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Geothermal Resource Assessment by Well Testing Methods, Case Study on Nw Sabalan Geothermal Field, Iran

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ABSTRACT

Assessment of the properties and capacity of geothermal resources involves various kinds of logging tests, data interpretation, monitoring and modeling. This ranges from the analysis of data collected during warm up and testing of single wells to the simulation of the response of geothermal reservoirs to utilization for years or even decades. The purpose of the well test analysis is to identify the type of reservoir involved and to determine the parameters of the reservoir quantitatively. Data from Well NWS-10D, that is, 10 th exploration well drilled towards the postulated up-flow area of the Sabalan Geothermal field has been analyzed by application of the computer software "Well Tester" developed at Icelandic geo survey company, ISOR. This work presents a comprehensive review of the theoretical background and methodology used in analyzing well test, temperature- and pressure logging data.

1. INTRODUCTION

Iran covers 1,648,000 km^2 in south-western Asia. It is bounded to the north by Azerbaijan, Armenia, Turkmenistan, and the Caspian Sea, to the east by Pakistan and Afghanistan, to the south by the Persian Gulf and the Gulf of Oman, and to the west by Turkey and Iraq. Iran also controls about a dozen islands in the Persian Gulf. More than 30 percent of its 4,770 - mile (7,680 km) boundary is seacoast. The capital is Tehran. One of the most ancient cities in Iran is Meshkin Shahr. It is located in the north-west of Iran in Azerbaijan and its distance from Tehran is 839 km and the distance to Tabriz (one of the large industry cities) is 160 km. Tabriz is the nearest city to the Sabalan high mountain. Sabalan is a large andesitic stratovolcano, the second highest volcano in Iranian Azerbaijan after Mount Damavand. The volcano is quite old, as its rocks have been dated to 5.6–1.4 million years. Some references state that volcanic activity continued into the Holocene, less than 10,000 years ago. The summit region has several peaks exceeding 4,500m a.s.l, primarily along a southwest-northeast trending ridge. The highest point 4,811m a.s.l is at the northeast end of the ridge. The mountain is located in a continental climate with hot, dry summers and extremely cold, snowy winters. Precipitation falls primarily as snow in the late autumn, winter and spring, and is sufficient to sustain seven glaciers near the summit above 4,000m a.s.l. The largest of these were more than 1.5km in length as of the 1970s. There are also extensive rock glaciers, several of which are more than 3km in length. The Mt Sabalan geothermal field is located in the Moil Valley on the north-western flank of Mt Sabalan. The resource area has been previously identified by geo-scientific studies as an approximately quadrangular shaped area that covers approximately 75km^2.

2. DOWNHOLE CONDITIONS IN SABALAN GEOTHERMAL FIELD

The eleven deep exploration and delineation wells that have been drilled well NWS-1was drilled from pad A, NWS-3, NWS-11RD was drilled from pad C, NWS-4, NWS-5D was drilled from pad B, NWS-6D, NWS-7D and NWS-10D was drilled from pad D, NWS-8D and NWS-9D was drilled from pad E. The wells vary in depth from 1901 m to 3197 m MD. Well NWS-1 was drilled vertically while NWS-3, NWS-4, NWS-5D, NWS-6D, NWS-7D, NWS-8D, NWS-9D, NWS-10D and NWS-11RD are deviated wells. Additionally, one shallow injection well, NWS-2, has been drilled to 600m depth, located on pad A alongside well NWS-1. The basic well completion data are summarized in Table 1 (Abdollahzadeh, Farhad 2015)

2.1 NWS-10D- Down hole well Surveys

Figure 1 shows the pressure and temperature profiles from the well. The main results are as follow:

- The temperatures are all below the BPD curve, indicating that the reservoir in this area of the field does not contain a two-phase mixture of steam and water. Temperatures behind the casing of NWS-10D at an elevation of about 990 m are close to BPD conditions, indicating possible proximity to two-phase fluid.
- Below 500 to 900 m temperatures increase with depth.
- The hottest temperature has been estimated is around 237^{o}C.
- Non artesian-no high-pressure on the wellhead and water level deep in the well. Must be stimulated to flow.
- The pivot point of well are at pressure of about 95 bar other pivot points are around 120 bar, but is not clear.

