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Evaluation of Hydraulic Stimulation-Induced Permeability Enhancement

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ABSTRACT

With permeability playing a major role in defining a geothermal well's production and injection capacity, a recently-drilled well in the Philippines with low permeability during its post-drilling completion, was subjected to a five-day hydraulic stimulation. Completion test after the stimulation was consequently conducted to quantify any permeability improvement that could be attributed to the procedure. The completion tests done in the well include moving pressure-temperature-spinner logs, injectivity, and pressure fall-off tests. Wellhead pressure was also monitored throughout the tests and during stimulation. Continuously declining WHP throughout the duration of the tests - from very high positive values to vacuum, increase in injectivity index and permeability-thickness, and additional permeable zones inferred by the moving logs suggest the success of the stimulation activity.

1. INTRODUCTION

The objective of drilling the well is to augment the steam supply of the sector by intersecting the permeability associated with the target structures which will be left open for production. The well is designed as a big hole following a single build-up, single azimuth welltrack on a three-string-two-liner casing configuration. It was spudded last August 19, 2013 and reached its programmed depth of 2200mMD on September 22, 2013 with no significant amount of losses during the drilling of both its 12-1/4" and 9-7/8" open hole sections. With this, it was then decided to extend the drilling by 150m in order to intersect additional fault. On September 23, 2013, the well was then successfully TD'ed at 2351mRT.

Upon conducting static flow check, however, it was observed that the well only accepts about 0.25bpm. Together with the observed little amount of losses during drilling, these phenomena triggered the conduct of an extended cold water-injection into the well as an attempt to increase the permeability around the well's surrounding formation (Yoshioka, et al., 2008).

This stimulation technique, known as hydraulic stimulation or fracturing, works by allowing the pressure to build up in the well which could cause fractures to manifest in the formation. A sudden drop in the wellhead pressure (WHP) denotes an improvement of the acceptance of the well and subsequently enhancement of permeability (Malibiran, et al., 2013; Pasikki, et al., 2010).

How the fracture develops depends on the rock stress. Pressure in a column of water increases with depth on a hydrostatic gradient. The weight of rock defines a lithostatic gradient of pressure equal to the weight of the overlying rock. If the fluid pressure in the rock pores is increased to lithostatic, then the fluid will lift the overlying rock. However, fractures normally occur at a lower pressure: the "fracture gradient." They happen at a lower pressure because rock stress in a horizontal direction is usually less than the lithostatic gradient. The fluid will fracture the rock in the easiest direction; it pushes in all directions, but the rock will part most readily in the direction of the least stress, and the fracture develops to this direction (Grant and Bixley, 2011).

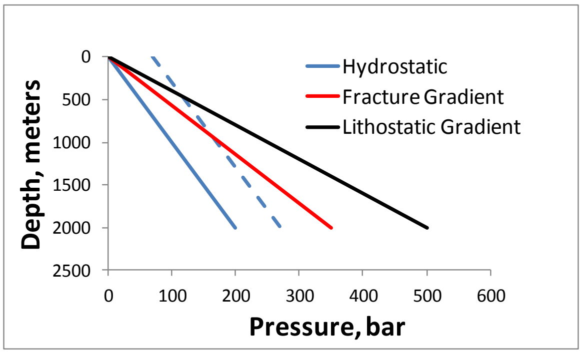

Figure 1: Concept of Hydraulic Fracturing

Referring to Figure 1, pressure build up will cause the formation to fracture as the hydrostatic gradient reaches and intersects the fracture gradient at a certain depth. Fractures would tend to grow upward rather than downward because of the difference between the fluid pressure gradient and the fracture gradient. There is more pressure excess in the top, rather than at the bottom (Grant and Bixley, 2011).

Shown in Figure 2 is the well casing profile with depths referenced to Casing Head Flange.

