Temperature and Well Test Analyses of Selected Wells of Aluto Langano Geothermal Field, Ethiopia

Teka Nigussie Gebru

Ethiopian Electric Power (EEP)

Addis Abeba, Ethiopia

e-mail:teka2005@yahoo.com

Keywords

Temperature inversion, Pressure pivot point, heating period, Welltester, Transmissivity, Storativity,Injectivity index, Skin factor.

ABSTRACT

Aluto Langano geothermal field is one of the 24 geothermal prospects with potential of more than 70 MWe located in the Ethiopian main Rift Valley/System and has confirmed temperature greater than 200°C at a depth of 1000 m. Two geothermal prospects out of the 24 geothermal fields are identified recently in 2017/2018. Of the 10 deep wells drilled in the area, two of them are the only directionally drilled in 2015 to a measured depth of 1921 m and 1950 m. The remaining 8 wells are all vertical, drilled in the 1980`s. The objective of this report is to analyse the temperature and pressure in the newly drilled wells (LA-9D and LA-10D) in order to estimate the formation temperature of the geothermal system as well as to estimate the reservoir parameters of the field based on well test analysis of the wells, LA-4 (the old well) and LA-10D (new drilled well).The formation temperatures of the wells were estimated using the Horner method. The ultimate goal of temperature and pressure logging in geothermal investigation is to determine formation temperature and reservoir pressure of a well. Bottom hole formation temperature of wells LA-9D and LA-10D were estimated by extrapolation of a short term heating period using Horner plot method and the evaluation of formation temperature for both wells suggest that the reservoir temperature is in the range of 300-310°C.The injection test was processed in Welltester software, which is developed at Iceland GeoSurvey to estimate reservoir and well parameters. The data from the injection tests were too scarce to use directly in Welltester, so manually adding data where there were gaps were used, followed by interpolation in Welltester, and gradually gave good results with respect to the quality of the data. Storativity and transmissivity were of the order of magnitude 10^{-8}, which is similar to Icelandic high temperature geothermal wells. The skin factor was generally negative, which indicates that the permeability in the closest surroundings of the well is higher than farther away. The injectivity index is rather low, between 1.3 and 2.2 (L/s)/bar, which can explain partly that the wells have not been good producers.

1. Introduction

Geothermal utilization in Ethiopia began in 1886, when "EtegeTayitu" the wife of King Menelik II, built a bathhouse for herself and members of the Showa Royal Court in Addis Ababa near the "Filwoha" an Amharic term which means "boiled water", hot mineral springs (Wikipedia, 2017). The hot springs are still open to the public. In 1969, geothermal surface exploration started with a regional geo-volcanological mapping and hydrothermal manifestation inventory in most of the Ethiopian Rift Valley and Afar Depression and revealed that high and low enthalpy geothermal resources.(Teklemariam et al., 2000).Then, after several years of exploration activities, which included geological, geochemical and geophysical investigation, about eighteen (18) geothermal prospect areas were selected for further feasibility studies through drilling of exploration wells. Todate only 6 prospects are completed with feasibility studies (Figure 1), namely AlutoLangano, Tendaho, Corbetti, Abaya, Tulu Moye, Dofan and Fentale geothermal fields, based on their strategic locations, i.e. proximity to the existing grid and population density (Ministry of Mines and Energy, 2008). Prefeasibilty study for the two new geothermal prospects namely Butajira and Meteka geothermal fields has been conducted as a result good anomalies for geothermal is observed.

A total of 10 deep exploratory wells have been drilled at the AlutoLangano geothermal field to a maximum depth of 2500m. Information about the wells are shown in Table 1, 8 of the wells (LA-1 to LA-8) are drilled vertical, between 1981 and 1986 (ELC 2016), and two of them, LA-9D and LA-10D, are the first directional drilled wells in Ethiopia, to a depth of 1920 and 1950 m respectively, completed in 2016 (WestJEC 2016). Four productive wells among the earliest wells (LA-3, LA 4, LA-6 and LA-8) of the geothermal field have been supplying steam and brine to operate a binary pilot power plant commissioned in 1999, with approximately 7.3 MWe.

Consultancy service agreement between Ethiopian Electric Power (EEP) and a consultant (West Japan Engineering Company, WestJEC) has been signed to construct a 5 MWe Wellhead Power Plant from the two directional drilled and the construction works are expected in early 2019. The grant is from Japanese Government.

Table 1: Information about the exploratory wells located in Aluto Langano geothermal field (ELC, 2016)

Well	WH Coordinates		WH Elevation	Total Meas. Depth	Total Vertical Depth	Elevation of well bottom	Coordinates of well bottom		9 5/8" Casing Shoe	7" slotted liner	Notes
	North	East	m asl	m	m	m asl	North	East	MD (m)	MD (m)	
LA-1	853,308	474,047	1601	1317	1317	284	vertical well		702	800-1317	Sterile well
LA-2	861,501	469,489	1724	1602	1602	122	vertical well		892	950-1602	Sterile well
LA-3	860,723	477,401	1921	2144	2144	-223	vertical well		748	1035-2140	
LA-4	860,839	478,359	1957	2062	2062	-106	vertical well		775	746-2035	
LA-5	859,410	478,757	2038	1869	1869	169	vertical well		752	-	Unproductive well
LA-6	861,278	477,649	1963	2201	2201	-239	vertical well		754	1499-2201	
LA-7	860,832	476,296	1891	2449	2449	-558	vertical well		956	1788-2449	
LA-8	862,190	476,944	1895	2501	2501	-606	vertical well		721	1867-2464	
LA-9D	860,736	477,863	1956	1920	1784	172	860,849	477,422	605	599-1915	
LA-10D	860,846	477,807	1956	1951	1816	140	861,256	477,409	807	815-1951	

The objective of this report is to assess the formation temperature and some reservoir parameters of selected wells from the Aluto Langano geothermal field, using the Horner method and well test analyses software respectively. Wells LA-9D and LA-10D are used for formation temperature assessment based on temperature and pressure logs, which were measured during warm up and after a 3-month discharge of the wells. Wells LA-4 and LA-10D

are used for well test analysis where the Welltester software developed at Iceland GeoSurvey is used to manipulate challenging injection test data measured in the 1980's and 2015`s.