3. THEORETICAL BACKGROUND ON WELL TESTING

3.1 Well and reservoir assessment procedures

In a hydrological well test, such as for a geothermal well, the pressure response of a given well and reservoir, due to production or injection, is monitored. Well testing is conducted in order to evaluate the conditions of a well, its flow capacity and the reservoir properties. The most important properties are the transmissivity or the permeability-thickness and formation storage coefficient of the reservoir. These are not evaluated directly from the data. The data has to be interpreted on the basis of the most appropriate model, resulting in average values. In addition the properties are model dependent. After a successful drilling programme, typical high-enthalpy well assessment in Iran is undertaken through multi-step injection tests, in order to estimate the main physical properties of the reservoir around the well like transmissivity and storativity. This is done by assuming some values for the porosity and compressibility of the basalt rock and fluid. Also well parameters such as injectivity index, wellbore storage factor and skin

Table 1: Basic Completion Information for Wells

Well	Comp.Date	T.D mMD	Production	Casing	Production	Liner
			Size (in)	Depth (mMD)	Size (in)	Depth (mMD)
NWS-1	01-Jun-03	3197	9-5/8	1586	7	3197
NWS-2	25-Jun-03	638	13-3/8	360	9-5/8	638
NWS-3	27-Nov-03	3166	13-3/8	1589	9-5/8	3160
NWS-4	27-Mar-04	2265.5	9-5/8"	1166	7	2255
NWS-5D	31-Aug-08	1901	9-5/8"	750	7	1901
NWS-6D	28-Feb-09	2377	9-5/8"	1250	7	2377
NWS-7D	11-Aug-09	2705	9-5/8"	1313	7	2705
NWS-8D	17-Jan-10	2413.5	9-5/8"	1438	7	2413.5
NWS-9D	07- Dec- 10	2703	9-5/8"	1101	7	2700
NWS-10D	08- Sep-10	2300	9-5/8"	977	7	2300
NWS-11RD	22-Apr-2011	2813	9-5/8"	1286	7	2813
The Total Drilled: Km						26.5

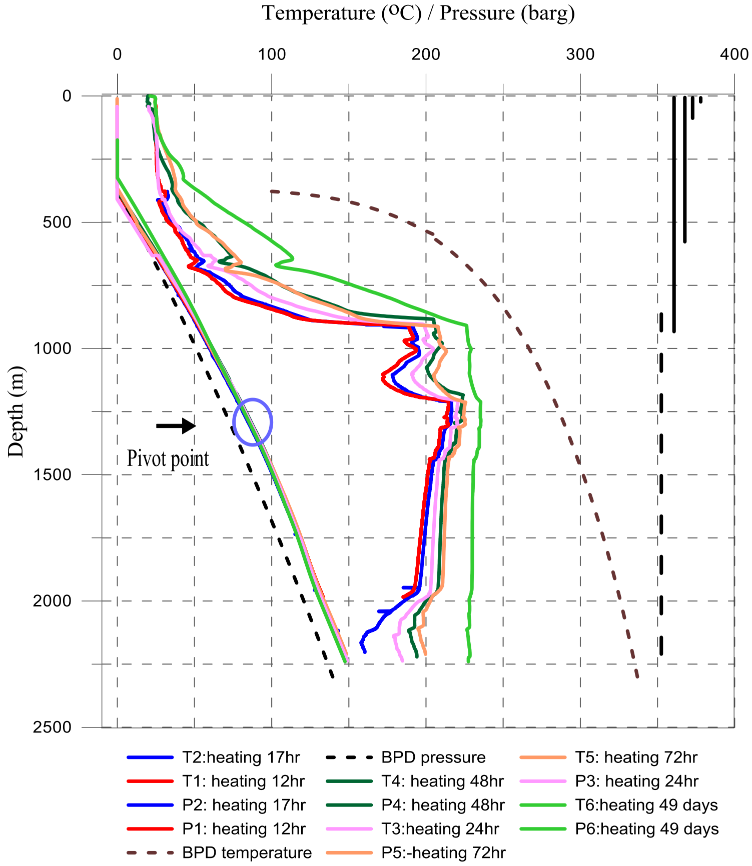

Figure 1: Down hole Survey Plot for Well NWS-10D (Abdollahzadeh, Farhad 2014).

