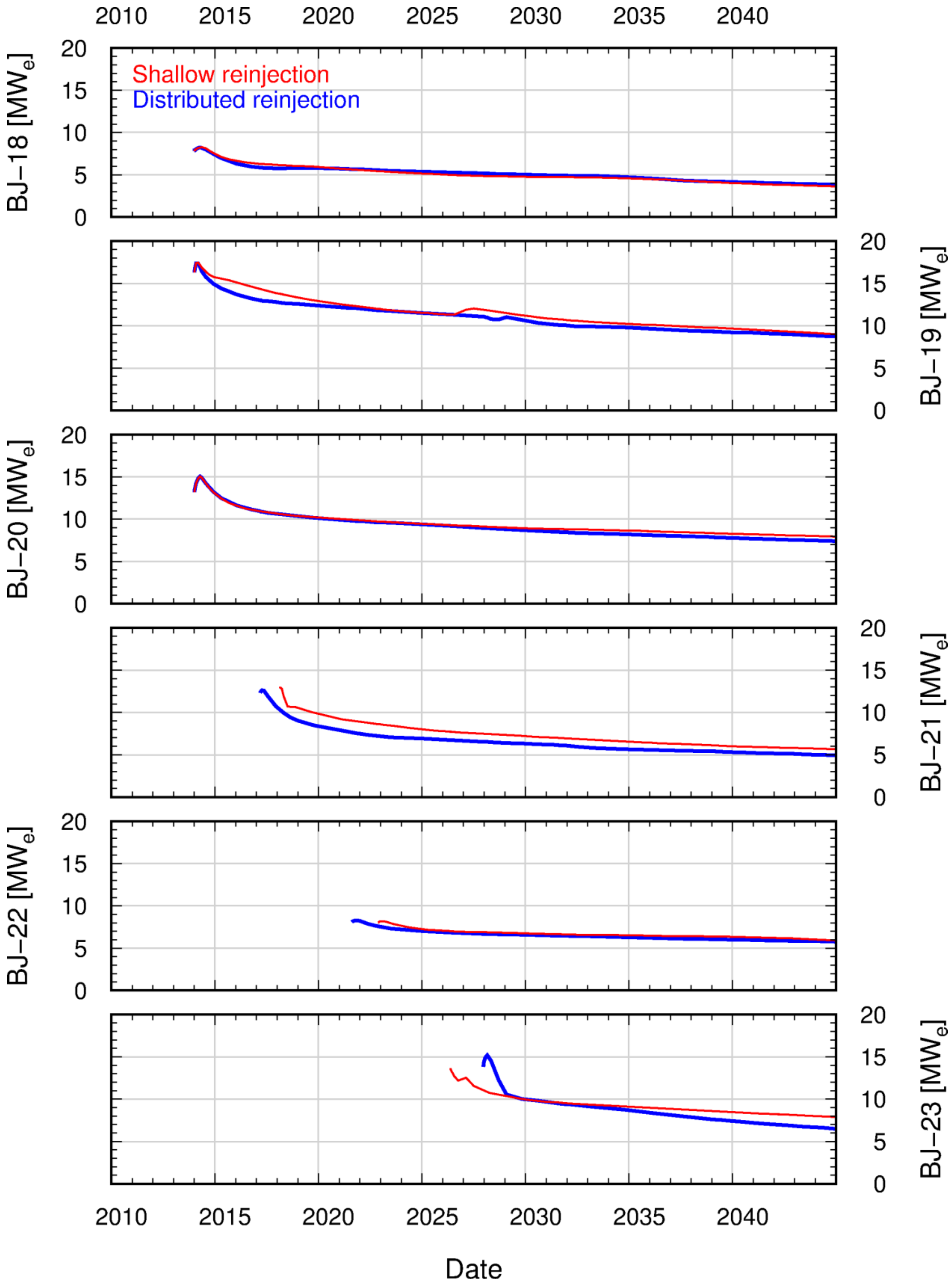

2010
2015
2020
2025
2030
2035
2040
W of B6 (C)
SE of B6 (D)
Combination
BJ−26
BJ−25
BJ−24
BJ−23
BJ−22
BJ−21
BJ−20
BJ−19
BJ−18
BJ−17
BJ−16
BJ−14
BJ−13
BJ−12
BJ−11

Appendix E: Annual Average Well Power (45 MW_e, 30 yrs)

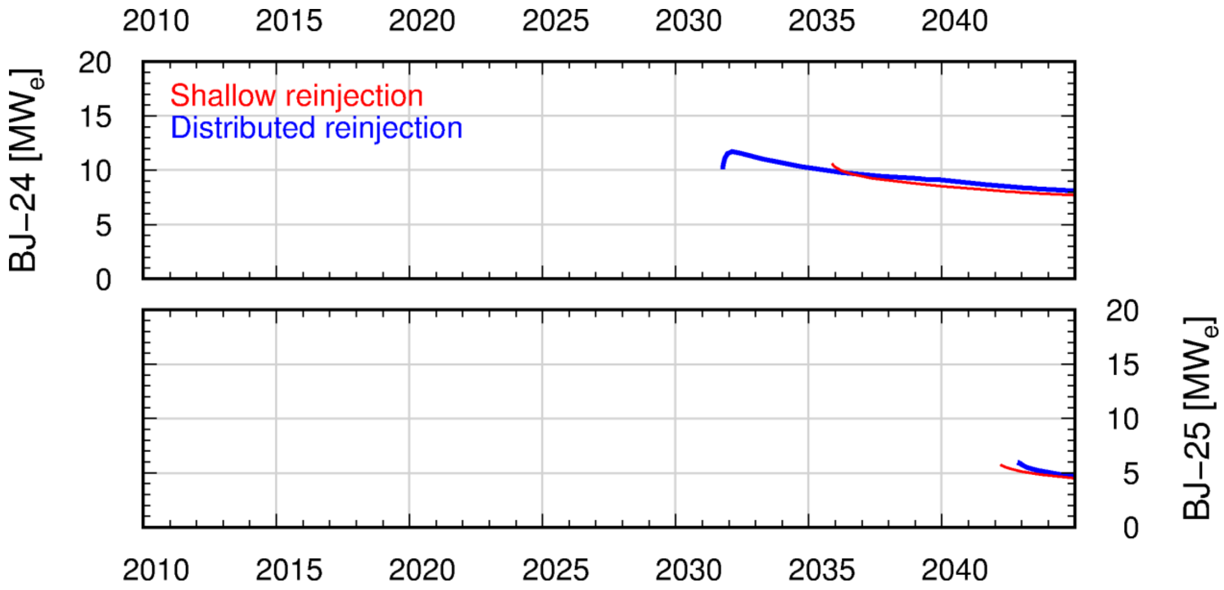


Appendix F: Annual Average Well Power (90 MWₑ, 30 yrs)





Shallow reinjection
Distributed reinjection
BJ−18 [MWe]
BJ−19 [MWe]
BJ−20 [MWe]
BJ−21 [MWe]
BJ−22 [MWe]
BJ−23 [MWe]
2010
2015
2020
2025
2030
2035
2040
0
5
10
15
20
Date


Shallow reinjection
Distributed reinjection
BJ−24 [MWe]
BJ−25 [MWe]
2010
2015
2020
2025
2030
2035
2040
0
5
10
15
20

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