2. Geologic and Stratigraphic Settings of Aluto Langano Geothermal Field

The Aluto Langano Geothermal field is located in the Lakes District, Ethiopian main Rift Valley, about 220 km South of Addis Ababa and covers an area of about 100 km^2. It lies between lakes Langano and Ziway and rises to about 690 m above the surrounding AdamiTullu Plain which has an elevation of about 1600 m a.s.l. (Figure 1). Volcanic activity at the Aluto volcanic centre is entirely of Quaternary age and initiated with a rhyolite dome building phase intervened by explosive pyroclastic pumice eruptions. The recent nature of these volcanic products indicates a heat source which is still hot enough at depth. An extensive cap rock having large lateral coverage exists at Aluto Langano in the form of lake sediments and associated with overlying pyroclastic. The stratigraphic setting of Aluto Langano geothermal field shows that its thickness increases westwards from 300 m to 1000 m and consists of three main units; pre-Aluto volcanic products aged 1.5 to 3.5 Ma, Aluto Volcanic Products aged 2 to 150 ka and Sedimentary formations (ELC,2016).

3. Temperature Assessment

Stabilized formation temperature is one of the most important parameters to evaluate for a geothermal reservoir condition, when a well is completed (Hyodo and Takasugi, 1995). Its determination from well logs, requires knowledge of the temperature disturbance produced by circulating drilling mud or fluid (Kutasov and Eppelbaum,2005). The formation temperature of thewellsis estimated using Horner plot method. The Horner plot method is the
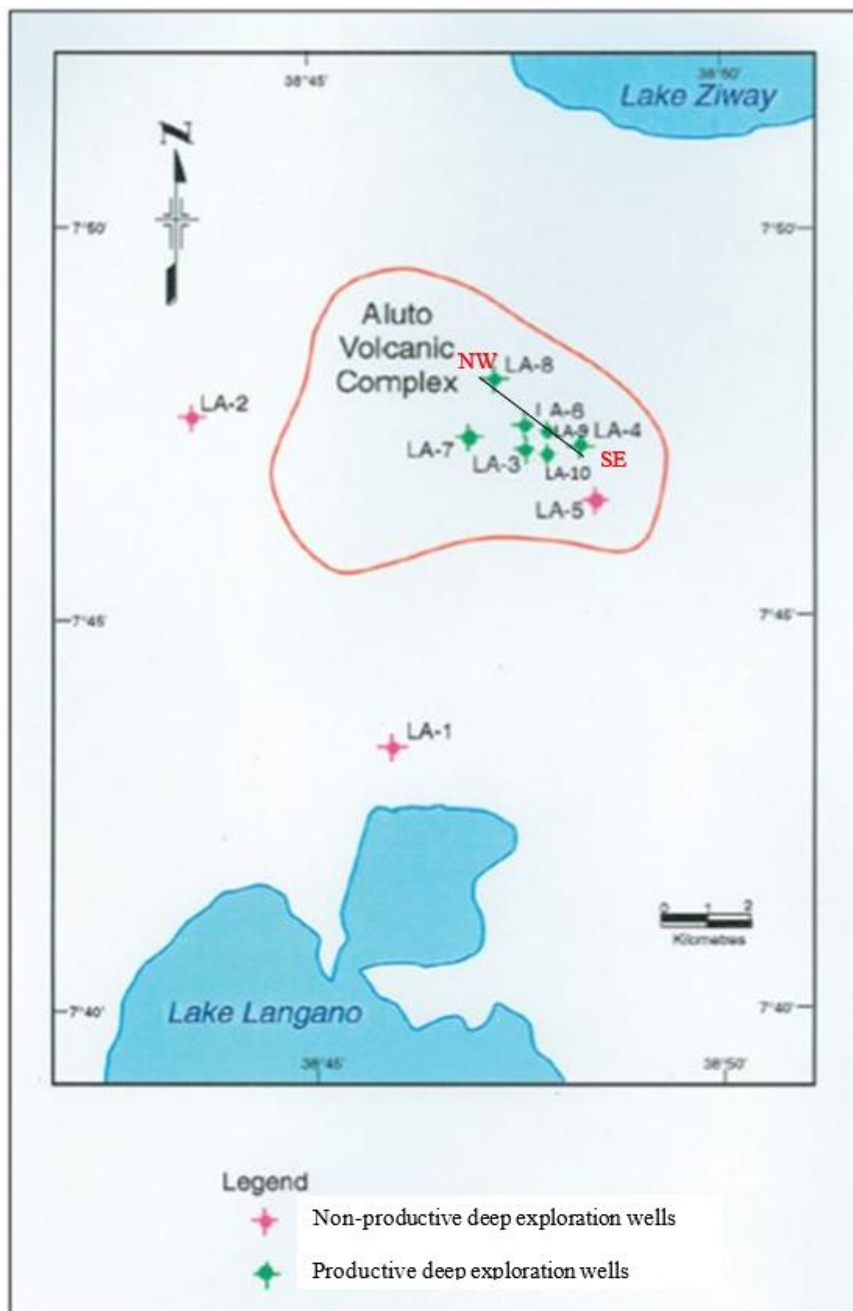

Figure 1: A: Location of Aluto Langano geothermal field (Worku, 2016).

most popular method to estimate formation temperature from down hole logging temperature data Dowdle and Cobb (1975), whereas Kutasov and Eppelbaum(2005), stated Horner method as the widely used in petroleum reservoir engineering and in hydrogeological exploration to process the pressure-build-up test data for wells producing at a constant flow rate.