factor are determined in the step injection test. In this study a well test simulator program Well Tester was used to simulate data from such tests and compared with the results from 'classic methods' like semi log, log-log and type curve methods. After this the well is closed in order to allow it to warm-up and reach the steady state formation temperature (often 3-4 months). During and after the well testing, the temperature and pressure profiles of the well are logged and from that information the phase conditions of the fluid, the real formation temperature, the flow paths and the main feed zones can be obtained. However, caution must be taken when interpreting logs as measurements are not made directly in the reservoir but in the well where internal flows and boiling can cause disturbances and give misleading results, even though the well is shut-in. When a well is not flowing, the aquifers (feed zones) usually warm up more slowly after drilling, than impermeable rock, making it easier to determine the feed zones. (Stefansson and Steingrimsson, 1990).

3.1.1 The pressure diffusion equation

The basic equation of well testing theory is the pressure diffusion equation. It is used to calculate the pressure (*P*) in the reservoir at a certain distance (*r*) from a production well producing at a given rate (*q*) as a function of time (*t*). The most commonly used solution of the pressure diffusion equation is the so-called Theis solution or the line source solution (Earlougher, 1977; Horne, 1995). The three governing laws used in deriving the pressure diffusion equation are the following (Earlougher, 1977; Horne, 1995):

Conservation of mass inside a given control volume:
Mass flow in - Mass flow out = Rate of change of mass within the control volume
Conservation of momentum, expressed by Darcy's law:

$$q = 2\pi rh\frac{k}{\mu}\frac{\partial P}{\partial r} \tag{1}$$

Where q = Volumetric flow rate (m^3/s), h = Reservoir thickness (m), k = Formation permeability (m^2), P = Reservoir pressure (Pa), r = Radial distance (m), μ = Dynamic viscosity of the fluid (Pa.s)

Equation of state of the fluid:

$$\rho = \rho(P,T) \tag{2}$$

Compressibility of the fluid:

$$c_f = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T \tag{3}$$

where c_f = compressibility of the fluid (Pa-1), ρ = Density of the fluid (kg/m3), T = Temperature (°C), P = Pressure (Pa)

By combining the three equations above and using the above assumptions, the pressure diffusion equation is given by:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\partial P(r,t)}{\partial r}\right) = \frac{\mu c_t}{k}\frac{\partial P(r,t)}{\partial t} = \frac{S}{T}\frac{\partial P(r,t)}{\partial t} \tag{4}$$

Where $c_t = \varphi c_f + (1-\varphi)\, c_r$ = Total compressibility of rock and water (Pa^{-1}), φ = Porosity, $c_r = \frac{1}{1-\varphi}\frac{\partial \varphi}{\partial P}$, is the compressibility of the porous rock., $S = c_t h$, is the storability, $T = \frac{kh}{\mu}$, is the transmissivity.

The solution to the radial diffusion equation with these boundary and initial conditions is given by:

$$P(r,t) = P_i + \frac{q\mu}{4\pi kh}Ei\left(\frac{-\mu c_t r^2}{4kt}\right) \tag{5}$$

Where $Ei(-x) = -\int_x^\infty \frac{e^{-u}}{u}du$ is the exponential integral function. If $t > 100\frac{\mu c_t r^2}{4k}$ the exponential integral function can be expanded by a convergent series and thus, the Theis solution, for a pumping well with skin gives the total pressure change as:

$$\Delta P_t = P_i - P(r,t) = -\frac{2.303 q\mu}{4\pi hk}\left[log\left(\frac{\mu c_t r^2}{4kt}\right) + \frac{0.5772-2s}{2.303}\right] \tag{6}$$

Where s = skin factor. Skin is an additional pressure change to the normal pressure change in the near vicinity of the well due to the drilling of the well. A negative skin factor indicates that the well is in good communication with the reservoir.

