Analysis of Welltest LSL-GT-01

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1 Summary

Well LSL-GT-01 was production tested from 18-21/10/2017 by a multi-rate test, followed by a shut-in period of 39 hours. The ESP generated production rates varied between 219 and 359 m3/hr. Cumulative water produced was about 2270 m^3.

Following are the main conclusions:

- Average reservoir permeability is about 565 mD assuming that the whole net sand of 88 m contributes to flow.
- The distance of investigation is more than 450 m: within this distance no flow barrier was observed.
- Static reservoir pressure at 1573 m tvBRT is 159 bara; at 1800 mtv it is 182.8 bara.
- Reservoir temperature at bottom well (~2100 m) is about 65 ºC.
- The correction for the changing temperature of the water column between the ESP and top reservoir is similar as in nearby water wells, but is less accurate, caused by the large noise of the ESP pressures.
- The transient flow capacity (PI) after 48 hours flow is 18.4 m3/hr/bar.
- The skin at the gauge depth of 1573 m is 1.2 at 220 m3/hr and 1.8 at 360 m3/hr, resulting in a damage skin of 0.3.

2 Resultaten van de put test

Gegevens voor test interpretatie	Waarde	Dimensie
Naam van de put	LSL-GT-01	
Coördinaten van de put (X, Y)	**E (m) = 94.640 m**	**N (m)= 446.403 m**
Coördinaten mid reservoir at 1800 mtv	**E (m) -650 m = 93.990 m**	**N (m) = -934 = 445.469 m**
Top aquifer	2005	m (langs boorgat)
	1621	en m (TVD)
Basis aquifer	~2540	m (langs boorgat)
	~1980	en m (TVD)
Netto dikte Aquifer	88	m (TVD)
Netto/bruto aquifer	47	%
Gemiddelde porositeit aquifer	19	%
Zoutgehalte formatiewater	121	Gr/ltr NaCl
Verwachte max. temperatuur geproduceerde water[1]	62	ºC
Diameter boorgat bij aquifer	8.5	Inch
Top productie-interval/filter	1999	m (langs boorgat)
	1617	en m (TVD)
Basis productie-interval/filter	2428	m (langs boorgat)
	1970	en m (TVD)
Locatie pomp	590	m (langs boorgat)
	590	en m (TVD)
Locatie meetsonde voor druk	595	m (langs boorgat)
	595	en m (TVD)
Clean up gegevens		
Pompdruk	548	psi
Debiet vs. tijd	359	m3/uur
Duur	2	uur
Meetreeksen Puttest[4]	Eind ESP druk, psi	Eind Debiet, m3/uur
Flow 0	824	0
Flow 1	636	238
Flow 2	625	282
Flow 3	548	359
Flow 4	655	219

[1] Deze temperatuur wordt als gemiddelde aquifer temperatuur beschouwd

Results test interpretation and analysis		
Permeability thickness kh	50.2	Dm (Darcy-meter)
Assumed net h	88	m
Permeability k_h	570	mD
Reservoir damage skin S	0.3*)	
Skin at 219 m3/hr	1.2	
Skin at 359 m3/hr	1.8	
No flow barrier within	450	m
Productivity Index (P.I.) (48hrs)	18.4	m^3/hr/bar

*) Extrapolated to zero rate in order to remove friction effects.

3 Introduction

Well LSL-GT-01 was production tested from 18-21/10/2017 by a multi-rate test, followed by a shut-in period of 24 hours. The ESP generated production rates varied between 219 and 359 m3/hr. Cumulative water produced was about 2300 m^3.
The pressure and temperature data were recorded both by the ESP gauge and a high-accuracy gauge stuck on the liner hanger at 1573 m tvBRT. That position became evident when the ESP was pulled out with an empty wire line partly curled around it. That depth is confirmed by the registered pressures and the measured water density.

The ESP pressure sensor is at 595 m tvBRT. The well was produced from three sandstone layers, the Berkel, Delft and Alblasserdam. These are covered partially by screens from a depth of 1617 to 1691 and 1845 to 1970 m tvBRT. From 1988 to TD at 2114 m tvBRT, the well is 8.5”open hole.

In view of the short distance between the deep gauge at 1573 and top reservoir at 1621 m tvBRT, no correction has been made for the cooling water column of only 48 m.

4 Reservoir and Rate data

The reservoir properties, including the expected permeability's, are presented in the table below.