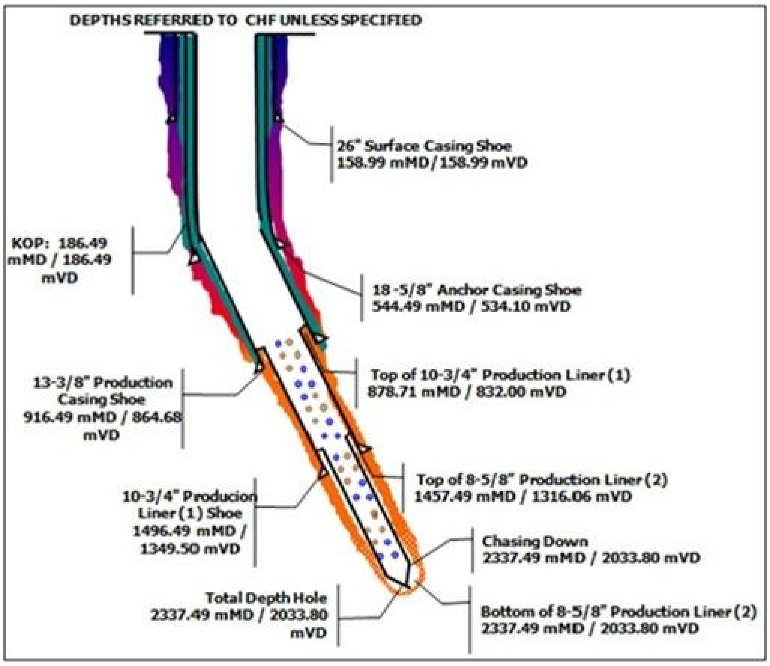

Figure 2: Well Casing Profile

2. HYDRAULIC STIMULATION TEST

Hydraulic Stimulation was conducted to enhance the permeability of the formation around the open-hole section of the well (Malate, 2003). While continuously injecting cold water at a specific pump rate, wellhead pressure was closely monitored to determine the trend and wait for a notable decrease in pressure before proceeding to higher pump rates.

The stimulation commenced at 2200H of September 29, 2013 at a pump rate of 16 bpm. Succeeding pump rates were 20, 24, and a two-day extension with 28 bpm. A decreasing trend in wellhead pressure was observed for every pump rate signifying an enhancement of the formation's permeability (Aqui and Zarrouk, 2011). The stimulation ended at 2200H, October 05, 2013. Shown in the figure below are the WHP data gathered during the duration of the activity.

