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WELL TEST ANALYSIS AND TEMPERATURE AND PRESSURE MONITORING OF KRAFLA AND NESJAVELLIR HIGH-TEMPERATURE GEOTHERMAL FIELDS, ICELAND

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ABSTRACT

The Krafla high-temperature geothermal field is located within the Krafla caldera lying within the active NE-SW striking rift zone of North-East Iceland, whereas the Nesjavellir geothermal field is a high-temperature geothermal system, part of the Hengill central volcano in SW-Iceland. Reservoir assessment and monitoring was conducted on wells NJ-15 and NJ-18, located in the Nesjavellir high-temperature geothermal field. For Krafla geothermal field, wells K-37 and K-38 were considered to assess the reservoir, and well K-18 was used for monitoring. Temperature and pressure logs, measured during the warm up of the wells, were analysed to estimate formation temperature and initial pressure. In order to understand the parameters that characterise the reservoir and the wells, injection tests were analysed and parameters such as the injectivity index, transmissivity, storativity, skin, wellbore storage, etc. were evaluated.

Transmissivity estimated for the wells selected in Nesjavellir were of the same order of magnitude as for the wells in Krafla, i.e. 10^{-8} $m^3/(Pa{\cdot}s)$. Storativity for Krafla was higher than that of Nesjavellir, as can be expected in a two-phase reservoir. The wells in Nesjavellir are located at the outer boundaries of the geothermal reservoir and are liquid-dominated. This was further established by analysing the formation temperature and initial pressure. Temperature and pressure monitoring analyses at various depths were performed for Krafla on well K-18 from 1981 to 2013 and for well NJ-15 from 1985 to 2013; and for Nesjavellir well NJ-18 from 1988 to 2013. No significant change in temperature was observed in wells NJ-15 and NJ-18, but a linear constant pressure draw down of about 13 bar was observed in well NJ-15 from 1985 to 2013 and a rapid decline in pressure (20 bar) was observed in well NJ-18 from 2006 to 2013. In well KJ-18 in Krafla, a slow pressure decrease was observed.

1. INTRODUCTION

This report is a result of a reservoir analysis conducted in two geothermal areas, i.e. Nesjavellir geothermal field and Krafla geothermal field. Wells NJ-15 and NJ-18, located in Nesjavellir, were selected while wells K-37 and K-38 were selected for Krafla. Formation temperature estimation, initial pressure and analysis of an injection test were performed on all wells. Moreover, pressure and temperature monitoring analyses were carried out on wells NJ-15, NJ-18 and K-38 as well as on well KJ-18 which is near well K-37. Formation temperature estimation at different borehole depths was obtained by using the ÍSOR software Berghiti (Arason et al., 2004). Formation temperature is important in decision making for selecting sites for new wells as well as for setting up a conceptual model. The ÍSOR software PREDYP (Arason et al., 2004) was applied to calculate the initial pressure. Injection test simulation was made by utilizing WellTester software (Júlíusson et al., 2008) based on non-linear regression. For each well, the injectivity index was estimated. The injectivity index is a simple relationship, approximately reflecting the capacity of a well, which is useful for determining whether a well is sufficiently open to be a successful producer and for comparison with other wells (Axelsson and Steingrímsson, 2012).

In the next section the geothermal fields at Nesjavellir and Krafla will be introduced after which the theory of well testing will be presented. Injection tests from four wells will be analysed in Section 3. Temperature and pressure profiles during warm up will be analysed to deduce the formation temperature and initial pressure in each of the wells in Section 4 and, finally, temperature and pressure monitoring studies for both fields will be presented in Section 5, followed by conclusions in Section 6.

2. NESJAVELLIR AND KRAFLA GEOTHERMAL FIELDS

2.1 Nesjavellir geothermal field

The Nesjavellir geothermal field is a high-temperature geothermal system located in the Hengill central volcano in Southwest Iceland (Gíslason et al., 2005) (Figure 1). Several geological studies have been performed to understand the geothermal conditions of the Nesjavellir reservoir (Franzson, 1998; Franzson, 2000; Steingrímsson et al., 1990).

The geology of the area is characterised by hyaloclastite accumulation, lava accumulation and intrusive rocks. Hyaloclastite accumulation is dominant down to about 400 m b.s.l. below which lava accumulation dominates. The intrusive rocks, composed of basaltic dykes or sheets, characterise the section below 800 m depth and increase up to 80-100% intensity below 2000 m depth. Shallow-dipping dioritic sheet-like intrusions are also found at various depths and they contribute substantially to the permeability in the field, along with the basaltic intrusions.

Exploration drilling at Nesjavellir started with five wells in 1965. Additional 13 wells were drilled during the period of 1981-1985. A further 10 wells were drilled as step out and

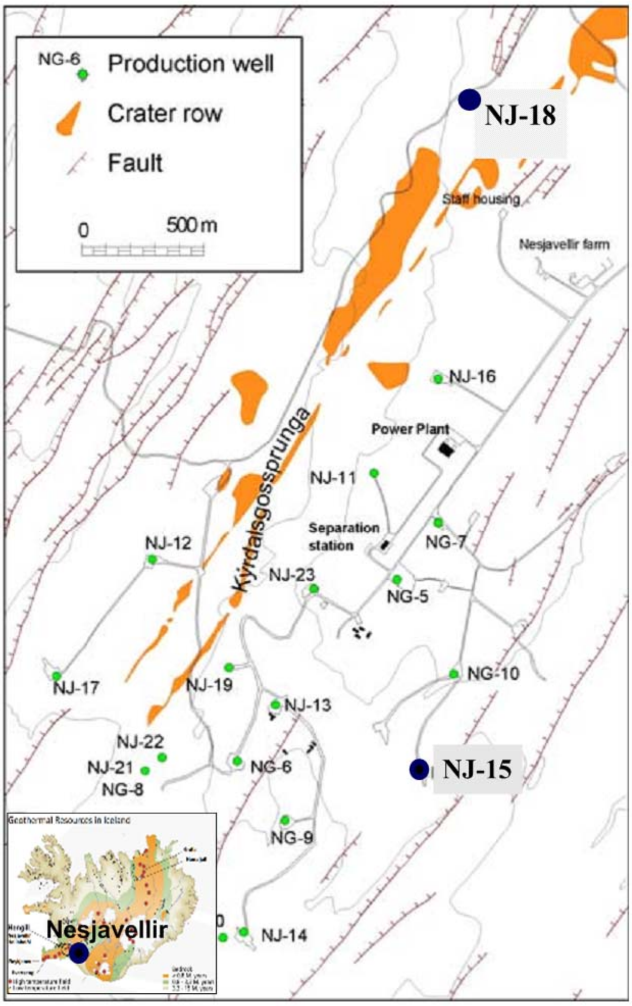

FIGURE 1: Locations of Wells NJ-15 and NJ-18 at Nesjavellir (modified from Gíslason et al., 2005)

make up wells, along with a few shallower reinjection wells.

Production of hot water from Nesjavellir for district heating in Reykjavík started in 1990 and power generation began in 1998. Reykjavik Energy (Orkuveita Reykjavíkur) is currently operating a 120 MW_e power plant and a 300 MW_{th} thermal unit in the Nesjavellir geothermal field.

Two wells, NJ-15 and NJ-18, in Nesjavellir (Figure 1) were selected for this study. Well NJ-15 is located at the outer border of the eastern part of the production area. It is a vertical well that was drilled in the autumn 1985 to a total depth of 1748 m. Well NJ-15 was connected to the steam supply system in October 1998 until July 1999. Since then, well NJ-15 has been closed and is currently used for temperature and pressure monitoring. Well NJ-18 is situated north of the production area. It is a vertical well, drilled in 1986 to a depth of 2136 m. It was not a productive well and was never connected to the steam supply system. It is currently used as a monitoring well.

2.2 Krafla geothermal field

The Krafla high-temperature geothermal system is located within the Krafla caldera (Figure 2) lying within an active N-S striking rift zone in Northeast Iceland (Ármannsson et al., 1987). The volcanic activity in this area is episodic, occurring every 250-1000 years, with each episode lasting 10-20 years. The most recent volcanic period started at the end of 1975 and ended in September 1984 with 9 eruptions and 21 tectonic events (Björnsson, 1985).

The Krafla geothermal field is subdivided into several sub-fields based on the chemical composition of the fluid from Krafla wells and geography (Ármannsson et al., 1987; Gíslason et al., 1978; Mortensen et al., 2009). These are Leirbotnar, Vítismór, Sudurhlídar, and Hvíthólar (Figure 2). The Leirbotnar sub-field is divided into an upper and a lower reservoir zone. The upper reservoir to a depth of 1000-1400 m is liquid-dominated with a temperature of 190-220°C (Ármannsson, 2010). The zone below 1400 m depth has a temperature of about 300°C and boiling conditions occur below 2000 m where the temperature is 350°C. Well KS-01 has discharged in Sandabotnar, suggesting a two-phase fluid (boiling point curve) from a reservoir at about 260°C. Hvíthólar sub-field exhibits boiling characteristics down to 1000 m depth but is cooler and liquid-dominated below that depth (Ármannsson, 2010). In Sudurhlídar (southern flanks of Mt. Krafla) and Vesturhlídar (western flanks of Mt. Krafla) the boiling point curve is followed and a two-phase fluid of about 300°C is delivered. Similar characteristics were observed for the one well drilled in the Leirhnúkur area.

The geology of Krafla high-temperature geothermal system is dominated by basaltic lava, sub-glacially erupted hyaloclastites as well as intrusive bodies of basalt, dolerites and gabbro. Exploration drilling started in 1974 when a decision was made to build a 60 MWe power plant concurrent with drilling. Up to 2012, a total of 44 wells had been drilled in Krafla geothermal field. Re-injection is mainly done through well K-26 below 2000 m depth, but abandoned wells have also served temporarily for this purpose (Ágústsson et al., 2012).

Wells K-37 and K-38 (Figure 2) will be considered for this study for an injection test and formation temperature estimation as well as initial pressure; well K-18 will be used for the monitoring of pressure and temperature. Well K-38 is drilled in the western flanks (Vesturhlídar) of mount Krafla which is a new site. Wells K-37 and KJ-18, on the other hand, are drilled into the southern flanks (Sudurhlídar) of mount Krafla where there has been substantial production since 1980. A revised conceptual model developed by ISOR (Mortensen et al., 2009) showed that a pressure draw down of about 5 bar occurred in Leirbotnar sub-area after the expansion of the plant in the year 1999; on the southern flanks, where there has been substantial production since 1980, the pressure dropped significantly, probably about 20-30 bar.

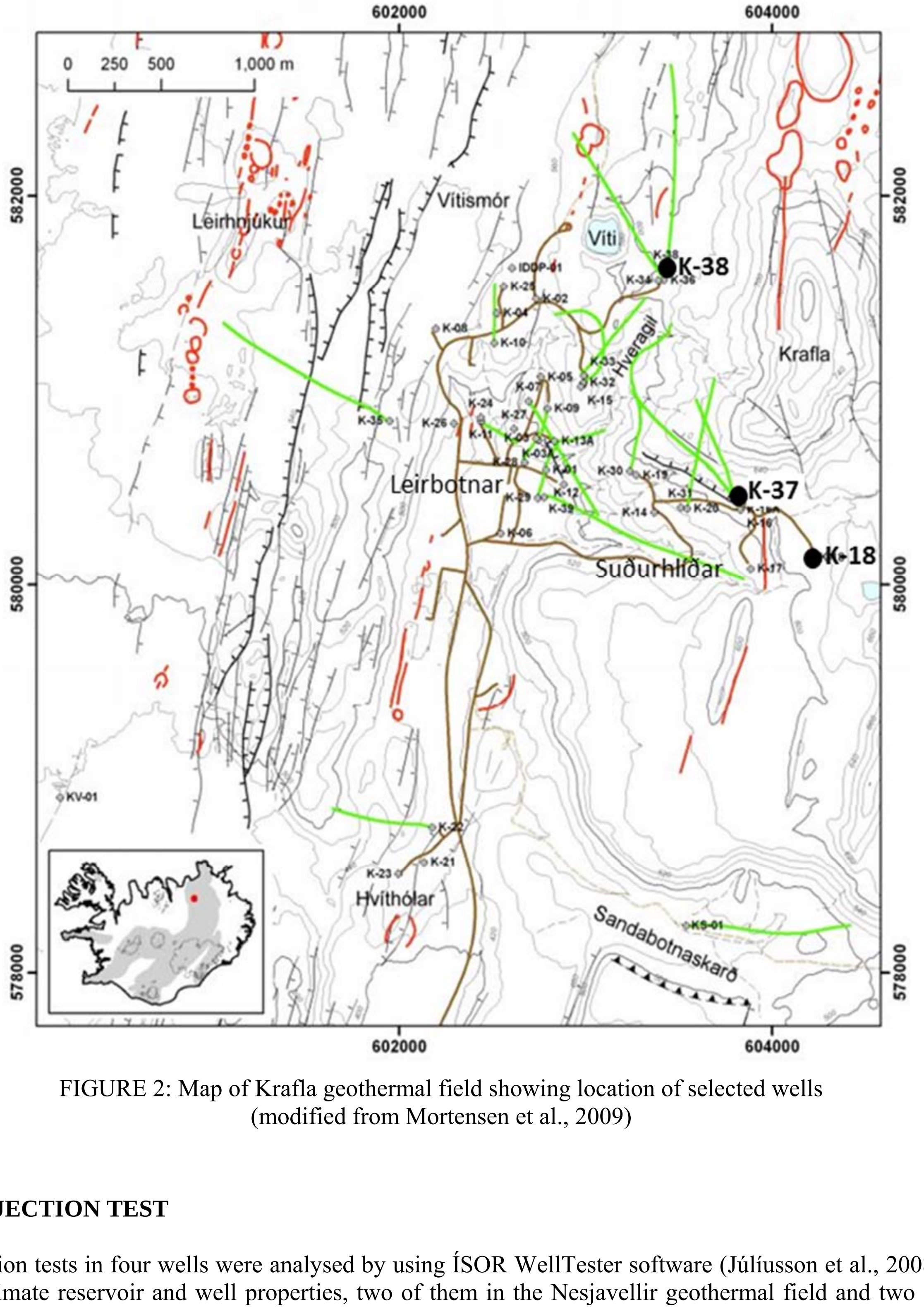

FIGURE 2: Map of Krafla geothermal field showing location of selected wells (modified from Mortensen et al., 2009)

3. INJECTION TEST

Injection tests in four wells were analysed by using ÍSOR WellTester software (Júlíusson et al., 2008) to estimate reservoir and well properties, two of them in the Nesjavellir geothermal field and two in the Krafla geothermal field. Injection tests are usually performed after drilling the production section of a well; the first parameter analysed is the injectivity index which gives an indication of how open the surroundings of the well are for flow, i.e. the change of pressure with change in the injection rate ((l/s)/bar).

