Appendix B

Pressure Transient Analysis in the Arbuckle (Step-Rate Test, Interference Test, and DST Analysis)

Description of the Step-Rate Test

A step-rate test was performed in August 2011 in well 1-32 at gauge depth of 5,025 ft using the pump schedule described below. Pressure responses were measured at observation well 1-28.

> A) Pump at 2 bpm for 20 minutes, then shut down for 15 minutes.
>
> B) Pump at 5 bpm for 20 minutes, then shut down for 15 minutes.
>
> C) Pump at 7.5 bpm for 20 minutes, then shut down for 15 minutes.
>
> D) Pump at 10 bpm for 20 minutes, then shut down for 15 minutes.
>
> E) Pump at 12.5 bpm for 20 minutes, then shut down for 15 minutes.
>
> F) Pump at 13.4 bpm for 20 minutes, then shut down for 23 minutes.
>
> G) Pump at 13.4 bpm for 1 hour 5 minutes, then shut down for 16 minutes
>
> H) Pump at 9.4 bpm for 35 minutes, then shut down. End of pumping.

Step-Rate Test Analysis

The step-rate test consisted of eight injection periods and eight fall-offs (fig. 1). All eight injection periods were selected and modeled (simulated) by Fekete WellTest commercial software. Because all injection periods were selected in this model, the model tries to match the pressures in all periods at the same time with a single skin. Measured pressures were simulated, and permeability and skin were calculated. Measured pressures are in good agreement with calculated pressures (fig. 1). However, an accurate match between the calculated and measured pressures with a single skin is not possible because each injection period has a different skin. An induced fracture occurred at injection period 5; fracture pressure and closure pressure were calculated and are discussed in following sections.

Results

Calculated permeability from the step-rate test is 113 mD for a 30 ft interval that is in vertical communication based on vertical permeability and Lorenz plot (fig. 11) ;where, results of flow units and flow capacity($\Sigma kh\%$) are shown in figure 12. Calculated permeability from the analysis is close to the log-derived average permeability (74 mD) for the same interval. There are vertical

barriers above and below this interval, and 25 ft of the interval is perforated. The calculated skin for injection period 7 is -7.6. This skin was used in the analysis for all injection periods.
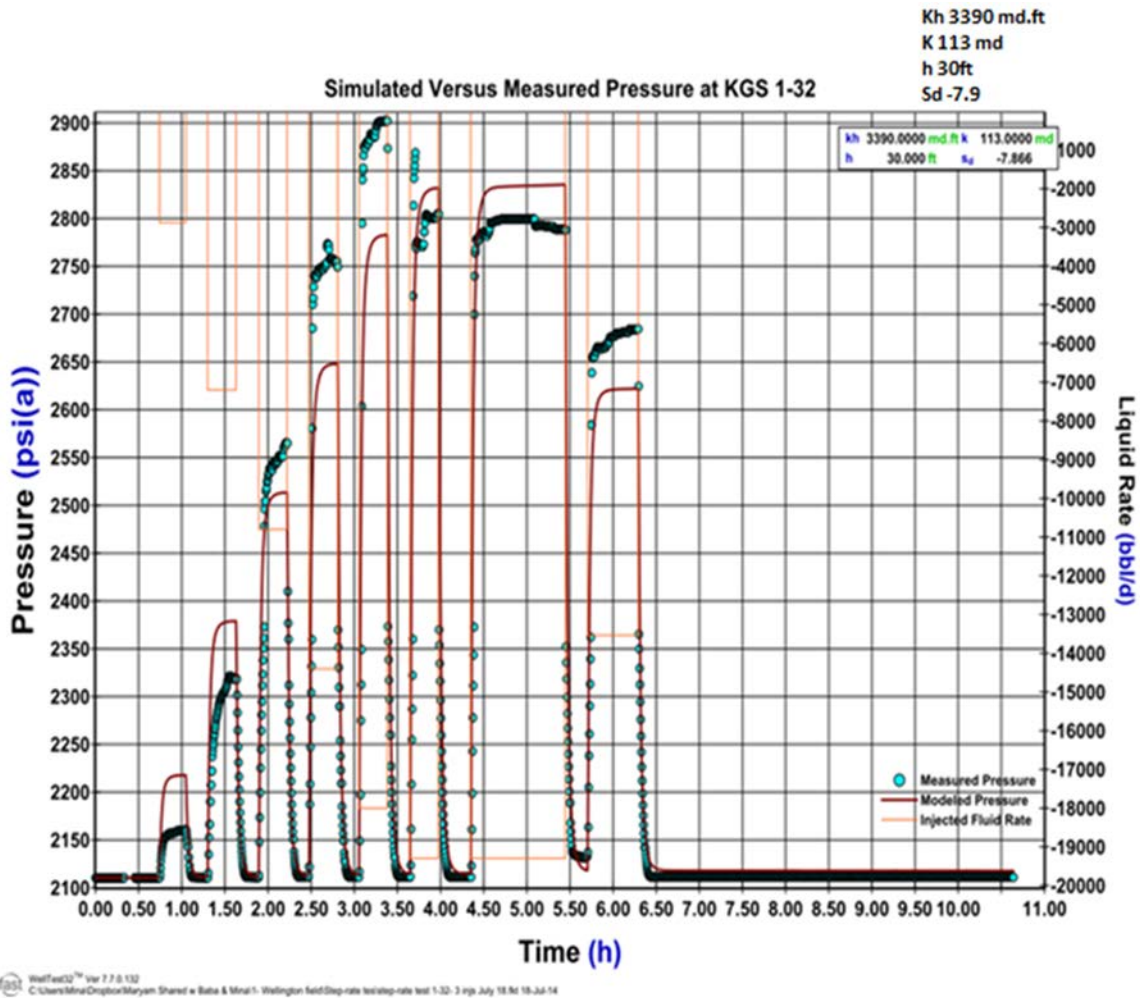

Figure 1. Simulated pressures in red versus measured pressures.

