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Skin Uncertainty in Multi-Layered Commingled Reservoirs with Non-Uniform Formation Damage

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC

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DECLARATION OF OWN WORK

I declare that this thesis:

Skin Uncertainty in Multi-Layered Commingled Reservoirs with Non-Uniform Formation Damage

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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Skin Uncertainty in Multi-layered Commingled Reservoirs with Non-uniform Formation Damage

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Abstract

Pressure build-up transient analysis is commonly used for estimating skin effect and permeability. In a multi-layered reservoir, however, skin and permeability values derived using single layer analysis can be misleading if damage is not uniform along the well; good pressure and pressure derivative matches may be obtained, but the existence of high skin factors in highly damaged layers may be missed.

The motivation of the present study comes from suspiciously low skin values observed in onshore oil producers in field "X" operated by Cairn India, whereas production was short of expectations. Although rock properties were uniform throughout, it was found that the field exhibited a multilayer behaviour, due to significant variation in oil viscosity with depth, thus requiring multi-layer testing and analysis.

A single well radial model has been used to generate a multi-layer test and illustrate the multi-layer interpretation procedure. It is shown to provide satisfactory results for both geologically layered formation and layered behaviour due to fluid property variation with depth. In addition, a field example of multi-layer test and interpretation has been presented.

Introduction

The degree of heterogeneity in the vertical direction in a reservoir depends on geological history and depositional environment. There can be permeable or semi-permeable barriers between two layers with contrast in properties like thickness, permeability, porosity and skin factor. Log and core data provide a clue to possible multi-layered characteristic in a reservoir. Multi-layer characterisation in terms of permeability, porosity and skin factor is crucial to establish well deliverability and to make development strategies. While porosity can be estimated using open hole logs and core data, well test interpretation has traditionally been the most popular method of estimating permeability and skin factor.

Early work in multi-layered reservoir well test interpretation was done by Lefkovits *et al.* (1961) who presented theoretical build-up curves for bounded layered reservoirs based on relative rates of depletion of layers. For a two layer commingled system, at early time, production rate from more permeable layer (layer 1) increases and approaches the value given by

$$q_1 = \frac{k_1 h_1}{k_1 h_1 + k_2 h_2} q_t \qquad (1)$$

q is the flowrate, k is the permeability and h is the layer thickness. Subscripts t, 1 and 2 refer to total, layer 1 and layer 2.

At late times, influence of boundary is first reflected in more permeable layer and later in less permeable layer. After this, production rate from more permeable layer approaches the value given by

$$q_1 = \frac{\phi_1 h_1}{\phi_1 h_1 + \phi_2 h_2} q_t \qquad (2)$$

ϕ is the porosity.

Cobb and Ramey (1972) analysed the characteristics of Muskat, MDH and Horner build-up curves for a two layer reservoir and showed that early portion of the curves with slope 1.151 provide a means of estimating flow capacity (kh) directly. Tariq and Ramey (1978) added the effect of skin and wellbore storage and different radius in each layer. The behaviour of multi-layered system with variation in skin factor can be approximated using following equation

$$S_t = \sum_{i=1}^{i=n} \frac{S_i k_i h_i}{k_i h_i} \tag{3}$$

$$(kh)_t = \sum_{i=1}^{i=n} k_i h_i \tag{4}$$

S is the skin. Subscripts t and i refer to total and ith layer respectively.

Prijambodo *et al.* (1985) compared pressure drawdown and pressure build-up behaviours of commingled flow and crossflow reservoirs. The early time response of a well in a two layer system with crossflow is identical to that of a commingled flow system with identical properties. The late time response of crossflow reservoir is described by the response of a well in a single layer system. During intermediate times, interlayer flow dominates and skin regions influence interlayer crossflow significantly. Bourdet (1985) extended dual porosity model (Warren and Root 1963) to dual permeability model. He introduced dimensionless variable κ and showed that depth of transition during intermediate time increases with increase in κ.

$$\kappa \text{ (kappa)} = \frac{k_1 h_1}{k_1 h_1 + k_2 h_2} \tag{5}$$

Kucuk *et al.* (1986) introduced a qualitative modelling and testing technique for multi-layered reservoirs to estimate individual layer permeabilities and skin factors uniquely. This is called Multi-Layer Testing (MLT) and this involves simultaneous measurement of wellbore pressure and layer flowrates. Interpretation techniques were presented using Sandface rate convolution and Non-linear least squares estimation. B. Pascal *et al.* (1992) proposed an analysis technique for conversion of a single layer transient pressure response into a multi-layer response. The technique produces a multi-layer description of the reservoir and reproduces both pressure transient behaviour and the layer rates for all the flow periods. Bidaux has also shown that an inconsistent single-layer analysis is likely to indicate multi-layer behaviour and single layer results in such case may be totally invalid. Larsen (1994) presented rigorous work on crossflow behaviour and showed that skin factors most severely affect analyses of data from commingled and crossflow reservoirs, both to obtain average formation and individual layer properties. Recently, Jackson and Benerjee (2000) proposed a new analysis technique for multi-layer testing incorporating numerical reservoir simulation and an automated history matching procedure.

It has been observed that conventional pressure build-up/ drawdown transient analyses are not sufficient to determine skin and permeability of individual layers in a multi-layered reservoir. Single layer interpretation carried out for a multi-layered system with one or more layers highly damaged is misleading as interpreted skin does not go beyond certain maximum value. In this paper, the effect of skin masking has been explained using a single well model in a bounded cylindrical reservoir.

Most of the published papers have discussed multi-layered behaviour based on contrast in permeability, porosity and skin factor. One of the objectives of this paper is to show that a reservoir with uniform rock properties can also behave as multi-layered system if there is significant variation in fluid viscosity with depth. API tracking has been used in single well radial model to capture viscosity variation with depth and it has been found that multi-layer testing and interpretation techniques proposed by early authors can also be applied in reservoirs behaving as multi-layered system due to viscosity variation.

The motivation of this study comes from suspiciously low skin values observed in onshore oil producers in field “X” operated by Cairn India, whereas production is short of expectations. Masking of skin in multi-layered reservoirs build-up data analysis presented in this paper is a possible explanation for this behaviour. Shale layers were also identified in open hole logs which supported existence of layers in the reservoir. Unique feature of field “X” is significant variation in oil viscosity with depth. In-situ oil viscosity varies from ~14 cp at crest to ~250cp at oil water contact. Based on the work presented in this paper, it has been shown that field “X” behaves as multi-layered system due to significant viscosity variation with depth.

Single Layer Interpretation in Multi-Layered Reservoirs Causes Skin Masking

Radial Model 1

A three layer cylindrical reservoir was considered with a well located at the centre (Fig. 1). To imitate multi-layered behaviour, three producing layers (layers 1, 2 and 3), each layer being 50 ft thick, were separated from each other by impermeable barriers. Horizontal permeabilities (k_h) for all three producing layers were taken equal to 3000 mD. 10 different cases were run by varying skin for layer 2 (S_2) between 0 and 500. Layer 1 skin (S_1) and layer 3 skin (S_3) were held constant at 0 for all cases. A dead oil model was used to keep the model simple. Viscosity variation was not included in this model as the aim of this exercise was to study variation of interpreted total skin with change in layer skin contrast. 12 hrs flow followed by 12 hrs shut-in was simulated in a commercial simulator (Eclipse 100, Schlumberger). The transient pressure data was exported and analysed using commercial well test interpretation software (Saphir, Kappa) using single layer model. *It should be noted that single layer interpretation was carried out to emphasize the amount of error that can be encountered while conducting a single layer interpretation in a multi-layered reservoir.* The interpretation plots for different cases are given in Appendix C and results have been summarised in Table 2.

Interpreted total skin and $(kh)_t$ were then plotted against layer 2 skin factor (Fig. 2). It can be seen from the plot that the maximum interpreted total skin using single layer interpretation is only 1.16 at S_2 = 10. On further increasing S_2, the total interpreted skin decreases instead of increasing. Also, at very high values of S_2, $(kh)_t$ decays to kh of remaining 2 layers. It is important to note here that good pressure, pressure derivative and rate history matches were obtained using single layer interpretation, but for very high values of S_2, the interpreted skin factors and permeabilities were representatives of two layers only (layer 1 and layer 3).

Table 1: Radial model 1 parameters

Fluid	Oil
PVT Model	Dead Oil
Porosity	0.27
Layer K_h, Horizontal Permeability	$K_{h1} = K_{h2} = K_{h3} = 3000$ mD
K_v/ K_h	0.3
Oil Viscosity (μ_o)	30 cp
Layer Skin (S)	S_1: 0 S_2: 0, 1, 2, 5, 10, 20, 50, 100, 200, 500 S_3: 0

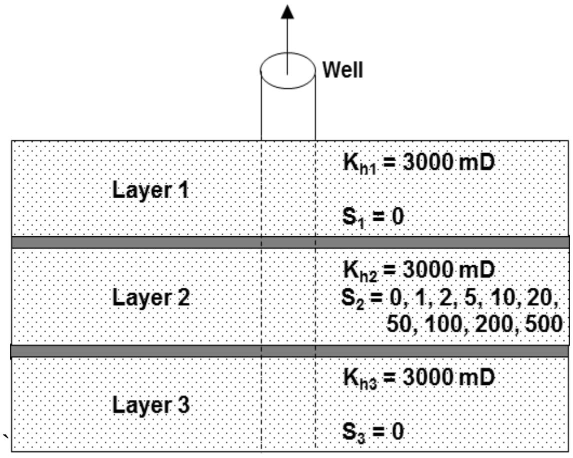

Fig. 1: Radial model 1

Table 2: Radial model 1 analysis results using single layer interpretation

Case	Model $(kh)_t$ (mD-ft)	Model S_2	Model Kh averaged Skin	Interpreted Total Skin, S_t	Interpreted $(Kh)_t$ (mD-ft)
1.1	450,000	0	0.00	0.50	415,500
1.2	450,000	1	0.33	0.78	412,500
1.3	450,000	2	0.67	0.94	408,000
1.4	450,000	5	1.67	1.13	388,350
1.5	450,000	10	3.33	1.16	361,500
1.6	450,000	20	6.67	1.05	330,000
1.7	450,000	50	16.67	0.87	301,500
1.8	450,000	100	33.33	0.80	289,500
1.9	450,000	200	66.67	0.74	283,500
1.10	450,000	500	166.67	0.72	279,000

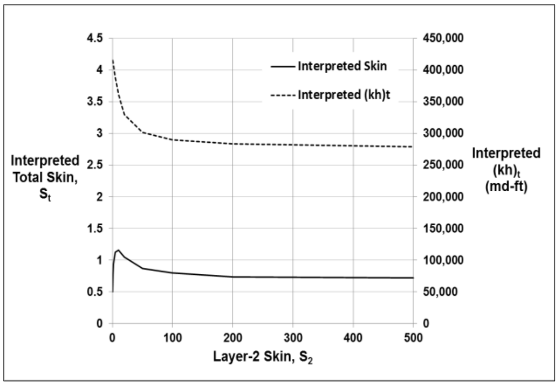

Fig. 2: Variation of interpreted skin and permeability (single layer interpretation) with input layer 2 skin for radial model 1

Model 1 Results Discussion

As S_2 is increased, the contribution from layer 2 to total production decreases. This impacts interpreted $(kh)_t$ and at very high values of S_2, $(kh)_t$ interpreted using single layer interpretation decays to kh of remaining two undamaged layers (Table 2). Similar effect is seen on interpreted skin. *In model 1 cases, for very high values of S_2, false radial flow stabilisation line was picked while performing analysis (refer plots in Appendix C).* At very high values of S_2, the stabilisation was corresponding to radial flow in layers 1 and 3 only. It would have taken infinite time for radial flow stabilisation to develop for all three layers. It has been shown by A.C. Gringarten (Imperial College MSc Well Test Analysis course note, 2010) that a commingled behaviour yields a radial flow stabilisation on the derivative only if all the layer skins are same. If there is large skin contrast, the derivative only stabilises at infinite times. In such cases, a slightly inclined line is obtained at a level higher than actual radial flow stabilisation level (Fig. 3). The higher the skin contrast, the higher the inclination level, and the lower the permeability if this level is taken as radial flow stabilisation.