In some cases the injection test is used for decision making and, in case of a too low injectivity index, drilling is continued in the hope of finding better feed zones at greater depth.

The following sections give a short theoretical background of injection well testing, followed by the summary of the well test results for wells NJ-15 and NJ-18 in Nesjavellir geothermal field, and wells K-37 and K-38, located in Krafla geothermal field.

3.1 Theoretical background

Well testing consists of producing from or injecting into a well at controlled rates and over periods of time and monitoring the response of the pressure in the same well and/or in adjacent observation wells. Well testing is performed in order to understand the conditions and flow capacity of a well and the parameters that characterise it and the reservoir. Parameters of interest include permeability, storativity, skin, wellbore storage, fracture properties, and the type of reservoir boundaries.

The pressure diffusion equation is used to calculate the pressure (p) in the reservoir after a given time (t) and at a certain distance (r) from an injection (or production) well receiving (or producing) fluid at a specific rate (Q). The following simplifying assumptions were made before the derivation of the equation:

- Horizontal radial flow;
- Darcy's Law applies;
- Homogeneous and isotropic reservoir and isothermal condition;
- Uniform thickness of reservoir (h);
- Single-phase flow and small pressure gradient;
- Constant permeability (k), porosity (φ), fluid viscosity (μ) and small and constant total compressibility (c_t); and
- The force of gravity is negligible.

The pressure diffusion equation is derived by combining the conservation of mass law, Darcy´s law (conservation of momentum), and the equation of state of the fluid.

Law of conservation of mass
Consider the flow through a cylindrical shell of thickness, *dr*, situated at a distance, *r*, from the centre of the radial cylinder (Figure 3).

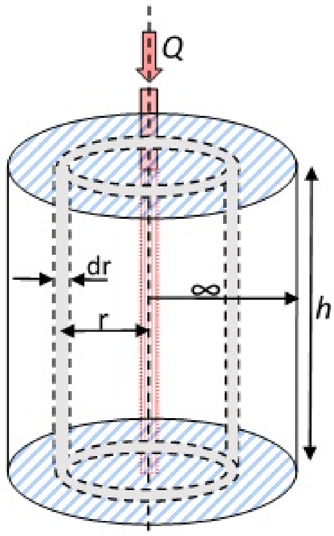

FIGURE 3: Radial flow through a cylindrical shell

Then applying the principle of conservation of mass, mass flow in – mass flow out = rate of change of mass within the control volume:

$$-\rho Q + (\rho Q + \frac{\partial(\rho Q)}{\partial r} dr) = 2\pi r \frac{\partial(\varphi \rho h)}{\partial t} dr \tag{1}$$

or

$$\frac{\partial(\rho Q)}{\partial r} = 2\pi r \frac{\partial(\varphi \rho h)}{\partial t} \tag{2}$$

where, ρ = The density (kg/m^3);
φ = The porosity (ratio 0<φ<1);
Q = The volumetric flow rate (m^3/s);
r = The radial distance (m) from the well;
t = The time (s);
h = The reservoir thickness (m).

Darcy´s law or law of conservation of momentum
Darcy´s law in radial form is

$$Q = 2\pi rh \frac{k}{\mu}\frac{\partial p}{\partial r} \tag{3}$$

where, p = The pressure (Pa);
μ = The dynamic viscosity (Pa·s); and
k = The formation permeability (m^2).

Equation of state of the fluid (fluid compressibility at constant temperature)

$$c_w = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right) \tag{4}$$

where c_w = Fluid compressibility;
ρ = The fluid density (kg/m^3);
p = The pressure (Pa).

By combining Equations 2, 3 and 4, we obtain the pressure diffusion equation given by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\partial p(r,t)}{\partial r}\right) = \frac{\mu c_t}{k}\frac{\partial p(r,t)}{\partial t} = \frac{S}{T}\frac{\partial p(r,t)}{\partial t}$$

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\left(\frac{\partial p(r,t)}{\partial r}\right) = \frac{\mu c_t}{k}\frac{\partial p(r,t)}{\partial t} = \frac{S}{T}\frac{\partial p(r,t)}{\partial t} \tag{5}$$

where $c_r = \frac{1}{1-\varphi}\frac{\partial \varphi}{\partial p}$ = The rock compressibility (Pa^{-1});
$c_t = \varphi c_w + (1-\varphi)c_r$ = The total compressibility (Pa^{-1});
$S = c_t h$ = The storativity ($m^3/(Pa \cdot m^2) = m/Pa = m^3/N$);
$T = \frac{kh}{\mu}$ = The transmissivity ($m^3/(Pa \cdot s)$).

Equation 5 is the basic equation for well testing. Solutions for this equation can be obtained for different regimes depending on the initial and boundary conditions but that is beyond the scope of this project. The analysis of the injection test was done using WellTester software (Júlíusson et al., 2008) which was developed by the Iceland GeoSurvey (ISOR). The main parameters deduced from the WellTester simulation are explained in the manual for WellTester (Júlíusson et al., 2008) and follow below. Some of them are explained as well in the formulas above.

Transmissivity (T) describes the ability of the reservoir to transmit fluid, hence largely affecting the pressure gradient between the well and the reservoir. The higher the transmissivity, the easier it is for the fluid to flow through the rock matrix.

$$T = \frac{kh}{\mu} \quad \text{or} \quad T = \frac{kh\rho}{\nu} \tag{6}$$

where $\nu = \frac{\mu}{\rho}$ = The kinematic viscosity of the fluid (m^2/s).

Storativity (S) is defined as the volume of fluid stored in the reservoir, per unit area, per unit increase in pressure ($m^3/(Pa \cdot m^2)$). It depends on rock and fluid compressibility and phase change activity (Grant et al., 1982).

The injectivity index (II) is controlled by the injection flow rate and the change in stabilized reservoir pressure. It describes how the well is connected to the surrounding reservoir. Mathematically, the injectivity index (*II*) is represented as

$$II = \left|\frac{\Delta Q}{\Delta p}\right| \tag{7}$$

where ΔQ is the change in the injection flow and Δp is the change in the stabilized reservoir pressure ((l/s)/bar).

Wellbore storage coefficient (C) represents the volume of fluid that the wellbore itself will produce due to a unit drop of pressure (Grant and Bixley, 2011; Horne, 1995) (m^3/Pa). This mostly occurs due to fluid expansion or changing of the fluid level in the well. It is represented mathematically by:

$$C = \frac{\Delta V}{\Delta P} \tag{8}$$

where ΔV = The change in fluid volume in the well for the change in pressure ΔP.

Skin factor (s) is a dimensionless parameter (Van Everdingen and Hurst, 1953) and it characterizes the well condition: for a damaged well the permeability in the skin zone is less than reservoir permeability and S > 0, and for a stimulated one S < 0, meaning that the permeability of the skin zone is greater than the reservoir permeability.

Radius of investigation (r_e) is the approximate distance (m) at which the pressure response from the well becomes undetectable. Hence, this radius defines the area around the well being investigated, although the value of the parameter should be regarded more qualitatively. When boundary effects are seen in the data, the approximate distance from the centre of the well to the boundary will define the radius of investigation.

3.2 Testing of well NJ-15

An injection test of well NJ-15 was performed on 21/10/1995 where the pressure sensor was placed at 1590 m depth. Before the injection test started, injection was constant at 28.9 l/s of water. The injection test was conducted in four steps as shown in Table 1.

TABLE 1: Injection rate and pressure response

21/10/1995	Before starting	Step 1	Step 2	Step 3	Step 4
Time period	-	03:49-06:20	06:20-09:08	09:08-11:47	11:47-14:00
Duration (hr)	-	2:31	2:48	2:39	2:13
Injection (l/s)	28.9	18.9	29.3	40.6	0
Change in injection $\|\Delta Q\|$		10	10.4	11.3	40.6
Pressure at the end of step (bar-g)	137.3	132.4	136.4	139.7	123.6
Change in pressure $\|\Delta p\|$		5	4	3.3	16

Initial parameters that were used to describe the reservoir and well dimensions in this analysis are estimated reservoir temperature 280°C, wellbore radius 0.12 m, and estimated reservoir pressure of 135 bar which was deduced by WellTester software. Two types of models were considered for the reservoir, on one hand a homogeneous reservoir and on the other hand a dual porosity reservoir. The best fit between the model and the data was obtained for a homogenous reservoir, constant pressure boundary, constant skin and wellbore storage.

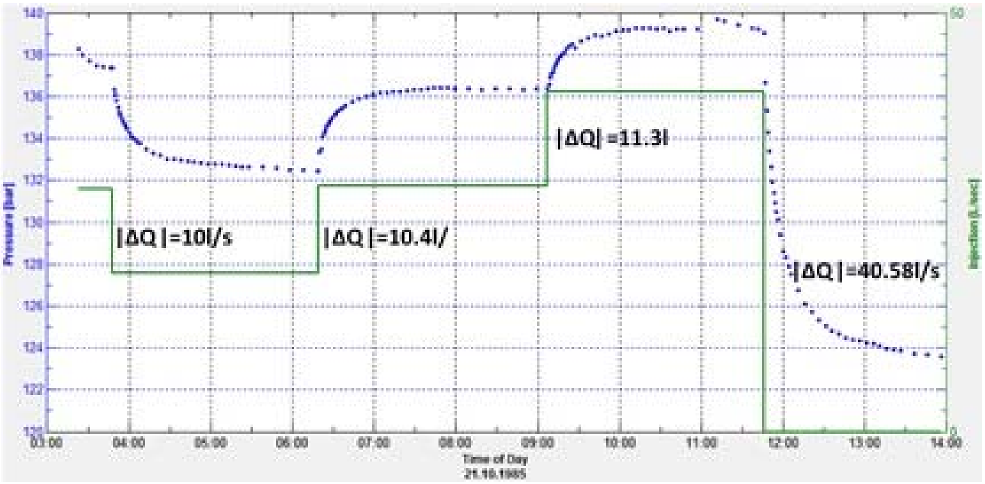

FIGURE 4: Step rate injection and pressure response for Well NJ-15

A non-linear regression analysis was performed to find the parameters of the model that best fit the data. The model fit with the data was best for step 1. Figure 4 shows the pressure response against time for various steps of injection as well as the change in injection for each step. In the following section the results from the interpretations of step one are shown in Figures 5, 6, and 7 and Table 2.

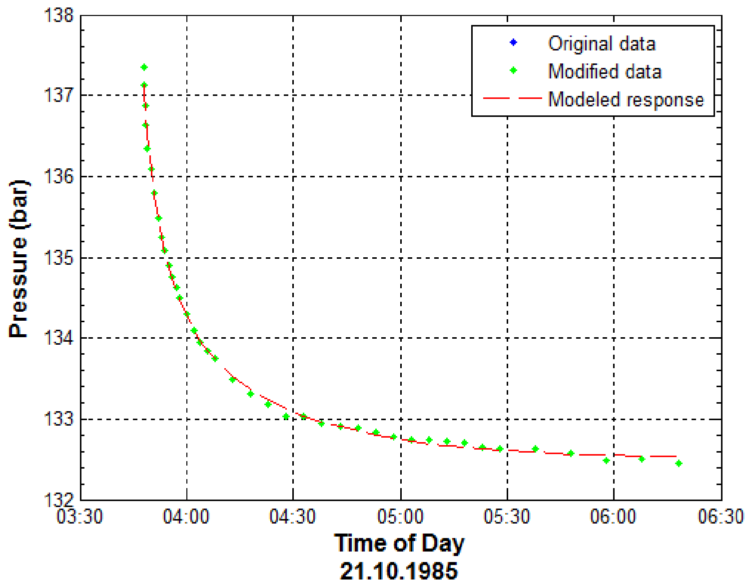

FIGURE 5: Pressure against time for model results and collected data for step 1

Figure 5 shows on a linear scale how the chosen model fits the data. Figure 6 shows the pressure measured for the step on a linear scale using a logarithmic timescale. Figure 7 shows the pressure change on a logarithmic scale, also using a logarithmic timescale, together with the derivative of the pressure response multiplied by the time passed since the beginning of the step. Table 2 shows the injectivity index and the reservoir parameters estimated by using the selected model. The skin factor is negative, as is usual in Iceland, which means that the well was enhanced and not damaged during drilling.