Interference Test Analysis

Well 1-32 was the injection well, and pressure responses were measured at observation well 1-28. The distance between wells 1-32 and 1-28 is 3,500 ft.

Results of the Interference Test Analysis

Pressure transient data of well 1-28 were modeled using a composite dual porosity-permeability model (zone/region 1 and 2). The composite model resulted in a better match between modeled pressures and measured pressures (fig. 2). Based on this model, permeability in the vicinity of well 1-32 to a radius of 2,493 ft (region 1) has a lower value (100 mD) for the 30 ft interval that is in vertical communication than permeability from a radius of 2,493 ft to the vicinity of 1-28 (region

2), where the value increased to 124 D (fig.3). Permeability for region 1 is close to the log-derived average permeability (74 mD). Greater permeability for the farther radius is associated with a fracture or runs from 1-32 toward1-28. Figure 4 shows results of the dual porosity-permeability model with its associated parameters and calculated permeability and skin.
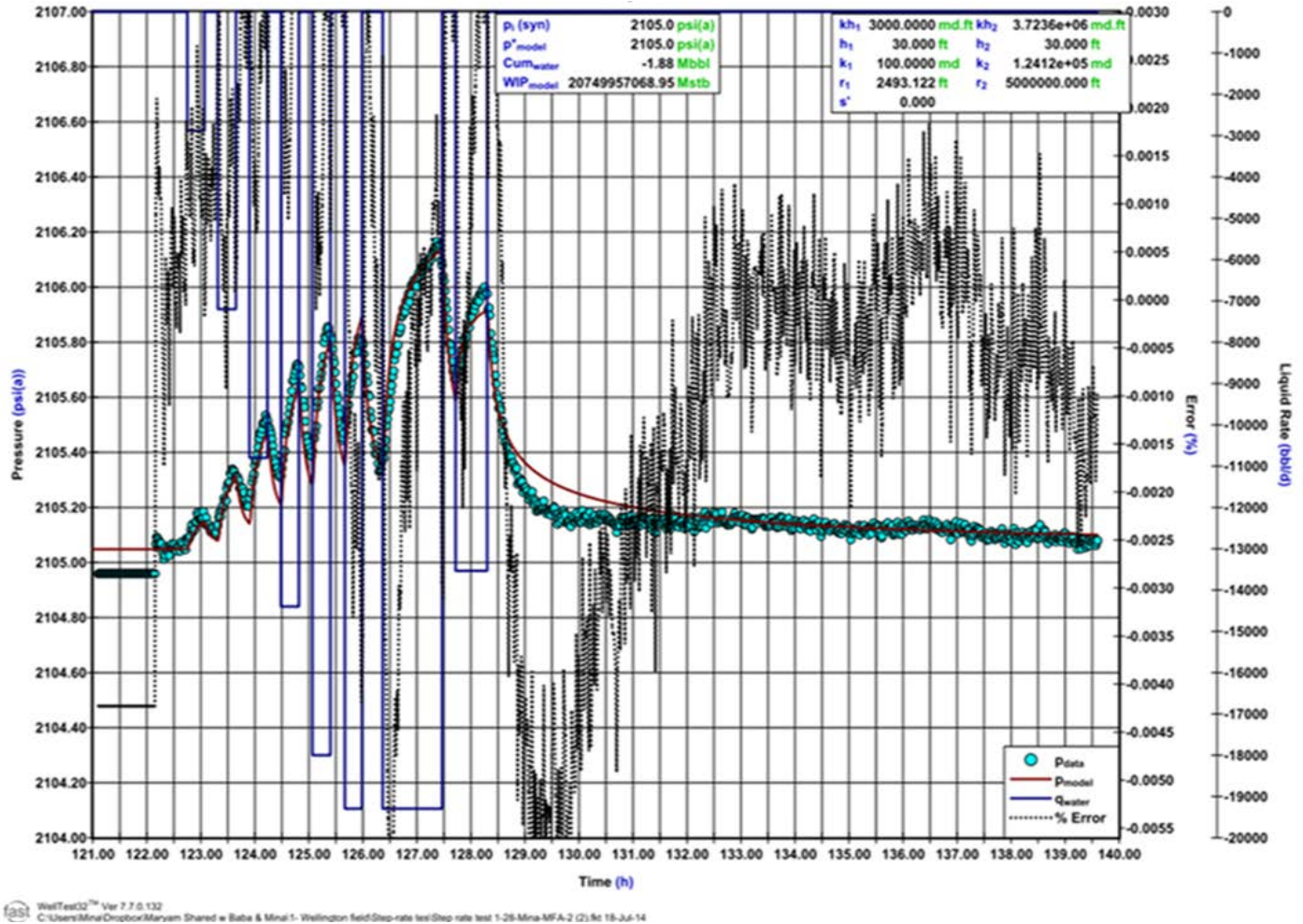