In real field cases, interpreter is usually unaware of presence of damaged layers. This can easily mislead the interpreter. False radial flow stabilisation can be picked while performing single layer analysis and skin of damaged layer can be masked. In such cases, a well can have low inflow despite low skin values in single layer build-up data analysis. This behaviour is a possible explanation for low productivity in field “X”. Shale layers have also been identified between sand layers which support existence of layers in the reservoir. A multi-layer test could not be conduted in field “X” during the course of this study due to operational constrains (all wells were producing on artificial lift). It has been agreed to conduct a multi-layer test in field “X” during any available opportunity in future (e.g. during workover to replace artificial lift).

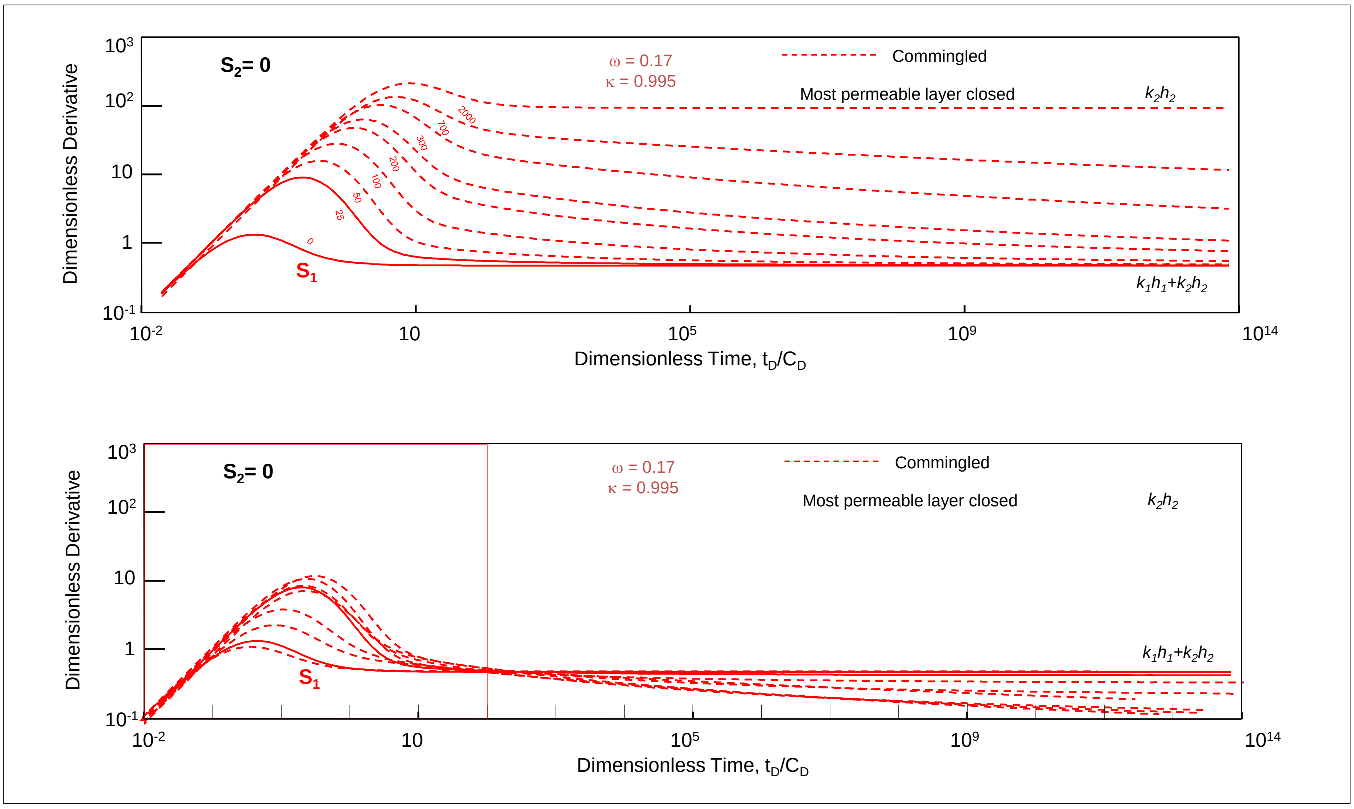

Fig. 3: Pressure derivative plots for 2 layers commingled flow (Imperial College MSc Well Test Analysis course note)

Behaviour of Multi-Layered Reservoirs

Radial Model 2

To illustrate the effect of layer permeability contrast, permeability anisotropy and layer skin contrast on pressure derivatives, a two layer cylindrical reservoir radial model (radial model 2, Fig. 4) was created in reservoir simulator. Same fluid properties were used in the model as used earlier for radial model 1. 60 different cases were run by varying S_2, k_{h1}/k_{h2} and K_v/k_h ratios.

Layer 1 skin and horizontal permeability were held constant for all 60 cases ($S_1 = 0$, $K_{h1} = 1000$ mD). Table 3 summarises different values of layer 2 skin (S_2), k_{h1}/k_{h2} and K_v/k_h ratios used to generate different cases. For each case, the well was flowed for 12 hrs followed by 500 hrs shut-in.

Table 3: S_2, k_{h1}/k_{h2} and k_v/k_h values used for model 2 cases

Model Layer 2 skin (S_2)	k_{h1}/k_{h2}	K_v/k_h
0	2	0, 0.1, 0.3, 0.5, 1
	5	0, 0.1, 0.3, 0.5, 1
	10	0, 0.1, 0.3, 0.5, 1
2	2	0, 0.1, 0.3, 0.5, 1
	5	0, 0.1, 0.3, 0.5, 1
	10	0, 0.1, 0.3, 0.5, 1
5	2	0, 0.1, 0.3, 0.5, 1
	5	0, 0.1, 0.3, 0.5, 1
	10	0, 0.1, 0.3, 0.5, 1
10	2	0, 0.1, 0.3, 0.5, 1
	5	0, 0.1, 0.3, 0.5, 1
	10	0, 0.1, 0.3, 0.5, 1

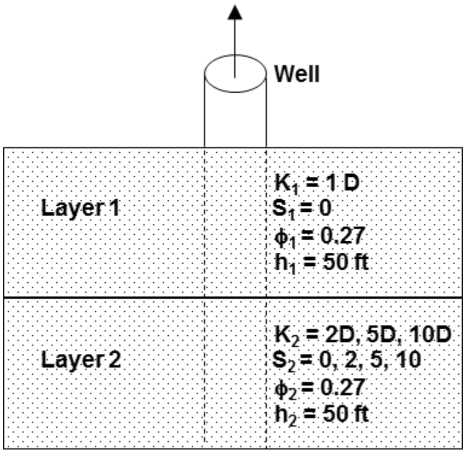

Fig. 4: Radial model 2

Model 2 Results Discussion

The build-up pressure derivatives for model 2 cases were plotted and compared (Fig. 5). The early time response of pressure derivative for crossflow system was found to be identical to commingled system. At late times, the derivatives again converged and the well behaved as a single layer system. During intermediate times, crossflow from less depleted layer to more depleted layer produced a depression in the derivative. This behaviour is in agreement with the build-up behavior proposed by Lefkovits *et al* (1961), Cobb and Ramey (1972), Prijambodo *et al* (1985) and D. Bourdet (1985).

The depth of transition during interlayer flow is found to increase with increase in permeability contrast. Increase in permeability anisotropy (K_v/k_h ratio) shifts the transition to the left indicating early start of interlayer crossflow. This is obvious as fluid movement in vertical direction becomes easier with increase in vertical permeability. D. Bourdet (1985) has shown that the start of interlayer crossflow depends on λ. λ was initially introduced by Warren and Root (1963) to define the start of matrix contribution during interporosity flow from matrix to fracture in a dual porosity model. D. Bourdet extended dual porosity model to dual permeability model and gave following equation to calculate λ for dual permeability model.

$$\lambda = \frac{r_w^2}{k_1 h_1 + k_2 h_2} * \frac{2}{\frac{h_1}{K_{v1}} + \frac{h_2}{K_{v2}}} \tag{6}$$

r_w is the wellbore radius

λ increases with increase in K_v/k_h ratio, and hence early start of crossflow is observed. Layer parameters estimated will be same for both commingled flow and crossflow as long as radial flow stabilization line is established. K_v/k_h ratio does not seem to affect the depth of depression with one exception of $K_v/k_h = 0$ as there is no interlayer flow in this case.

With increase in layer skin contrast, the radial flow stabilization is deferred. Radial flow stabilisation may occur at infinite time if one of the layers is highly damaged. In such cases, there is high possibility of picking false radial flow stabilisation. The highly damaged layer is ignored and interpreted total skin may appear very low. This observation is in line with the results shown in previous section.

If layer skins are similar and radial flow stabilisation exists, reasonably correct average parameters can be estimated even if there is significant contrast in layer permeabilities. The actual problem arises if there is contrast in layer skin factors. In case of high skin contrast, conventional well test interpretation results are unreliable.

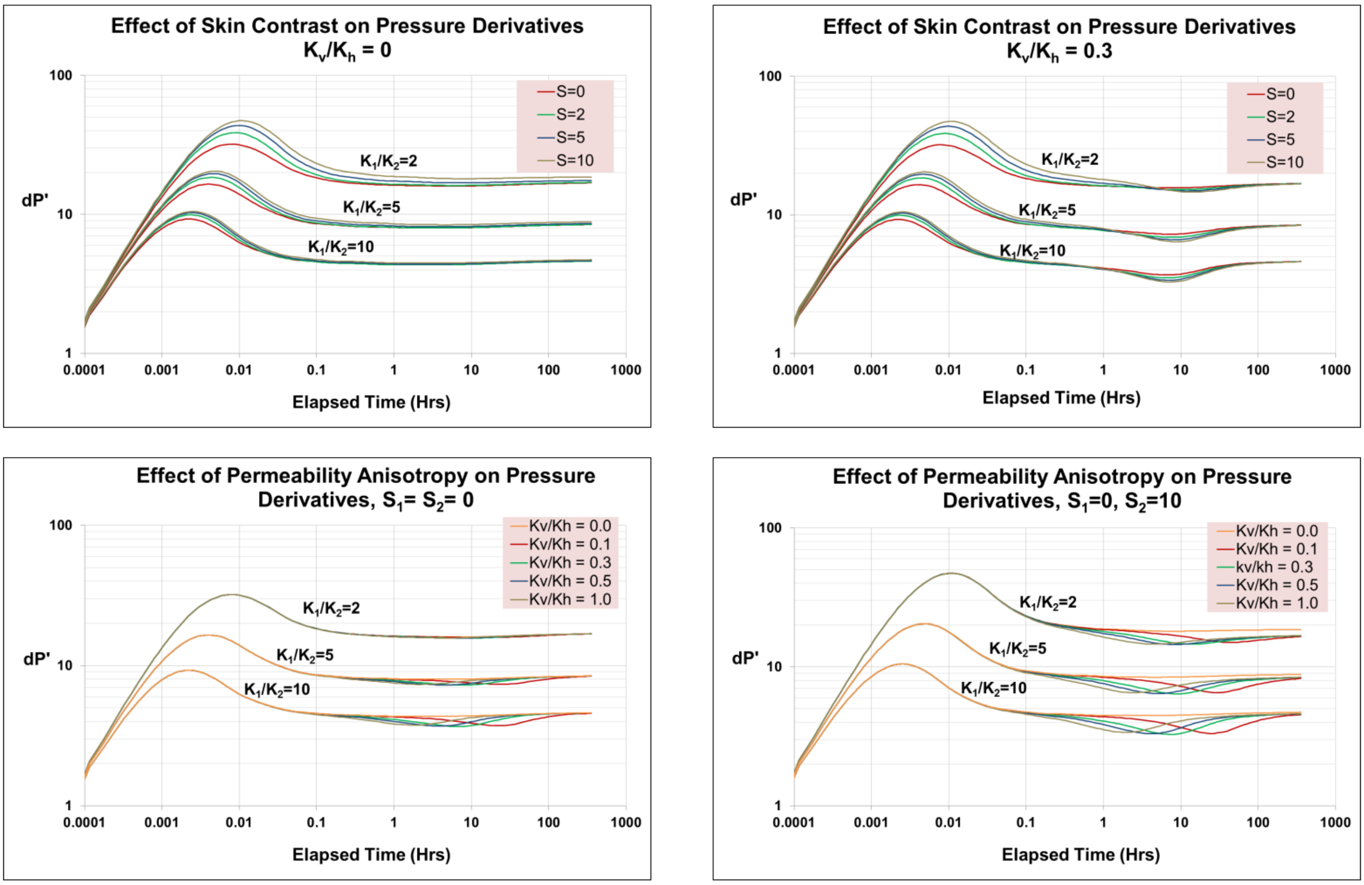

Fig. 5: Effect of skin contrast, permeability contrast and permeability anisotropy on build-up pressure derivatives

When do we need a Multi-Layer Test (MLT)?