3.1.2 Semi-logarithmic well test analysis

A plot of the Theis solution for ΔP vs. log t gives a semi-log straight line with a slope m per log cycle. This gives the response for the infinite acting radial flow period of a well, and this method is referred to as semi-log analysis (Earlougher, 1977; Horne, 1995).

$$m = \frac{2.303 q\mu}{4\pi kh}\ (Pa\ /\ log\ cycle) \tag{7}$$

The skin-factor is given by:

$$s = 1.151 * \left[\frac{\Delta P_t}{m} - log\left(\frac{k}{\varphi\mu C_t r_w^2}\right) - log(t) - 0.351\right] \tag{8}$$

"The semi-log analysis is based on the interpretation of the semi-log straight line response that represents the infinite acting radial flow behaviour of the well. However, an actual wellbore has finite volume, and it becomes necessary to determine the duration of the wellbore storage effect or the time at which the semi-log straight line begins. The wellbore storage effect can be identified by a unit slope relationship when the data is plotted on a log (ΔP) vs. log (t) graph. After about 1½ log cycle from the end of the unit slope line, the semi log straight line is expected to start" (Earlougher, 1977; Horne, 1995).

"As time proceeds, the response is characteristic of conditions further and further away from the wellbore. At very late time, the pressure response is affected by the influence of reservoir boundaries, but prior to those late times the pressure response does not "see" the reservoir boundaries, and the reservoir acts as if it were infinite in extent. This intermediate time response, between the early wellbore-dominated response and the late time boundary-dominated response, is known as the infinite acting period" (Earlougher, 1977; Horne, 1995).

3.1.3 Injection tests

Injection testing is in principle a simple variant of discharge flow testing, with the flow reversed. Water is injected into a well and the flow rate recorded along with the changes in the down-hole pressure or the depth to the water level. A quasi-stable flow versus pressure curve can be obtained, and transient behavior measured at changes in flow rate. Injection is a simple inverse of production if the fluid injected is of the same enthalpy (quality or temperature) as that produced. Generally, the fluid injected is water that is cooler than the reservoir temperature and thus has different viscosity and compressibility than the reservoir fluid (Grant et al., 1982). The non-isothermal injectivity index obtained from these tests depends on the mobility ratio of the cold region to the hot reservoir and the extent of the cold spot. Sigurdsson et al. (1983) propose a method for estimating the apparent viscosity, which accounts for these effects and relates the non-isothermal injectivity index to the isothermal injectivity index. The injectivity index (*II*) obtained from injection tests, is often used as a rough estimate of the connectivity of the well to the surrounding reservoir. Here it is given in the units [(L/s)/bar] and it is defined as the change in the injection flow rate divided by the change in the stabilized reservoir pressure.

$$II = \left|\frac{\Delta Q}{\Delta P}\right| \tag{9}$$

Where $\Delta Q = Q_{end\ of\ step} - Q_{beginning\ of\ step}$ and $\Delta P = P_{end\ of\ step} - P_{beginning\ of\ step}$.

In Well Tester, the pressure values used to calculate II are taken from the modeled response (not the actual data collected).

4. INJECTION TEST DATA AND INTERPRETATION

Most of the text in this section is generated from the Well Tester report generator. (Júlíusson et al., 2007)

4.1 NWS-10D injection test

A four-rate step injection test was conducted on 09.03.2010 lasting about 13 hours on NWS-10D. The pressure gauge used to monitor the pressure changes in the well was installed at around 1100 m depth. The four step injection rates were 21, 31, 47 and 2 L/s, respectively. (Figure 2)