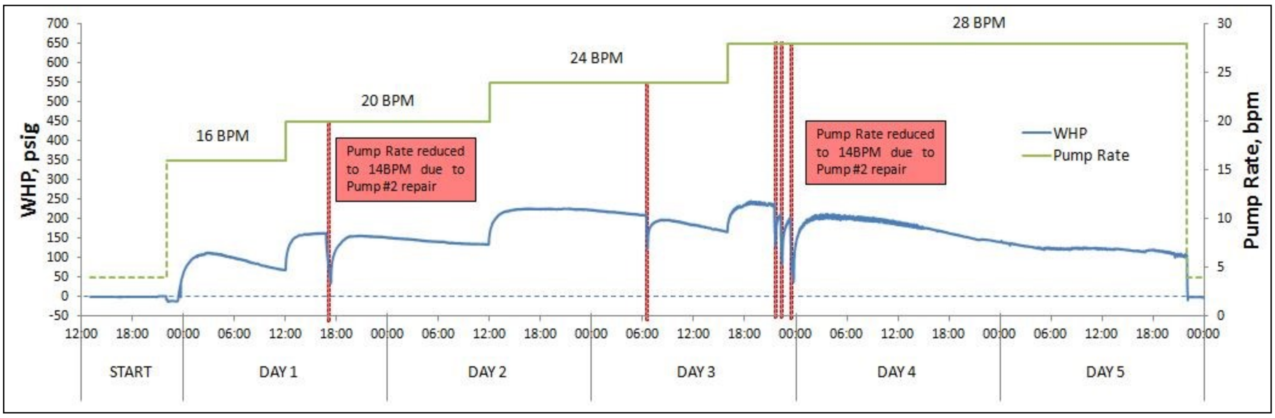

Figure 3: Monitoring Plot of WHP against time at different pump rates

3. RESULTS AND DISCUSSION

3.1 Permeable Zones

Permeable zones were identified by interpreting Pressure-Temperature-Spinner profiles of pre- and post- hydraulic stimulation as shown in Figures 4 and 5. Prior to the hydraulic stimulation, permeable zones were identified at 2000mMD – 2050mMD and at the well's bottom.

Though not evident in the spinner response, notable changes in temperature gradient infer the presence of permeable zones at 950mMD – 1000mMD and 1075mMD – 1150mMD**.** Another permeable zone, located at 1875mMD – 1950mMD, was delineated through noticeable changes in spinner response and a slight adjustment in temperature gradient (Malate, et al., 2000). These permeable zones are noted to not have been identified during the pre-hydraulic stimulation test.

Zones seen prior to hydraulic stimulation were again seen during this test. Noticeable changes in spinner response and a slight adjustment in temperature profiles locate the permeable zone at 2000mMD – 2150mMD while the non-heating-up-at-the-bottom temperature profile infers the loss zone at the well's bottom.

Table 1: Summary of Permeable Zones

Permeable Zones, meters Measured Depth	
Pre-Hydraulic	Post-Hydraulic
-	950 – 1000
-	1075 – 1150
-	1875 – 1950
2000 – 2050	2000 – 2150
Bottom	Bottom

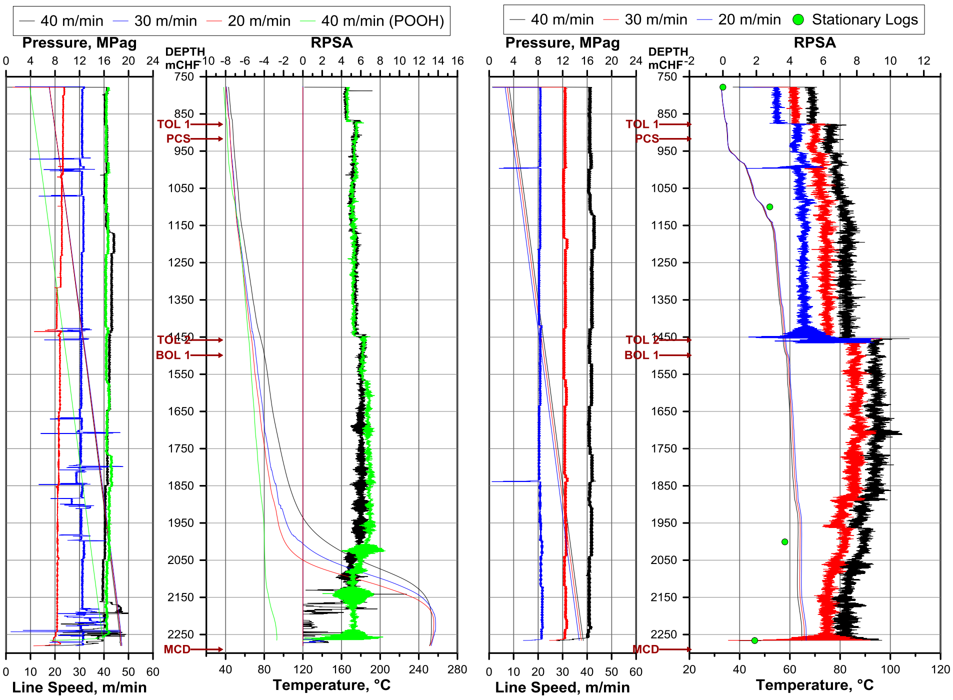

Figure 4: 4 bpm Pump Rate at Different Line Speeds (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