A multi-layer test involves simultaneous measurement of pressure and flow rates above each layer sequentially (Kucuk *et al.* 1986). Flowing production log passes are also conducted across all layers after each flow stabilisation. This can sometimes be very costly if numerous layers are identified across payzone and especially in offshore wells, regular multi-layer tests may not be economically justified. Considering these factors, it is useful to differentiate between conditions where MLT can be avoided from conditions where an MLT is warranted. For this, it was investigated to find the conditions under which only stabilised flow rates instead of entire rate history for layers can be used to conduct a multi-layer analysis.

Sequential Interpretation Using Stabilised Layer Flowrates

Five different cases were selected from radial model 2 (Fig. 4) used in previous section. For each case, the well was flowed for 12 hrs followed by 24 hrs shut-in. Stabilised flowrate for each layer was noted from layer flowrate vs time plot (refer Appendix D, Fig. D 2). *In real field cases, stabilised layer flow rates can be estimated using a flowing production log survey.* For layer 1 analysis, layer 1 stabilised rate and build up pressure data were used as input. For layer 2 analysis, layer 2 stabilised rate was used as rate input and bottom hole pressure measured above layer 1was hydrostatically corrected to estimate layer 2 bottom hole pressure (See Appendix D for analysis plots).

Table 4: Radial model 2 input and interpretation results

Case	Model input parameters				Multirate analysis using stabilized layer rates	
	Skin	K_h	K_{h1}/K_{h2}	K_v/K_h	Skin	K_h
2-1	$S_1 = 0$ $S_2 = 0$	K_{h1} = 2000 mD K_{h2} = 1000 mD	2	0.3	$S_1 = -0.2$ $S_2 = 0.1$	K_{h1} = 1850 mD K_{h2} = 950 mD
2-2	$S_1 = 0$ $S_2 = 0$	K_{h1} = 5000 mD K_{h2} = 1000 mD	5	0.3	$S_1 = -0.17$ $S_2 = 0.6$	K_{h1} = 4690 mD K_{h2} = 990 mD
2-3	$S_1 = 0$ $S_2 = 0$	K_{h1} = 10000 mD K_{h2} = 1000 mD	10	0.3	$S_1 = -0.01$ $S_2 = 0.9$	K_{h1} = 9700 mD K_{h2} = 990 mD
2-4	$S_1 = 0$ $S_2 = 2$	K_{h1} = 2000 mD K_{h2} = 1000 mD	2	0.3	$S_1 = 0.6$ $S_2 = 0.8$	K_{h1} = 2130 mD **K_{h2} = 765 mD**
2-5	$S_1 = 0$ $S_2 = 5$	K_{h1} = 2000 mD K_{h2} = 1000 mD	2	0.3	$S_1 = 0.56$ $S_2 = 1.25$	K_{h1} = 2130 mD **K_{h2} = 576 mD**

The results have been presented in Table 4. It can be seen that reasonable estimates are obtained using stabilised layer flowrates if skin values for the two layers are similar but estimated parameter values start deviating from actual values if layer skin contrast is increased. This is in line with the behaviour of multi-layered reservoirs discussed in previous section. So it can be concluded that a single build-up survey and a flowing production log survey is sufficient to estimate layer properties if skin values for the two layers are similar. However, if there is skin contrast between the layers, entire rate history of layers is required and an MLT is recommended.

MLT Theory

MLT was first introduced by Kucuk *et al.* (1985). MLT includes flow tests above each layer sequentially with a production logging tool that simultaneously measures the wellbore pressure and flowrate at top of each layer. Kucuk presented Sand face rate convolution method (SFRC) and Non-linear least squares method to interpret multi-layer test data. This was followed by rigorous work in MLT interpretation by several authors and a systematic multi-layer test procedure and interpretation techniques have been established by now. The two most common interpretation techniques are: Simultaneous interpretation technique and Sequential interpretation technique.

MLT Operation

As discussed in previous section, stabilised layer flowrates are sufficient to estimate layer properties if layer skin factors are similar, however complete layer flow rate history is required if there is contrast in layer skin factors. It is practically impossible to measure flowrates for all the layers simultaneously as the production log tool can be stationed at only one depth at a time. This operational limitation however does not seem to affect the results in an MLT interpretation and following sequence of operations is generally followed for an MLT.

- Station the tool above bottom layer. Flow the well (rate q_1) till the flowrate stabilises. Change the flowrate ($q_1 \rightarrow q_2$) by either decreasing or increasing the flowrate. Wait to stabilise the flowrate. Pass the production logging tool across all layers to establish flow profile at this stabilised rate.
- Move the tool up and position above layer 2. Change the flowrate ($q_2 \rightarrow q_3$) by either decreasing or increasing the flowrate (consistent with previous step). Wait to stabilise the flowrate. Pass the production logging tool across all layers to establish flow profile at this stabilised rate.
- Repeat the same procedure for all layers. With tool stationed above top layer, shut-in the well to collect pressure build-up survey data. Conduct a shut-in production log survey.

MLT Interpretation

Selective Inflow Performance (SIP) Analysis

Using conventional production log interpretation technique, individual layer flowrates (q_i) are estimated at each stabilised flowrate. For each layer, layer bottom hole flowing pressure (P_{wfi}) is plotted against layer flowrate (q_i) to generate selective inflow performance (SIP) curve. Extrapolation to $P_{wfi} = 0$ gives corresponding layer pressure (P_i).

Simultaneous Interpretation Technique

This interpretation technique involves matching all the flow periods simultaneously. Values of permeabilities and skin factors for individual layers are varied until a satisfactory match is obtained for all measured flowrate data. Initial layer pressures can be estimated using SIP analysis.

Sequential Interpretation Technique

Single layer interpretation is carried out for the bottom layer using flow transients acquired with tool stationed above bottom layer. Skin factor and permeability for bottom layer are estimated using sandface rate convolution method. These parameters are then fixed for analysis of next transient which uses transient data collected with tool stationed above next to bottom layer. A two layer model is used and skin and permeability for next to bottom layer are estimated. The procedure is repeated for all layers and hence skin factor and permeability for each layer are uniquely estimated.

As a special case of multi-layered reservoir, if skin factors for different layers are close, a single build-up pressure data and a flowing production log survey data can also be used to conduct a sequential interpretation. Each layer can be analysed sequentially using same build-up pressure data as pressure input and stabilised layer flow rate of corresponding layer as rate input.

MLT Examples

Three synthetic examples and a real field case have been presented in this paper. First example considers a reservoir behaving as multi-layered due to contrast in permeability and skin factor between different layers, while second and third examples have been included to demonstrate multi-layering effect in a homogeneous reservoir due to significant viscosity variation with depth. Layering effect due to variation in oil viscosity is the possible cause of multi-layering effect observed in field “X”. A field test was conducted in field “Y” operated by Cairn India. This has been included as fourth example.

MLT Example 1: Permeability and Skin Contrast between Layers

A multi-layer test was simulated in a three layer cylindrical reservoir bounded at top and bottom and at outer radius (Radial model 3, Fig. 6). 50 ft thick producing layers were separated from each other by impermeable barriers. Typical field “X” rock and fluid properties were used in the model. Viscosity variation was however not considered in this model and a constant viscosity of 30 cp was assumed. The test sequence simulated in reservoir simulator is tabulated in Table 5.

Table 5: Flow sequence for MLT Example 1

Tool position	Flow rate (BOPD)	Duration (Hrs)
Above layer-3	2000	6
	1000	6
Above layer-2	1000	6
	500	6
Above layer-1	500	6
	0	12

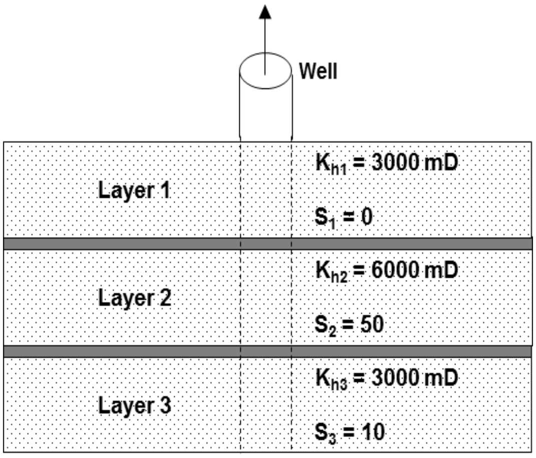

Fig. 6: MLT Example 1 model (Radial model 3)

Fig. 7 presents the MLT sequence and data obtained from the simulator. The flowrate data that can be aquired in an MLT operation have been highlighted and only these rates were used for interpretation purpose. The plot also includes entire rate history for all three layers, but these cannot be measured in field and hence have not been used in interpretation. SIP Analysis has not been conducted in this case as all layers had same initial pressures at datum. A sequential interpretation was then carried out using synthetic pressure and flowrate data generated from the simulator to estimate layer properties. The basic methodology and results obtained have been briefed below. Pressure and rate matches have been included in Fig. 8.

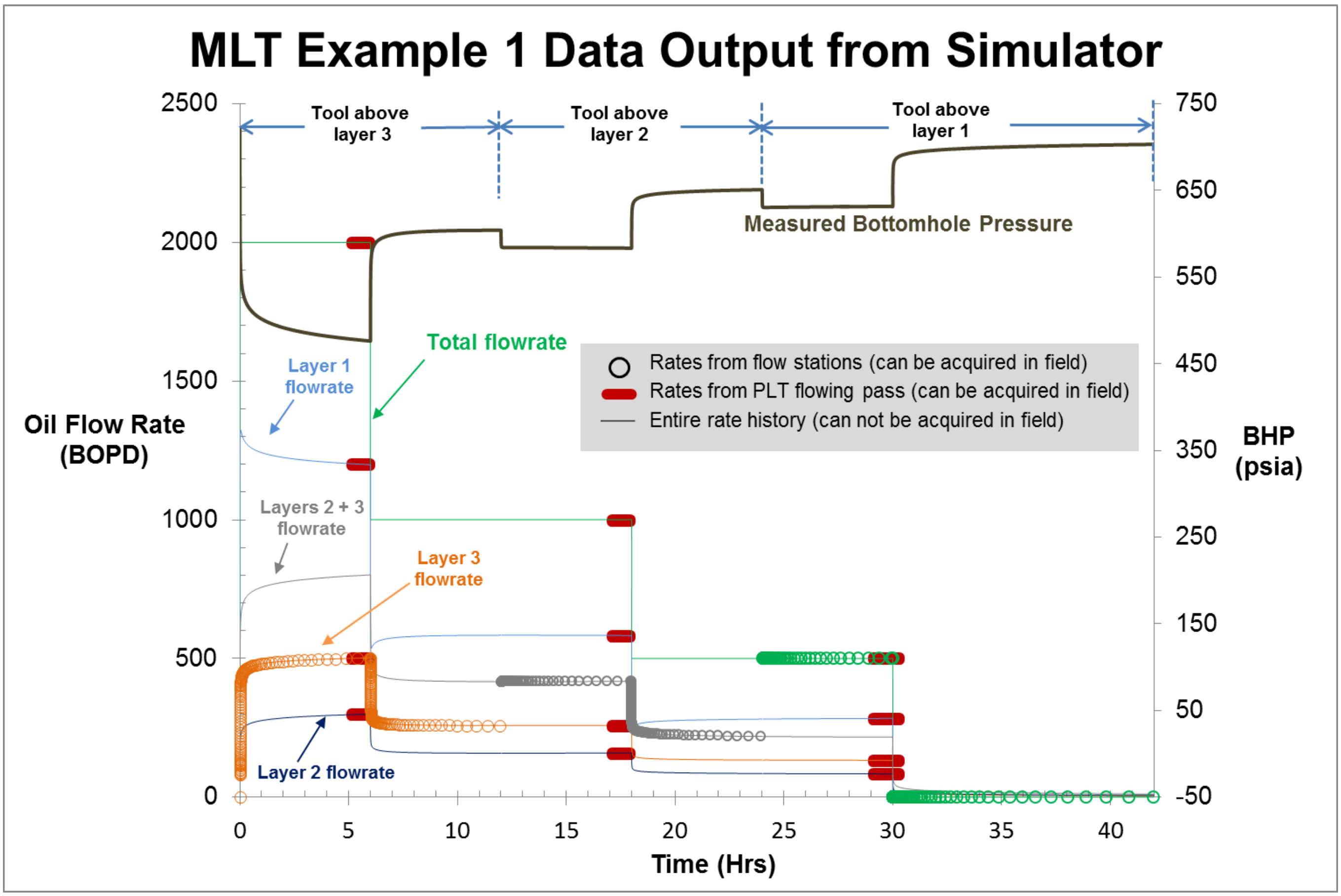

Fig. 7: MLT Example 1 pressure and rate data from simulator, Data that can be acquired in field have been highlighted

Layer 3 Interpretation

Drawdown transient data analysis was carried out for layer 3 (bottom layer). Input data included pressure and flowrate data acquired with tool stationed above layer 3. A conventional single layer interpretation was conducted as measured flowrate corresponded to layer 3 only. The results obtained using single layer interpretation have been compared with model input data in Table 6. It can be seen that reasonably good estimates for layer 3 skin and permeability have been obtained.