	Berkel Sandstone	Delft Sandstone	Alblasserdam
Top (m MD)	2005	2362	2440
Base (m MD)	2093	2440	2540*
Gross Thickness (m MD)	87	77	100
Top (m TVD)	1621	1849	1904
Base (m TVD)	1679	1904	1980*
Gross Thickness (m TVD)	58	55	75
Net Thickness (m TVD)	35	35	18
N/G (%)	60	63	24
Average net porosity (%)	18.7	20.0	15.9
Average net permeability (mD)	449	607	147

The wellbore radius Rw has been set to the bit size of 8.5", or 0. 354 ft.
In view of the deviation of the well with an average angle of about 48 degrees through the reservoir, the wellbore radius was adjusted to $Rw*\sqrt{\{(1+1/\cos\alpha^2)/2\}}$ = 0.45 ft, for the analysis with a vertical well model.
The reservoir temperature at bottom well was registered by the deep gauge at 65.6 C, when it fell to ~1980m during the first retrieval attempt. During production the maximum water temperature at 1573 m tvBRT was 61 C.
The water salinity is obtained from the observed pressure gradient at 48.4 ºC of 0.1050 bar/m. This has to be multiplied by 10197.16 to convert into a water density of 1070.8 kg/m3. This is consistent with a water salinity of 121 gr/ltr NaCl.
Standard tables show for this salinity and 62 C a water compressibility of 3.6 E-6 psi^{-1}, and a water viscosity of 0.6 cP.
As earlier measurements by Panterra for similar formation water showed a much higher Cw due to dissolved gas (methane mostly), the Cw has been set to 8 E-6 psi-1.
The pore compressibility is assumed to be 4E-6 psi^{-1}.
The porosity and total compressibility (Cw + Cf) may have to be changed after the interference test with the next well.

The next table lists the used rate sequence during the production test.

Delta time, hours	Flow Rate, m3/hr
1.09	238
0.93	282
2	359
4.75	219
39.2	0

The high flow rate had to be reduced and the final, lower, flow stopped earlier than planned, as the production-water basin could not handle more water pressure.

5 Correction for water column cooling on ESP data

The pressures of the downhole gauge were correlated with the ESP pressures as function of the ESP temperature in Fig-A. The resulting correction formula, matching on the EST temperatures below 79 ºC:

$\Delta P = CDC*L*[1063.7+0.45*\Delta T -0.005*\Delta T^2]$,

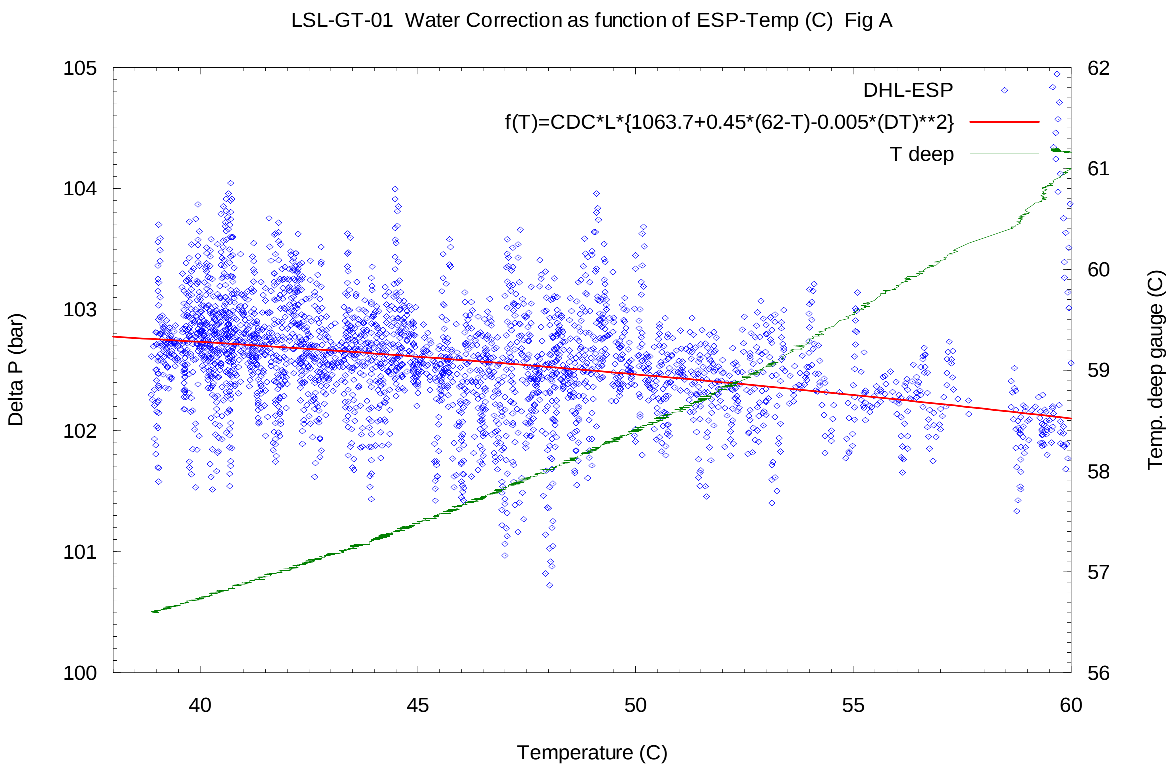
With ΔP the pressure correction, CDC a constant [CDC= 9.8063E-5 if pressure in bar and L in meters], L the vertical depth difference between deep gauge and ESP depth (978 mtv), and ΔT the difference between the maximum and current ESP temperature in ºC.