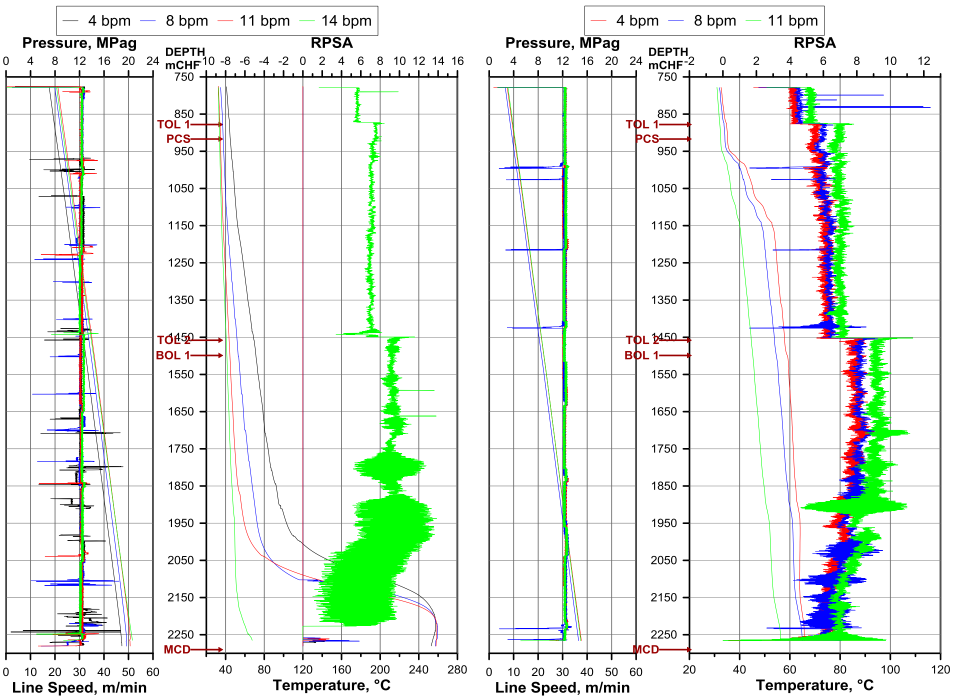

Figure 5: Consolidated 30m/min Log-ups at Different Pump Rates (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

3.2 Injectivity Index

Post-Hydraulic injectivity index, computed to be 14.34 L/s-MPag, is higher than that of pre-hydraulic stimulation, 11.27 L/s-MPag. This, along with the vacuum wellhead pressures observed throughout the entire duration of the post-hydraulic stimulation completion test, infer permeability improvement. Pressure responses at different pumping rates during the pre- and post-hydraulic stimulation injectivity tests are summarized in Tables 2 and 3, respectively.

Figure 6 shows the plot of injectivity indices from both the pre- and post- hydraulic stimulation completion test. Aside from developing vacuum wellhead pressure at all the pump rates utilized during the completion test, lower downhole pressures and lower projected downhole pressures at zero-pump rate are noted during the post-stimulation completion test despite the tool being set at a slightly deeper portion of the well. These infer permeability improvement.