The validity of the Horner plot is based on Fourier's heat conduction equation, which describes the change in temperature (T) as a function of time (t) and position/space (x).

$$c_p\rho\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \qquad (1)$$

Where cp = Heat capacity of the material (J/m$^{3\circ}$C);
ρ = Density (kg/m^3);
k = Thermal conductivity (W/m°C);

The Horner plot method uses the measured temperature at a given depth from several temperature logs. So, the Horner time (τ) is given by Equation 2 below

$$\tau = \frac{\Delta t}{\Delta t + t_k} \qquad (2)$$

Where t_k = Circulation time before shut-in (hrs);
Δt = The time elapsed since the circulation stops (hrs);

The circulation time (t_κ) is an important parameter in the Horner plot method and should therefore be determined accurately. Since drilling (and thus injection of cold fluid) reaches different depths at different times, the circulation time varies with depth. The temperature recovery data is plotted logarithmically with the Horner time and the temperature will gather up as a straight line at infinite time, $\tau = 1$ or log (τ) =0. Figure 2 shows and example of Horner plot of the evaluation of the formation temperature at 1200 m depth in well LA-4. It is known that the temperature found from a Horner plot is usually lower than the actual formation temperature (Helga Tulinius,Senior Geophysicist, ISOR, personal communication, 30 Aug2017).
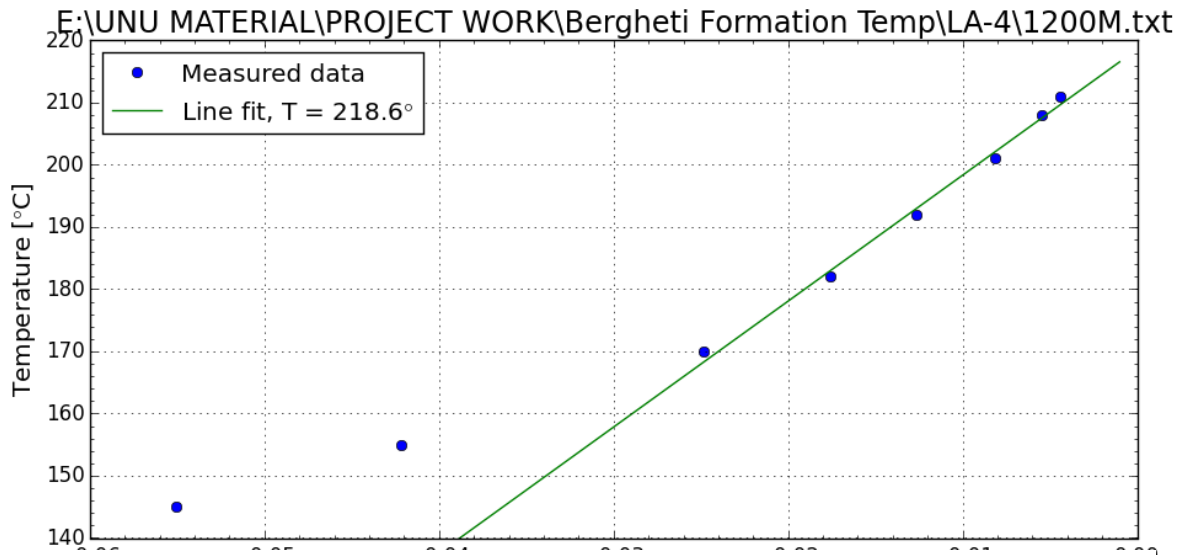

Figure 2: Example of a Horner Plot to estimate formation temperature of well LA-4 at a depth of 1200 m
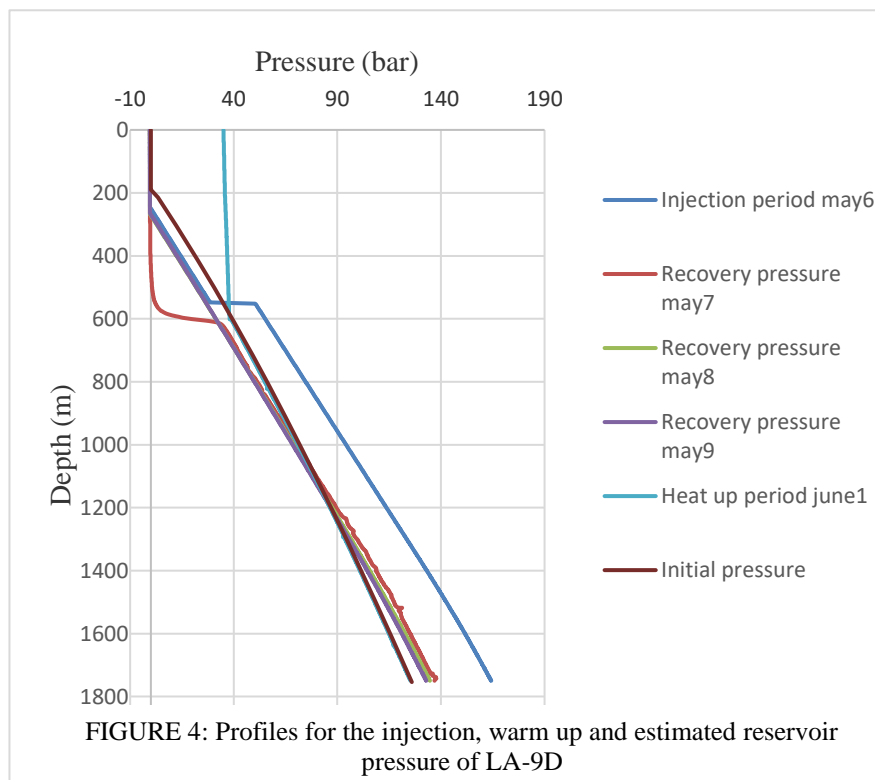
3.3. Estimation of Formation Temperature and Pressure Control Point of well LA-9D

In well LA-9D Seven small feed zones were located at depth of 760m, 830m, 940m, 1000m, 1140m, 1640m, 1800m, while large feed zone is encountered at depth of 1350m.