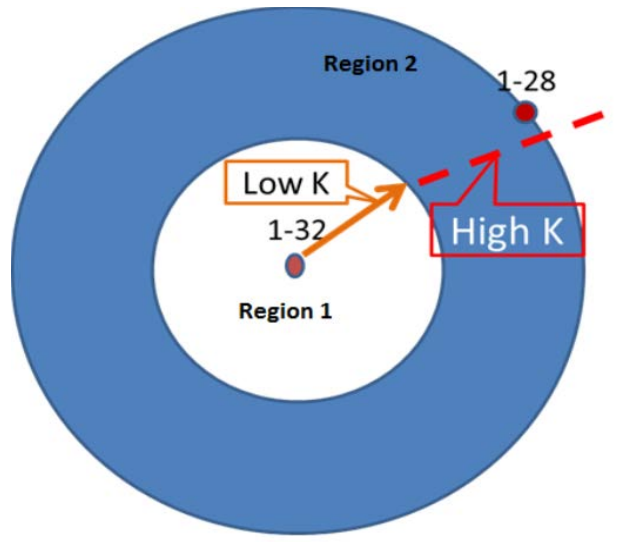Figure 2. Interference analysis results (modeled pressures in red and measured pressures in blue).

Figure 3. Diagram of Interference analysis showing regions 1 and 2 associated with two permeabilities.

Figure 4. Results of the interference analysis showing the dual porosity-permeability model and its associated calculated permeability and skin.

Fracture/Breakdown Pressure Calculation

Fracture occurred at injection period 5, where injection pressure exceeded formation fracture pressure. Fracture (breakdown) pressure is about 2,900 psi (figs. 5 and 6). The fracture gradient is 0.58 psi/ft in the Arbuckle at the gauge depth of 5,025 ft.
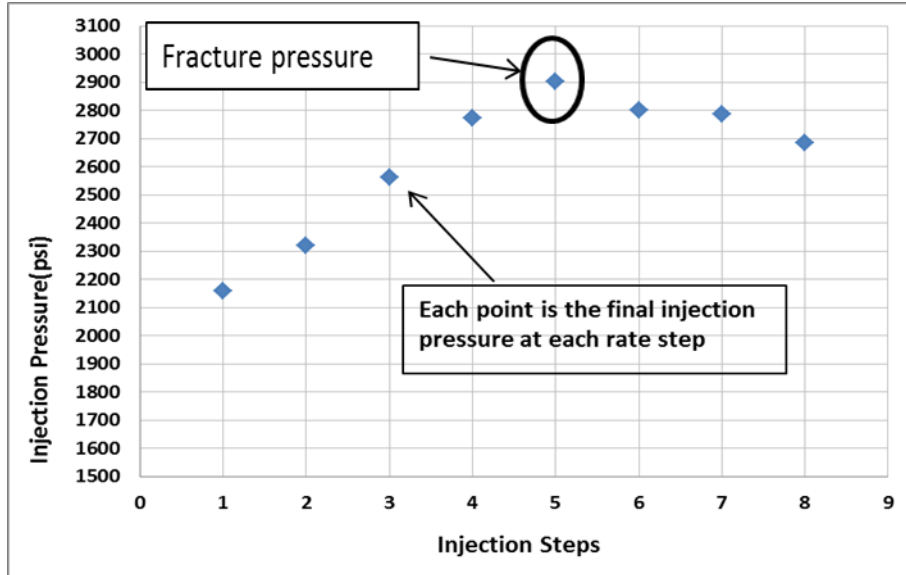

Figure 5. Injection pressure versus injection step showing that fracture occurred at injection step 5.
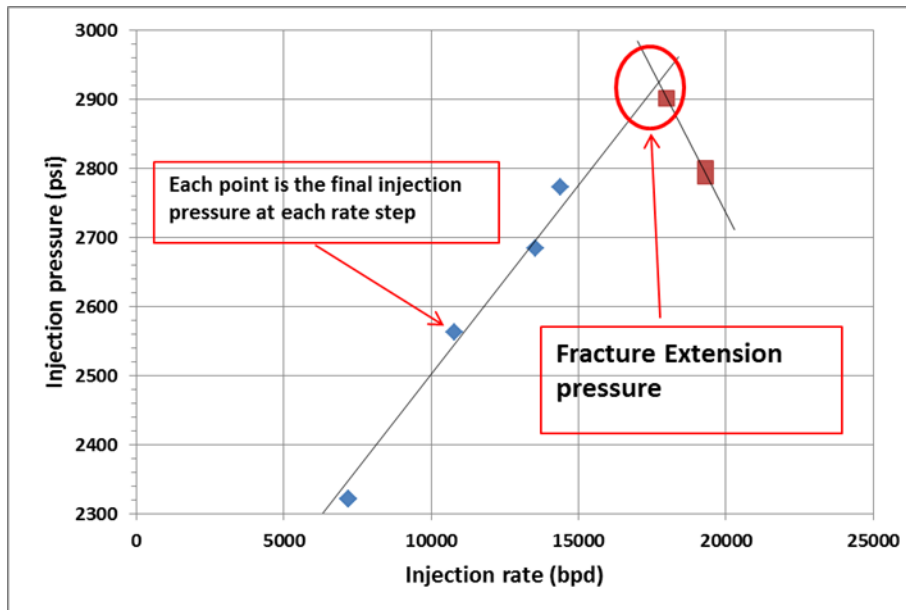

Figure 6. Injection pressure versus injection rate (bbl/D) where the intersection is the fracture pressure.