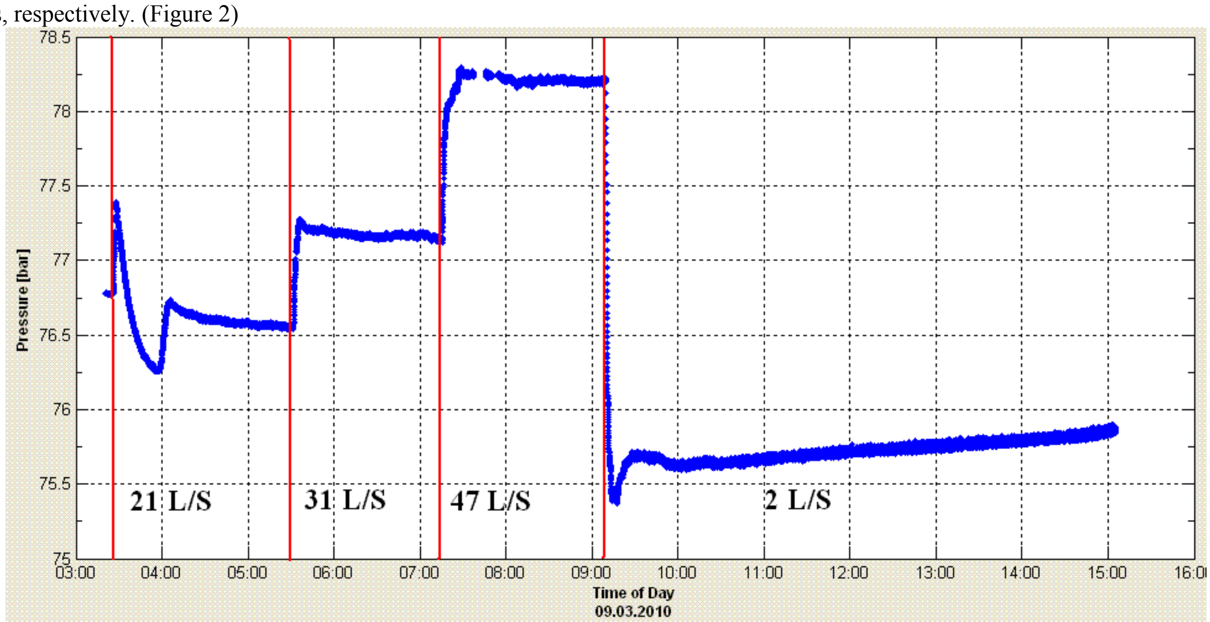

Figure 2: Pressures changes at 1100 m depth in well NWS-10D during injection testing of the well on 09.03.2010.

4.2 Initial Parameters

The Estimated Reservoir Pressure (P_{est}) and Estimated Reservoir Temperature (T_{est}) are average estimates for the part of the reservoir that is being investigated in the well test. These values are used to calculate approximate values of the dynamic viscosity of reservoir fluid and total compressibility. Wellbore Radius (r_w) is the average radius of the well at the reservoir depth, given in meters. Dynamic Viscosity of Reservoir Fluid (μ) is the estimated average viscosity of the fluid at reservoir conditions. In cases where the fluid is in two phases the average viscosity can be taken as the weighted harmonic average of the two phases. If x-curve relative permeability is assumed, the weighting can depend on the mass fraction of each phase (Horne, 2006). Total Compressibility (c_t) describes the ability of the fluid and reservoir rock to compress or expand as a function of pressure. Formulations for computing compressibility will be slightly different, depending on the physics of fluid and the reservoir, but a further discussion on that can be found in Grant et.al. (1982). Total compressibility will typically be on the order of 10^{-9} for a liquid-dominated reservoir, 10^{-7} for a dry-steam reservoir and 10^{-6} for a two-phase steam-water reservoir. Porosity (φ) is the volume fraction of the rock which is porous.

Table 2: Summary of initial parameter

Parameter Name	Parameter Value	Parameter Unit
Estimated Reservoir Temperature (T_{est})	180	[°C]
Estimated Reservoir Pressure (P_{est})	75.8	[bar]
Wellbore Radius (r_w)	0.20	[m]
Dynamic Viscosity of Reservoir Fluid (μ)	$1.52 \cdot 10^{-4}$	[Pa·s]
Total Compressibility (c_t)	$5.23 \cdot 10^{-10}$	[1/Pa]
Porosity (φ)	0.10	[-]

4.3 Selected models for welltester software

Table 3: Summary of model selected

Well Testing Model	
Reservoir	Dual Porosity
Boundary	Constant Pressure
Well	Constant Skin
Wellbore	Wellbore Storage

Figures 3, 4, 5 and 6 show plots of the data on a log-log scale. The plots show the derivative of the pressure response, multiplied with the time passed since the beginning of the step. This trend is commonly used to determine which type of model is most appropriate for the observed data. Using this model, nonlinear regression analysis was used to find the parameters that best fit the observed data. The resulting fit is shown graphically in Figure 8. Moreover, the regression analysis gives information on the quality of the parameter estimate, represented here by the upper and lower limits of a 95% confidence interval and by the coefficient of variation C_v, given as a percentage in Table 4.