The feed zones were identified from the warm up periods of 7 May to 9 May, 2015 and with the help of loss of circulation data´s (Figure 3).
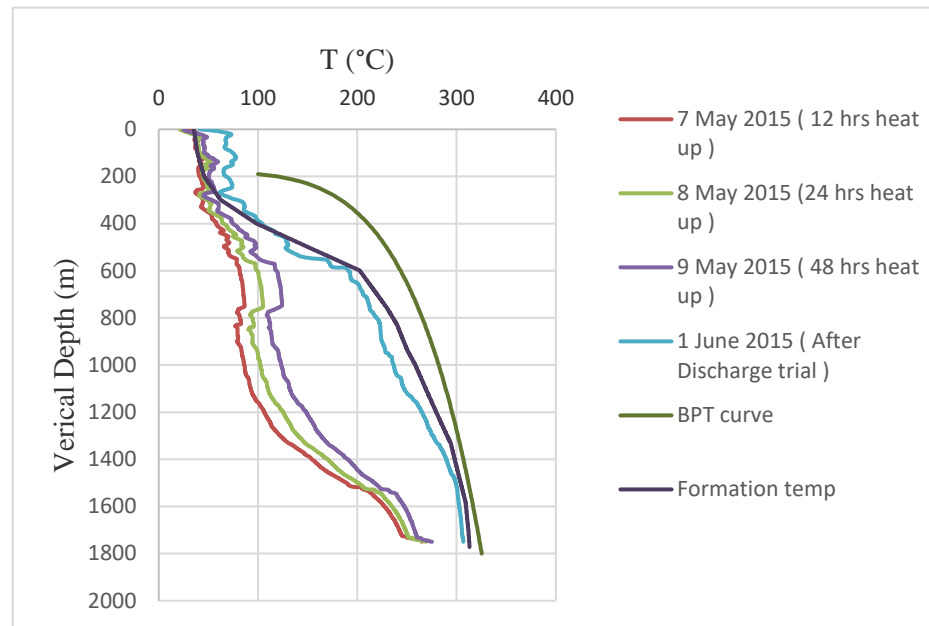
The stabilized formation temperature was estimated from the data set of temperature recovery test and temperature logging during shut in condition. The estimated formation temperature increases with depth and reaches about 309°C at the well bottom which is in line with the West JEC 2016 report.

FIGURE 4: Profiles for the injection, warm up and estimated reservoir pressure of LA-9D

The data points used were selected from the temperature logs at the depth of the feed zones, their estimated formation temperature were determined and then plotted in the same Figure 3. The formation temperature of the well was estimated from these points. The formation temperature appears to increase in the production part of the well 300-311°C.

The pressure profile obtained during the warm up period and the initial pressure profile are shown in Figure 4. The pressure pivot point is located at around 1120 m and the pressure is 89 bar at that point with vertical depth measurement.

3.4. Estimation of Formation Temperature and Pressure Control Point of well LA-10D.

Drilling of well LA-10D was started on June 25, 2015 and completed on October 2, 2015. The directional drilling kick off point (KOP) is at 450m to a direction of N43°W with a maximum inclination of 27.75°.

In well LA-10D six small feed zones were located at 920m, 1280m, 1320m, 1620m,1760m, while large feed zone at 700m were encountered (circulation loss zone) with rapid increase in temperature. The feed zones were identified from injection test and from temperature recovery measurements that were taken on October 5, 6, and 24 2015 and also from circulation loss zone (Figure 5).
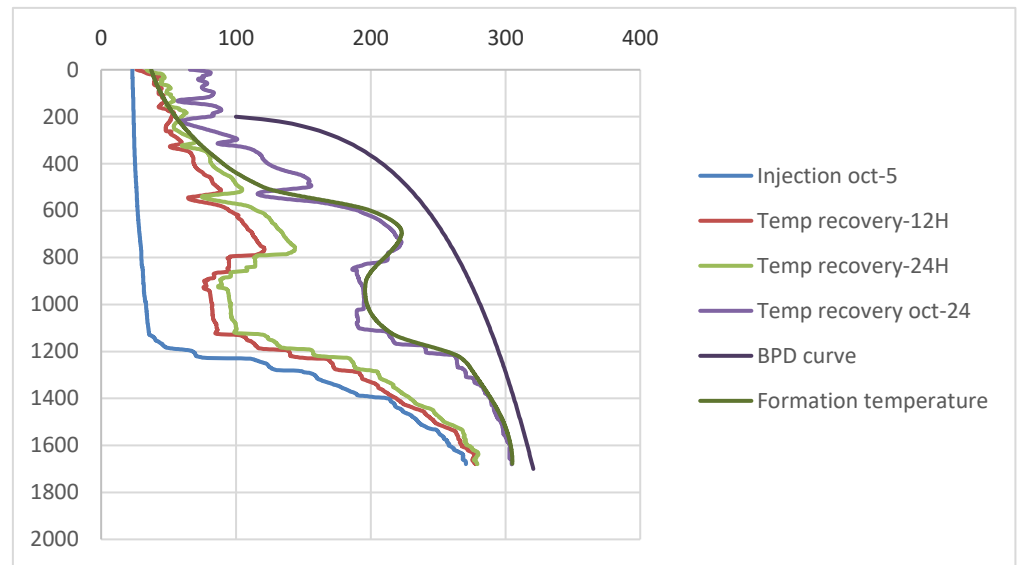

FIGURE 5: Profiles for the injection, warm up and estimated temperature of LA-10D

The formation temperature was estimated from the data set of temperature recovery test of October 6 (12H &24H) and 24 October. The estimated formation temperature simply increases with depth and reach about 305°C at the well bottom 1800 m depth this is also in line with the West JEC 2016 report.