Layer 2 Interpretation

Drawdown transient data analysis was carried out for pressure and flowrate data collected with tool stationed above layer 2. Only highlighted part of layers 2+3 flowrate (Fig. 7) was used for interpretation as entire rate history can not be acquired in real field test. A multi-layer model with 2 layers was used. S_3 and K_{h3} were fixed based on results obtained in previous step. Skin and permeability for layer 2 were varied till reasonable matches were obtained on log-log pressure plot and individual layer flowrates plot. The results for layer 2 skin and permeability were found to be close to model input parameters (Table 6).

Layer 1 Interpretation

Build-up data analysis was carried out for pressure and flowrate data collected with tool stationed above layer 1. A multi-layer model with 3 layers was used. Layer 3 and layer 2 skin and permeabilities were fixed as per results of previous steps. Skin and permeability for layer 1 were varied till reasonable matches were obtained on log-log pressure plot and individual layer flowrates plot. The results for layer 1 skin and permeability were found to be close to model input parameters (Table 6).

Table 6: MLT Example 1 comparison of results with model input parameters

Layer	Parameter	Model Input	Interpretation Result
Layer 1	Permeability (mD) Skin	3000 0	2780 0.21
Layer 2	Permeability (mD) Skin	6000 50	5432 50
Layer 3	Permeability (mD) Skin	3000 10	2800 10.5

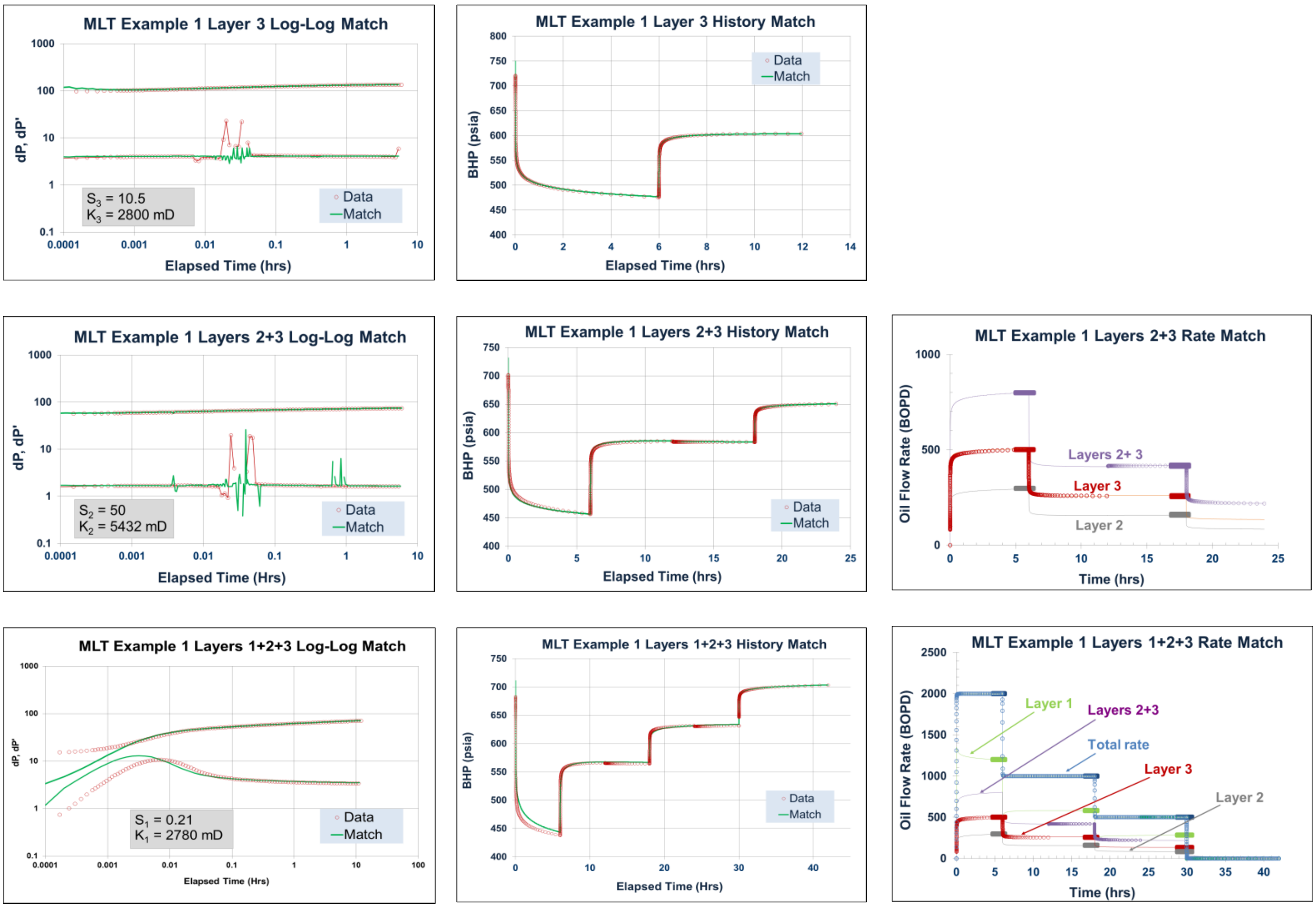

Fig. 8: MLT Example 1 analysis plots

A single layer interpretation was also carried out for last pressure build-up data to compare single layer interpretation results with sequential interpretation results (Fig. 9). It was found that false radial flow stabilisation was picked during single layer interpretation and results obtained were totally different from actual thickness averaged properties. Estimated total skin was only 2.4 using single layer interpretation while it was found to be 27.3 using MLT analysis which is close to kh averaged skin calculated using equation 3.

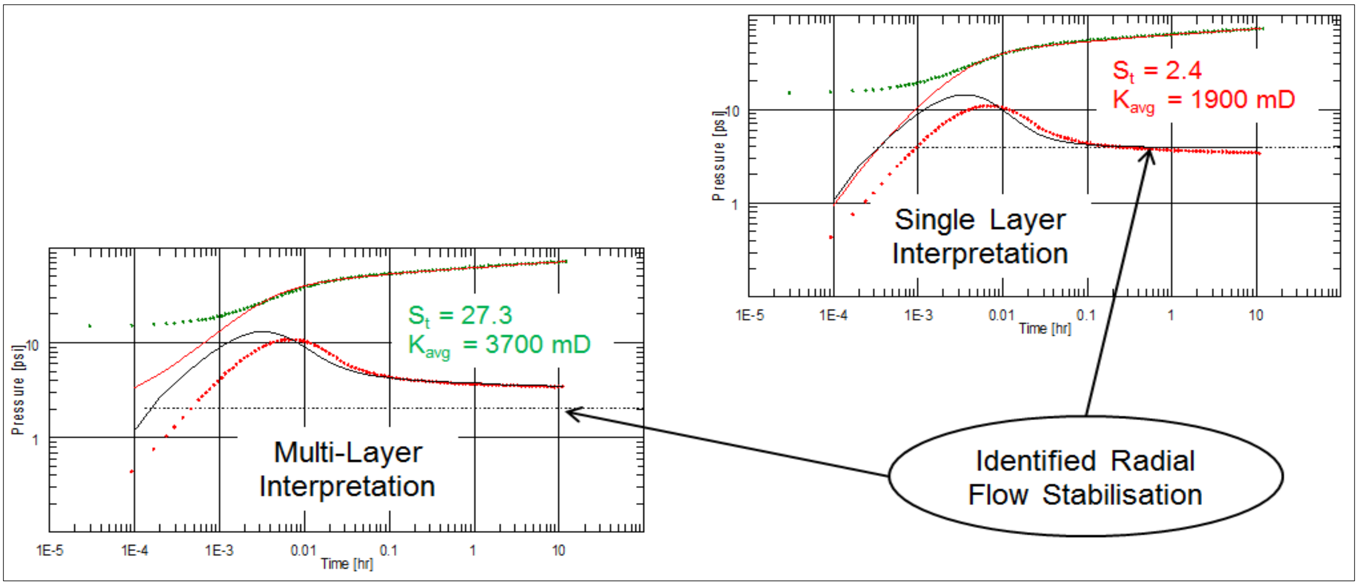

Fig. 9: Comparison of single layer interpretation and multi-layer interpretation results of last build-up

MLT Example 2: Homogeneous Reservoirs with Viscosity Variation

As discussed, the unique behaviour of field "X" is significant viscosity variation with depth. In-situ oil viscosity varies from ~14 cp at crest to ~250 cp at oil water contact. To study the effect of viscosity variation with depth, API tracking was used in the simulator with oil API values decreasing monotonically with depth. No barriers were included between the layers and properties like porosity, permeability, skin factor were taken uniform throughout. 100 ft thick layers were used and the depths of layer tops were chosen in such a way that each layer had one distinct value of viscosity (Table 7).

Table 7: API tracking used in MLT Example 2

Layer	Oil API	Oil Viscosity (cp)
1	29.26	30 (μ_1)
2	26.06	48 (μ_2)
3	22.87	95 (μ_3)

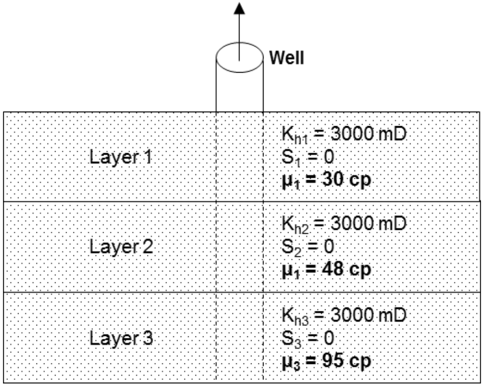

Fig. 10: MLT Example 2 model (Radial model 4)

Multi-layer test with test sequence same as MLT Example 1 (Table 5) was simulated in the reservoir simulator. A sequential interpretation was carried out to unmask layer properties. Pressure and rate matches have been shown in Fig. 11.

Layer 3 Interpretation

Drawdown transient data analysis was carried out for layer 3 (bottom layer). Input oil viscosity corresponding to layer 3 viscosity (95 cp) was used in the interpretation. It should be noted that even if input viscosity is changed, mobility remains constant and to keep mobility constant, output permeability is altered by a factor of viscosity ratio.

Layer 2 Interpretation

Drawdown transient data analysis was carried out for pressure and flowrate data collected with tool stationed above layer 2. A multi-layer model with 2 layers was used. Input viscosity used for interpretation was layer 2 oil viscosity of 48 cp. Layer 3 skin and permeability were fixed based on results obtained in previous step. *It should be noted that input layer 2 permeability used was 1622 mD (corresponding to 48 cp input oil viscosity for layer 3 interpretation) to keep layer 2 fluid mobility undisturbed.* Skin and permeability for layer 2 were varied till reasonable matches were obtained on log-log pressure plot and individual layer flowrates plot.

Layer 3 Interpretation

Build-up data analysis was carried out for pressure and flowrate data collected with tool stationed above layer 1. A multi-layer model with 3 layers was used. Layer 3 and layer 2 skin and permeabilities were fixed based on results obtained in previous steps (layer 2 and layer 3 results corresponding to 30 cp input oil viscosity). Skin and permeability for layer 1 were varied till reasonable matches were obtained on log-log pressure plot and individual layer flowrates plot.