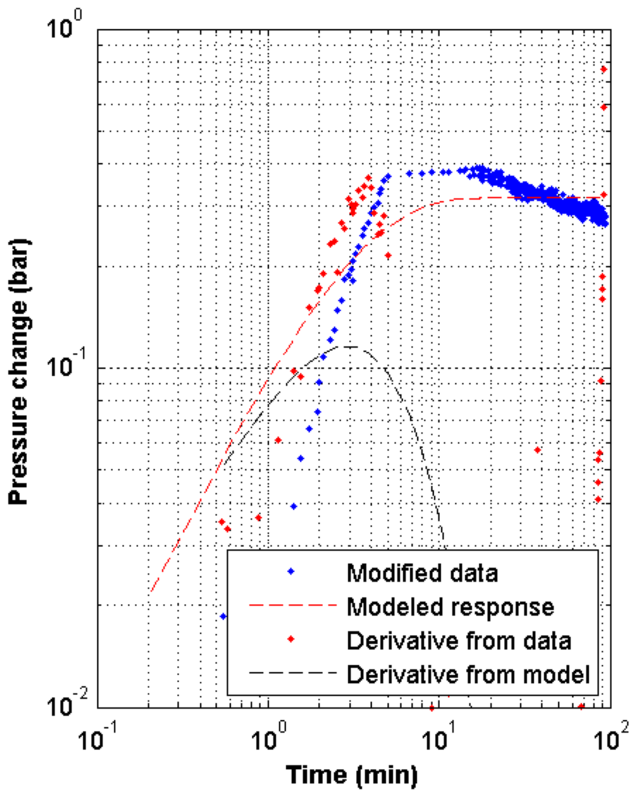

Figure 3: log-log scale for step 1.

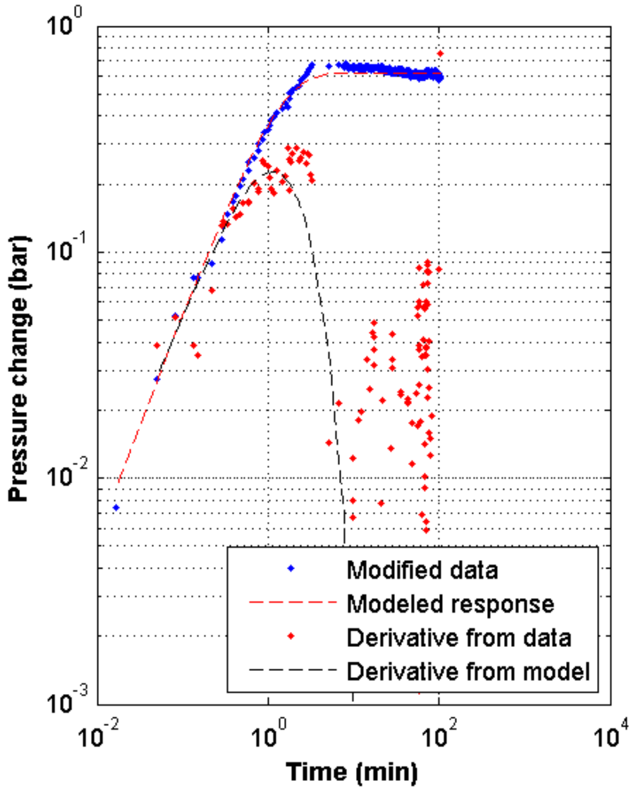

Figure 4: log-log scale for step 2.