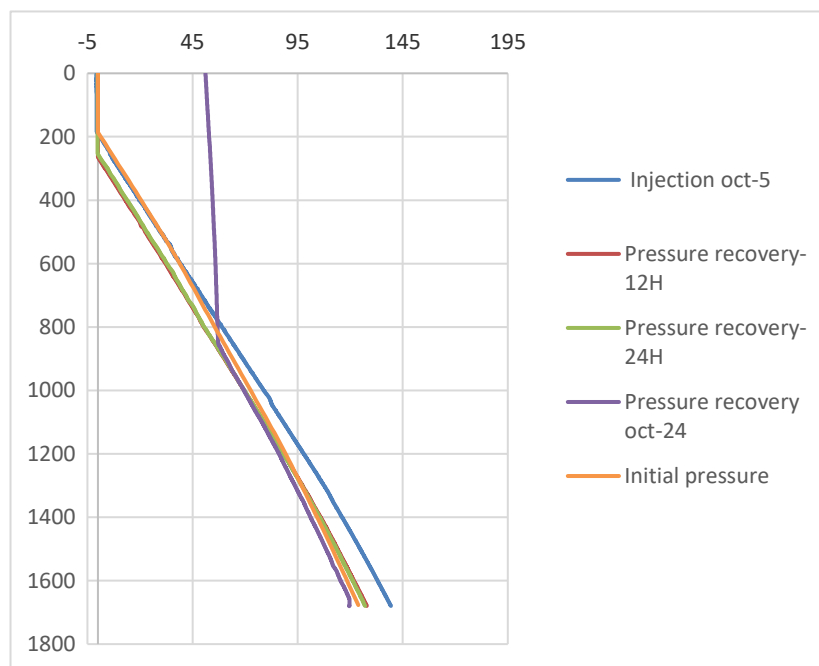To calculate the initial pressure, the estimated formation temperature profile from Figure 6 was inserted in to the PREDYP (part of the Icebox software package). The water level was adjusted in the calculations until the calculated profile matched the pressure pivot point. The pressure match was achieved more or less with water levels at 200 m depth. The pressure pivot

FIGURE 6: Profiles for the injection, warm up and estimated Reservoir Pressure of LA-10D

6

point can be observed around 1288m vertical depth with 96 bar pressure, that this is the major feed zone to the reservoir (Fig 6).

3.3 Temperature Cross Section (Southeast-to-Northwest direction)
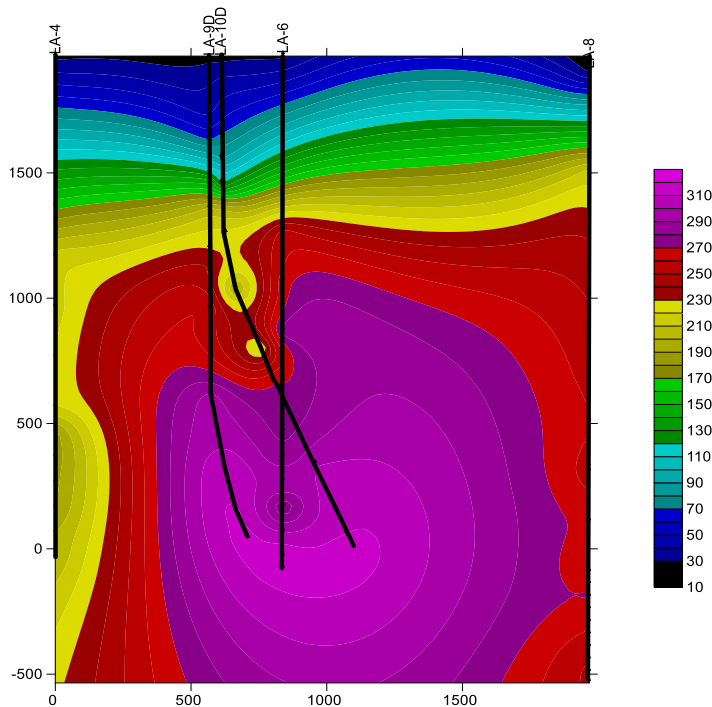

FIGURE 7: Temperature cross-section from southeast to northwest through the system using estimated formation temperature. Location of the cross-section is shown in figure 3.

The estimated formation temperatures of wells LA-4, LA-9D, LA-10D, LA-6 and LA-8 are shown in a cross-section from SE to NW (Figures 7 and 1). The formation temperature of LA-4, LA-6, LA-9D and LA-10D was derived mostly from the latest (January 2017) logging data while LA-8 is based on data from 1980`s. As clearly observed from the cross section, the hot up flow seems to be in the vicinity of wells LA-6, LA-9D and LA-10D, which reaches the warmest part (>300°C), probably from the main up flow zone of the reservoir. Well LA-4 is farther away from the warmest part of the reservoir, temperature ranging from 210°C to 230°C while well LA-8 is closer to the warmest part of the reservoir. This can probably be caused by cold water inflow/outflow towards wells LA-4 from eastern escarpment of the rift. The above profile supports the idea, which most authors wrote about the up flow zone location in the vicinity of wells LA-6 and LA-3 (Kebede et al., 2002). The upper clay cap, indicating temperature less than 140°C is clearly correlating to Figure 14 and extends up to 700-800m depth, which are cased off in most of the wells.