TABLE 2: Results from non-linear regression parameter estimate using injection data from well NJ-15

Reservoir parameters	**1. step**	**2. step**	**3. step**	**4. step**	**Best estimate (Step 1)**	**Units**
Transmissivity (T)	$1.3 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$2.5 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$m^3/(Pa \cdot s)$
Storativity (S)	$6.4 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$6.4 \cdot 10^{-8}$	$m^3/(Pa \cdot m^2)$
Radius of investing. (r_e)	46	67	85	68	46	m
Skin factor (s)	-2.2	-3	-2.5	-3.5	-2.2	-
Wellbore storage (C)	$8.4 \cdot 10^{-6}$	$6.7 \cdot 10^{-6}$	$2.2 \cdot 10^{-5}$	$8 \cdot 10^{-6}$	$8.4 \cdot 10^{-6}$	$m^3/(Pa)$
Permeability (k)	$4 \cdot 10^{-15}$	$1.3 \cdot 10^{-14}$	$2.7 \cdot 10^{-14}$	$1.3 \cdot 10^{-14}$	$4 \cdot 10^{-15}$	m^2
Reservoir thickness	296	106	92	91	296	m
Injectivity index (II)	2	2.6	3.4	2.6	2	(l/s)/bar

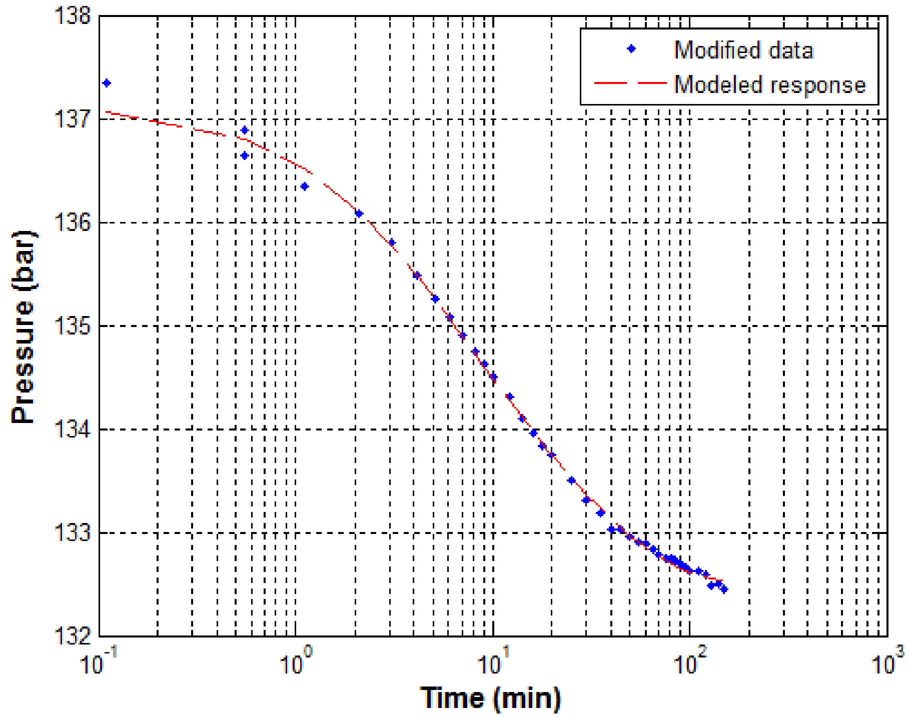

FIGURE 6: Pressure against time for model results and collected data for step 1 using logarithmic time scale

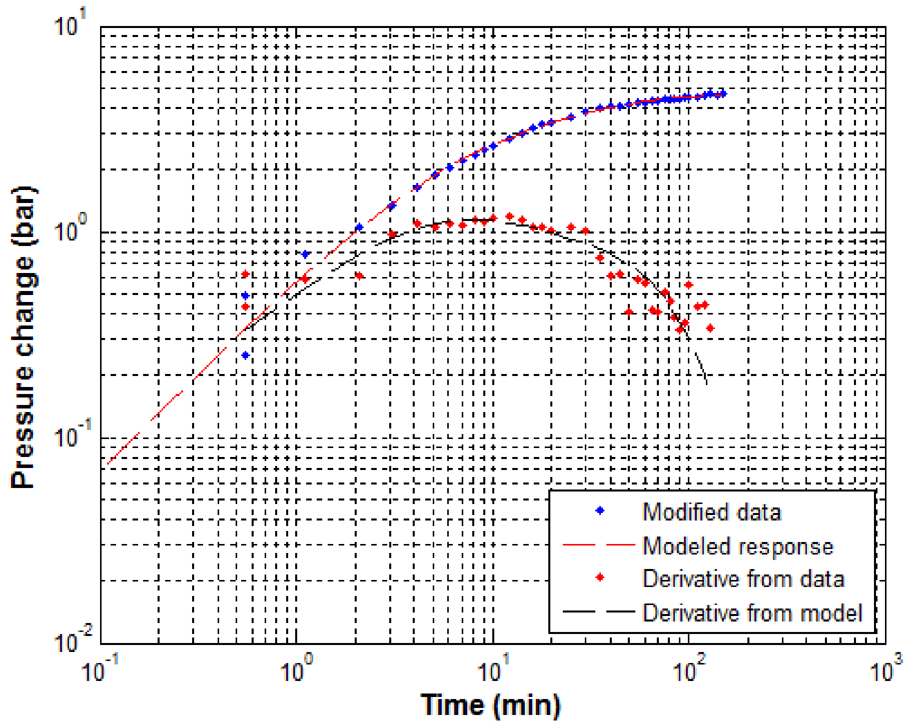

FIGURE 7: Pressure and its derivative against time for model results and collected data for step 1 on a log-log scale (see text)

3.3 Testing of well NJ-18

An injection test was performed in this well on 15/10/1986. The pressure sensor was stationed at 1710 m depth which was assumed to be the depth of the main feed zone. Before the injection test started, injection was constant at 24.2 l/s of water. The injection test was conducted in three steps as shown in Table 3.

TABLE 3: Injection rate and pressure response

15/10/1986	Before starting	Step 1	Step 2	Step 3
Time period	-	08:21-11:43	11:43-14:45	14:45-17:18
Duration (hr)	-	3:22	3:02	2:27
Injection (l/s)	24.2	36.7	24.2	0
Change in injection $\|\Delta Q\|$		12.5	12.5	24.2
Pressure at the end of step (bar-g)	157.3	162.3	155.5	144
Change in pressure $\|\Delta p\|$		5	6.8	11.6

To find the parameters of the model that best fit the data, a non-linear regression analysis was performed by using WellTester. The following initial parameters were taken to describe the reservoir: estimated reservoir temperature 280°C, wellbore radius 0.12 m and an estimated reservoir pressure of 135 bar, deduced from WellTester software. Homogenous reservoir, constant pressure boundary, constant skin and wellbore storage were selected for the reservoir model. Figure 8 illustrates the pressure response against time for various flow rates as well as the change in injection for each step. Figure 9 shows on a linear scale how the chosen model fits the data in step 3. Figure 10 shows the pressure measured for the step on a linear scale using a logarithmic timescale. Figure 11 shows the pressure change on a logarithmic scale, also using a logarithmic timescale, together with the derivative of the pressure response multiplied by the time passed since the beginning of the step. Table 4 shows the reservoir parameters estimated by using the selected model in WellTester. The results of the simulations for step 3 showed to be the best of the simulations.

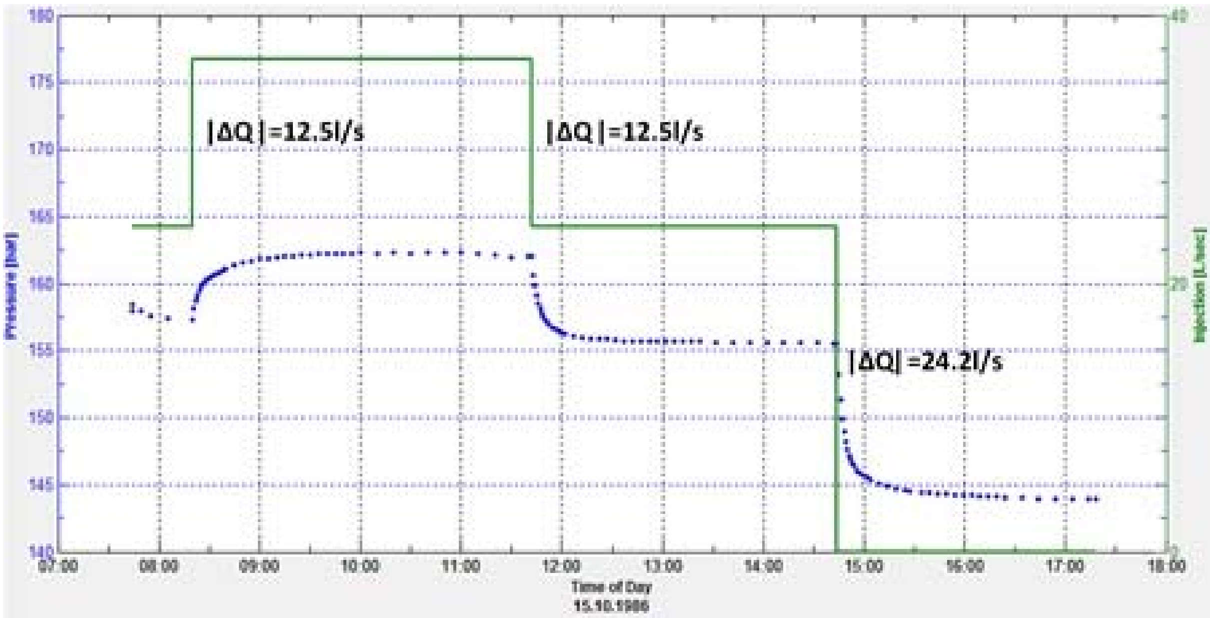

FIGURE 8: Step rate injection and pressure response for Well NJ-18

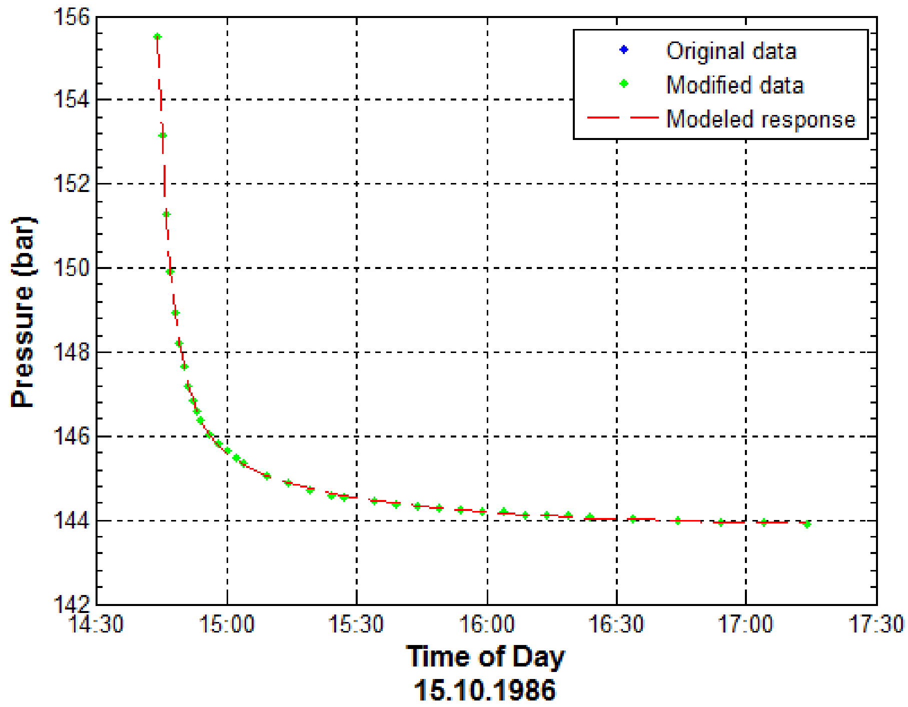

FIGURE 9: Pressure against time for model results and collected data for step 3

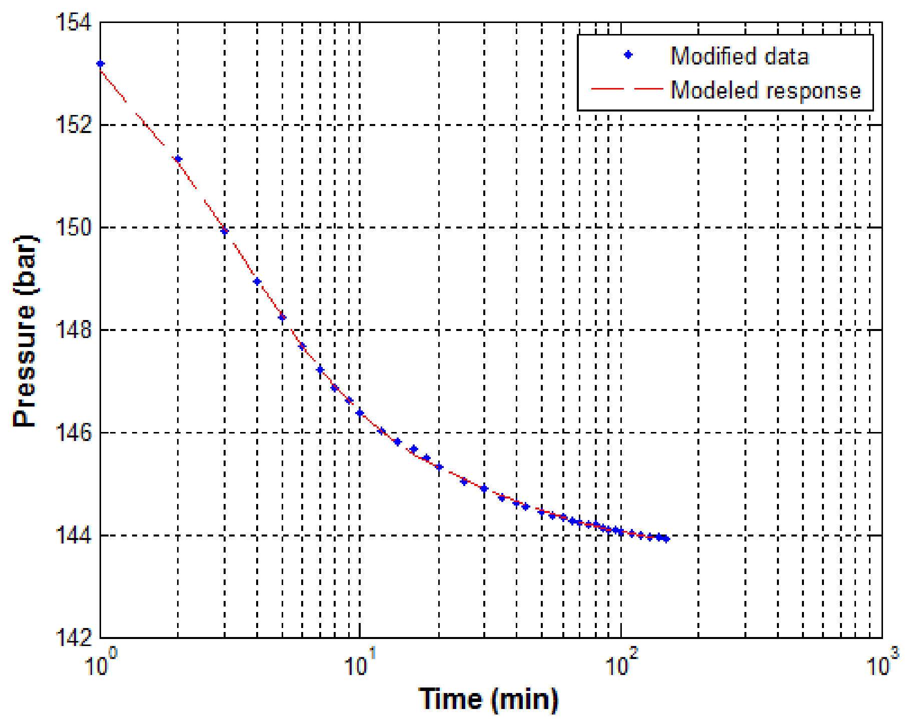

FIGURE 10: Pressure against time for model results and collected data for step 3, using a logarithmic time scale

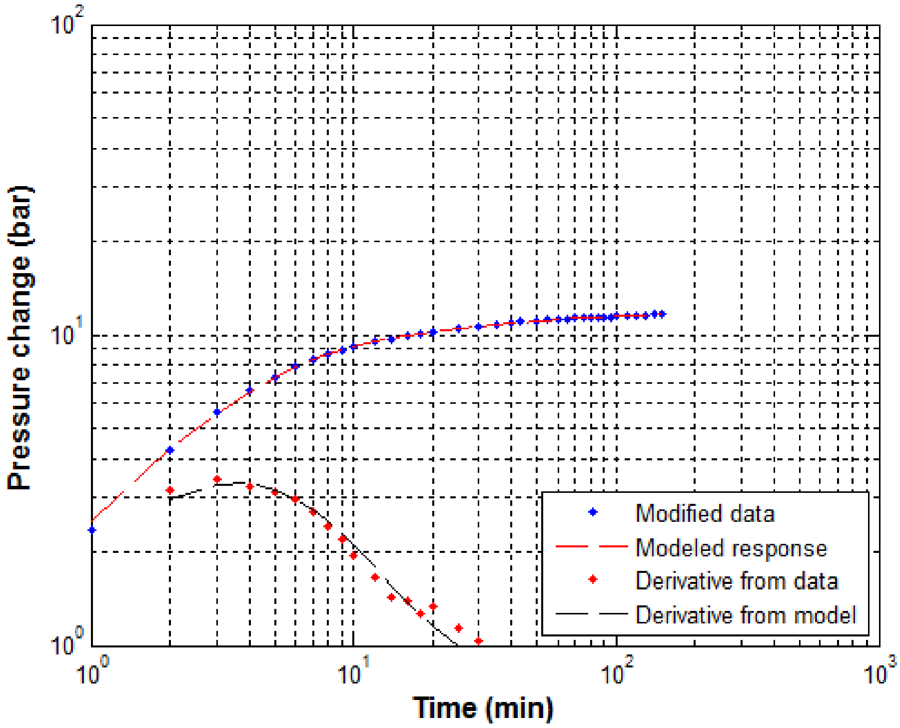

FIGURE 11: Pressure and its derivative against time for model results and collected data for step 3 on a log-log scale (see text)

TABLE 4: Results from non-linear regression parameter estimate using injection data from well NJ-18

Reservoir parameters	1. step	2. step	3. step	Best estimate (Step 3)	Unit
Transmissivity (T)	$1.1 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	$2.8 \cdot 10^{-8}$	$2.8 \cdot 10^{-8}$	$m^3/(Pa \cdot s)$
Storativity (S)	$7 \cdot 10^{-8}$	$4.6 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$m^3/(Pa \cdot m^2)$
Radius of investigation (r_e)	34	45	174	174	m
Skin factor (s)	-3.	-0.3	1.3	1.3	-
Wellbore storage (C)	$4.6 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$m^3/(Pa)$
Permeability (k)	$3.1 \cdot 10^{-15}$	$7.6 \cdot 10^{-15}$	$4.6 \cdot 10^{-14}$	$4.6 \cdot 10^{-14}$	m^2
Reservoir thickness (h)	329	220	60	60	(m)
Injectivity index	2.5	2	2.1	2.1	(l/s)/bar

The values of transmissivity and storativity for NJ-18 are within the same range of magnitude as the value obtained from well NJ-15, and these values are within the range which is generally expected in Iceland.