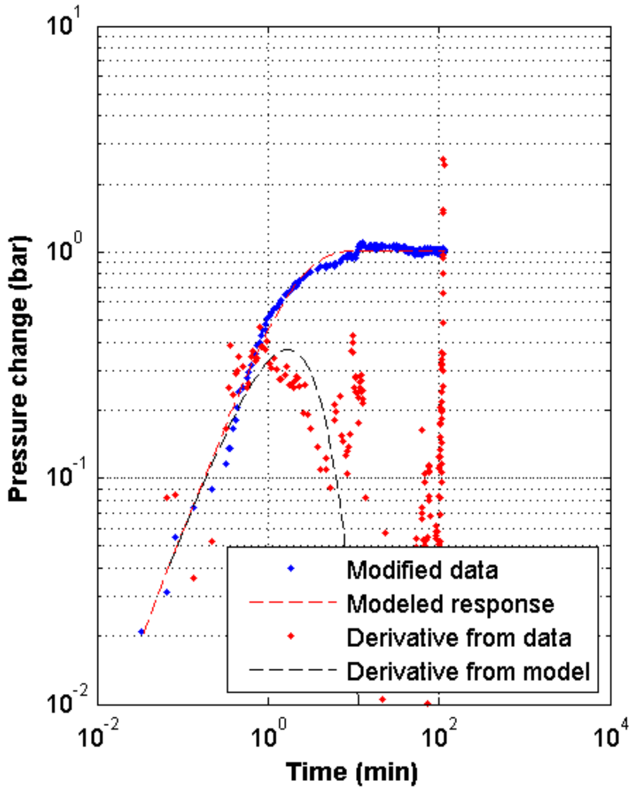

Figure 5: log-log scale for step 3.

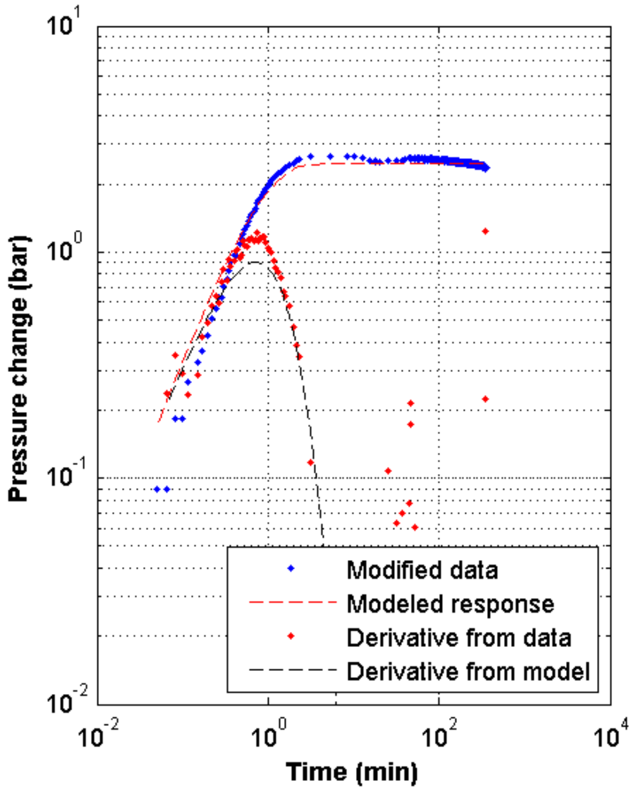

Figure 6: log-log scale for step 4.

The values obtained for transmissivity and storativity can be used in conjunction with the given initial parameters to deduce an estimate on the reservoir thickness and effective permeability. The estimated reservoir thickness is 1.8 km and the effective permeability is ≈ 22.12 mD.