The constants in this formula are close to those in nearby deep hot-water projects.

As maximum temperature 62 ºC was used, based on the extrapolation of the observed downhole temperature. This formula corrects thus from ESP to BHP depth and can be used in the second well.

Despite the poor quality of the ESP pressures, the so corrected ESP data gave about the same analysis results as the deep gauge data.

The green points are the pressure differences between BHP and ESP, with the fitted blue curve through those points. The red line is the temperature of the deep gauge on the right-hand scale. The early build-up data with an ESP temperature above 59.8 ºC cannot be used for the model matching as they are clearly disturbed by the latent heat of the ESP motor, influencing the recorded ESP temperature just after shut-in.
No gauge movement is seen on the blue dots at the large scale, obviously as the gauge was stuck on the liner hanger.



6 Pressure recordings

Fig-1 shows the original downhole gauge data. Only the deep gauge recorded the P and T at TD, when it fell from the liner hanger down to TD (2114 mtv).

In Fig-1Z, the same pressures are presented excluding the non-test periods, indicating that both deep gauges gave exactly the same pressures: only the deeper gauge data have been used.

Finally, in Fig-1ESP, the ESP pressures are presented, together with the rate data.
These pressure data show large fluctuations. For the analysis a "moving-average" of 100 previous and 100 later points was used, but still rather poor pressure data.
As the corrected pressures, extrapolated to 1800 mtv, are much higher than the original ones, 130 bar is subtracted from them to fit on the same pressure scale.

The depth of the deep gauge was checked to be the same as the liner hanger, 1573 mtv. The pressure difference with the ESP at 595 mtv is 102.7 bar at the ESP T of 40 C. The deep T is then 56.75 C, or average 48.4 C: 102.7/ (1573-595) = 0.1050 bar/m = 1070.8 kg/m3. Minus a pressure correction of 4, this agrees with a NaCl salinity of 121. The gauge depth is thus correct!