3.4 Testing of well K-37

Well K-37 in Krafla is a directional well which was drilled from 04.10.2007 to 18.01.2008 to a total depth of 2187 m. An injection test of the well was performed at the end of drilling on 18.1.2008. The pressure sensor was positioned at 1420 m depth which was assumed to be the main feed zone. Before the injection test started, injection was constant at 20 l/s of water. The injection test was conducted in three steps as shown in Table 5.

TABLE 5: Injection rate and pressure response

18.01.2008	Before starting	Step 1	Step 2	Step 3
Time period	-	14:17 - 17:18	17:18 - 20:18	20:18 - 23:18
Duration (hr)	-	3:01	3:00	3:00
Injection (l/s)	20	35	50	20
Change in injection |ΔQ|	-	15	15	30
Pressure at the end of step (bar-g)	80	84	88	80.0
Change in pressure |Δp|		4	4	8

Initial parameters that were used to describe the reservoir in this analysis are estimated reservoir temperature 320°C, wellbore radius 0.18 m, and an estimated reservoir pressure of 80 bar which was found by WellTester. Two types of models were considered for the reservoir: on one hand a homogeneous reservoir and, on the other hand, a dual porosity reservoir. A non-linear regression analysis was done to find the parameters of the model that best fits the data. The model best fitted the data in step 3, and the best results were obtained for a homogenous reservoir, constant pressure boundary, constant skin and wellbore storage.

Figure 12 shows the steps of the injection and the pressure response against time as well as the change in injection for each step during the test. Figure 13 illustrates on a linear scale how the chosen model fits the data for step 3. Figure 14 shows the pressure measured for the step on a linear scale using a logarithmic timescale. Figure 15 shows the pressure change on a logarithmic scale, also using a logarithmic timescale, together with the derivative of the pressure response multiplied by the time passed since the beginning of the step. Table 6 shows the reservoir parameters estimated by using the selected model.

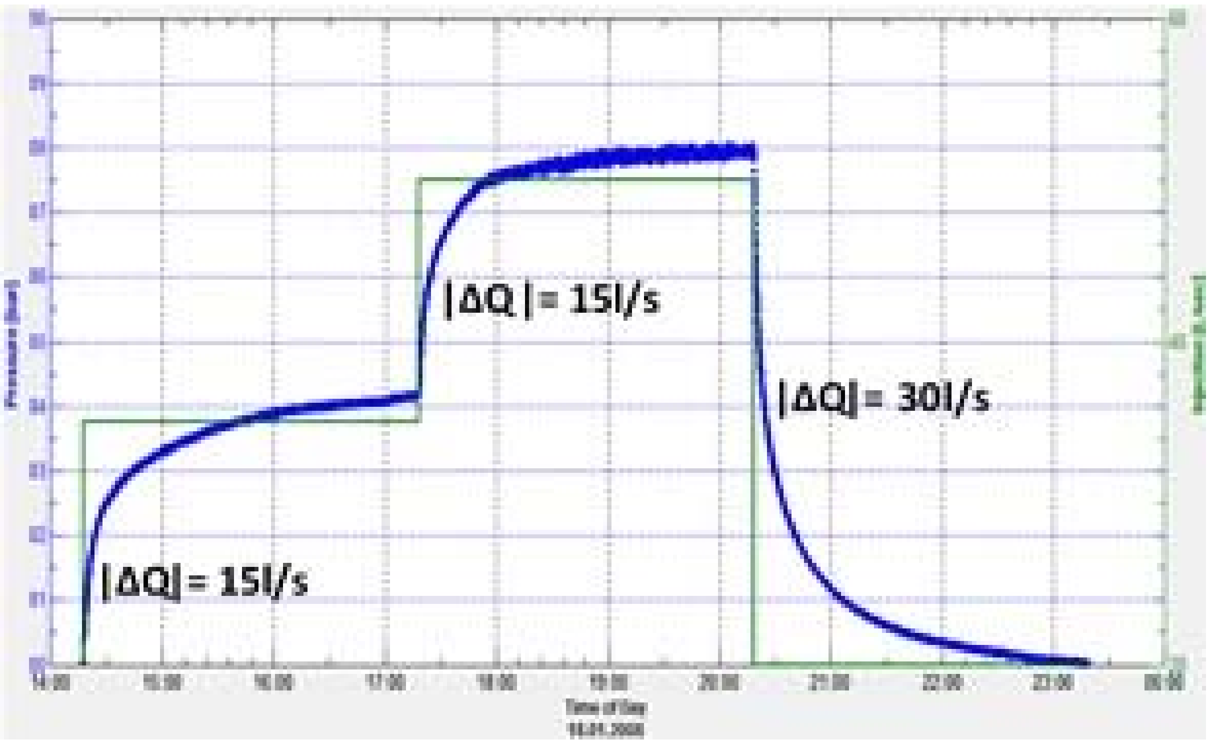

FIGURE 12: Step rate injection and pressure response for Well K-37

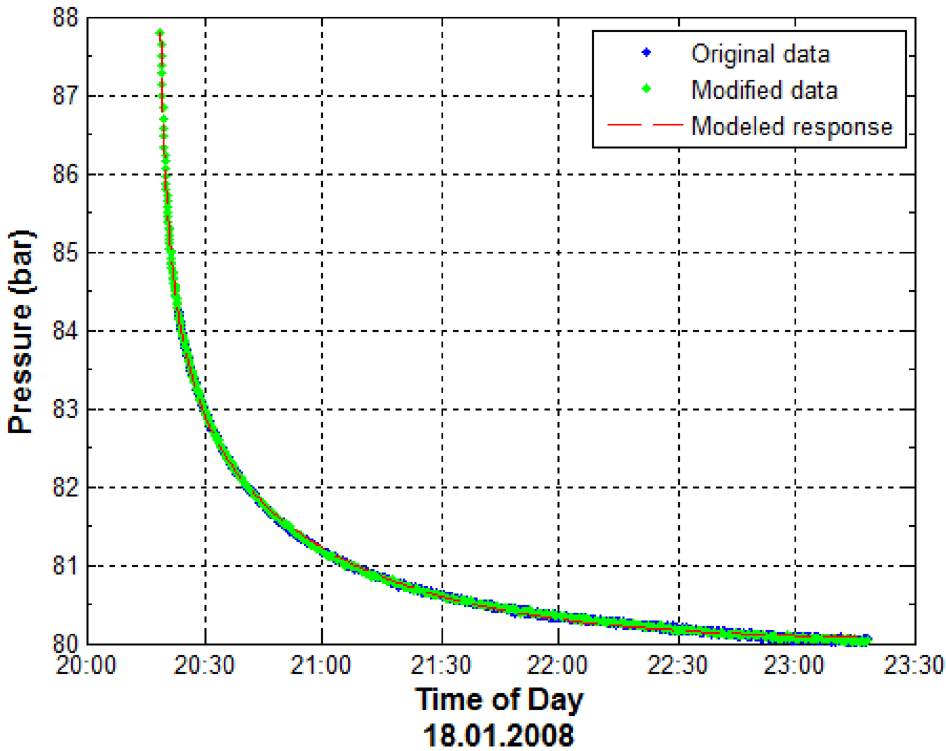

FIGURE 13: Pressure against time for model results and collected data for step 3

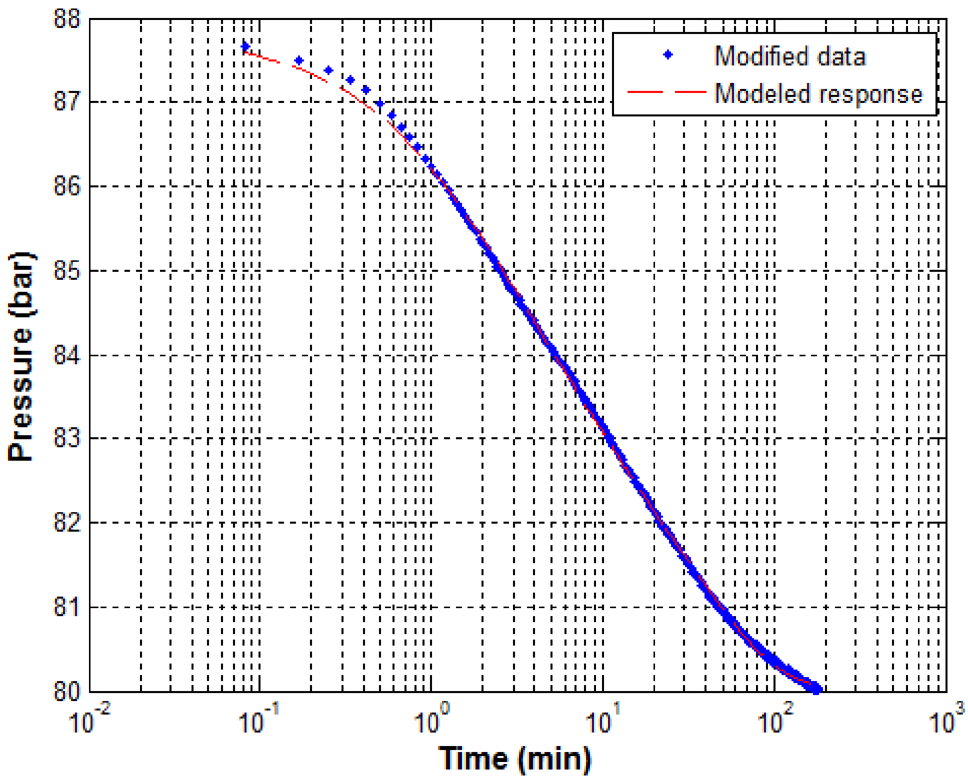

FIGURE 14: Pressure against time for model results and collected data for step 3, using a logarithmic time scale

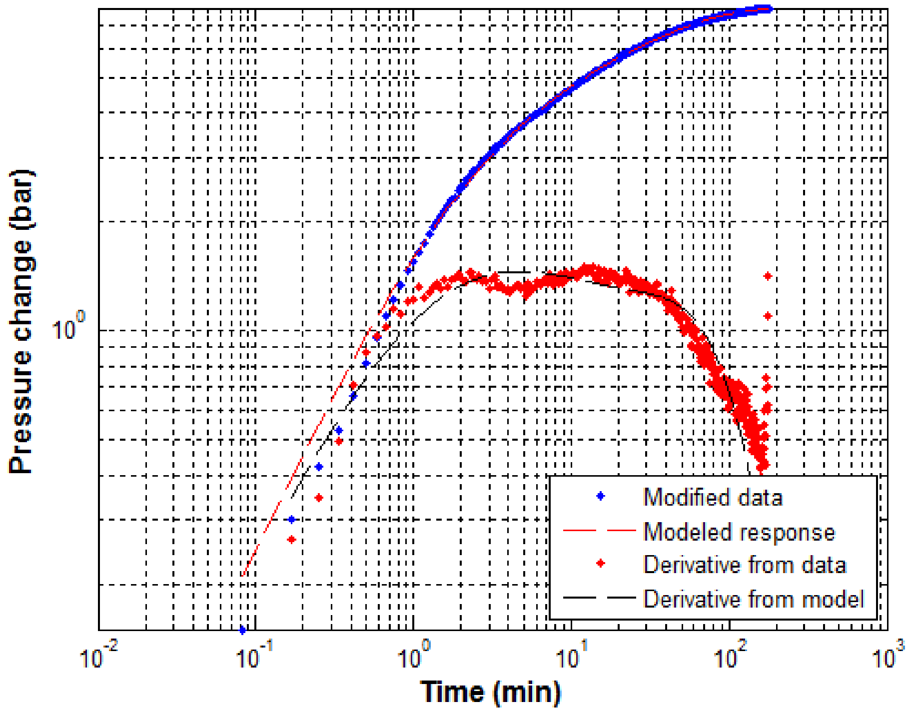

FIGURE 15: Pressure and its derivative against time for model results and collected data for step 3 on a log-log scale (see text)

TABLE 6: Results from non-linear regression parameter estimate using injection data from well K-37

Reservoir parameters	1. step	2. step	3. step	Best estimate (Step 3)	Units
Transmissivity (T)	$2.2 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$m^3/(P \cdot s)$
Storativity (S)	$6.6 \cdot 10^{-8}$	$6.2 \cdot 10^{-8}$	$7.7 \cdot 10^{-8}$	$7.7\ 10^{-8}$	$m^3/(Pa \cdot m^2)$
Radius of investigation (r_e)	287	60	61	61	m
Skin factor (s)	-2.4	-2.3	-2.5	-2.5	-
Wellbore storage (C)	$9.3 \cdot 10^{-6}$	$1.1 \cdot 10^{-5}$	$6. \cdot 10^{-6}$	$6. \cdot 10^{-6}$	$m^3/(Pa)$
Permeability (k)	$1.36 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$	m^2
Injectivity index	3.6	4	3.9	3.9	(l/s)/bar

3.5 Testing of well K-38

Well K-38 is a directional well which was drilled from 26.04.2008 to 20.07.2008 to a total measured depth of 2693 m. An injection test was performed on 20/07/2008. The injection rate was constant, 45 l/s, before the injection test started. The injection was conducted in three steps, as illustrated in Table 7 and in Figure 16.