Determination of Closure Pressure/Minimum Stress

Fracture occurred on rate step 5, and the fracture remained open during injection periods 5 and 6 until the injectivity index started to drop (fig. 7). The fracture closes at the point where the injectivity index returns

5

to its value before initiation of fracture. Closure pressure or minimum stress is slightly less than 2,666 psi, and its gradient is 0.53 psi/ft (fig. 8). One or two more rate steps at lower rates were needed to give a more accurate closure pressure.
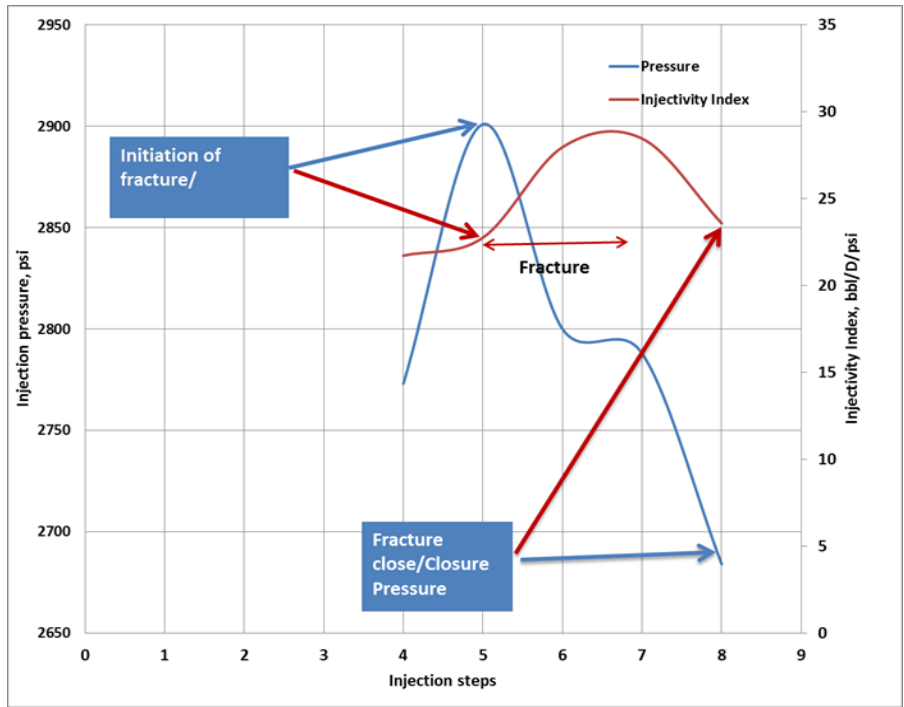

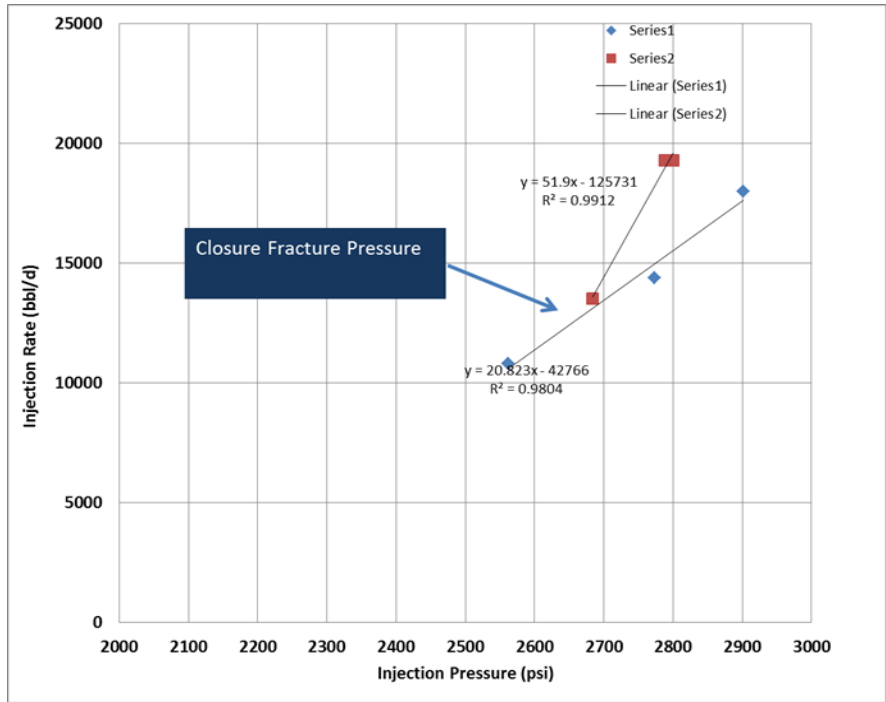**Figure 7. Injection pressure versus injection steps.**

Figure 8. Injection rate versus injection pressure.

DST Analysis in Well 1-32 and 1-28

DST Validity in Well 1-32

Only DST 1 and 4 are valid for analysis. DST 2 and 3 are not suitable for analysis, and they would give inferior results if they were analyzed. Flowing pressure of DST 2 is equal to shut-in pressure; therefore, there is no build up to be analyzed. Only temperature and reservoir pressure are valid in DST 2. The same issues apply to DST 3.