FIG-01 Total Test Gauge Data Fig 1

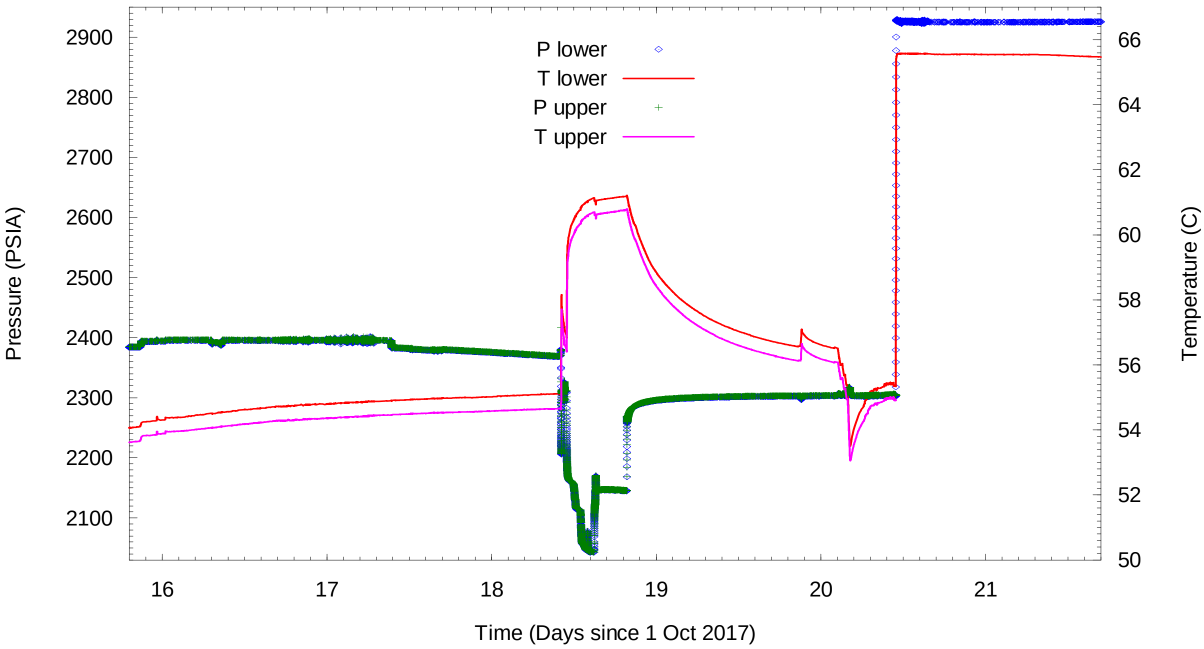