TABLE 7: Injection rate and pressure response

20/07/2008	Before starting	Step 1	Step 2	Step 3
Time period	-	02:59 - 05:58	05:58 - 10:30	10:30 - 13:35
Duration (hr)	-	3	4.5	3
Injection (l/s)	45	25	35	45
Change in injection $\|\Delta Q\|$ (l/s)	-	20	10	10
Pressure at the end of step (bar-g)	117	109	113	116
Change in pressure $\|\Delta p\|$ (bar-g)	-	8	4	3

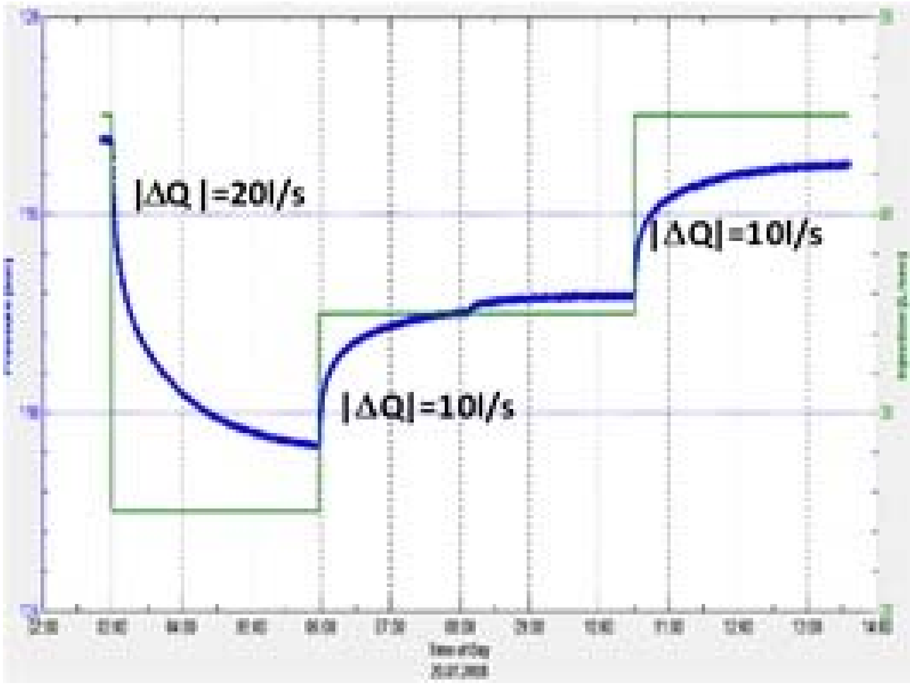

FIGURE 16: Step rate injection and pressure response for Well K-38

A non-linear regression analysis was done to find the parameters of the model that best fit the data. Initial parameters that were used to describe the reservoir in this analysis are estimated reservoir temperature 320°C, wellbore radius 0.18 m, and an estimated reservoir pressure 113 bar was found by WellTester. Two types of models were considered for the reservoir, on one hand a homogeneous reservoir and on the other hand a dual porosity reservoir. The best fit between the model and the data was obtained for a homogenous reservoir, constant pressure boundary, constant skin and wellbore storage.

Pressure change during step rate injection in K-38 as well as the change in injection for each step are illustrated in Figure 16. Figure 17 shows on a linear scale how the chosen model fits the data in step 3 and Figure 18 shows the pressure on a linear scale using a logarithmic timescale. Figure 19 shows the pressure change on a logarithmic scale, also using a logarithmic timescale, together with the derivative of the pressure response multiplied by the time passed since the beginning of the step.

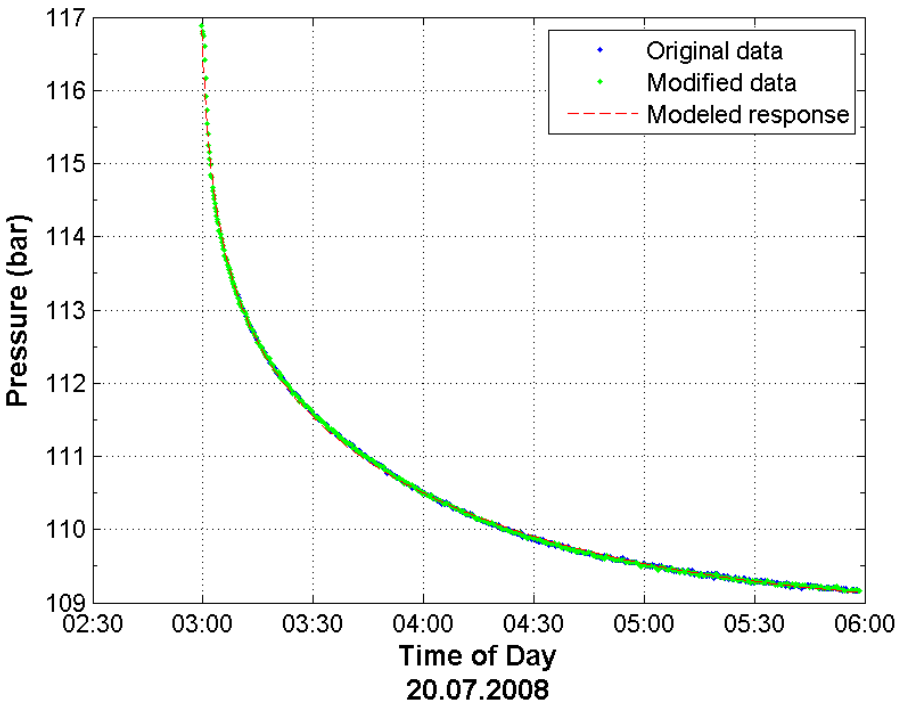

FIGURE 17: Pressure against time for model results and collected data for step 3

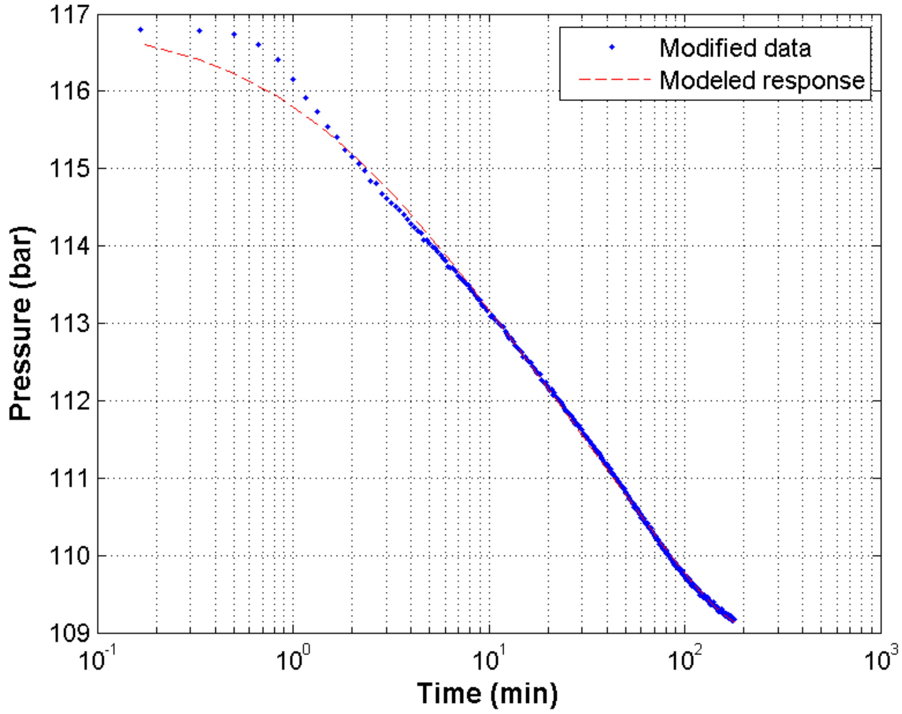

FIGURE 18: Pressure against time for model results and collected data for step 3, using a logarithmic time scale

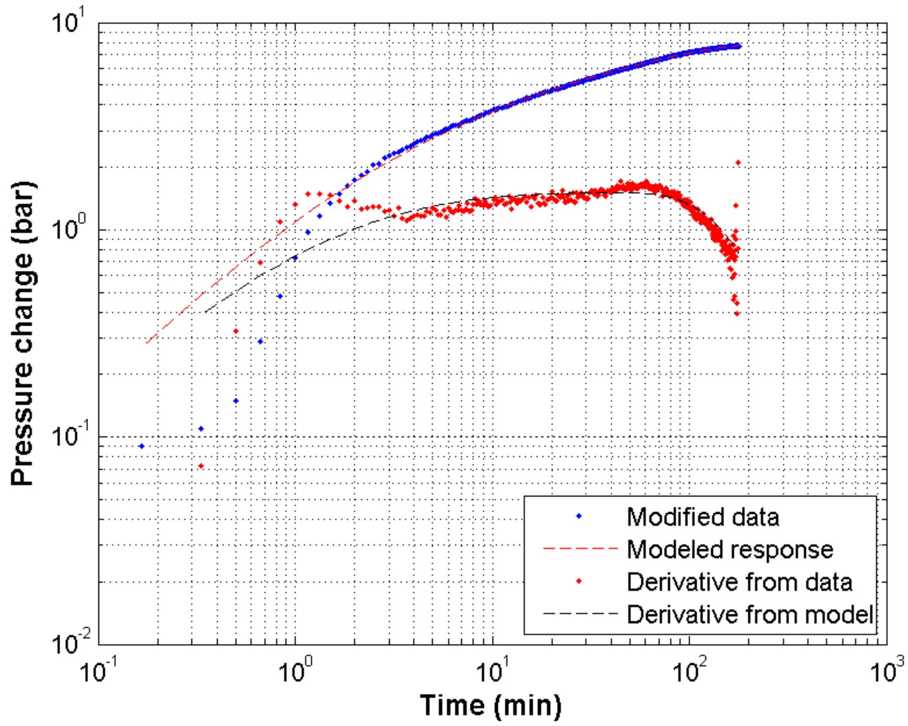

FIGURE 19: Pressure and its derivative against time for model results and collected data for step 3 on a log-log scale

Table 8 shows the reservoir parameters estimated by using the selected model.

TABLE 8: Results from non-linear regression parameter estimate using injection data from well K-38

Reservoir parameters	1. step	2. step	3. step	Best estimate	Units
Transmissivity (T)	$1.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	$m^3/(Pa.s)$
Storativity (S)	$5.5 \cdot 10^{-7}$	$4.6 \cdot 10^{-7}$	$4.6 \cdot 10^{-7}$	$4.6 \cdot 10^{-7}$	$m^3/(Pa.m^2)$
Radius of investigation (r_e)	71	83	26	26	M
Skin factor (s)	-1.9	-1.7	-1.8	-1.8	-
Wellbore storage (C)	$6.6 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$	$m^3/(Pa)$
Permeability (k)	$1.1 \cdot 10^{-10}$	$1.4 \cdot 10^{-10}$	$1.6 \cdot 10^{-10}$	$1.6 \cdot 10^{-10}$	m^2
Injectivity index	2.6	2.7	3	3	(l/s)/bar

The injectivity index for well K-38 is lower than for well K-37, showing a lower permeability in this part of the reservoir. This could mean that well K-37 intersects more permeable structures than well K-38. This could also be partly due to the higher negative values of skin factor for well K-37.

3.6 Summary of injection test results

Table 9 summarises the results obtained by well test analysis of injection tests in four wells, two at Nesjavellir and two at Krafla. Transmissivity estimated for selected wells in Nesjavellir is of the same order of magnitude as that of the wells in Krafla, i.e. 10^{-8} $m^3/(Pa.s)$, which is common in geothermal reservoirs in Iceland according to the report from WellTester with results and descriptions of the resulting parameters (Júlíusson et al., 2008). The storativity for Krafla was higher than that of Nesjavellir for the selected wells which is also according to the report from WellTester, which says: "Common values for liquid-dominated geothermal reservoirs are around 10^{-8} $[m^3/(Pa \cdot m^2)]$ while two-phase reservoirs might have values on the order of 10^{-5} $[m^3/(Pa \cdot m^2)]$. Some of the wells in Krafla have a steam cap, including the two wells analysed, which shows a two-phase reservoir, but the selected wells in Nesjavellir are at the boundary of the reservoir and are liquid-dominated. Skin factor for the selected wells for both fields was negative as it usually is in Iceland. Permeability for wells in Krafla was higher than in the selected wells in Nesjavellir.

TABLE 9: Summary of the results of well test analysis for Krafla and Nesjavellir geothermal fields

Reservoir parameters	NJ-15	NJ-18	K-37	K-38	Unit
Transmissivity (T)	$1.3 \cdot 10^{-8}$	$2.8 \cdot 10^{-8}$	$2.1 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	$m^3/(Pa \cdot s)$
Storativity (S)	$6.4 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$7.7 \cdot 10^{-8}$	$4.6 \cdot 10^{-7}$	$m^3/(Pa \cdot m^2)$
Radius of investigation (r_e)	46	174	61.0	26	m
Skin factor (s)	-2.2	-1.3	-2.5	-1.8	-
Wellbore storage (C)	$8.4 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$6. \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$	$m^3/(Pa)$
Permeability (k)	$4 \cdot 10^{-15}$	$4.6 \cdot 10^{-14}$	$1.3 \cdot 10^{-13}$	$1.6 \cdot 10^{-10}$	m^2
Injectivity Index	2.7	2.2	3.8	2.8	((l/s)/bar)

4. TEMPERATURE AND PRESSURE PROFILES ANALYSIS

An analysis of temperature and pressure profiles was performed in four wells, two at Nesjavellir (NJ-15 and NJ-18) and two at Krafla (K-37 and K-38). The purpose of the analysis was to estimate the undisturbed conditions of the reservoir before drilling, i.e. formation temperature and initial pressure conditions. Berghiti and PREDYP programs included in the ISOR software package ICEBOX (Arason et al., 2004), were used to estimate the formation temperature and initial pressure, respectively. The software BOILCURV (Arason et al., 2004), also from the ICEBOX package, was used to estimate boiling conditions in the well. The following section outlines the theory related to the estimation of the formation temperature, initial pressure and the boiling depth curve. After that, interpretation of the analysis of downhole temperature and pressure profiles for the selected wells is presented.

4.1 Formation temperature, initial pressure and boiling depth curve

4.1.1 Formation temperature

Knowledge of the formation temperature is important in the development and exploitation of geothermal reservoirs and especially in the estimation of reservoir potential. During drilling operations, the well and the close surroundings are cooled down by drilling fluid circulation and cold water injection. After drilling, the well is usually allowed to recover in temperature (warm up) from the cooling. The principal reservoir engineering research conducted during this period is repeated temperature and pressure logging. The temperature data thus collected is used to estimate the undisturbed system temperature, often called the formation temperature, as wells usually do not recover completely during the recovery period. Different methods can be used for this estimation, but the method most often applied is the so-called Horner method (Grant and Bixley, 2011).