DST Results

DST 4 was analyzed by the FEKETE WellTest build up module, and permeability and skin were calculated (fig. 9). The test interval was 4,175–4,190 ft.
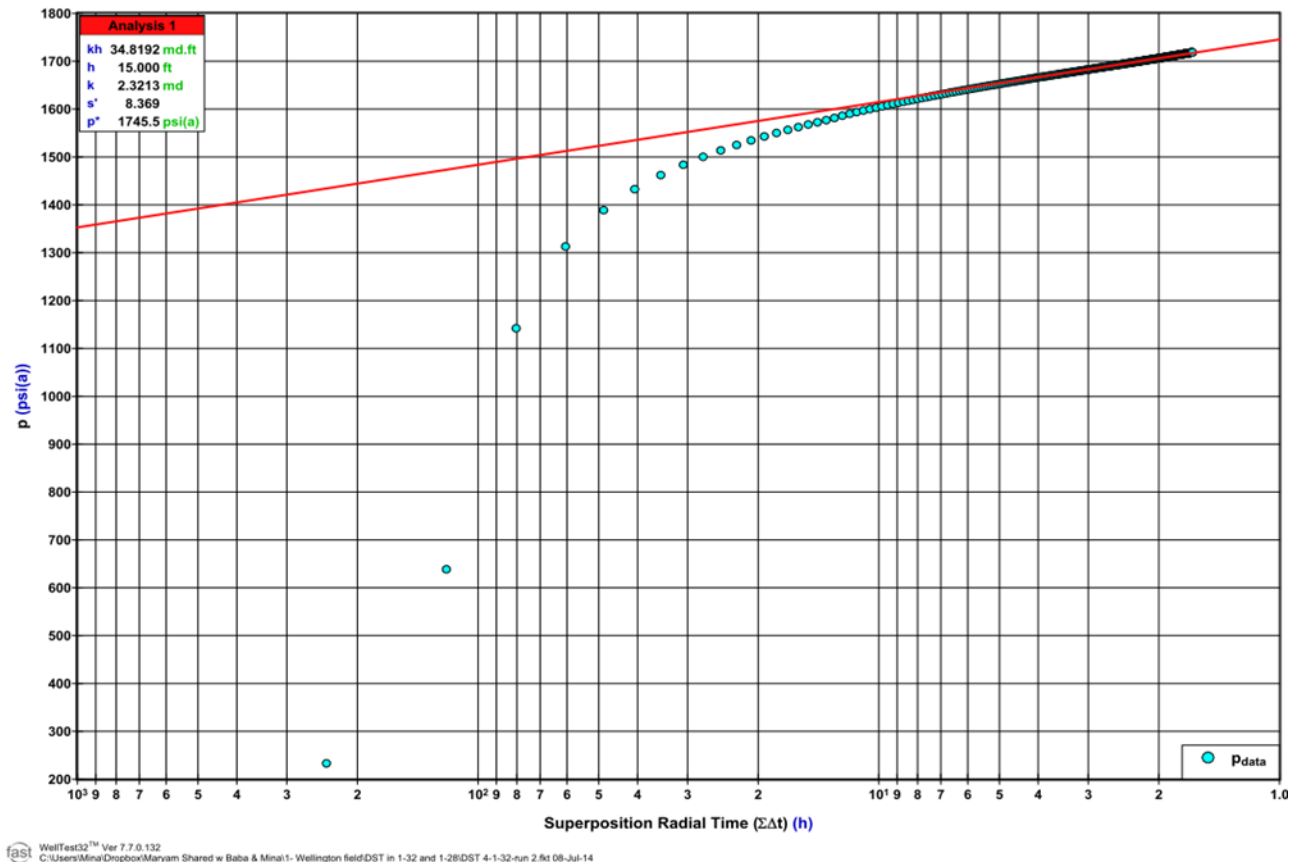

Figure 9. DST 4 radial flow analysis results.

DST Validity in Well 1-28

Only DST 1 is valid for analysis. DST 2 has a short flow period and does not have a transient period. Only reservoir pressure measurements during shut-in periods from DST 2 are valid. DST 3 and 4, like DST 2, have short transient times and are not valid for analysis.