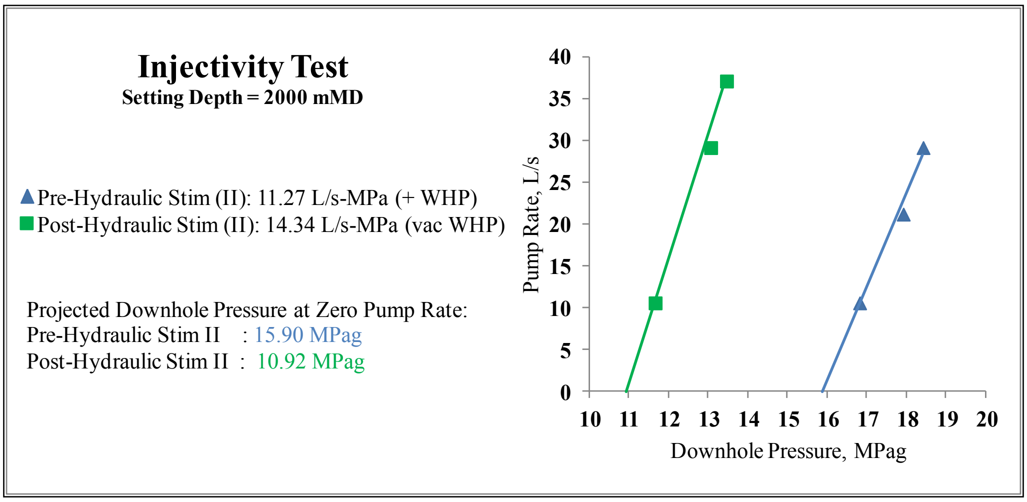

Figure 6: Pre- and Post- Hydraulic Stimulation Injectivity Plot. Pre-stimulation Setting Depth: 2000mMD, Post-stimulation Setting Depth: 2067mMD (plot shown is projected to 2000mMD)

Table 2: Pre-Hydraulic Stimulation Injectivity Index

PUMP RATES		Downhole Pressure at 2000 mMD, MPag	Wellhead Pressure, MPag
Bpm	L/s		
4	10.6	16.8	Vacuum
8	21.2	17.9	0.4
11	29.2	18.4	0.9
14	37.1	-	-
INJECTIVITY INDEX, L/s-MPag : 11.27			

Table 3: Post-Hydraulic Stimulation Injectivity Index

PUMP RATES		Downhole Pressure at 2067 mMD, MPag	Wellhead Pressure, MPag
Bpm	L/s		
11	29.2	13.7	vacuum
14	37.1	14.1	vacuum
4	10.6	12.3	vacuum
INJECTIVITY INDEX, L/s-MPag : 14.34			

3.3 Pressure Transient Analysis

Reservoir properties can be inferred by analyzing the pressure response data obtained from well testing. For this study, pressure decline was measured subsequent to the reduction of pump rate. The well test conducted is known as the pressure falloff (Horne, 1995).

The data from the PFO test was analyzed using the pressure transient analysis software, Saphir. The following were set in making an analytical model of the well and its surrounding reservoir:

a. Wellbore Model: Changing Storage
b. Reservoir Model: Homogeneous
c. Boundary Model: Infinite

Simulated curves were generated from the inferred wellbore and reservoir parameters and were allowed to match measured data. Through matching of the log-log pressure vs. time, semi-log pressure vs. time, pressure vs. time, and bourdet derivative plots, the following well characteristics were determined as shown in Table 4:

Table 4: Saphir Analyses of Pre- and Post- Hydraulic Stimulation

Parameter	Pre-Hydraulic Stimulation	Post-Hydraulic Stimulation
Wellbore Storage Constant (m^3/kPa)	0.0376	0.146
Permeability-thickness (da-m)	1.06	1.82
Skin	-1.45	-2.62

Figures 7 to 9 show that simulated curves closely match the curves generated from measured data. As shown in Table 5, the relatively low transmissivity and injectivity index calculated for the well, as compared those of nearby wells, suggest the relatively poor permeability of the immediate formation surrounding it (Bayrante, et al., 2010; Malate, 2003).