4. WELL TEST ANALYSIS

4.1 Introduction

In an injection step test the injection to a well is increased or decreased in steps while the pressure is monitored at a fixed location, fixed depth. The Welltester software (Marteinson, 2017, Júlíusson et al., 2008, Horne, 1995), which was developed at Iceland GeoSurvey for welltest analysis, is used to simulate pressure response data, measured during a step test (Figure 8) as a function of time. Welltester deduces reservoir parameters and parameters of the well by iterating, starting with guessed parameters and getting closer and closer to the measured pressure.
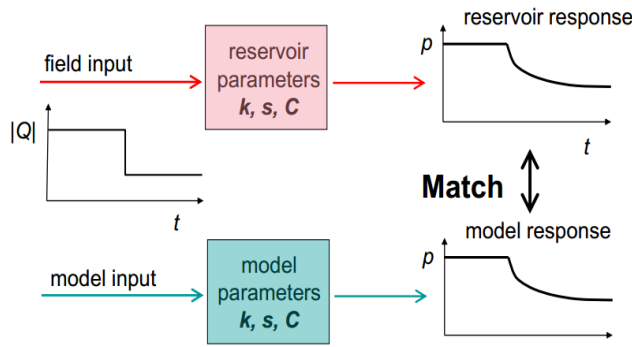
FIGURE 8: Well test analysis procedure (modified by Haraldsdóttir, 2017, from Horne, 1995)

Axelsson and Steingrímsson, 2012, briefly explain about well test which is a fluid flow test (Figure 8) conducted in geothermal wells to obtain parameters of the reservoir as well as the well. Well tests are done at the completion of a well, possibly leading to a decision of continuing drilling, but also after a period of production, to see whether and how much the reservoir properties have changed.

A well test may be analysed using Theis model and its variants which assumes a model of homogeneous, isotropic and horizontal permeable layer of constant thickness, confined aquifer, and two dimensional and horizontal flow towards the producing well by fitting the pressure response of the model to the measured pressure response data (Axelsson, 2013). In a similar way the flow in an injection well test is assumed to be horizontal from the well to the surroundings. The possible boundary conditions are illustrated in Figure 9.
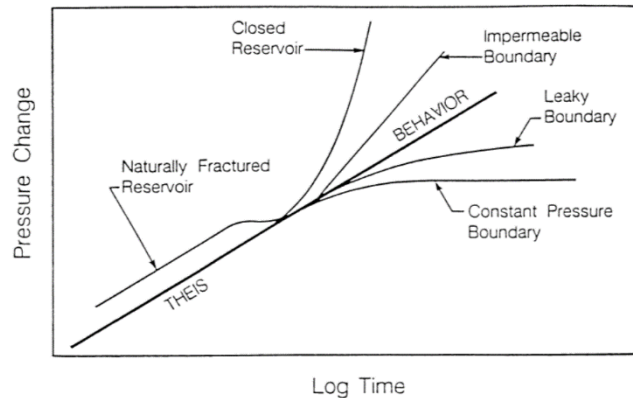

FIGURE 9: Pressure response of Theis model on a semi-logarithmic plot (linear pressure change vs. logarithmic time) demonstrating the linear behaviour, which is the basis of the semi-logarithmic analysis method (Bödvarsson and Whiterspoon, 1989)

4.2 Pressure Diffusion Equation

According to Haraldsdóttir (2017), pressure diffusion equation is a mathematical description of fluid flow in porous medium and used to calculate the pressure (p) in the reservoir at a certain distance (r) from the producing well pro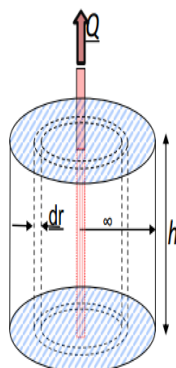ducing at rate (Q) after a given time (t) (Figure 10). It consists of three main physical principles; the law of conservation of mass, Darcy's law and equation of state of the fluid. There are several assumptions to develop the pressure diffusion equation.

The law of conservation of mass is based on continuity equation of fluid flow in a porous medium which can be expressed as:

FIGURE 10: Radial flow in a cylinder around a wellbore (Haraldsdóttir, 2017)

$$Flux\ in - Flux\ out = Increase\ in\ amount\ stored$$

$$\frac{\partial(\rho Q)}{\partial r} = 2\pi r \frac{\partial(\varphi \rho h)}{\partial t} \qquad (3)$$

Where   Q   = Fluid flow (mass introduced (source) or mass removed (sink)) (L/s)

       ρ = Density of the fluid (kg/m^3);

       φ = Porosity of the medium (%);

       t   = Time(s);

The momentum equation (Darcy's law) expresses the fact that the volumetric rate of flow at any point in a uniform porous medium is proportional to the gradient of potential in the direction of flow at that point.

$$Q = \frac{2\pi r k h}{\mu} \frac{\partial p}{\partial r} \qquad (4)$$

Where P   = pressure (bar)

       r   = Radius of investigation (m)

       μ = Dynamic viscosity (Ns/m^2)

The third principle is the equation of state of the fluid (fluid compressibiltiy at constant temperature). The compressibility of a substance is the change in volume per unit volume per unit change in pressure. In a reservoir which consists of rock (C_r) and pore space occupied by oil, water, and gas (C_w), the total compressibility (C_t) is defined as follows:

$$C_w = \frac{1}{\rho}\frac{\partial(\rho)}{\partial p} \quad ; \quad C_t = \varphi C_w + (1-\varphi)C_r \quad and \quad C_r = \frac{1}{1-\varphi}\frac{\partial \varphi}{\partial p} \qquad (5)$$