The Horner method is a simple analytical technique for analysing recovery temperature to determine the formation temperature. In this method, the temperature recovery data is plotted against the logarithm of dimensionless Horner time, $\frac{(t_p+\Delta t)}{\Delta t}$, where t_p is the time at which circulation was stopped and Δt is the time passed since circulation stopped. A straight line is fitted to the data points, which is extrapolated to infinite Δt, i.e. when the Horner time becomes 1. The extrapolated temperature corresponding to this point is taken as the true reservoir temperature (Helgason, 1993). Figure 20 presents an example of a fit of the semi-log straight line relationship at 800 m for well NJ-15. The method is not applicable for all cases or at all depths in a well, for example not at depths where cross flow screens the actual temperature conditions.

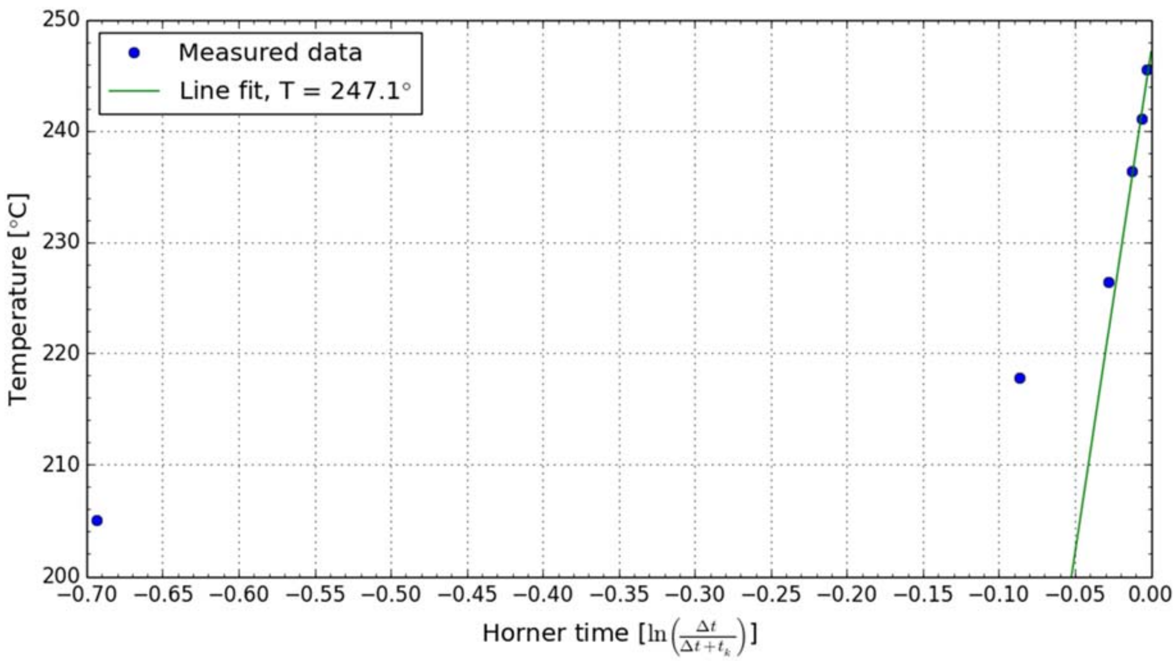

FIGURE 20: Formation temperature at 800 m in Well NJ-15

4.1.2 Boiling depth curve and initial pressure

Boiling curve with depth is described by the following integral (Arason et al., 2004):

$$p(z) = p_0 + g \int_{z_0}^{z} \rho_{sat}(p(z))dz \tag{9}$$

where ρ_{sat} is a function of p(z), which is the pressure at any depth z, p_0 is the pressure at some initial elevation z_0, g is the acceleration of gravity and $\rho_{sat}(p(z))$ is the fluid density in a column of single-phase water at saturation pressure.

This formula is also used for PREDYP but in this case $\rho_{sat}(p(z))$ is replaced by $\rho(T(z))$, where T(z) is the formation temperature with depth.

Equation 9 is non-linear and is solved numerically with the following formula:

$$p(z) = p_0 + g \sum_{i=1}^{n} \rho_{mean} \Delta z \tag{10}$$

where

$$\rho_{mean} = \frac{[\rho_{i-1}(p_{i-1}) + \rho_i(p_i)]}{2} \tag{11}$$

The total length z has been divided into n segments of length Δz and ρ_{mean} is the average density between the two depths z and Δz.

The problem is now to find the pressure and, hence, the saturation density $\rho_i(p_i)$ at our new depth z+Δz. This is done by using the Newton-Raphson iteration in the program BOILCURV. PREDYP program is used to calculate the initial pressure. The program calculates pressure in a static water column, if the temperature of the column is known (Arason and Björnsson, 1994). Both PREDYP and ICEBOX programs are found in the ICEBOX package.

4.2 Interpretation of temperature and pressure profiles for well NJ-15

Well NJ-15 is located in the eastern part of Nesjavellir geothermal field. It is a vertical well that was drilled in autumn 1985 to a total depth of 1748 m. Well NJ-15 was connected to the steam supply system from October 1998 until July 1999. Since then, well NJ-15 has been closed and is currently used for temperature and pressure monitoring. In the following section, temperature data which were collected during the warming up period were used to estimate formation temperature (Figure 21).

The temperature profiles in Figure 21 show a high gradient and linear profile, from 300 to 800 m, indicating a conductive zone. From 800 to 1300 m, there is a much lower gradient which could be due to a convective system and in this section the temperature is slightly less than a boiling condition but follows the boiling curve. Below 1300 m, there is an inversion in temperature down to 1500 m and an increase in temperature down to 1700 m. This inversion in temperature could be explained by a cold inflow at 1300 m.

The pressure profiles obtained during the warm up period and the initial pressure profile are shown in Figure 22. The pressure pivot point is located at around 1600 m and the pressure is 120 bar at that point.

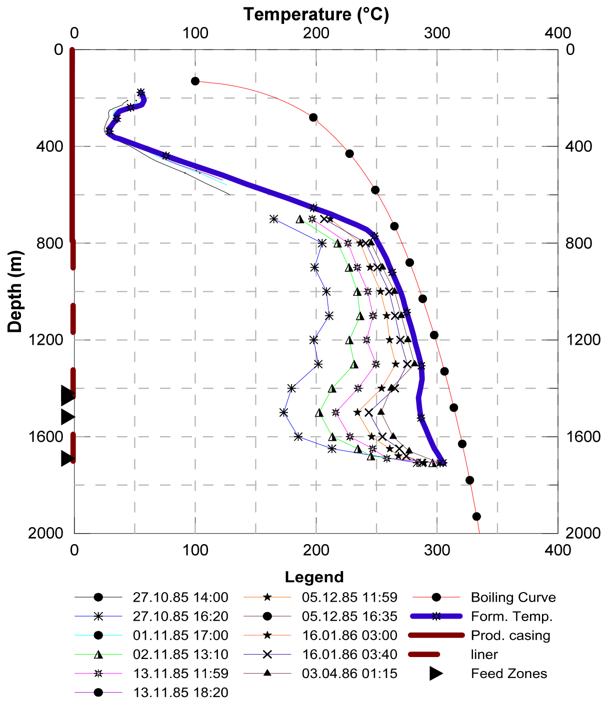

FIGURE 21: Temperature profiles for well NJ-15

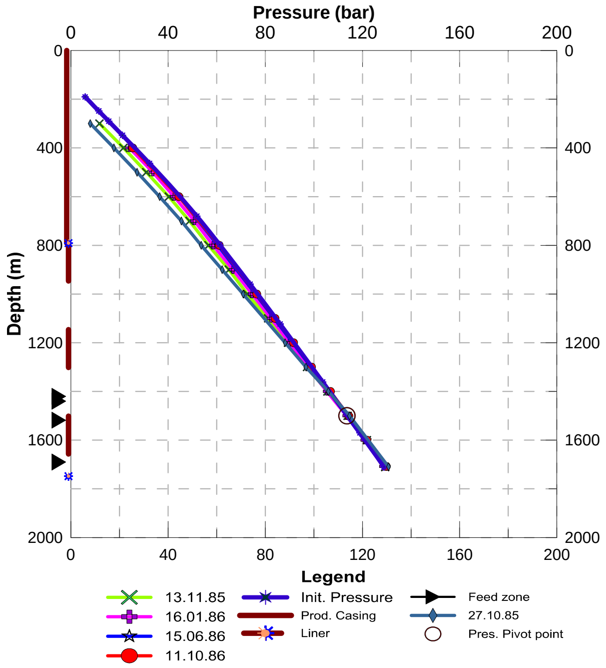

FIGURE 22: Pressure profiles for well NJ-15

To calculate the initial pressure, the estimated formation temperature profile from Figure 21 was substituted in the PREDYP program. The water level was adjusted in the calculations until the calculated profile matched the pivot point pressure. The pressure match was achieved with water levels at 203 m.

4.3 Interpretation of temperature and pressure profiles for well NJ-18

Well NJ-18 was drilled in 1986. It was not a productive well and was never connected to the steam supply system. It is currently used as a monitoring well. Temperature and pressure data were collected during the warm up period and were used to find the formation temperature and the initial pressure in a similar way as described for well NJ-15 in the previous section. Temperature profiles (Figure 23) show an increasing temperature with depth in the first 700 m. From 700 to 900 m, the temperature increases rapidly from 75 to 170 °C, and this suggests the possibility of a hot inflow within this range. Below 900 m there is a lower thermal gradient down to 1500 m and the zone can be interpreted as a convective zone but with poor permeability. Finally below 1700 m, the temperature gradient increases again down to the bottom of the well. Two feed zones are seen at 800 and 1700 m, respectively. The latest temperature profile is the same as the formation temperature profile between 800 and 1300 m.

Figure 24 shows the pressure profiles during warm up along with a pivot point that lies around 1700 m depth with a pressure of 150 bar.

To calculate the initial pressure, the estimated formation temperature profile from Figure 23 was inserted into the PREDYP software. The water level was adjusted in the calculations until the calculated profile matched the pressure pivot point.

4.4 Interpretation of temperature and pressure profiles for well K-38

Well K-38 in Krafla is a directional well located on the western flanks of Mt. Krafla which is a new

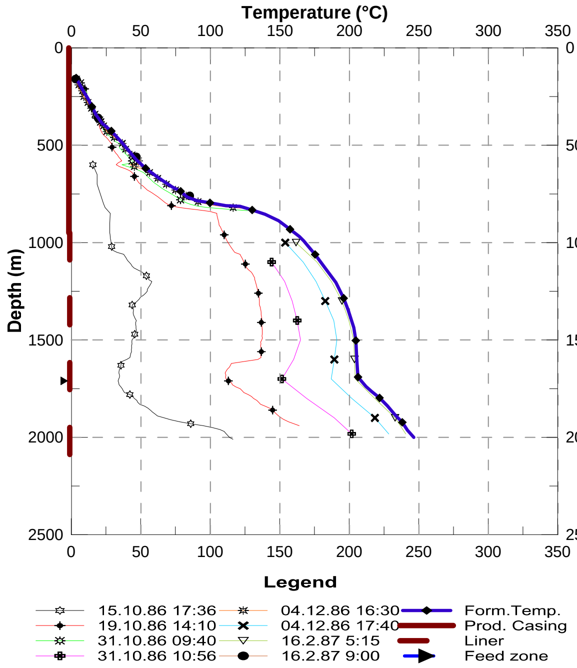

FIGURE 23: Temperature profiles for NJ-18

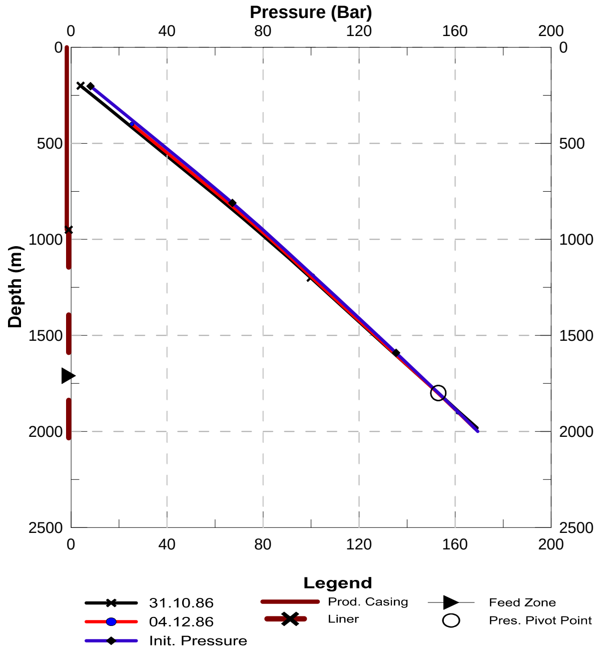

FIGURE 24: Pressure profiles for well NJ-18

well site in the field. It was drilled from 26.04.2008 to 21.07.2008 to a total depth of 2700 m with respect to the platform (2391.6 m TVD from the ground surface). Temperature profiles from July, August and September 2008 were used to estimate formation temperature (Figure 25). The formation temperature profile follows the boiling point curve in the top 1000 m. Two conductive layers were observed in the temperature profiles. The first layer (caprock) is located in the uppermost 300 m and the second layer (basement) between 1750 and 2000 m. There is a constant temperature zone between 300 and 1750 m depth. This zone can be interpreted as the reservoir (convective zone).