Table 5: Post-Drilling Completion Test Injectivity Indices and Transmissivity Comparison of Nearby Wells

Well	Transmissivity, da-m	Injectivity Index, L/s-MPa	Skin Factor
A	9.4 - 9.6	106	-1.5 to -2.2
B	2.1	23	-4.4
C	2.6	11.1	-5
D	14.2 - 15.4	109 – 113	-4.64 to -4.68
Pre – Hydraulic	1.06	11.3	-1.45
Post – Hydraulic	1.82	14.3	-2.62

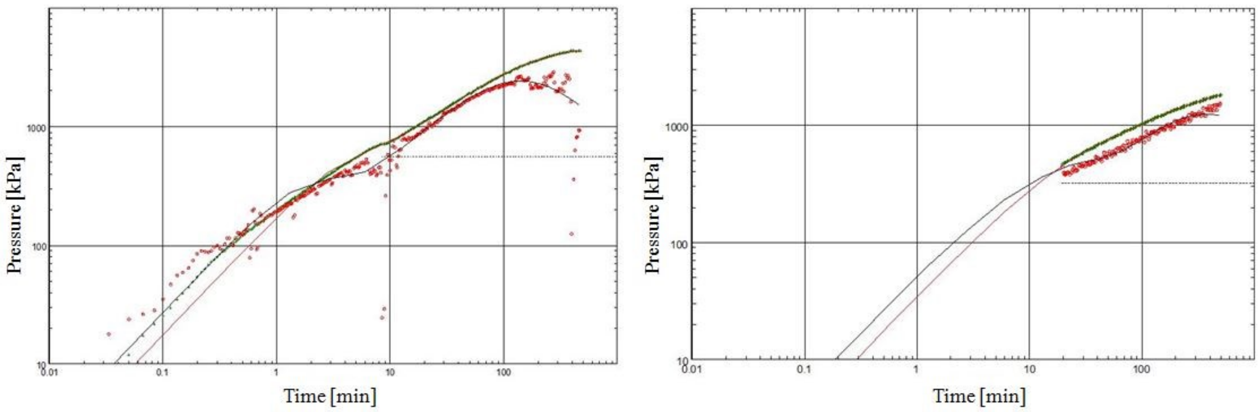

Figure 7: Measured and Simulated Pressure vs. Time and Bourdet Derivative in a Log-Log Plot (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

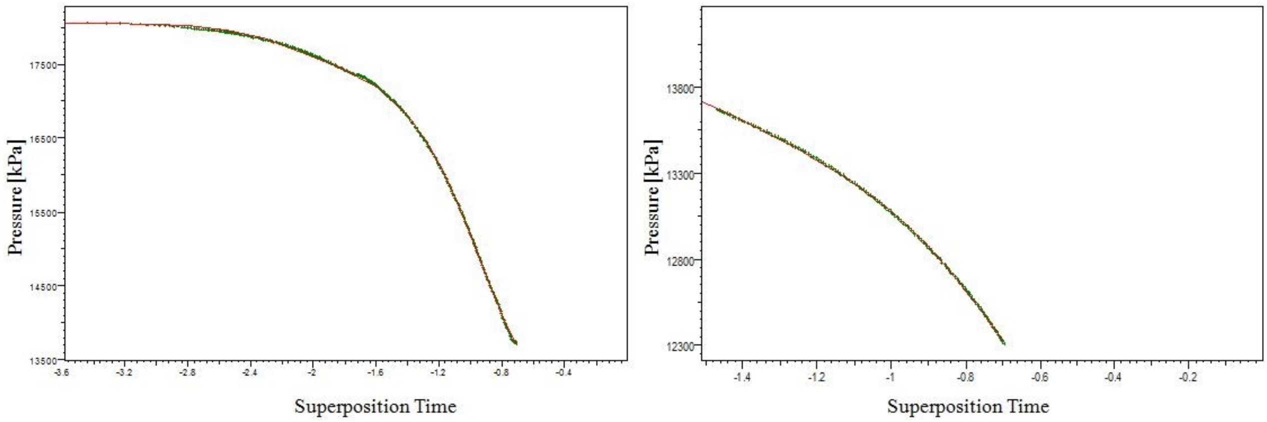

Figure 8: Measured and Simulated Pressure vs. Time on a Semi-Log Plot (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