Finally, the pressure diffusion equation will be deduced to a one dimensional second order partial differential Equation (6) which describes isothermal flow of a fluid in porous media, i.e. how the pressure (p) diffuses radially through the reservoir as a function of the distance (r) from the well and the time (t) since the start of production.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = \frac{\mu C_t}{k}\frac{\partial p}{\partial t} = \frac{S}{T}\frac{\partial p}{\partial t} \quad or \quad \frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\mu C_t}{k}\frac{\partial p}{\partial t} = \frac{S}{T}\frac{\partial p}{\partial t} \qquad (6)$$

Axelsson and Steingrímsson(2012) explain in detail the parameters of a well and reservoir to be estimated from well-logs during step-rate well-test and its purpose, which is conducted at the end of drilling a well. Step-tests are done to obtain a first estimate of the possible production capacity of a well and to estimate its production characteristics. In the case of high-temperature wells this estimate is only indirect since it's not performed at high-temperature, production conditions. Step-rate well-testing usually lasts from several hours to a few days.

4.3 Injection step test analysis of well LA-4

Three injection rates are performed during the multi rate injection test analysis. The injection rates are 6.6 L/s, 17.2 L/s and 27.5 L/s. The results from the simulations of Welltester are shown in Table2 for the first step and the fall off step. The coefficient of variation (CV) for the two steps is within reasonable range except for the storativity(S) in the first step and radius of

investigation in the fall off step, probably because the data is very limited and manually modified and interpolated in the software.

TABLE 2: Well test results from nonlinear regression parameter estimate of dual porosity, constant pressure, constant skin and constant wellbore storage reservoir of well LA-4 for step 1 and the fall off step

Parameter	Step 1		Fall off Step	
	Value	CV (%)	Value	CV (%)
Transmissivity,T (m^3/(Pa.s))	$4.8*10^{-09}$	2.8	$2.1*10^{-08}$	1.1
Storativity,S (m^3/(m^{2}Pa))	$1.8*10^{-08}$	26	$3.2*10^{-08}$	4.6
Radius of Investigation,r_e (m)	100	30	250	9
Skin factor, s	-3.0		-0.7	
Wellbore storage, C (m^3/Pa)	$4.3*10^{-06}$	2.4	$4.2*10^{-06}$	- 0.7
Reservoir Thickness, h (m)	260		450	
Injectivity Index, II ((L/s)/bar)	1.5		2.2	

The reservoir parameters estimated for well LA-4 using Welltester for the well test analysis show the best fit of the model for the second step.

4.3 Injection step test analysis of well LA-10D

This is the second directional well drilled in AlutoLangano geothermal project located in the central part of the main Ethiopian rift system, which is about 200km away from Addis Ababa. It is the 10th deep drilling well in Aluto volcanic complex completed drilling in October 2015. The well is drilled to the maximum geological depth of 1951m in the direction of N43°W with an inclination of 27.75°. With a maximum temperature of 310°C at the bottom of well. The directional drilling kick of point (KOP) is 450m. The PTS tool was set at 551m depth and the water injection at the rate increased from 0 l/s to 14.9 L/s. Then, the injection rate was increased as 17, 19.34 and 21.73 L/s in the following steps and the pressure in the well was recorded. The injection rate of each step was one hour (Figure 11).
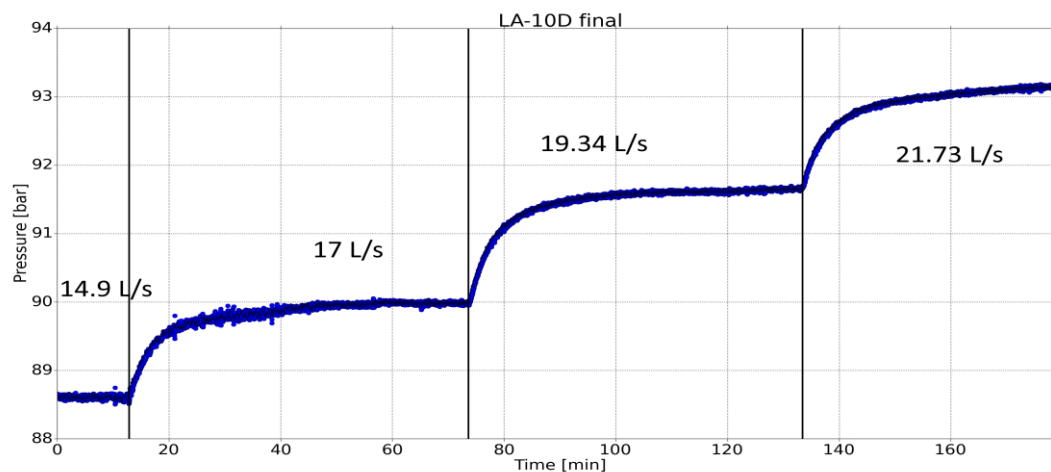

FIGURE 11: LA-10D injection steps for a duration of 3 hours with respective pumping rates

The reservoir parameters for all steps are summarized in Table 3 and Step three was selected as the best model, having lower CV values than other steps.

TABLE 3: Summary of Reservoir parameters estimated using nonlinear regression model for well LA-10D

Parameter	Step 1	CV %	Step 2	CV %	Step 3	CV%
Transmissivity, T (m^3/(Pa.s))	1.26×10^{-9}	0.71	1.99×10^{-8}	0.71	1.32×10^{-8}	0.41
Storativity, S (m^3/(m^{2}Pa))	5.1×10^{-9}	2.17	3×10^{-9}	3.45	5.7×10^{-9}	2.13
Radius of investigation, r_e (m)	122	5.61	62	2.45	119	4.81
Skin factor, s	0.07	-	3.08	-	-0.26	-
Wellbore storage, C (m^3/Pa)	3.08×10^{-6}	0.68	4.13×10^{-6}	0.24	4.31×10^{-6}	0.34
Reservoir thickness, h (m)	152		87		168	
Injectivity index, II ((L/s)/bar)	1.41		1.4		1.63	

Injection well test analyses done for wells LA-3 and LA-10D gave the best result for step number 4 and 3 model assuming homogenous reservoir and constant boundary pressure. The skin factor values for the selected model step is negative, which indicates that the nearest surroundings of the wells have higher permeability than the surrounding reservoir and are in good connection with the reservoir. Both wells LA-4 and LA-10D are characterized to be in liquid dominated reservoir.