Table 8: MLT Example 2 analysis results, All Layers

Input oil viscosity (cp)	Layer 3			Layer 2			Layer 1		
	$(kh)_3$ (mD-ft)	K_3 (mD)	S_3	$(kh)_2$ (mD-ft)	K_2 (mD)	S_2	$(kh)_1$ (mD-ft)	K_1 (mD)	S_1
30	101,400	1014	-0.15	197,700	1977	0.03	286,300	2863	-0.24
48	162,000	1622	-0.15	316,300	3163	0.03	458,100	4581	-0.24
95	321,000	3210	-0.15	626,000	6260	0.03	906,600	9066	-0.24

In this example, it is observed that a homogeneous reservoir but with significant variation in oil viscosity with depth behaves as a multi-layered system. Using a single value of input oil viscosity for well test interpretation (well test interpretation software used in this study allowed only one value of input viscosity) will not produce actual rock permeability at all depths. The interpreted permeability using a single input oil viscosity must be multiplied by viscosity ratio to obtain actual rock permeability. For instance, if all three layers in this example are interpreted using layer 1 oil viscosity of 30 cp, the results will be

- Layer 1 permeability = 2863 mD (close to actual permeability)
- Layer 2 apparent permeability (say K_{a2}) = 1977 mD

- Layer 3 apparent permeability (say K_{a3}) = 1014 mD

To report actual rock permeability, correction must be applied to layer 2 and layer 3 permeabilities. The correction factor is the ratio of fluid viscosity of the layer under investigation and fluid viscosity used for well test interpretation.

- Layer 2 corrected rock permeability = $K_{a2}*(\mu_2/\mu_1)$ = 1977*(48/30) = 3163 mD
- Layer 3 corrected rock permeability = $K_{a3}*(\mu_3/\mu_1)$ = 1014*(95/30) = 3210 mD

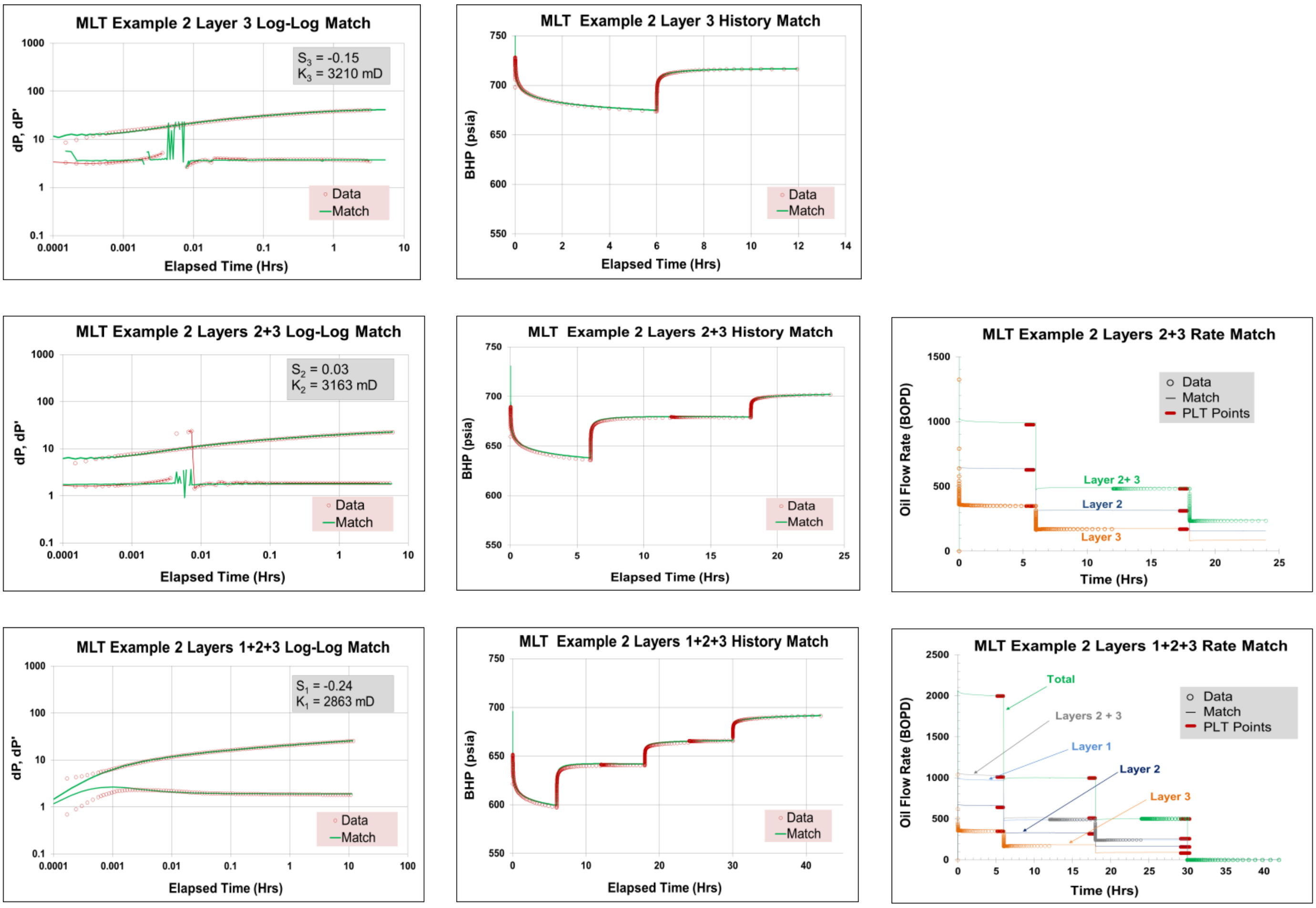

Fig. 11: MLT Example 2 analysis plots

MLT Example 3: Reservoirs with Viscosity Variation, Non-uniform Skin

In real cases, different layers can not have a single distinct value of viscosity. There will be gradational change in viscosity with depth. To bring the model closer to real field case, radial model 5 was created by refining MLT Example 2 model in vertical direction. Each 100 ft layer (called as “group” hereafter) was subdivided into 10 numbers of 10 ft fine layers. Besides, five layers in group 2 (layer 13 to layer 17, layers numbered from top to bottom) were assigned a positive skin value of 5 (Fig. 12). Multi-rate test with same test sequence (Table 5) was simulated in the simulator. A sequential interpretation was carried out using thickness weighted harmonic average of oil viscosity of corresponding group as input oil viscosity. The justification for using harmonic average of viscosity is as below.

For each group, total number of layers = 10

Total flowrate from 10 layers; $q_t = \frac{2\pi k h_t \Delta P}{\mu_{eff} \ln\frac{r_e}{r_w}}$; h_t is the total group thickness, r_e is the drainage radius, r_w is the wellbore radius

Layerwise flowrates; $q_1 = \frac{2\pi k h_1 \Delta P}{\mu_1 \ln\frac{r_e}{r_w}}$, $q_2 = \frac{2\pi k h_2 \Delta P}{\mu_2 \ln\frac{r_e}{r_w}}$, … , $q_{10} = \frac{2\pi k h_{10} \Delta P}{\mu_{10} \ln\frac{r_e}{r_w}}$

Now, $q_t = q_1 + q_2 + \cdots + q_{10}$

$$\frac{2\pi k h_t \Delta P}{\mu_{eff}\ln\frac{r_e}{r_w}} = \frac{2\pi k h_1 \Delta P}{\mu_1 \ln\frac{r_e}{r_w}} + \frac{2\pi k h_2 \Delta P}{\mu_2 \ln\frac{r_e}{r_w}} + \cdots + \frac{2\pi k h_{10} \Delta P}{\mu_{10} \ln\frac{r_e}{r_w}}$$

Hence, $\mu_{eff} = \frac{h_t}{\frac{h_1}{\mu_1}+\frac{h_2}{\mu_2}+\cdots+\frac{h_{10}}{\mu_{10}}}$

Table 9: Oil viscosity used in MLT Example 3 analysis

Group	Thickness weighted harmonic average of oil viscosity (cp)
1	30 (μ_{avg1})
2	48 (μ_{avg2})
3	95 (μ_{avg3})

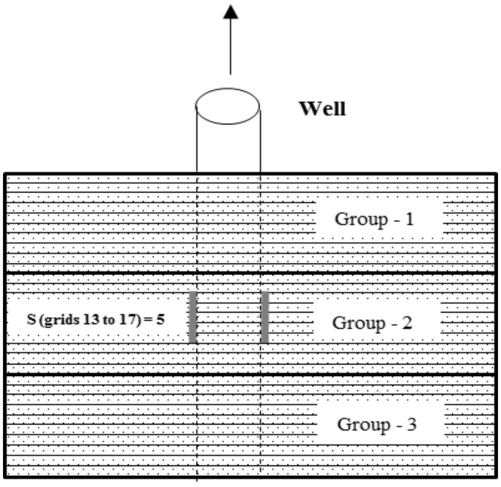

Fig. 12: MLT Example 3 model (Radial model 5)

It was found that individual group properties could be established within acceptable range of accuracy (Table 10). A positive skin of 1.52 was estimated for the damaged group 2. Based on the results, it can be concluded that dividing the payzone interval into groups and using corresponding group average (thickness weighted harmonic average) oil viscosity for interpretation helps to identify the group where damage has occurred.

Table 10: MLT Example 3 analysis results, All Groups

Input oil viscosity (cp)	Group 3			Group 2			Group 1		
	$(kh)_3$ (mD-ft)	K_3 (mD)	S_3	$(kh)_2$ (mD-ft)	K_2 (mD)	S_2	$(kh)_1$ (mD-ft)	K_1 (mD)	S_1
30	97,500	975	-0.08	178,600	1786	1.52	306,000	3006	-0.3
48	156,100	1561	-0.08	285,700	2857	1.52	481,000	4810	-0.3
95	309,000	3090	-0.08	565,400	5654	1.52	951,900	9519	-0.3

MLT Example 4: Field Example

A field test was conducted in an oil producer "YY" in field "Y" operated by Cairn India. The bottomhole pressure was well above reservoir bubble point pressure and the well was producing under single phase flow. Viscosity variation with depth is not very significant in field "Y" and a constant oil viscosity of 25 cp was assumed for interpretation. *The test could not be conducted in field "X" as all oil producers in field "X" were producing on artificial lift making any well intervention not feasible.* Based on open hole logs, two producing layers were identified, separated from each other by shale barriers.

Table 11: Well "YY" Layers depths

Layer	Depth (ft MDORT)	Net thickness (ft)
Layer 1 (Upper Layer)	4568.8 – 4670.8	64
Layer 2 (Lower Layer)	4735.8 – 4766.6	25

Operation Summary

Day 1:

- Initial well rate = 1403 BOPD.
- RIH with production logging tool and stationed at 4734 ft MDORT (top of layer 2) for 1 hour.
- Picked up and stationed tool at 4564 ft MDORT (top of layer 1) for 1 hour. Reduced well rate to 946 BOPD and collected data for 1 hour.
- RIH to 4734 ft MDORT (top of layer 2) and stationed for 1 hour. POOH.

Day-2:

- Repeated the same procedure with well rates 771 BOPD and 532 BOPD.

Day-3:

- Conducted pressure build up (PBU) survey for 24 hours.

MLT Analysis

In this test, flowing survey stations were taken for only 1 hour that could not produce stabilised data. However, the test was conducted as a learning exercise and it proved very helpful in understanding various steps involved in a multi-layer test interpretation. The basic methodology and results obtained have been briefed below.

SIP Analysis

Individual layer pressures were estimated using SIP analysis. The calculated layer pressures were then hydrostatically corrected to same datum depth.

Table 12: Well “YY” Layer pressures with hydrostatic correction

Layer	SIP Pressure, psia	Layer pressure (P_i) corrected to datum (PBU gauge depth), psia
1	1420	1422
2	1473	1424

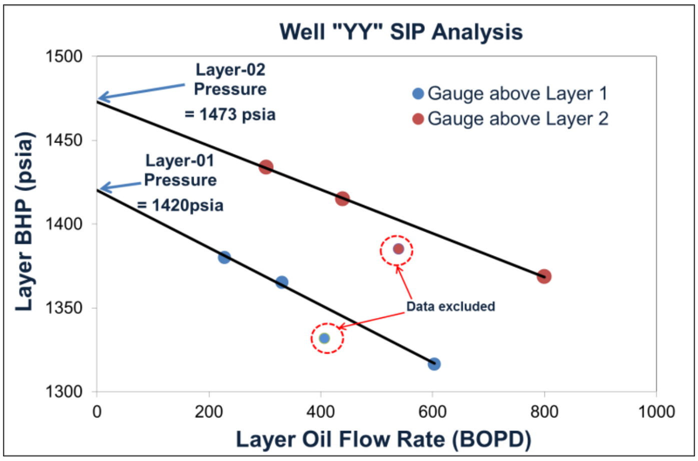

Fig. 13: Layer pressure estimation using SIP Plots

Single Layer Interpretation

A single layer interpretation was first carried out to estimate thickness averaged permeability and kh averaged skin factor (See Appendix G).