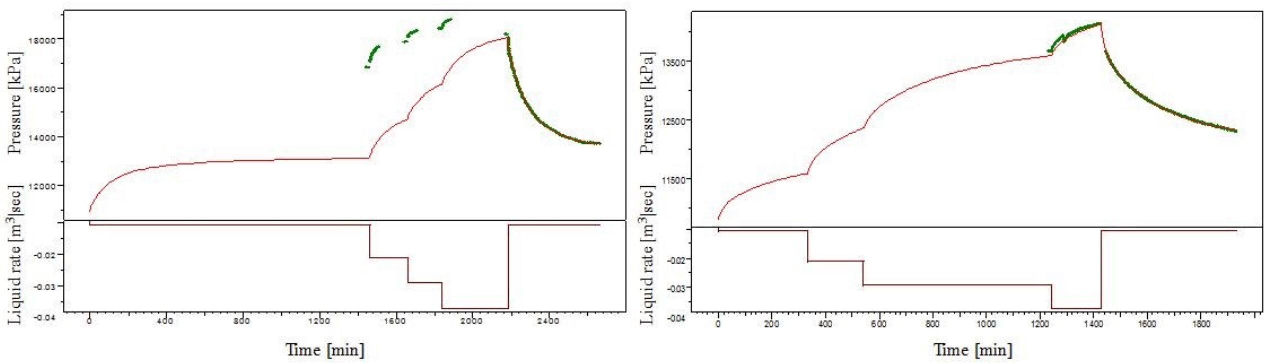

Figure 9: Injection History with Measured and Simulated Pressure (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

3.4 Production Logging Analysis

Production logging analysis using Emeraude was made for the moving logs of both pre- and post- hydraulic stimulation completion tests to verify the location of permeable zones and quantify their corresponding mass flow contributions (Mukerji, 2013).

Through the matching of density and velocity profiles as seen in Figure 10, mass contributions and calculated injectivity/productivity indices for the inferred permeable zones are summarized in Tables 6 and 7. Results of the simulation show that the major permeable zone is the bottom feed:

Table 6: Mass Contribution for Pre-Hydraulic Stimulation Completion Test

Permeable Zones (mMD)	4 bpm (10.6 l/s)		14 bpm (37.1 l/s)		Injectivity/Productivity Index (L/s-MPag)
	Mass Flow (L/s)	Downhole	Mass Flow (L/s)	Downhole	

		Pressure (MPag)		Pressure (MPag)	
2000 – 2050	-10.4 (out)	17.0	-17.1 (out)	19.0	3.35
bottom	-0.2 (out)	18.8	-20.0 (out)	20.6	11.0

Table 7: Mass Contribution for Post-Hydraulic Stimulation Completion Test

Permeable Zones (mMD)	4 bpm (10.6 l/s)		8 bpm (21.2 l/s)		11 bpm (29.2 l/s)		Injectivity/ Productivity Index (L/s-MPag)
	Mass Flow (L/s)	Downhole Pressure (MPag)	Mass Flow (L/s)	Downhole Pressure (MPag)	Mass Flow (L/s)	Downhole Pressure (MPag)	
950 – 1000	7.2 (in)	4.6	0.7 (in)	4.3	0.1 (in)	4.7	3.85
1075 – 1150	4.4 (in)	6.1	2.3 (in)	5.4	1.8 (in)	5.9	2.23
1875 – 1950	-3.7 (out)	12.3	-3.8 (out)	11.8	-5.7 (out)	12.2	1.21
2000 – 2150	-4.4 (out)	13.2	-4.2 (out)	13.1	-6.7 (out)	13.4	8.79
bottom	-14.1 (out)	14.7	-16.2 (out)	14.6	-18.7 (out)	15.0	8.35