Results of DST 1

DST 1 was analyzed by the FEKETE WellTest build up module, and permeability and skin were calculated for test interval 5,133–5,250 ft.
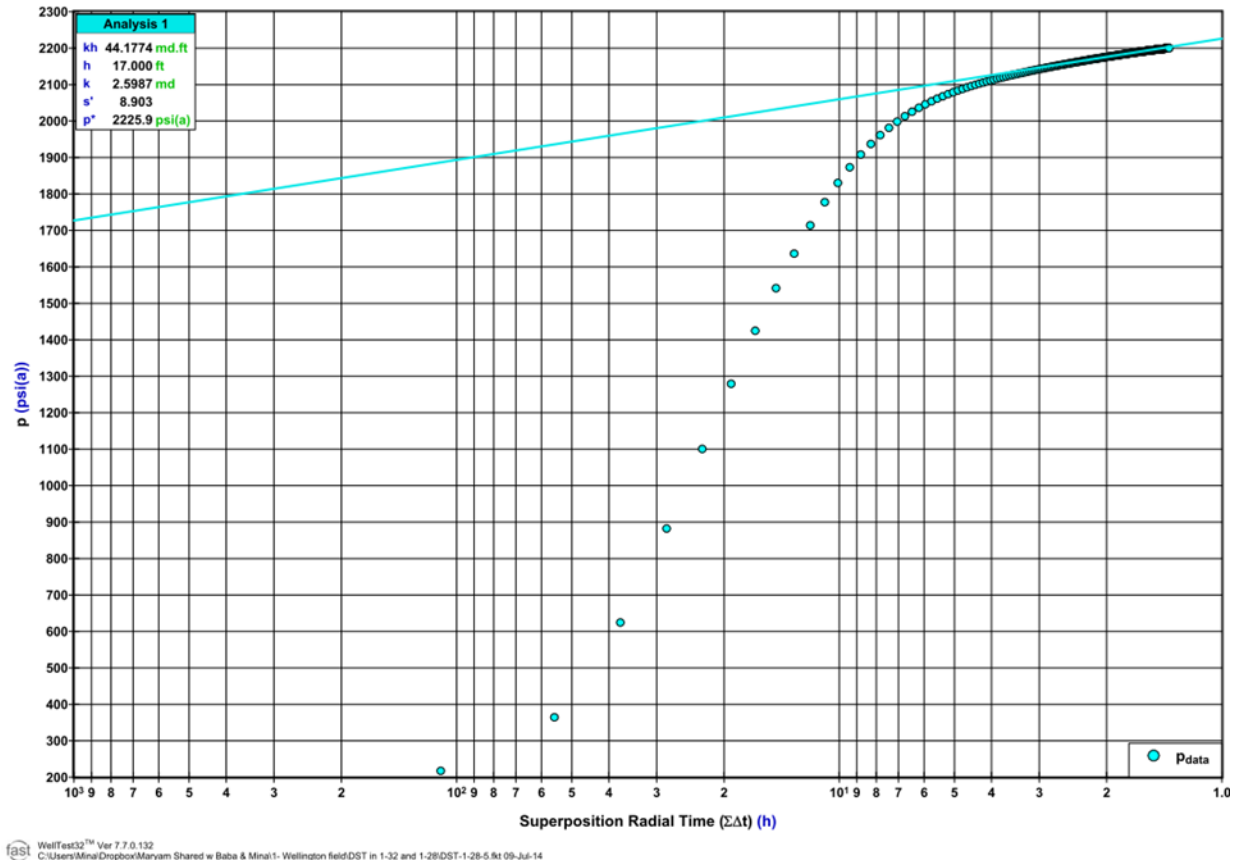

Figure 10. DST 1 radial flow analysis results.

Results of Calculated Permeability from Pressure Transient Analysis (Step-Rate, Interference, and DSTs) Compared to Log-Derived Permeability and Core Permeability 90 Degree (If Available)

Well 1-32				
DST Interval	K from DST	Log connectivity	Average Log Derived K90	Average Core K90
ft	mD	ft	mD	mD
4175-4190	2.32	4175-4090	4.61	4.59

Well 1-28				
DST Interval	K from DST	Log Connectivity	Average Log Derived K90	Average Core K90
ft	mD	ft	mD	mD
5133-5250	2.60 mD	5133-5160	2.17 (5133-5160)	NA

Step-Rate Test results				
Interval	Gauge Depth@	K from Step-Rate Test	Average Log Derived K90	Average Core K90
ft	ft	mD	mD	mD
30	4869	113	74	NA