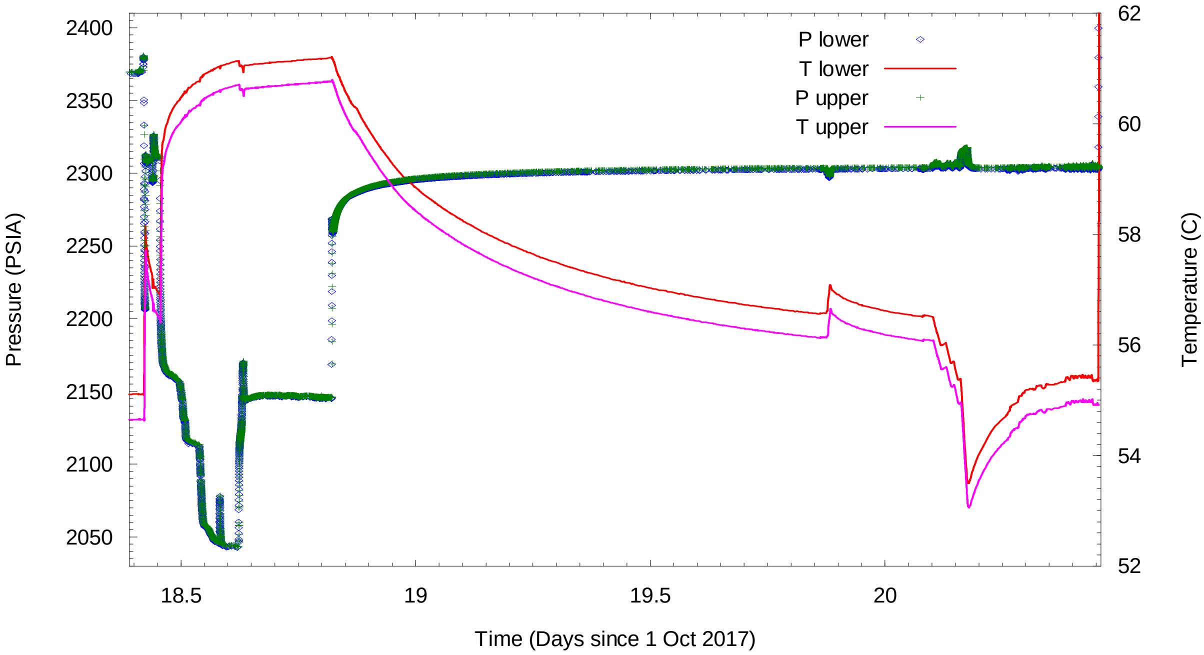
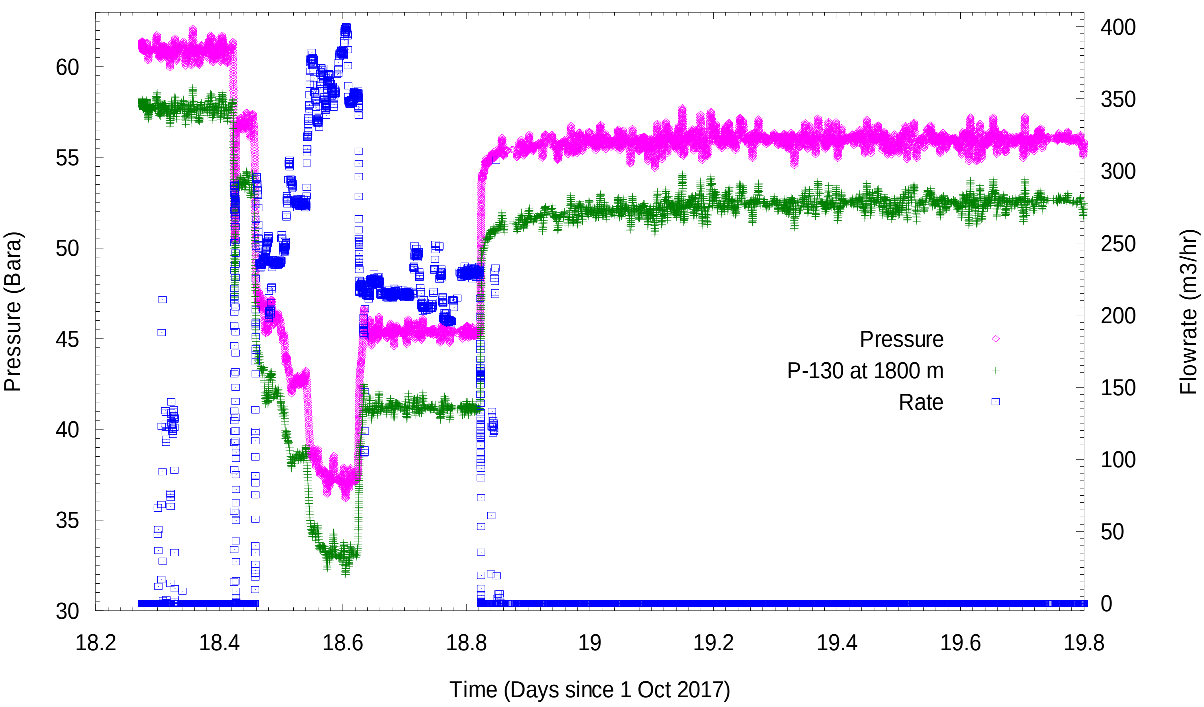