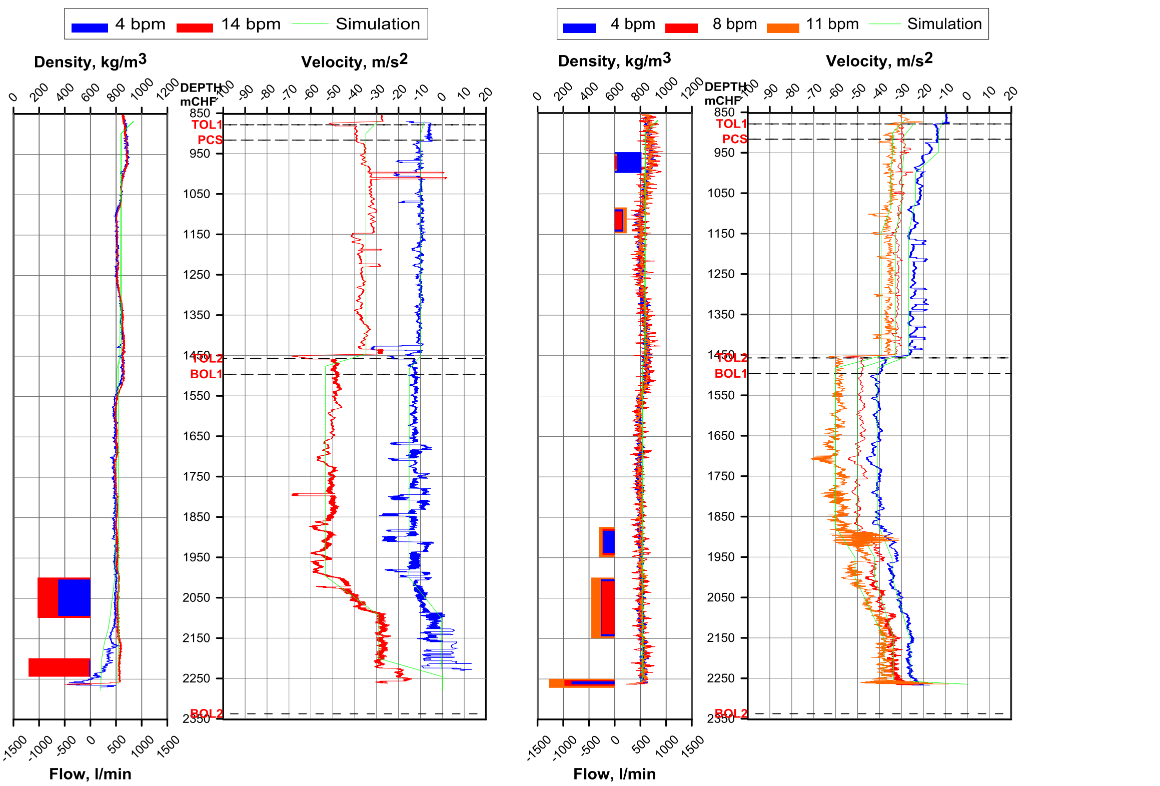

Figure 10: Density and Velocity Matches with Calculated Flow Rates per Permeable Zone (Pre-Hydraulic Stimulation on the left; Post-Hydraulic Stimulation on the right)

4. CONCLUSION

Hydraulic stimulation is a standard technique to improve the flow of a well whose surrounding formation has an existing permeability too poor for sufficient flow. By pumping in fluid, newly induced fractures form when hydrostatic pressure exceeds the fracture gradient (Grant and Bixley, 2011). Reduction in the wellhead pressure during monitoring may indicate an enhancement in the well's permeability (Aqui and Zarrouk, 2011).

In this study, the measure of the permeability enhancement is quantified through the analysis of data obtained from downhole surveys. Two approaches were presented: 1.) manual interpretation and calculation, and 2.) use of computer software.

Using plots, number and location of permeable zones are inferred while injectivity indices are calculated. Computer programs, on the other hand, provide more detailed downhole information like formation properties and downhole flow mechanism. These computer-generated interpretations give engineers a better picture of downhole wellbore environment (Mukerji, 2013).

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