TABLE 4: Comparing estimated reservoir parameter results of LA-4 and LA-10D of best model

Parameter	LA-4		LA-10D	
	Step 2	CV %	Step 3	CV %
Transmissivity, T (m^3/(Pa.s))	$2.1*10^{-08}$	0.37	$1.32*10^{-8}$	0.41
Storativity, S (m^3/(m^{2}Pa))	$3.2*10^{-08}$	1.16	5.7×10^{-8}	2.13
Skin factor, s	-0.65	-	-0.26	-
Wellbore storage, C (m^3/Pa)	$4.2*10^{-06}$	0.45	$4.13*10^{-6}$	0.34
Reservoir thickness, h (m)	450		168	
Injectivity index, II ((L/s)/bar)	2.2		1.63	
Porosity, φ	0.1		0.1	

6. CONCLUSION

AlutoLangano geothermal field is classified as high temperature geothermal field as the temperature is greater than 200°C at a depth of 1000 m, which was confirmed in this project. The main conclusions can be summarised as follows:

➤ Results from LA-9D shows an estimated formation temperature ranging from 300 – 311°C in the well bottom. The pivot point of LA-9D is located around 1100m-1250m depth with pressure ranging from 85-95 bar.

➤ Whereas the formation temperature of LA-10D is 300-305 °C while the pivot point is located around 1200-1400m depth with pressure ranging from 85-100 bar.

➤ The formation temperature reaches over 300°C in LA-6 and 230°C in LA-4. LA-4was drilled in the eastern and colder part of the geothermal field compared to wells LA-6,

LA-9D and LA-10D, which were drilled in the warmest part of the field. This confirms results already shown in previous reports about the AlutoLangano geothermal field (ELC, 2016, WestJEC, 2016).

➢ The Welltester software used in this project to manipulate and analyse the injection step tests was helpful in estimating the reservoir parameters of the wells. The results from the analysis in wells LA-4 and LA-10D were fairly good, especially with respect to the data quality, which was scarce and limited. After manually fixing the data and using interpolation, the best simulations were for dual porosity reservoir, constant pressure boundary and constant skin.

➢ The transmissivity and storativity of wells LA-4 and LA-10D were found to be in the order of magnitude of 10^{-8}, which are similar or lower than in Icelandic geothermal wells, where they are in the order of magnitude 10^{-8}.

➢ AlutoLangano is classified as a high temperature geothermal field but the injectivity index is rather low, in the range of 1.0 to 2.4 (L/s)/bar which indicates that the wells are perhaps not very well connected to the reservoir. Low values of transmissivity indicate low permeability of the system. The field is therefore not necessarily a good producer in spite of the high temperature. This is in agreement with results of WestJEC (2016).

REFERENCES

Axelsson, G. "Geothermal well testing" *Presented at "Short Course V on Conceptual Modelling of Geothermal Systems", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador*, 2013, UNU-GTP SC-16, 30 pp.

Axelsson, G. and Steingrímsson, B. "Logging, testing and monitoring geothermal wells." *Proceedings of "Short Course IV on Geothermal Development and Geothermal Wells, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador,* 2012, UNU-GTP SC-14, 20 pp.

Dowdle, W.L., and Cobb, W.M.."Static formation temperature from well logs – an empirical method."*J. Petroleum Technology, 27,*1975, 1326-1330.

ELC,"Geothermal surface exploration in Aluto-Langano, Ethiopia. Conceptual model report." Electro Consult – ELC, Milan, Italy, 2016, report, 141 pp.

Hyodo, M., and Takasugi S." Evaluation of the curve-fitting method and the Horner plot method for the estimation of the true formation temperature using temperature recovery logging data." *Proceedings of the 20th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca,*1995, 7 pp.

Horne, R. N. "Modern well test analysis: a computer aided approach (2nded.)." Petroway Inc., Palo Alto, Ca, 1995, 257 pp.

Júlíusson, E., Grétarsson, G.J., and Jónsson, P. *WellTester 1.0b, user's guide*. ÍSOR – Iceland GeoSurvey, Reykjavík, 2008, 27 pp.

Kebede, Y., Kebede, S., Teklemariam, M., and Amdeberhan, Y. "Compiled summary report on Aluto Langano geothermal field." Geological Survey of Ethiopia, Addis Ababa, 2002, unpubl. report, 141 pp.

Kutasov, I.M., and Eppelbaum, L.V."Determination of formation temperature from bottom-hole temperature logs." *J. Geophysics and Engineering, 3-4*, 8 pp. From Nanjing Institute of Geophysical Prospecting. Nanjing, China, 2005.

Marteinson, K. *Welltester user manual, vs. 2.* ÍSOR – Iceland GeoSurvey, Reykjavik, 2017, 15 pp.

Ministry of Mines and Energy "Investment opportunities in geothermal energy development in six selected geothermal prospects in Ethiopia."Ministry of Energy and Mines, Addis-Ababa, Ethiopia, 2008.

WestJEC "Resource assessment report on Aluto Langano geothermal field." WestJEC, appraisal project, Ethiopia, 2016, unpubl. report, 258 pp.

Wikipedia *"History of geothermal in Addis Ababa, Ethiopia."Wikipedia*, website: *en.wikipedia.org/wiki/Addis_Ababa*, 2017.

.