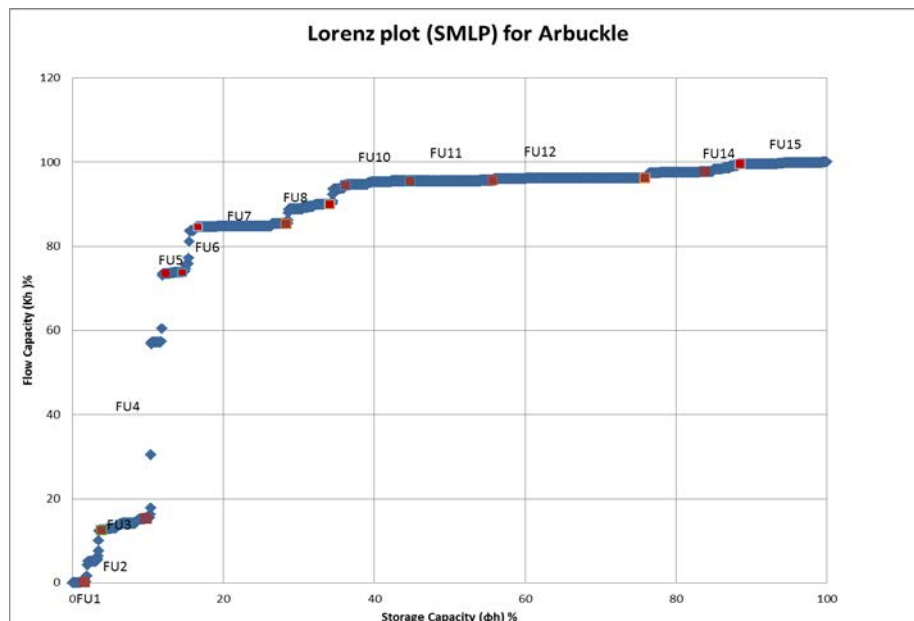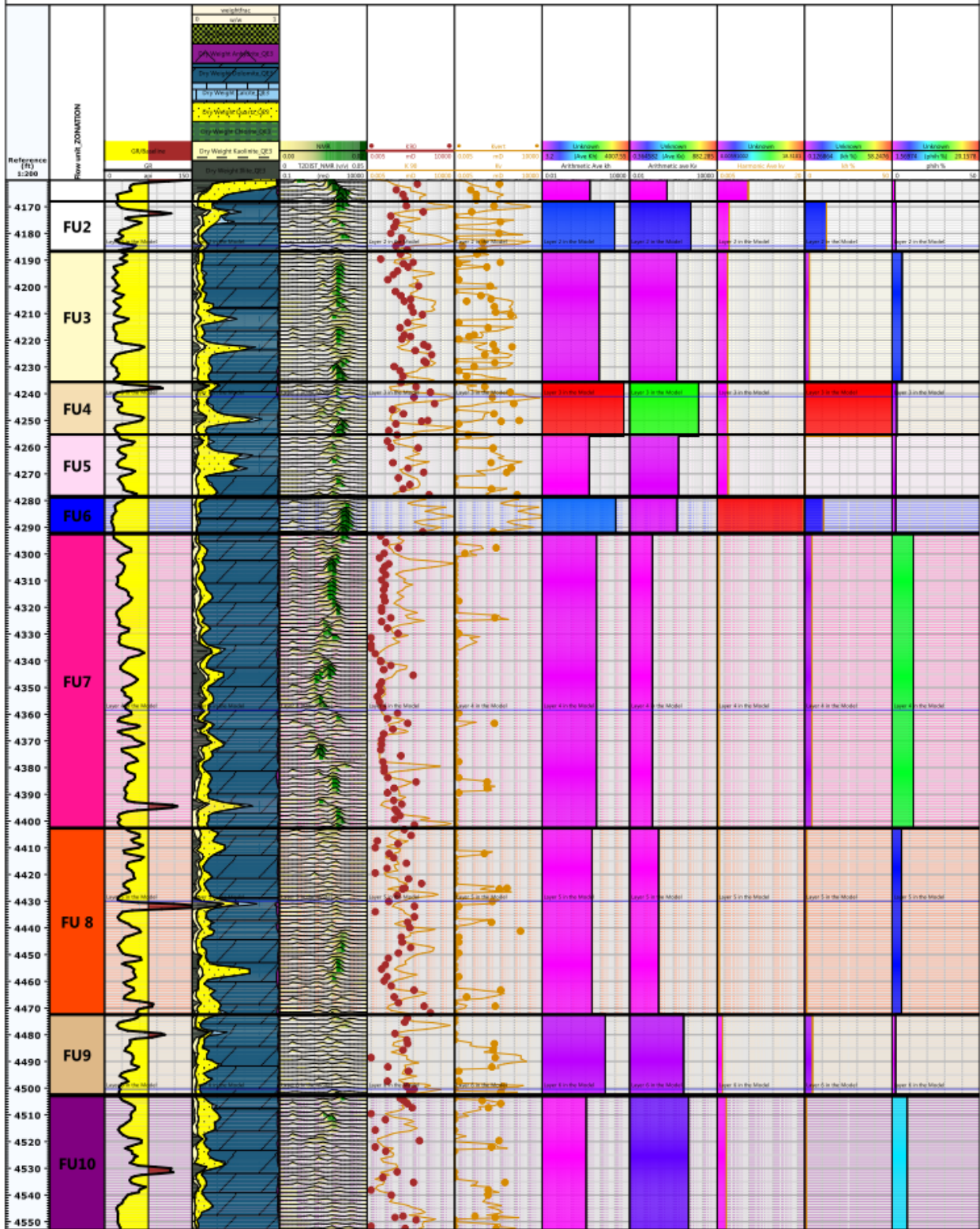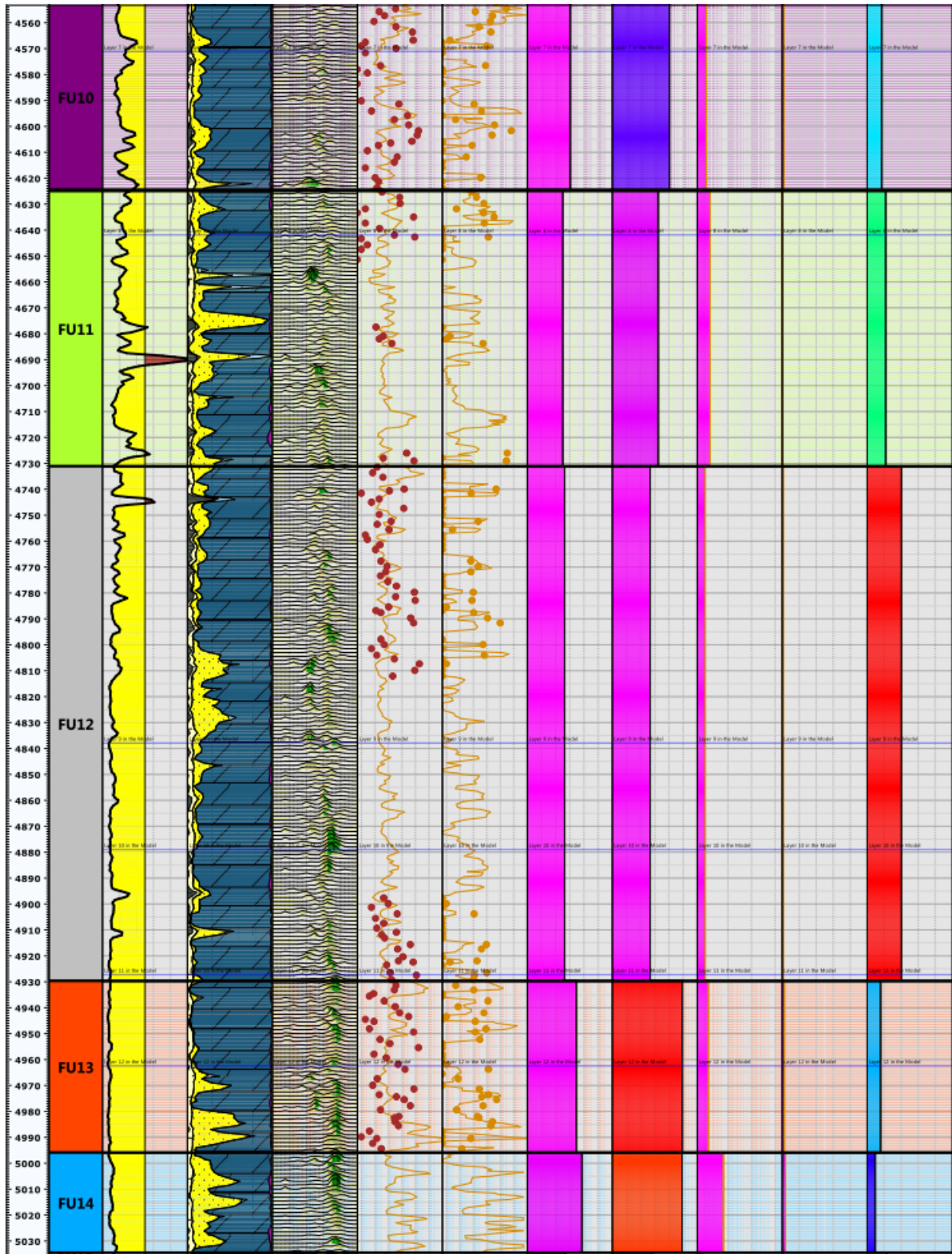| Interference test result				
Interval	K for Zone 1	K for Zone 2	Ave K90 from Log for Zone1	Average Core K90
ft	mD	D	mD	mD
30	100	124	74	NA