Figure 26 shows the pressure profiles during the warm up period. The pressure profiles show a pivot point at 2125 m where the pressure is about 130 bar (Figure 26). The pressure at the pivot point was

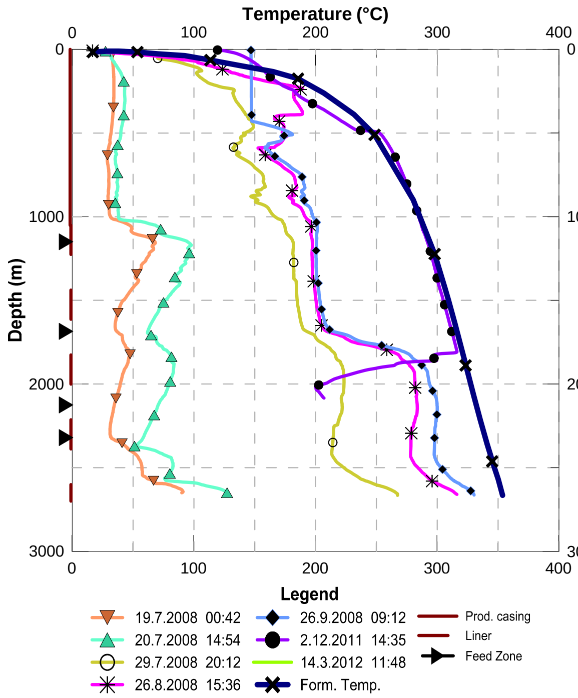

FIGURE 25: Temperature profiles for well K-38

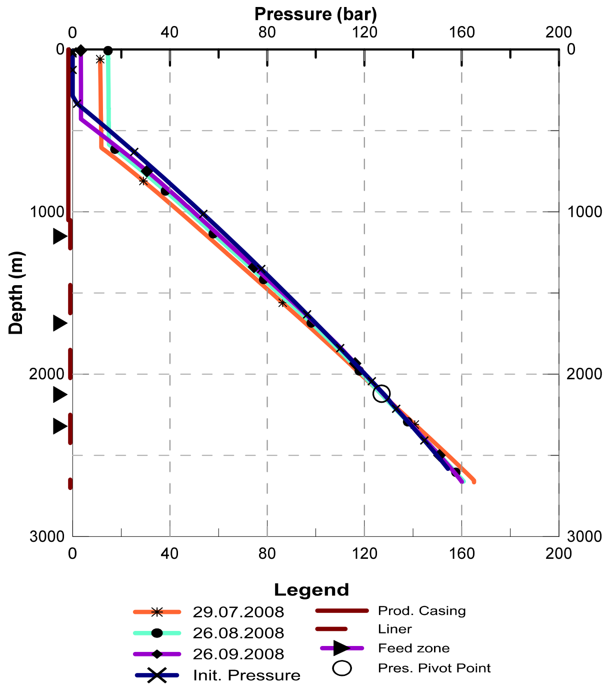

FIGURE 26: Pressure profiles for well K-38

used as a control point to estimate the initial pressure in a similar way as was described for wells NJ-15 and NJ-18 in the previous subsection.

4.5 Interpretation of temperature and pressure profiles for well K-37

Well K-37 in Krafla is a directional well drilled into the southern flanks of Mt. Krafla where there has been substantial production since 1980. It was drilled from 04.10.2007 to 18.01.2008 to a total depth of 2187 m. Downhole temperature and pressure data measured in January, March and April 2008 were used to estimate the formation temperature and initial pressure as shown in Figures 27 and 28.

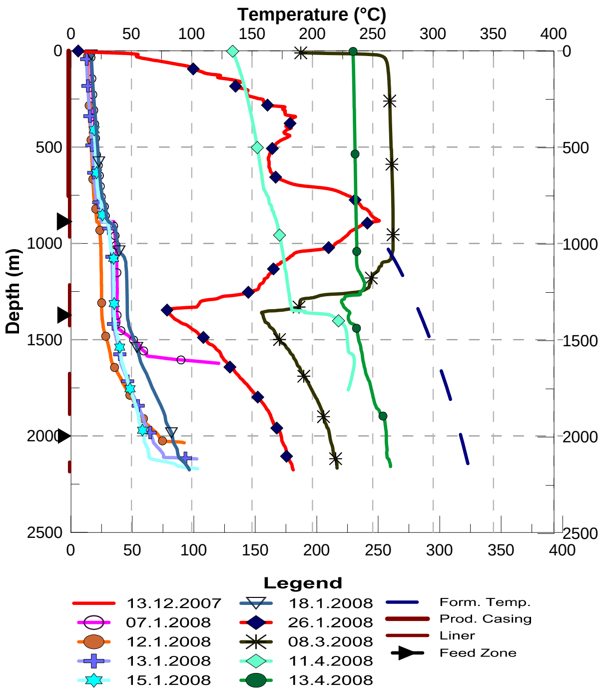

FIGURE 27: Temperature profiles for well K-37

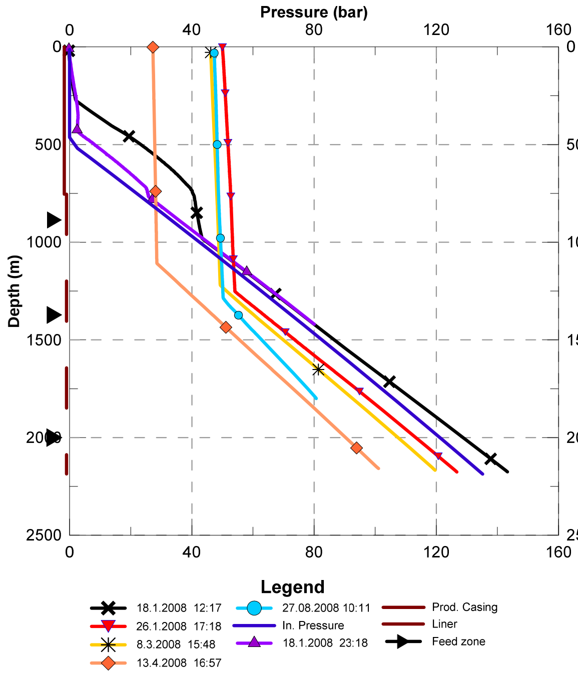

FIGURE 28: Pressure profiles for well K-37

Figure 27 shows the downhole temperature profiles and the formation temperature which follows the boiling point depth curve. However, the boiling point curve is shifted about 50 m due to drawdown in the system. Two major feed zones can be identified in the warm up temperature profiles: a hot inflow can be seen at 875 m depth and another feed zone can be observed at 1340 m. Between 0 and 300 m, the well shows conductive heating. Temperature profiles also indicate minor feed points at 590 and 1980 m.

Figure 28 illustrates the pressure profile during warm up. The pressure pivot point was not identified and the latest pressure profile (i.e. data measured on 27.08.2008) was used to determine the water level. Assuming this profile represents the actual reservoir conditions, the water level is at 450 m depth. Both formation temperature and initial pressure follow a boiling point curve as other wells on the southern flanks of the Krafla geothermal field (Mortensen et al., 2009).

5. PRESSURE AND TEMPERATURE MONITORING OF KRAFLA AND NESJAVELLIR GEOTHERMAL FIELDS

The purpose of careful monitoring of geothermal fields in utilization is to increase understanding of the geothermal fields, to prevent and to solve problems; the data is also necessary for simulation of geothermal fields. The effect of "large-scale" mass-extraction on geothermal systems may induce pressure decline within the system which, in turn, causes flow from hot springs (and wells) to decline, discharge from steam-vents often to increase, increased recharge (often colder water) from outside, cooling of the reservoir, chemical changes (sometimes detrimental), surface subsidence as well as changes in micro-seismic activity (Axelsson and Halldórsdóttir, 2014). Three wells, two located in Nesjavellir geothermal field and one located in Krafla were considered for a monitoring analysis in this report.

5.1 Monitoring wells in Nesjavellir geothermal field

Through the existence of the Nesjavellir project, an extensive monitoring programme was carried out to monitor the response of the Nesjavellir geothermal system as well as to record the influence of utilization on the environment. A programme was set up to monitor the natural runoff from the field in the early 1980s, prior to the drilling and testing of production wells (Gíslason et al., 2005).

Since the start of drilling in the 1980s, downhole measurements, flow testing and chemical sampling have been included in the monitoring programme. Water levels or wellhead pressure are monitored when boreholes are not in production, depending on the characteristics of each borehole.

Since 1985, annual downhole temperature and pressure logs in idle wells have been measured and the data stored in the ÍSOR database (Gíslason et al., 2005). In the beginning several wells were available for the monitoring but, since production started, most production wells have been connected to the power plant, limiting the current monitoring programme to two wells: Well NJ-15 in the eastern part of the production area and well NJ-18, north of the production zone (Figure 1).

In this field, therefore, we will focus on the downhole pressure and temperature measurements performed on the two monitoring wells, i.e. wells NJ-15 and NJ-18, and continue the studies of these two wells. Data used for the analysis was collected from 1985 to 2013 and 1986 to 2013 for wells NJ-15 and NJ-18, respectively.

Figure 29 shows the formation temperature and initial pressure with the temperature and pressure history at 810 and 1590 m depths, considered to be the main feed zones for well NJ-15. Figure 30 illustrates formation temperature and initial pressure with temperature and pressure history at 1710 m, which is expected to be the main feed zone for well NJ-18. Formation temperature and initial pressure values at different depths were estimated from warm up data collected after drilling.

Measurement of temperatures at various depths for wells NJ-15 and NJ-18 shows no significant change in temperature with time, except in 2011 when a slight decrease in temperature was seen, and in 2012 a small increase in temperature was recorded for well NJ-15. This can be explained by the fact that, in May 2011, a flow test was carried out over a two week period; this could have allowed cold inflow from the eastern part of the hydrothermal system since well NJ-15 is located close to the eastern edge of the geothermal system. In March 2002, an injection test was conducted at well NJ-18 with 10 kg/s of 55°C of hot water injected into the well for three weeks. Temperature data measured during this period were not considered for this analysis. Since 2002 and up to 2013, there was a slow temperature recovery from 200 to 225°C.

Figure 29 shows a small decrease in pressure up to 1999, then a rapid decline from 1999 to 2013 at 810 and 1590 m. This rapid decrease in pressure may be due to the increase in production since 1999, observed in Figure 30. A linear constant pressure drawdown of about 7 bars was observed in well NJ-18 from 1985 to 2005 whereas from 2005 to 2013 the pressure decreased drastically to about 12 bars. Figure 31 shows the yearly production (kg/s) against time from 1984 to 2013.

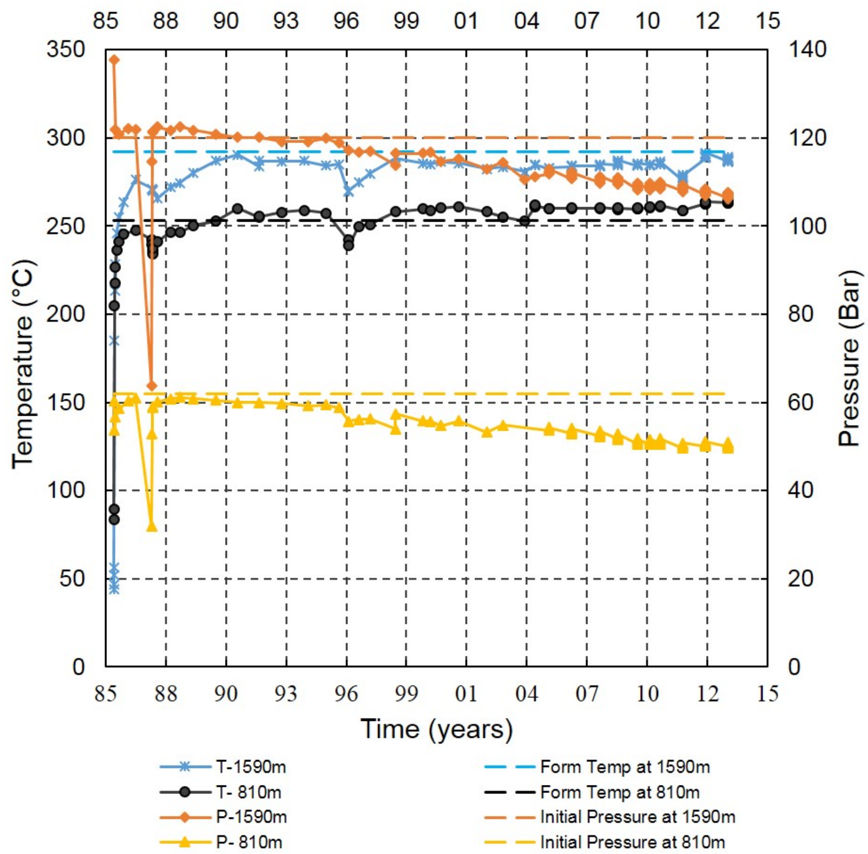

FIGURE 29: Temperature and pressure evolution from 1985 to 2013 for well NJ-15

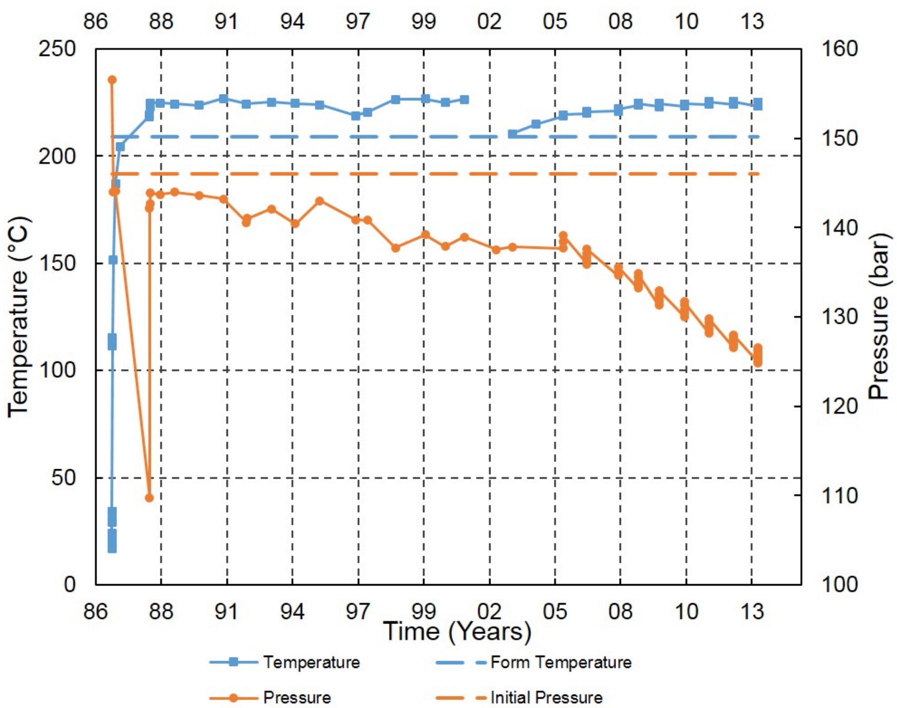

FIGURE 30: Temperature and pressure evolution at 1710 m from 1986 to 2013 for well NJ-18