Table 13: Well “YY” Single layer analysis results

Total Skin (S_t)	-1.04
$(kh)_t$	4E+5 md-ft
k_{avg}	4490 mD
Boundary	Intersecting faults Angle: 65.6 degree

Simultaneous Multi-Layer Test Interpretation

A Multi-layer interpretation was then initiated with 2 layers. Same well/reservoir/boundary models were selected as obtained from single layer interpretation. Initial estimates for skin and reservoir pressures were same for both layers and were taken from single layer interpretation results. Uniform skin was assumed for calculation of initial estimates of individual layer permeabilities. Under these assumptions, using Darcy law for each layer,

$$(kh)_1 \propto \frac{q_1\mu_1}{(P_1-P_0)} \quad \text{and} \quad (kh)_2 \propto \frac{q_2\mu_2}{(P_2-P_0)} \tag{7}$$

P_0 is the initial estimate of reservoir pressure using single layer analysis.

Since, oil viscosity is fairly constant in field “Y”, $\mu_1 = \mu_2$. Hence,

$$(kh)_1 \propto \frac{q_1}{(P_1-P_0)} \quad \text{and} \quad (kh)_2 \propto \frac{q_2}{(P_2-P_0)} \tag{8}$$

$$(kh)_{1\text{fraction}} = \frac{(kh)_1}{(kh)_1+(kh)_2} = \frac{\frac{q_1}{(P_1-P_0)}}{\frac{q_1}{(P_1-P_0)}+\frac{q_2}{(P_2-P_0)}} \tag{9}$$

Using above assumption, Table 14 was generated to calculate initial estimates of k_1 and k_2.

Table 14: Well "YY" initial parameter estimates calculation

Layer	Layer $(kh)_{fraction}$	Layer kh, $(kh)_i$ (mD-ft)	Layer permeability, k_i (mD)
1	$(kh)_{1_{fraction}} = \frac{\frac{q_1}{(P_1 - P_0)}}{\frac{q_1}{(P_1 - P_0)} + \frac{q_2}{(P_2 - P_0)}}$ **= 0.43**	$(kh)_1 = (kh)_t * (kh)_{1_{fraction}}$ **= 170,800**	$k_1 = \frac{(kh)_1}{h_1}$ **= 2670**
2	$(kh)_{2_{fraction}} = \frac{\frac{q_2}{(P_2 - P_0)}}{\frac{q_1}{(P_1 - P_0)} + \frac{q_2}{(P_2 - P_0)}}$ **= 0.57**	$(kh)_2 = (kh)_t * (kh)_{2_{fraction}}$ **= 229,000**	$k_2 = \frac{(kh)_2}{h_2}$ **= 9170**

With initial estimates, reasonable matches were obtained for log-log pressure plot and total rate history as $(kh)_t$ and total skin (S_t) were undisturbed; however, individual layer rates did not match indicating S_1, S_2, k_1 and k_2 were not correct (See Appendix H, Fig. H 1).

$(kh)_{1fraction}$ and $(kh)_{2fraction}$ and accordingly k_1 and k_2 were then varied while keeping total flow capacity $(kh)_t$ undisturbed.

$$(kh)_t = (kh)_{1_{fraction}} * (kh)_t + (kh)_{2_{fraction}} * (kh)_t = 400{,}000 \text{ (fixed)}$$

S_1 and S_2 were also varied while keeping $(kh)_i$ averaged skin undisturbed.

$$S_t = \frac{(S_1k_1h_1 + S_2k_2h_2)}{k_1h_1 + k_2h_2} = -1.04 \text{ (fixed)}$$

The iterations were continued with different k_1, k_2, S_1 and S_2 values till reasonable match was obtained for layer-wise rate history for both layers. Finally $(kh)_t$ was slightly adjusted to get a good match on log-log pressure plot (See Appendix H, Fig. H 2) and following layer parameters were estimated.

Table 15: Well "YY" Simultaneous MLT analysis results

Layer	Permeability (mD)	Skin
Layer 1	2625	-0.8
Layer 2	10080	-1.2

Sequential Multi-layer Test Interpretation

As discussed earlier, a single build-up combined with a production log data is sufficient to conduct sequential MLT analysis if skin contrast is not very significant. From results obtained using simultaneous interpretation, it was found that skin for the two layers for well "YY" were close. Hence, a sequential interpretation was carried out using only final build-up and stabilised layer flow rates for the two layers. It should be noted here that this is a special case of sequential interpretation where skin contrast is not significant. To carry out a sequential interpretation in case of high skin contrast, MLT sequence should be similar to procedure discussed in MLT example 1.

Using conventional flowing production log survey interpretation, layer 1 flowrate fraction was estimated. This was then multiplied to total flow rate and rate history for layer 1 was generated. A conventional well test interpretation was carried out using build-up pressure data and layer 1 rate history. Similarly, layer 2 rate history was calculated and a conventional well test interpretation was carried out for layer 2 using same build-up pressure data and layer 2 rate history. The results using sequential interpretation were found to be close to the results obtained using simultaneous interpretation (Table 16). The interpretation plots are shown in Appendix I.

Table 16: Well "YY" Sequential MLT analysis results

Layer	Permeability (mD)	Skin
Layer 1	2680	-0.8
Layer 2	9310	-1.31

Discussion

The aim of this study was to investigate the problems associated with conventional PBU analysis in a multi-layered reservoir and to provide a possible explanation for low skin values observed in pressure build-up analyses in field “X” wells. In this paper, it was shown that a pressure build-up data, if interpreted alone could produce misleading results if there was high contrast in layer properties. Skin of highly damaged layer can be masked and erroneous estimate of permeability can be made.

Formation permeability is a vital component of reservoir model and unreliable permeability can induce serious errors in making development strategy. This has direct impact of field economics. Logs and core data can provide a clue to possible multi-layered behaviour. If there is a doubt that reservoir has multi-layered characteristic, a multi-layer test is strongly recommended instead of a PBU survey.

Interpretation of multi-layered reservoir has been an area of interest for last few decades. Rigorous work has been done in this field by several authors and reliable interpretation techniques are available in industry. In this paper, MLT operational procedure and different interpretation techniques were discussed. Synthetic models were presented to describe sequential MLT interpretation in detail. The results were then compared with single layer interpretation results to highlight the degree of error that can be encountered while conducting a PBU survey instead of a multi-layer test. It was also shown that reasonably good estimates could be obtained in special cases where layer skin factors were similar by using a single build-up pressure data and a flowing production logging survey.

In addition, an unusual multi-layered behaviour due to significant fluid viscosity variation observed in field “X” operated by Cairn India was discussed. Using synthetic model based on field “X” properties, it was shown that if a single value of viscosity was used for interpretation, a conventional multi-layer test interpretation could not produce actual rock permeabilities at all depths. In this paper, simple steps were presented to utilise existing MLT analysis techniques to estimate layer parameters in reservoirs behaving as multi-layered system due to viscosity variation. Obtaining reliable estimates of rock permeabilities as all depths is very vital in deciding production/ injection intervals and in predicting water/ gas front movement while making development strategies. Possible reason for significant viscosity variation with depth can be associated with bidegradation of the oil at deeper depths. Analysis of PVT samples collected at different depths can be used to predict the viscosity variation with depth. If significant contrast is observed, precaution must be taken while conducting a well test interpretation.

A field example of SIP and MLT analysis was also discussed which can be used as a direct reference for other fields to conduct similar test and interpretation.

Conclusions

Based upon the results of this research effort, following conclusions can be drawn.

- Skin factor of a highly damaged zone is masked if build-up data in a multi-layered reservoir is interpreted with a single layer model. This is the possible cause of suspiciously low skin values obtained in field “X” wells build-up data analyses, whereas production was short of expectations.
- A multi-layer test enables unveiling layer properties. If there is a possibility of multi-layered behaviour in the reservoir, MLT is strongly recommended.
- A single build-up survey and a flowing production log survey produces reasonable estimates of layer properties if layer skin factors are similar.
- A homogeneous reservoir but with significant variation in oil viscosity with depth behaves as a multi-layered system. This is because both viscosity and permeability impact fluid mobility. Increase in permeability increases mobility while increase in oil viscosity decreases mobility.
- If oil viscosity varies significantly with depth, using a single input value of oil viscosity for well test interpretation will not produce actual rock permeabilities at all depths.
- Dividing the perforated interval into different groups and using average viscosity for each group enables estimating close to actual skin and permeability.

Nomenclature

BOPD	barrels of oil per day	PBU	pressure build-up
cp	centipoise	PLT	production logging tool
D	darcy	POOH	pull out of hole
ft	feet	PVT	pressure volume temperature
h	thickness	Psia	pounds per square inch absolute
hr/ hrs	hour/ hours	P_0	reservoir pressure
k, k_h	horizontal permeability	P_{wf}	flowing bottom hole pressure
k_v	vertical permeability	q	flowrate
kh	formation capacity	RIH	run in hole
mD	millidarcy	S	skin
MDORT	metres below original rotary table	SFRC	sand face rate convolution

MLT	multi-layer test
P	pressure

Subscripts

i	i^{th} layer (i = 1, 2, 3 …)
t	total

SIP	selective inflow performance
STB	stock tank barrel

Greek

ϕ	porosity
λ	Interporosity/ interlayer flow coefficient
μ, μ_o	oil viscosity
κ	kappa, $\kappa = (k_1h_1)/(k_1h_1 + k_2h_2)$
ω	Storativity ratio

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Warren, J. E. and Root, P.J.: "Behaviour of Naturally Fractured Reservoirs," SPEJ. (Sep. 1963) 245

Appendix A: Milestones in Well Test Analysis of Multi-layered Reservoirs

SPE Paper no	Year	Title	Authors	Contribution
1329	1961	"A Study of the Behaviour of Bounded Reservoirs Composed of Stratified Layers"	H.C. Lefkovits, P. Hazebroek, E.E. Allen, and C.S. Matthews	First to quantify layer flowrate fractions for early time and late time in commingled flow in a two layer bounded reservoir. Limitation: Did not take cross-flow into account.
426	1963	"Behavior of Naturally Fractured Reservoirs"	J. E. Warren, P. J. Root	Introduced parameters (ω, λ) to characterise the dual porosity medium.
3014	1972	"Well-Test Analysis for Wells Producing Commingled Zones"	Cobb, William M., Ramey Jr., H.J., Miller, Frank G.,	Compared different procedures to calculate static pressure in multi-layered reservoirs.
7453	1978	"Drawdown behaviour of a well with wellbore storage and skin effect communicating with layers of different radii and other characteristics"	Tariq, Syed M., Ramey Jr., Henry J.	First to include the wellbore storage and different radii in each layer in a commingled multi-layered reservoir.
10262	1985	"Well Test Analysis for wells producing layered reservoir with cross-flow"	R. Prijambodo, R. Raghavan, A. C. Reynolds	First to illustrate that Sand face rates are proportional to the layer flow capacities only if the skin factors are zero or equal to one another. If skin values are not same, layer rate is proportional to flow capacity of skin region.
13628	1985	"Pressure Behaviour of Layered Reservoirs With Cross-flow"	Bourdet, D.	First to introduce the concept of dual permeability model to analyse layered reservoir with crossflow.
13081	1986	"Well testing and Analysis techniques for layered reservoirs"	Kucuk, F., Karakas, M., Ayestaran, L.	First to introduce concept of multi-layer test (MLT), a new testing technique for layered reservoirs to estimate individual layer permeabilities and skin factors uniquely.
15860	1986	"Evaluation of Single-Layer Transients in a Multi-layered System"	Ehlig-Economides, C., Joseph, J., Erba, M., Vik, S.A.,	Proposed a new testing technique (Commingled single layer transient test) to determine flow rate of an individual zone in commingled flow that can be used to establish zone parameters.
24679	1992	"Analysis of pressure and rate transient data from wells in multi-layered reservoirs – Theory and Application"	A.C. Gringarten T.M. Whittle Pascal Bidaux P.J. Coveney	Proposed a technique for analytical conversion of a single-layer transient pressure response into a multi-layer response.
27973	1994	"Experiences With Combined Analyses of PLT and Pressure-Transient Data From Layered Reservoirs"	Larsen, Leif	Highlighted the effect of contrast in layer skin factors on multi-layer analyses both for commingled and crossflow reservoirs.
62917	2000	"Advances in Multilayer Reservoir Testing and Analysis using Numerical Well Testing and Reservoir Simulation"	R.R. Jackson, R. Banerjee, Schlumberger	Proposed an integrated workflow incorporating numerical reservoir simulation and an automated history matching procedure.
132596	2010	"Best practices in testing and analysing multi-layer reservoirs"	Yan Pan Michael Sullivan David Belanger	Demonstrated use of pulse neutron logs to measure effectiveness of acid stimulation in each layer and its usefulness to reduce uncertainty in obtaining individual layer formation properties.