Figure 11. Lorenz plot (SMLP) and flow units FU1 to FU15.
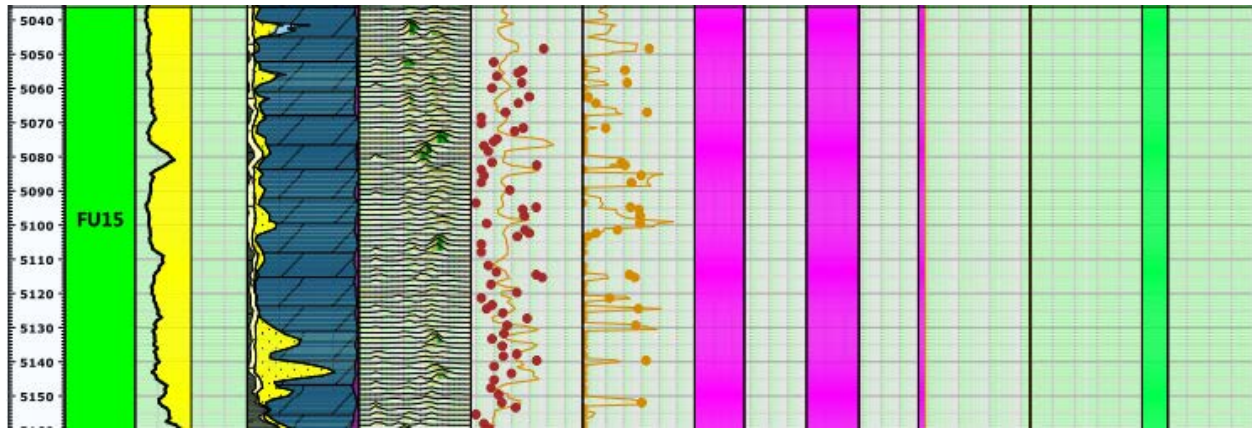
Well: **WELLINGTON KGS #1-32**

Figure 12. Layout of 1-32 showing flow units from Lorenz plot and flow capacity (ΣKh%).

Conclusion

- Permeability values calculated from step-rate and interference tests are close to log-derived permeability values.
- The lower permeability value (74 mD) from the interference analysis is matrix permeability and is in agreement with log-derived permeability (100 mD).
- Greater permeability (124 D) in zone/region 2 from the interference test analysis is associated with a radius farther from the 1-32 wellbore to the vicinity of well 1-28. This greater permeability, which is not matrix permeability, is associated with fault or fracture.
- Composite dual porosity-permeability model resulted in accurate permeability estimations in the two regions.
- Permeability values calculated from DSTs in wells 1-32 and 1-28 are in agreement with log-derived permeability and core data, when present.