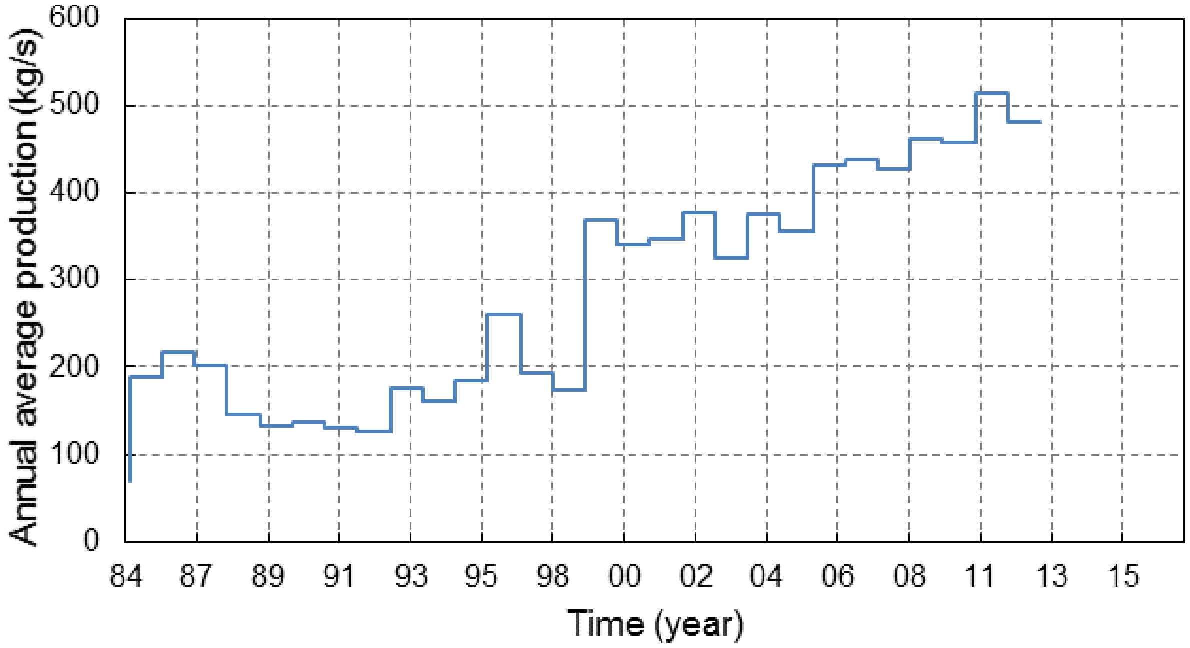

FIGURE 31: Average annual production in Nesjavellir from 1984 to 2013

5.2 Monitoring programme of Krafla geothermal field

Well KJ-18 was used for the monitoring programme of pressure and temperature evolution in Krafla geothermal system in this study. Well KJ-18 is located in the southeast part of Krafla geothermal field. It was drilled in 1981 to a total depth of 2215 m. During drilling, well KJ-18 was found to be very tight and it was decided not to put a slotted liner into it; production casing was set at 663m. During temperature recovery, it was found that the well was much colder than the wells to the west in the production area (Steingrímsson and Björnsson, 1996). Well KJ-18 was not a productive well and is currently used as one of the monitoring wells for Krafla geothermal system. Figure 32 shows the evolution of temperature at 1000, 1500 and 2000 m from 1981 to 2013 with the estimated formation temperature.

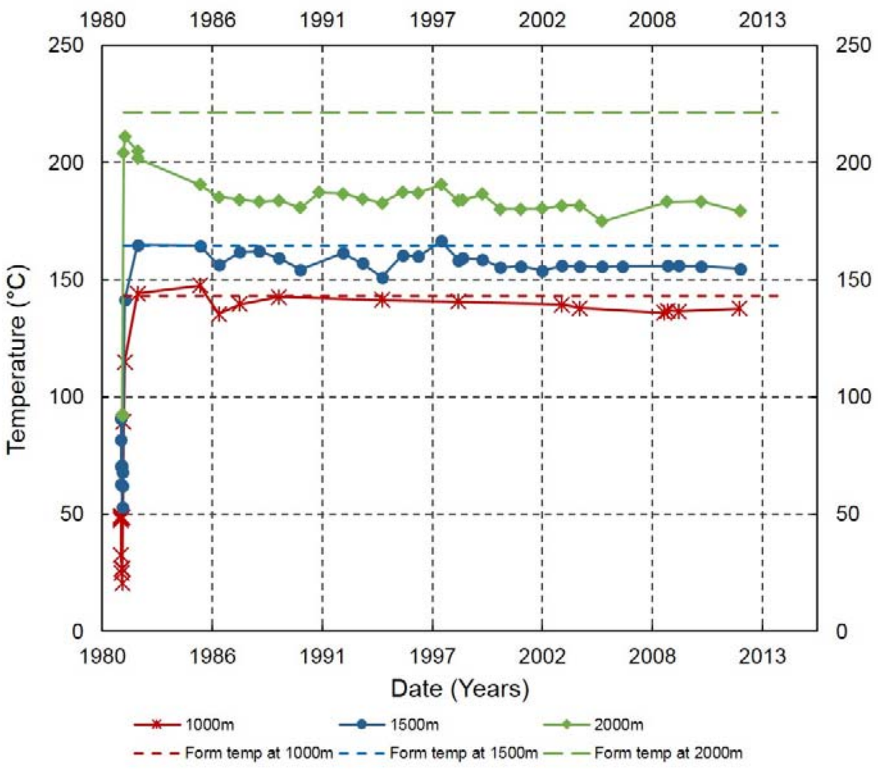

FIGURE 32: Pressure history for well K-18

As can be observed in Figure 32, there is a small change in temperature at 1000 m and 1500 m from 1981 to 2013. At 2000 m depth there is a rapid decrease from 1981 to 1988 and a small change in temperature since 1988 up to 2013. The rapid decrease in temperature at 2000 m was caused by a cold down flow from 1000 m feed point to the bottom of the well.

The pressure history is shown in Figure 33. From 1981 to 1991, the pressure had fallen by 6 bar once the production started in the area (Figure 34). The well showed little response to increased production in 1997. The well showed gradual linear pressure drawdown, about 15 bar since the beginning of production. Since the well is drilled at the eastern boundary of the geothermal field, the drawdown estimated from the monitoring data is probably an underestimate. Newly drilled wells on the southern flanks of Mt. Krafla show drawdown up to 30 bar (Mortensen et al., 2009). This was found by comparing the initial pressures of the wells. This corresponds roughly to 300 m change in water level and explains the depth to the water level in well K-37, as mentioned in the previous section.

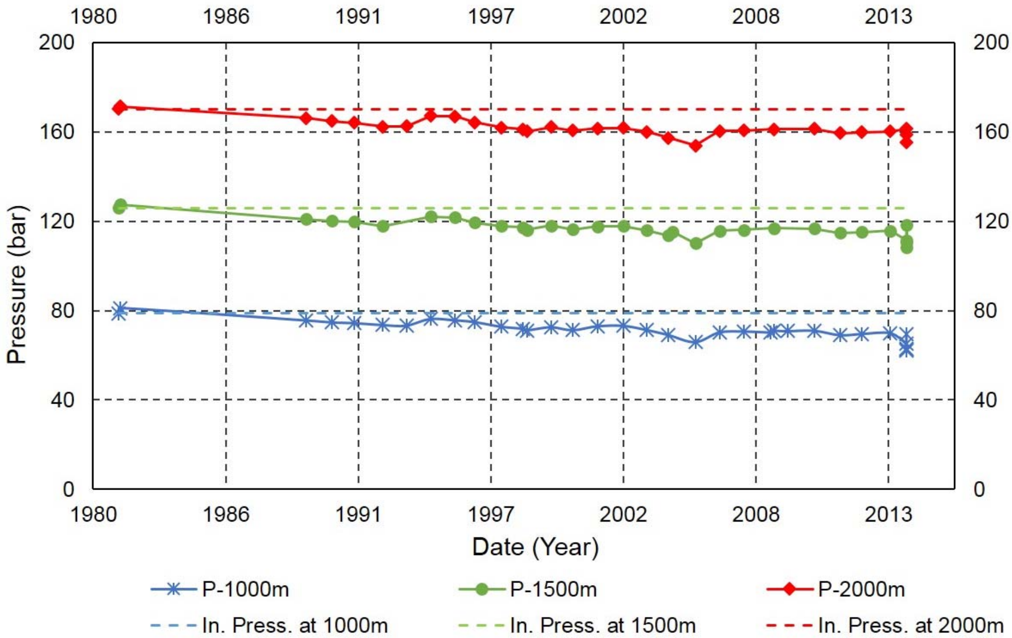

FIGURE 33: Pressure history for well K-38

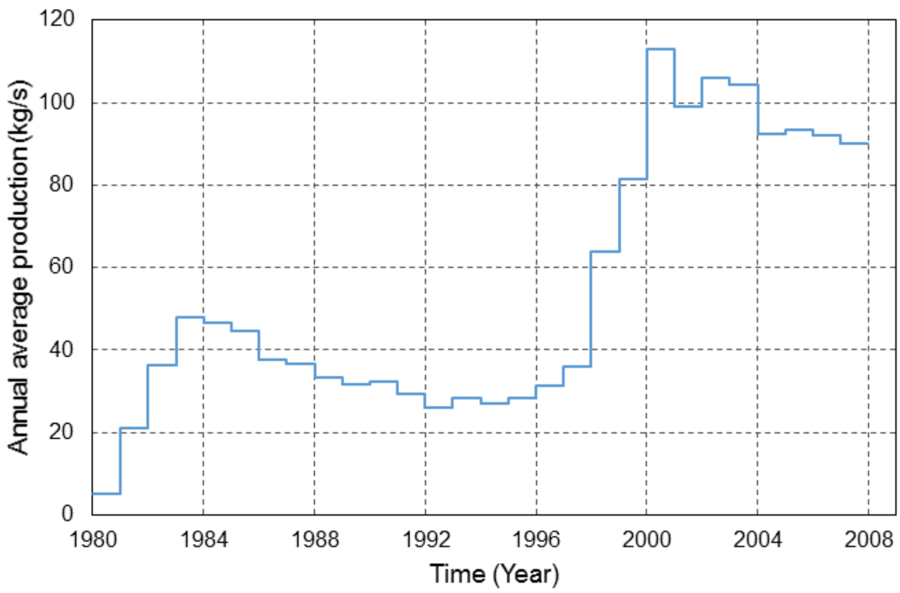

FIGURE 34: Average annual production from wells on the southern flanks of Krafla

6. CONCLUSION

Reservoir assessment and monitoring were conducted on selected wells in the Nesjavellir and Krafla high-temperature geothermal fields. Two wells, NJ-15 and NJ-18, were selected for reservoir assessment and monitoring for Nesjavellir and two other wells, K-37 and K-38, were selected for well test analysis for Krafla. Monitoring analysis was conducted only on well KJ-18 for Krafla.

In order to understand the parameters that characterise the reservoir and flow capacity of the selected wells, injection test analysis was performed and parameters such as injectivity index, transmissivity, storativity, skin, wellbore storage, etc. were evaluated. The WellTester program was used for the injection test analysis.

Transmissivity estimated for selected wells in Nesjavellir was of the same order of magnitude as for the wells in Krafla, i.e. 10^{-8} $m^3/(Pa·s)$, which is common in geothermal reservoirs in Iceland. The storativity for Krafla was higher than that of Nesjavellir for the selected wells. Some of the wells in Krafla have indeed, a steam cap, including the two wells analysed, which shows a two-phase reservoir, but the selected wells in Nesjavellir are at the boundary of the reservoir and are liquid-dominated. Skin factor for the selected wells for both fields was negative, as it usually is in Iceland. Permeability for the wells in Krafla was a little bit higher than in the selected wells in Nesjavellir. Wells NJ-15 and NJ-18 are probably not representative of the wells in Nesjavellir because they are located at the field boundaries. Perhaps these wells were drilled into a less permeable sector of the field.

Temperature and pressure profiles were analysed to estimate formation temperature and initial pressure. For wells NJ-18 and NJ-15, the highest formation temperatures were 250 and 300°C, respectively. Boiling was not observed for these wells, which indicates that these wells were drilled in a lower temperature part or at the boundary of the Nesjavellir field. Formation temperatures varied between 10 and 350°C and boiling was observed in the upper 1800 and 1000 m for wells K-38 and K-37, respectively. This indicates that these wells were drilled in a high-temperature reservoir.

Temperature and pressure monitoring at various depths were performed on well K-18 from 1981 to 2013 for Krafla, on well NJ-15 from 1985 to 2013, and on well NJ-18 from 1988 to 2013 for Nesjavellir. No significant change in temperature was observed in wells NJ-15 and NJ-18 but a linear constant pressure drawdown of about 13 bar was observed in well NJ-15 from 1985 to 2013 and a rapid decline in pressure (20 bar) was observed in well NJ-18 from 2006 to 2013. For Krafla geothermal system, slow pressure and temperature decreases were observed in well KJ-18 in general. The decrease in temperature is due to cold water down flow in the well, but the pressure decline is the effect of production in this part of the field. The well showed little response to increased production in 1997. The dynamic modelling methods such as lumped parameter models could be applied to calculate future predictions for future studies.

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NOMENCLATURE

c_t	: Total compressibility (Pa^{-1});
c_w	: Fluid compressibility (Pa^{-1});
c_r	: Rock compressibility (Pa^{-1});
h	: Reservoir thickness (m);
II	: Injectivity index ((l/s)/bar);
φ	: Porosity (%);
k	: Formation permeability (m^2);
p	: Pressure (Pa);
Q	: Volumetric flow rate (m^3/s);
ρ	: Fluid density (kg/m^3);
r	: Radial distance (m);
S	: Storativity ($m^3/(Pa \cdot m^2)$);
t	: Time (s);
T	: Transmissivity ($m^3/(Pa \cdot s)$);
Δp	: Change in reservoir pressure (Pa);
ΔQ	: Change in the injection flow (m^3/s);
v	: kinematic viscosity of the fluid;
C	: Wellbore storage coefficient (m^3/Pa);
ΔV	: Change in fluid volume (m^3);
s	: Skin factor;
r_e	: Radius of investigation (m);
t_p	: Circulation stop time (h);
hr	: Hour (h.);
T	: Temperature (°C);
ρ_{sat}	: Saturation density (kg/m^3);
ρ_{mean}	: Average density (kg/m^3);
z	: Depth (m);
g	: Acceleration of gravity (m/s^2);
μ	: Dynamic viscosity ($Pa \cdot s$).