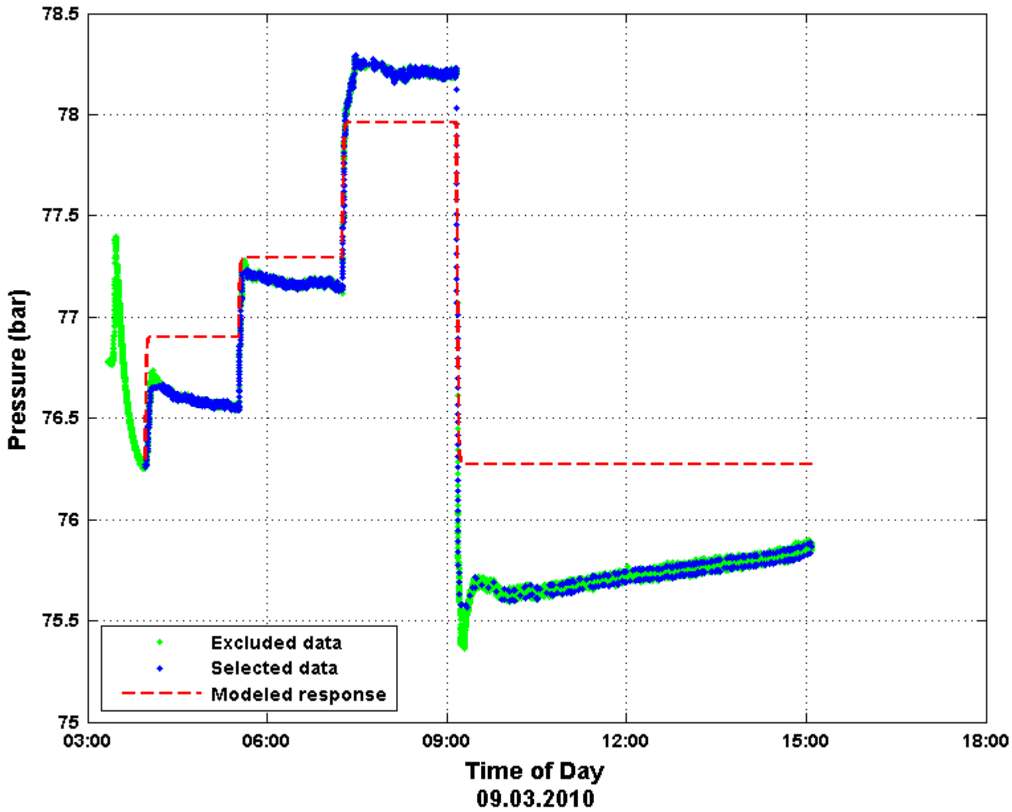

Figure 7: Fit between model and collected data

Table 4: Summary of results from nonlinear regression parameter

Parameter Name	Parameter Value	Lower bound 95 % C.I.	Upper bound 95 % C.I.	CV [%]	Parameter Unit
Transmissivity (T)	$3.82 \cdot 10^{-8}$	$2.74 \cdot 10^{-8}$	$4.90 \cdot 10^{-8}$	14.2	$m^3/(Pa \cdot s)$
Storativity (S)	$3.07 \cdot 10^{-7}$	$2.13 \cdot 10^{-7}$	$4.01 \cdot 10^{-7}$	15.3	$m^3/(Pa \cdot m^2)$
Transmissivity Ratio (λ)	$1.12 \cdot 10^{-6}$	$-1.53 \cdot 10^{-6}$	$3.76 \cdot 10^{-6}$	118.2	-
Storativity Ratio (ω)	0.01	0.01	0.01	15.4	-
Radius of Investigation (r_e)	35.26	8.32	62.20	38.2	m
Skin Factor (s)	-4.23	-4.99	-3.47		-
Wellbore Storage (C)	$9.23 \cdot 10^{-6}$	$6.22 \cdot 10^{-6}$	$1.22 \cdot 10^{-5}$	16.3	m^3/Pa
Injectivity Index (II)	25.35				(L/s)/bar

CONCLUSION

Sabalan reservoir is a high-temperature and low pressure system.

The temperature of Sabalan reservoir is below boiling point so Sabalan is a liquid-dominated reservoir.

According to down hole data from NWS-10D, system has at least around 1.9 km tick convective zone below approximately 500 m and around 700 m thick cap rock with conductive heat flow.

The estimated permeability for well NWS-10D is about 22 mD, skin factor is -4 and II is about and 25 (l/s)/bar. Main feed zone of Well NWS-10D is around 1000-1200 and 2000- 2200-meter depth.

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