FIG-01 Total Test Gauge Data Fig 1Z



BGH-GT-01 Total Test Gauge Data Fig 1ESP



7 Analysis method

The analysis is carried out by the match of the most appropriate analytical well/reservoir model with the total test history. In this way, no approximations have to be used, as for the model response the flow equations are solved with great precision for the reported flow rates. It should be noted that each pressure point measured in a well depends on the total previous rate history of that well, both in the real reservoir as in the analytical model. Analysis of only one rate period can thus give only an approximation of the real reservoir/well parameters.

As no model for a deviated well is available, a vertical well model has been used, based on the assumption that the flow in the reservoir at some distance from the well will be horizontal, as the vertical permeability is normally lower than the horizontal one in sandstone. The matched-model response for short times can be expected to deviate somewhat from the observed pressures. But these early build-up pressures are also expected to be influenced by cold water, falling down from the annulus above the pump, gas bubbling upwards and expanding, by water hammer and (ESP Data) by the latent motor heat.

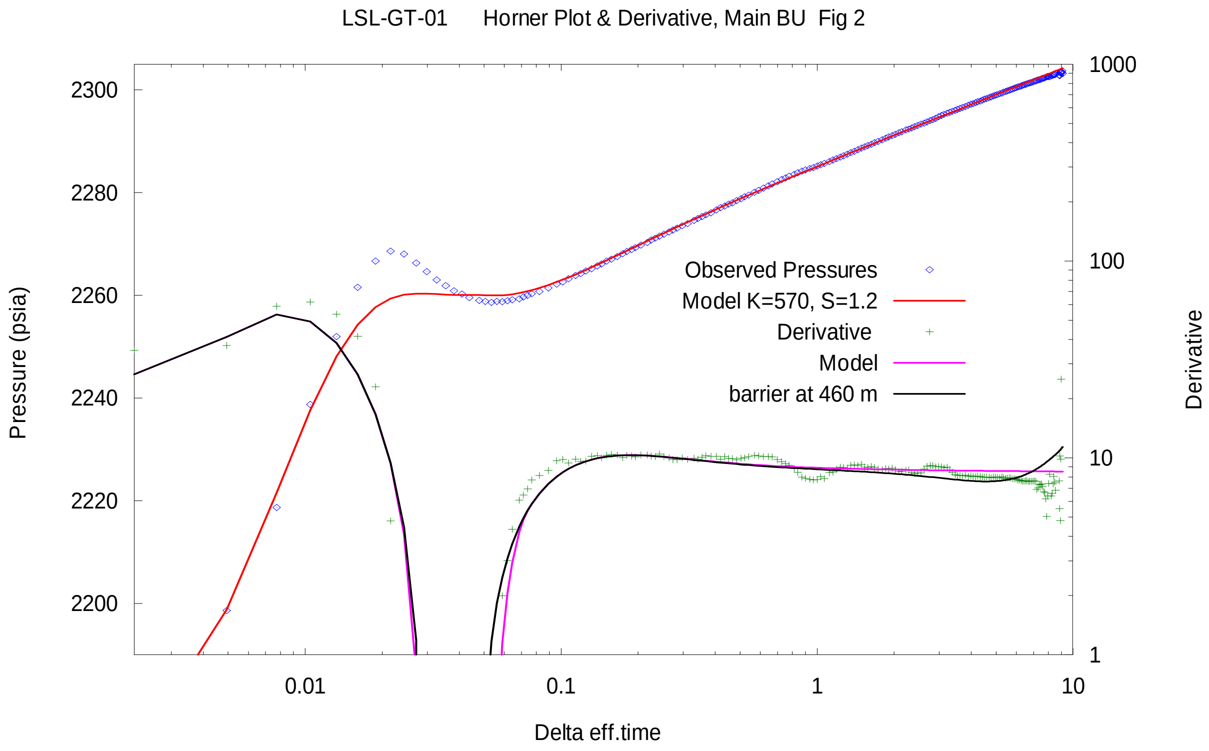
8 Analysis of pressure data

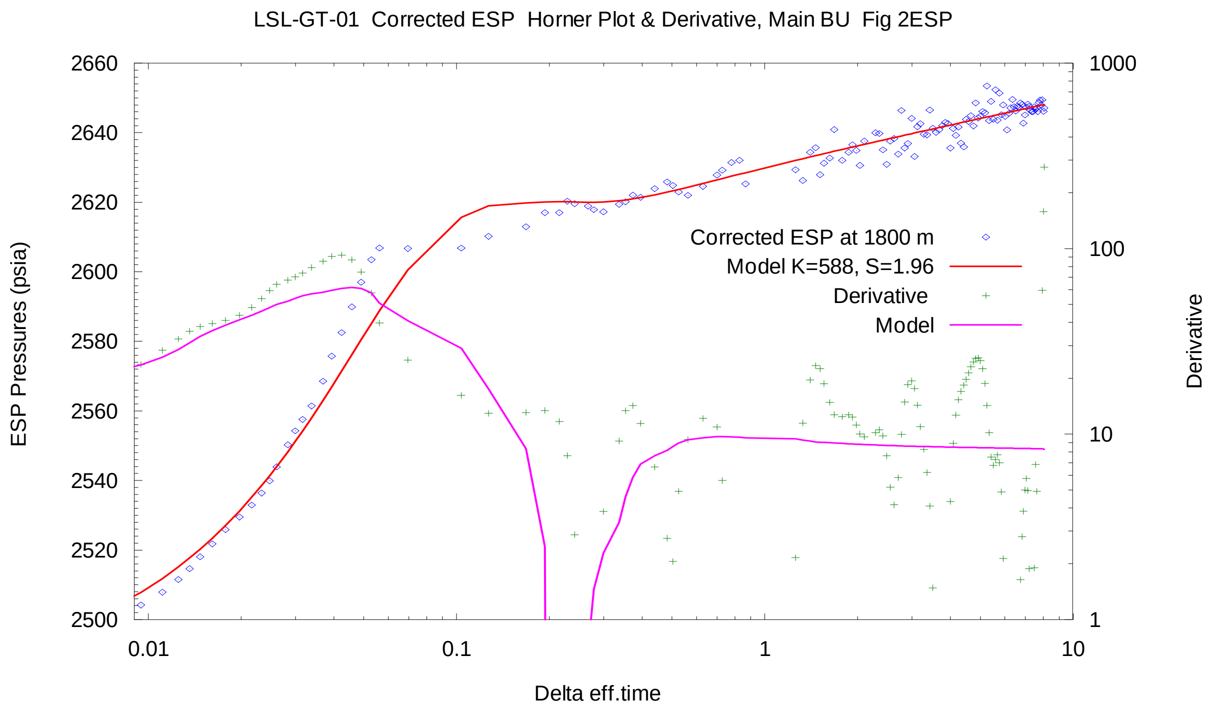
The downhole gauge pressures have been matched with an infinite homogeneous model.
The average reservoir permeability is 570 mD, and the skin a low 1.2 (matching on the final flowing point before the build-up). The initial wellbore storage coefficient is 0.117 b/psi, increasing by a factor 3.5 after a dimensionless time of 9.7 (this approximates the effect of water hammer, in which the kinetic energy of the flowing water is converted into pressure). The static reservoir pressure at the gauge depth of 1573 mtv is 159.0 bara. The transient productivity (at 48 hrs) is 18.4 m3/hr/bar.