Appendix B: Critical Literature Review

SPE 1329 (1961)

A Study of the Behaviour of Bounded Reservoirs Composed of Stratified Layers

Authors: H. C. Lefkovits, P. Hazebroek, E. E. Allen, C. S. Matthews

Contributions to interpretation of layered reservoirs:

First to quantify layer flowrate fractions for early time and late time in commingled flow in a bounded reservoir.

Objective of the paper:

Study relative rates of depletion of layers and present theoretical build-up curves for bounded layered reservoirs.

Methodology used:

Generalized formulas developed by Tempelaar-Lietz and used it to predict differential depletion between layers of multi-layered reservoirs and to predict pressure decline at the well.

Conclusion reached:

1. At early time, production rate from more permeable layer is increasing and it approaches asymptotically the value $\frac{q_1}{q_t} = \frac{k_1 h_1}{k_1 h_1 + k_2 h_2}$. At late times, influence of boundary is first reflected in more permeable layer and later in less permeable layer. After this, curves approach asymptotically constant values $\frac{q_1}{q_t} = \frac{\phi_1 h_1}{\phi_1 h_1 + \phi_2 h_2}$ and $\frac{q_2}{q_t} = \frac{\phi_2 h_2}{\phi_1 h_1 + \phi_2 h_2}$.
2. In a single layer system, build-up curve is initially a straight line and then it levels off at average reservoir pressure. In a multi-layered system, the pressure again rises and then finally levels off at a higher pressure. The rise in pressure is due to repressuring of more depleted, more permeable layer by less depleted, less permeable layer. The magnitude of this pressure rise depends on the contrast of the properties of the layers.

Comments:

This paper was major breakthrough in multi-layered reservoir interpretation and formed basis for further work in this field. The limitation of this paper was that crossflow was not taken into account.

SPE 3014 (1972)

Well Test Analysis for Wells Producing Commingled Zones

Authors: William M. Cobb, H. J. Ramey, Frank G. Miller

Contributions to interpretation of layered reservoirs:

Compared different procedures to calculate static pressure in multi-layered reservoirs.

Objective of the paper:

Provide improved methods of estimating fully static reservoir pressure in multi-layered reservoirs under commingled flow.

Methodology used:

Analysis of characteristics of Muskat, MDH and Horner build-up plots for a two layer reservoir with contrasting permeabilities.

Conclusion reached:

1. Duration of transients is often orders of magnitude longer for multilayer systems than for a single layer. Late transient flow is much longer than for a single layer and this flow period is a function of permeability ratio.
2. The early portion of Horner build-up and MDH plots with slope 1.151 provide a means of estimating kh directly.
3. Horner plots are characterized by apparent levelling of build-up pressure followed by a late period of additional build-up. Late build-up is due to differential depletion. It depends on permeability contrast and producing time.

Comments:

The work and results presented in this paper were limited to commingled flow.

SPE 7453 (1978)

Drawdown Behaviour of a Well with Storage and Skin Effect Communicating With Layers of Different Radii and Other Characteristics

Authors: Syed M. Tariq, Henry J. Ramey

Contributions to interpretation of layered reservoirs:

First to include the wellbore storage and different radius in each layer.

Objective of the paper:

To study the effect of wellbore storage, skin effect and differences in thicknesses among layers on drawdown data.

Methodology used:

Problem of a constant rate, bounded multi-layered system was reformulated to include the skin effect in each layer and wellbore storage in mathematical model. Partial differential equations were transformed into Laplace space to obtain a solution and finally numerical inversion was done using Stehfest algorithm.

A computer program was developed to generate drawdown and build-up data for any number of layers and with any combination of system parameters.

Conclusion reached:

1. The late transient stage of depletion is much longer than for single layer system and the length of this period is a function of permeability ratio, skin effect and pore volume ratio.
2. The effect of differences in thicknesses and layer radii is negligible during early transient stage.
3. The behaviour of layered system with variation in skin factor can be approximated by following equation:

$$\bar{S} = \frac{\sum_{i=1}^{n} S_i K_i h_i}{\sum_{i=1}^{n} K_i h_i}, \qquad \text{before pseudo-steady state}$$

$$\overline{S_{ps}} = \frac{\sum_{i=1}^{n} S_i \phi_i h_i r_i^2}{\sum_{i=1}^{n} \phi_i h_i r_i^2}, \quad \text{for pseudo-steady state}$$

4. For two layer systems having different layer radii, two straight lines may exist on semi-log plot. The slope of first semilog straight line corresponds to permeability-thickness of both layers, while the slope of second straight line corresponds to larger radius layer only.

   A computer program was developed to generate drawdown and build-up data for any number of layers and with any combination of system parameters.

Comments:

This paper was the first work to combine the effects of skin, wellbore storage and layer radii on pressure transient response.

SPE 10262 (1985)

Well Test Analysis for Wells Producing Layered Reservoirs with Crossflow

Authors: R. Prijambodo, R. Raghavan, A.C. Reynolds

Contributions to interpretation of layered reservoirs:

First to illustrate that Sand face rates are proportional to the layer flow capacities only if the skin factors are zero or equal to one another. If skin values are not same, layer rate is proportional to flow capacity of skin region.

Objective of the paper:

Thorough examination of performance of a well in a reservoir with interlayer crossflow. Study characteristics of transition period from early time (commingled flow behaviour) to late time (Single layer behaviour).

Methodology used:

Analytical solutions for a reservoir model with two layers in communication. Influence of layer skin factors studied using different skin regions for the layers.

Conclusion reached:

1. The early time response of a well in a two-layer system with crossflow is identical to that of a commingled system with identical properties. The late time response can be described by the response of a well in a single layer system.
2. At intermediate times, a transitional period governs the well response. Interlayer flow is dominant during this period and this can dominate short-time (build-up) tests.
3. Skin regions have dominant influence on interlayer crossflow. After stimulation, drawdown or build-up tests should be long enough so that plane radial flow conditions dominate the flow.
4. If skin factor in layer with higher permeability is much greater than the skin factor in layer with lower permeability, reservoir size has a dominant influence on the existence of proper straight line.
5. If inter-layer crossflow becomes negligible, skin factor of equivalent single-layer system is equal to the sum of the products of the layer skin factors and the layer $S_e = \left(\frac{S_1 q_1 + S_2 q_2 + \cdots}{q_1 + q_2 + \cdots}\right)$.
6. The sandface rates are proportional to the layer flow capacities only if skin factors are zero or are equal to one another.

Comments:

This paper has been a breakthrough in studying crossflow reservoirs as it captures the effect of layerwise skin factors on interpretation results.

SPE 13628 (1985)

Pressure Behaviour of Layered Reservoirs with Crossflow

Authors: D. Bourdet

Contributions to interpretation of layered reservoirs:

First to introduce the concept of dual permeability model to analyse layered reservoir with crossflow.

Objective of the paper:

Propose a new analytical solution to describe the pressure response of a well intercepting a layered reservoir with crossflow.

Methodology used:

Extended Warren and Root dual porosity model to adapt it to dual permeability models. Matrix permeability was not neglected in this case. Radial flow was assumed both within the matrix system and from matrix to well. Introduced kappa (k); ratio of permability thickness of layer-1 to total permeability thickness

Conclusion reached:

1. Three different regimes occur in a double permeability response:
    a. Early time: Behaviour same as two layers without crossflow. Response is defined by four parameters: $(C_D e^{2s})_{1+2}, \kappa, \lambda e^{-2s}$and ω.
    b. Intermediate time: Transition period
       $\kappa(\text{kappa}) = \frac{K_1 h_1}{K_1 h_1 + K_2 h_2}$; affects shape of transition. The depth of transition increases with κ.
       $\omega(\text{storativity ratio}) = \frac{\phi_1 C_{t1} h_1}{\phi_1 C_{t1} h_1 + \phi_2 C_{t2} h_2}$; low storativity ratio means deep depression in derivative curve and longer transition period. For large ω values, the global response tends to the homogeneous behavior curve for the total system
    c. Late time: Homogeneous behaviour characterizing the total producing system (total kh, total $\emptyset C_t h$). At late time, only governing group is $C_D e^{2s}$. The time of start of total system flow is independent of κ.
2. The solution is shown to be general and includes the homogeneous reservoir solution, two layers without crossflow solution and double porosity pseudo steady state interporosity flow solution as limiting forms.

Comments:

This paper has proposed a new analytical solution to describe pressure response of layered reservoirs with crossflow. This method is still being used by modern well test interpretation softwares.

SPE 13081 (1986)

Well Testing and Analysis Techniques for Layered Reservoirs

Authors: F. Kucuk, M. Karakas, L. Ayestaran

Contributions to interpretation of layered reservoirs:

First to introduce concept of multi-layer test (MLT), a new testing technique for layered reservoirs to estimate individual layer permeabilities and skin factors uniquely.

Objective of the paper:

Estimation of individual layer permeabilities and skin factors from simultaneously measured wellbore pressure and layer flow rates.

Methodology used:

Convolution integrals were used as basic mathematical model for estimation of layer parameters from simultaneously measured wellbore pressure and flow-rate data. MLT testing and analysis techniques were applied to different synthetic multi-layer reservoirs.

MLT test sequence:

- Obtain a complete production flow profile to define contributing layers to establish number of layers and hence depths for flow tests.
- Perform MLT by increasing or decreasing the surface rate while positioning the tool at different depths. Each flow test should be run until an approximate stabilization rate is reached.

MLT Analysis:

- Logarithmic convolution or sandface rate convolution: Bottom layer permeability and skin estimated directly from bottom layer flow test. Average estimates of kh and S obtained for remaining flow tests. Remaining skin and permeabilities obtained recursively using:
  $S_t = \frac{\sum s_i q_i}{\sum q_i}$ and $k_{avg} = \frac{\sum k_i h_i}{\sum h_i}$
- Nonlinear least squares estimation: Used to refine the estimates from logarithmic convolution method. Works on minimization of an objective function to reduce errors.

Conclusion reached:

1. Conventional drawdown and build-up tests reveal behaviour of total system only.
2. Wellbore pressure is a function of parameters of all layers whereas wellbore flow rate at any given depth is a strong function of layer parameters below measurement point.
3. Early transient flow rate behaviour is governed by layer permeabilities, thickness and skin factors below measurement point. As transients dissipate, flow rate depends increasingly on vertical permeability; porosity, compressibility and thickness product $(\phi C_t h)$; drainage radius and external boundary pressure of each layer.
4. MLT can be applied to reservoirs with and without crossflow. Reservoir crossflow has negligible effect on estimation of layer permeabilities and skin factors if the early time data are used.
5. Logarithmic convolution method is easy to use and works reasonably well if layer system behaviour can be approximated by an equivalent single-layer reservoir, however, it does not work if wellbore geometry is different from radial e.g., for fractured wells.

Comments:

MLT has been first presented in this paper and has been widely accepted in the industry. This is a robust technique to interpret layered reservoirs.

SPE 15860 (1986)

Evaluation of Single-Layer Transients in a Multi-layered System

Authors: C. Ehlig-Economides, J. Joseph

Contributions to interpretation of layered reservoirs:

Introduced commingled single layer testing using two spinners.

Objective of the paper:

Propose a new testing technique to determine flow rate of an individual zone in commingled flow that can be used to establish zone parameters (permeability, skin).

Methodology used:

Commingled single layer transient test (CSLT) was proposed. In this test, two flowmeters are positioned such that one is just above the layer perforation and the other just below. Difference in flowmeter readings is equal to the layer flowrate. Convolution techniques were used for interpretation of data.

CSLT Analysis:

- The layer flow rate is difference of flow rates from two spinners. $\mathrm{q_L(t) = q_A(t) - q_B(t)}$
- The transient rates and pressure are given by:
  $\mathrm{\Delta q_L(\Delta t) = q_L(t_1) - q_L(\Delta t)}$
  $\mathrm{\Delta P_{wf}(\Delta t) = P_{wf}(t_1) - P_{wf}(\Delta t)}$
- Rate normalized pressure (RNP) and Rate convolved time function (RCTF) are calculated. $\mathrm{RNP = \frac{\Delta P_{wf}(\Delta t)}{\Delta q_L(\Delta t)}}$
- Semilog analysis of RNP Vs Log(RCTF) is same as conventional well test analysis.
- Derivative log-log plot is plotted as derivative of RNP w.r.t. RCTF Vs log (Δt).