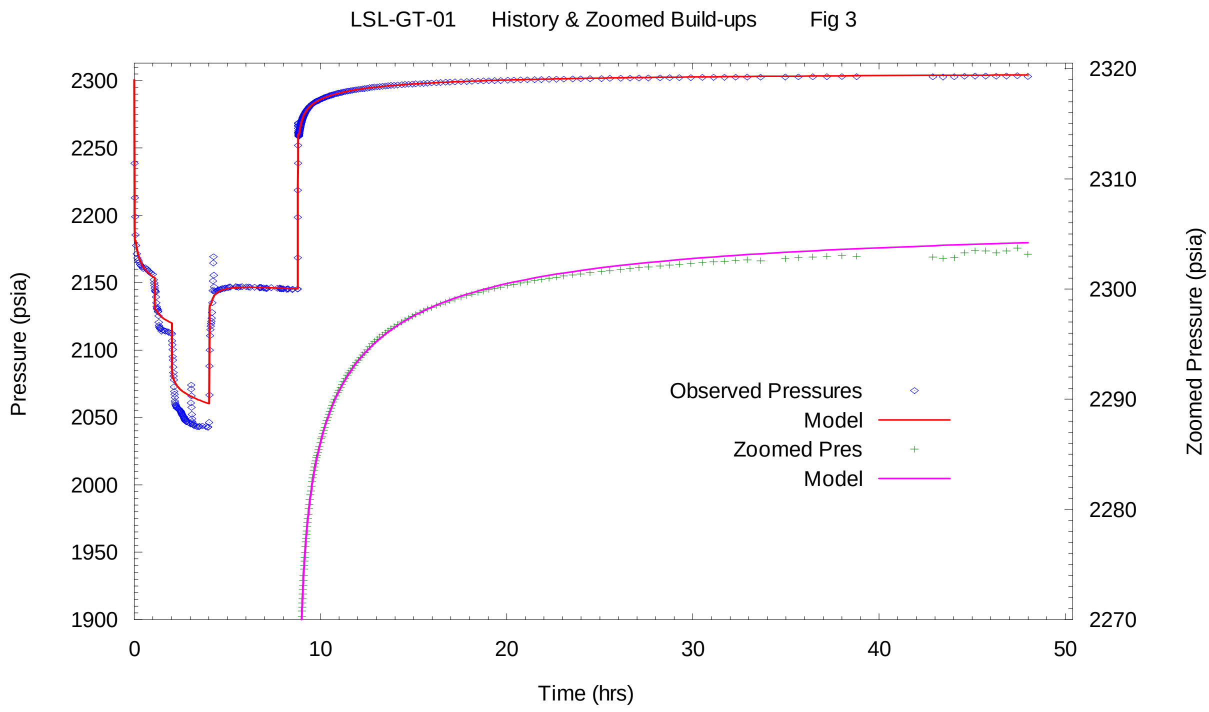
The radius of investigation was determined by placing a single flow barrier at an increasing distance:
At 450 m distance, the barrier would certainly have been observed on the derivative, FIG-02.
Conclusion: no sealing flow barrier is present within 450 m.

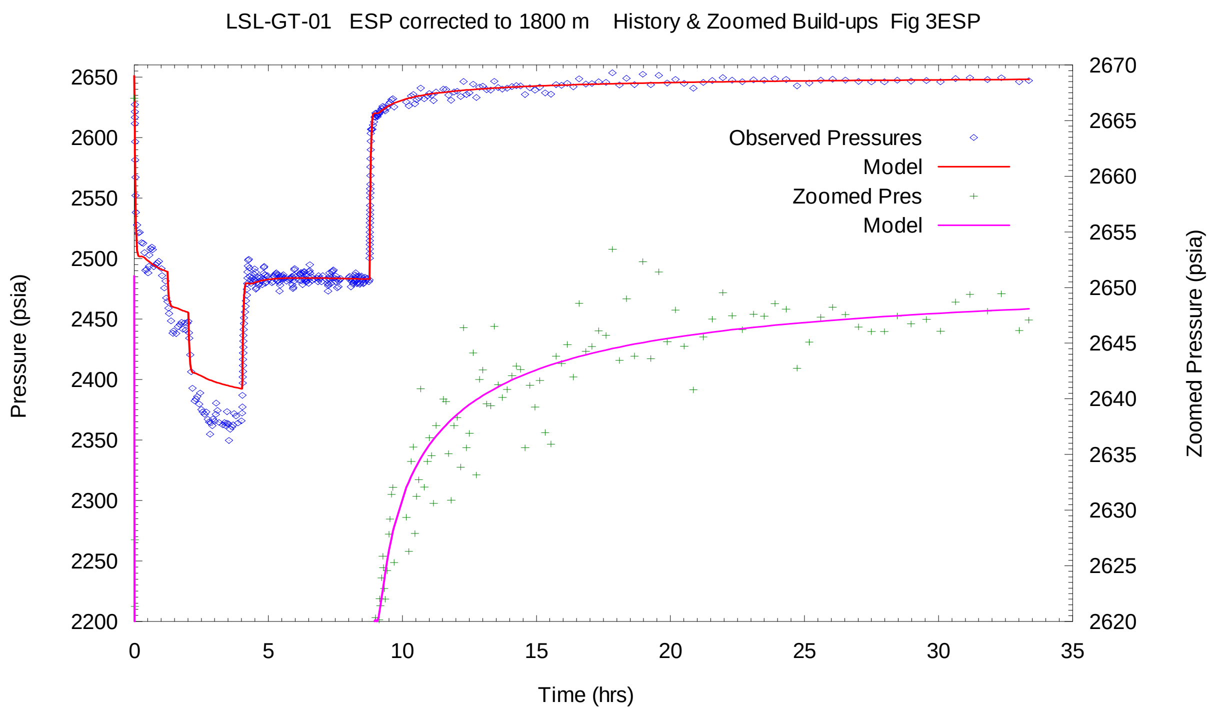
Fig-02 presents the match of the main build-up, both the Horner "straight" line (dark blue) as its derivative (green). Note that the first minute can be matched as pure wellbore storage. Next for about 3 minutes, the derivative shows severe wellbore effects, deviating far from the smooth model performance. But after 5 minutes, the build-up can be matched very well with the infinite analytical well model.

Fig-2ESP presents the match of the ESP pressures, corrected to a depth of 1800 mtv (mid reservoir depth). The permeability is only slightly higher at 588 mD, but the skin is really higher at 1.96. This higher skin is obviously caused by the friction in the casing between 1573 and 595 mtv. Note that the derivative is too poor to draw conclusions about a far-away flow barrier.
Figs-3 and 3ESP present the linear time plots of both gauges.
In Fig-3, the final observed pressures go below the model line, whereas this does not happen in Fig-3ESP. This is caused by the lack of correction from 1573 m to 1800 m: the cooling of this 227 m water column makes the final build-up pressures being too low.


LSL-GT-01 Horner Plot & Derivative, Main BU Fig 2
Pressure (psia)
2300
2280
2260
2240
2220
2200
Derivative
1000
100
10
1
0.01
0.1
1
10
Delta eff.time
Observed Pressures
Model K=570, S=1.2
Derivative
Model
barrier at 460 m


LSL-GT-01 Corrected ESP Horner Plot & Derivative, Main BU Fig 2ESP
ESP Pressures (psia)
2660
2640
2620
2600
2580
2560
2540
2520
2500
Derivative
1000
100
10
1
0.01
0.1
1
10
Delta eff.time
Corrected ESP at 1800 m
Model K=588, S=1.96
Derivative
Model


LSL-GT-01 History & Zoomed Build-ups Fig 3
Pressure (psia)
Zoomed Pressure (psia)
Time (hrs)
Observed Pressures
Model
Zoomed Pres
Model
2300
2250
2200
2150
2100
2050
2000
1950
1900
2320
2310
2300
2290
2280
2270
0
10
20
30
40
50


LSL-GT-01 ESP corrected to 1800 m History & Zoomed Build-ups Fig 3ESP
Pressure (psia)
Zoomed Pressure (psia)
Time (hrs)
Observed Pressures
Model
Zoomed Pres
Model
2650
2600
2550
2500
2450
2400
2350
2300
2250
2200
2670
2665
2660
2655
2650
2645
2640
2635
2630
2625
2620
0
5
10
15
20
25
30
35

9 Recommendations

The ESP pressure data can be improved by hanging a gauge at 50 to a few hundred meter below the ESP, using part of the damaged wireline.

Another way to improve the ESP pressure quality may be a reduction in the sampling frequency from 1/sec to 3/min. As the early shut-in is anyhow disturbed by wellbore phenomena, even 2/minute is enough.

Anyhow, Fig-03ESP proves that an analysis of the ESP data of the second well is possible, using the correction formula obtained from this well test.