Conclusion reached:

1. CSLT is a reliable means for determination of zone parameters in a commingled completion.
2. Wellbore storage is reduced using this test configuration which allows identification of near wellbore parameters usually masked by wellbore storage.
3. The test can be conducted with minimal interruption to production schedule.

Comments:

CSLT test and analysis presented in this paper is in many respects similar to MLT proposed earlier by F. Kucuk. The test technique is slightly different as it gives individual layer flowrate directly. Since the distance between two spinners can not be changed downhole, this test is limited to testing of only one zone in one intervention and can be time consuming and costly if several layers are expected.

SPE 24679 (1992)

Analysis of Pressure and Rate Transient Data from Wells in Multi-layered Reservoirs: Theory and Application

Authors: Pascal Bidaux, T.M. Whittle, P.J. Coveney, A.C. Gringarten

Contributions to interpretation of layered reservoirs:

Proposed a technique for analytical conversion of a single-layer transient pressure response into a multi-layer response.

Objective of the paper:

To propose an MLT analysis that follows same diagnostic/ validation pattern, and be as transparent as conventional analysis, with the vertical dimension added.

Methodology used:

A reservoir with n layers was assumed. Each layer had distinct porosity, total compressibility, thickness, horizontal permeability, vertical permeability, fluid viscosity and skin factor. Dimensionless variables were defined for each layer. Laplace space solutions for wellbore pressure and sandface rates were presented which could be inverted using Stehfest algorithm.

The aim of analysis technique is to find a reservoir model that leads to consistent results between the build-up and the fall off and that reproduces the measured downhole rate profiles. Analysis technique involves simultaneous regression on permeabilities by layer and on skins by flow period and by layer to match the data before boundary effects are observed. Boundaries are then added and regression is carried out on distances to match late time pressure response.

Conclusion reached:

1. The proposed analysis technique provides a multi-layer description of the reservoir that reproduces both the observed pressure transient behaviour and the layer rates for all the flow periods when single layer analysis fails to do so.
2. The technique is computationally efficient and general enough to be used for practical purposes. It handles formation crossflow and a wide range of boundary conditions.
3. An inconsistent single-layer analysis is likely to indicate that the reservoir exhibits a specific multi-layer behaviour and in which case the results may be totally invalid.
4. During validation phase of multi-layer analysis, it is advisable to reduce the degree of non-uniqueness of the solution by fixing the parameters which are known from external sources.

Comments:

The technique presented is a strong tool to compute layer parameters as it can take formation crossflow and effect of boundaries into account. Uncertainties associated with single layer analysis has been highlighted which is crucial for layered reservoirs.

SPE 27973 (1994)

Experiences with Combined Analyses of PLT and Pressure-Transient Data from Layered Reservoirs

Authors: Leif Larsen

Contributions to interpretation of layered reservoirs:

Highlighted the effect of contrast in layer skin values on multi-layer analyses both for commingled and crossflow reservoirs.

Objective of the paper:

To present problems and possibilities with combined analyses of PLT and pressure-transient data from layered reservoirs.

Methodology used:

Mathematical equations were presented based on crossflow parameters. Effect of unequal layer pressures and unequal layer skin factors on crossflow parameter was studied.

Conclusion reached:

1. Average pressures can be obtained from build-up data even with severe crossflow if skin values are fairly uniform. PLT profiles obtained before and after shut-in in such cases can be used to obtain layer flow capacity and skin.
2. Contrast in layer skin factors most severely affect analyses of data from commingled and crossflow reservoirs, both to obtain average formation and individual layer properties.
3. Supporting information is required to reduce non-uniqueness. This can include permeability distribution from logs, cores etc.

Comments:

The paper presents that unequal skin factors bring highest degree of uncertainty in multi-layer test interpretation and hence interpretation of layered reservoir with unequal skins demands data from external sources (log, core) and more tests (e.g., PLT) to reduce uncertainty. This is an important result.

SPE 62917 (2000)

Advances in Multilayer Reservoir Testing and Analysis using Numerical Well Testing and Reservoir Simulation

Authors: R. R. Jackson, R. Banerjee

Contributions to interpretation of layered reservoirs:

An integrated workflow for multilayer test was presented with a new analysis technique incorporating numerical reservoir simulation and an automated history matching procedure.

Objective of the paper:

To formalize MLT interpretation technique and demonstrate benefits of automated history matching and gradient method to reduce errors in results.

Methodology used:

Following analysis technique was applied to both simulated data and field data.

- Conventional production log data analysis to determine flow profile and layer contribution.
- Selective Inflow Performance (SIP) analysis to establish layer IPR and layer pressures.
- Sandface rate convolution (SFRC) for initial parameter estimation (Slope and intercept of linear plot of normalized pressure vs logarithmic convolution time yield permeability and skin).
- Sequential and simultaneous analysis using a layered model with analytic or numeric methods using a reservoir simulator. Initial inputs as per SFRC analysis.
- Simulation and automated history matching and sensitivity analysis of MLT test.

Conclusion reached:

1. Application of numerical well test analysis using reservoir simulation helps in automated history matching.
2. Gradient method can be applied to modify model parameters to match simulation model pressure data with test data.

Comments:

Though automated history matching is not a new procedure, this paper has very effectively demonstrated existing MLT interpretation techniques. Besides, a new technique (gradient method) has been presented to reduce errors in parameter estimation.

SPE 132596 (2010)

Best Practices in Testing and Analysing Multilayer Reservoirs

Authors: Yan Pan, Michael Sullivan, David Belanger

Contributions to interpretation of layered reservoirs:

Not much as the technique shown in this paper has been suggested earlier by others, however it is an example of multilayer test and analyses on wider scale.

Objective of the paper:

To present best practices in design, execution and analysis of multilayer pressure transients in Tengiz oil field in western Kazakhstan.

Methodology used:

MLT was conducted in wells in Tengiz field as per standard MLT procedure. SIP, single layer analysis and simultaneous multilayer analysis was carried out on the acquired data. Pulsed neutron logs have been used to provide information about stimulation effectiveness in each zone. This helped in reducing uncertainties in layer skins.

Conclusion reached:

1. Simple commingled flow test is not sufficient. Either isolate each layer and test selectively OR gather more data like production logging, PNC etc.
2. Pulsed neutron log helps to reduce uncertainties in multilayer test analysis.

Comments:

This paper presents real field example and a complete workflow to conduct and analyse multilayer test. This can be used as a guide for conducting similar tests in other fields.

Appendix C: Radial Model 1 Details and Analysis Plots

Table C 1: Radial model 1 parameters

Reservoir	Cylindrical, Bounded at top and bottom and outer radius
Fluid	Oil
PVT Model	Dead Oil
Layer Thickness	$h_1 = h_2 = h_3 = 50$ ft
Barriers	5 ft thick shale layers between producing layers
Porosity	0.27
k_h, Horizontal Permeability	$k_{h1} = k_{h2} = k_{h3} =$ 3000 mD
k_v / k_h	0.3
Oil Viscosity (μ_o)	30 cp
Skin (S)	S_1: 0 S_2 : 0, 1, 2, 5, 10, 20, 50, 100, 200, 500 S_3: 0
Flow Sequence	12 hrs flow followed by12 hrs shut-in

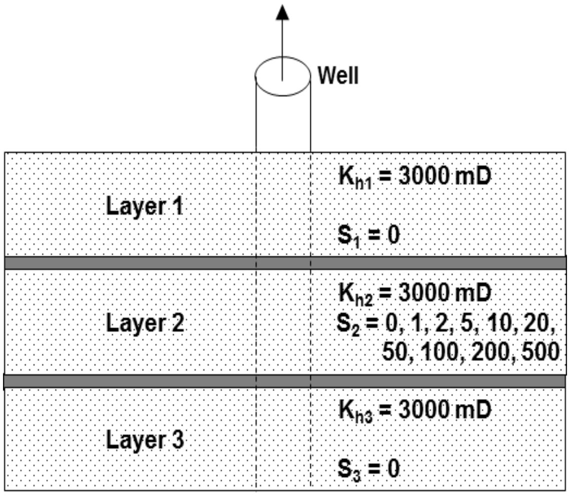


Fig. C 1: Radial model 1

Table C 2: Model 1 analysis results

Case	Model $(kh)_t$ (mD-ft)	Model S_2	Model Kh averaged Skin	Interpreted Total Skin, S_t	Interpreted $(Kh)_t$ (mD-ft)
1.1	4.50,000	0	0.00	0.5	415,500
1.2	450,000	1	0.33	0.78	412,500
1.3	450,000	2	0.67	0.94	408,000
1.4	450,000	5	1.67	1.13	388,350
1.5	450,000	10	3.33	1.16	361,500
1.6	450,000	20	6.67	1.05	330,000
1.7	450,000	50	16.67	0.87	301,500
1.8	450,000	100	33.33	0.8	289,500
1.9	450,000	200	66.67	0.74	283,500
1.10	450,000	500	166.67	0.72	279,000

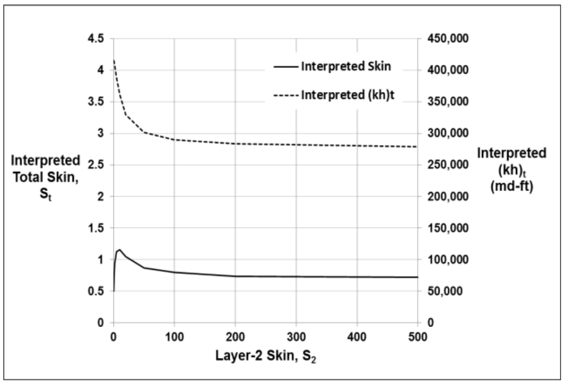
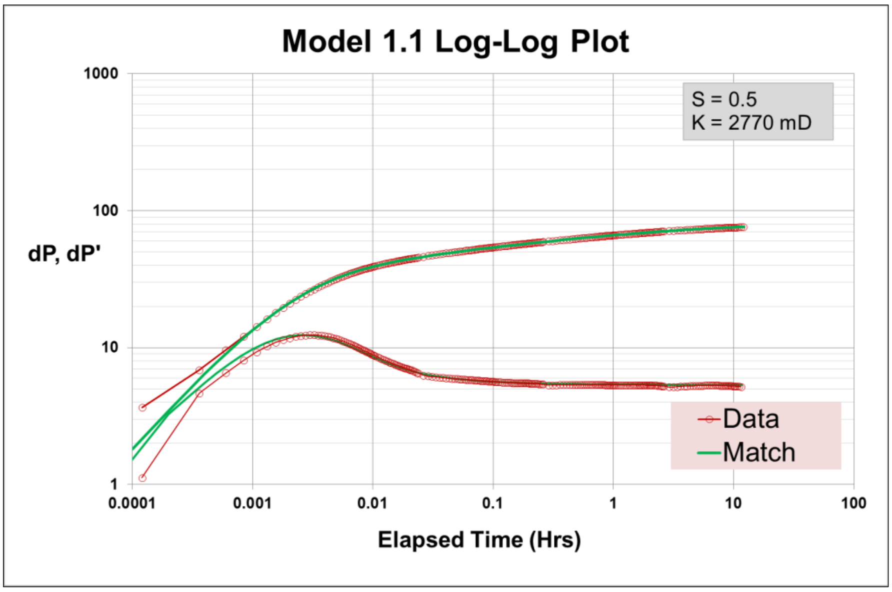
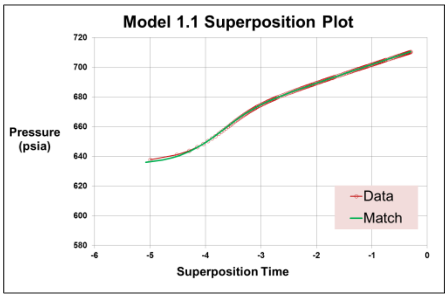
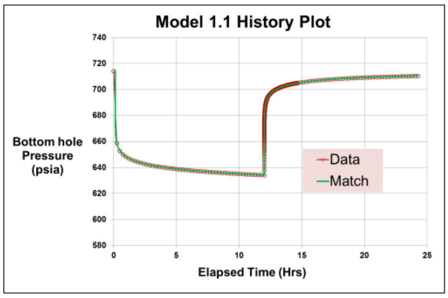
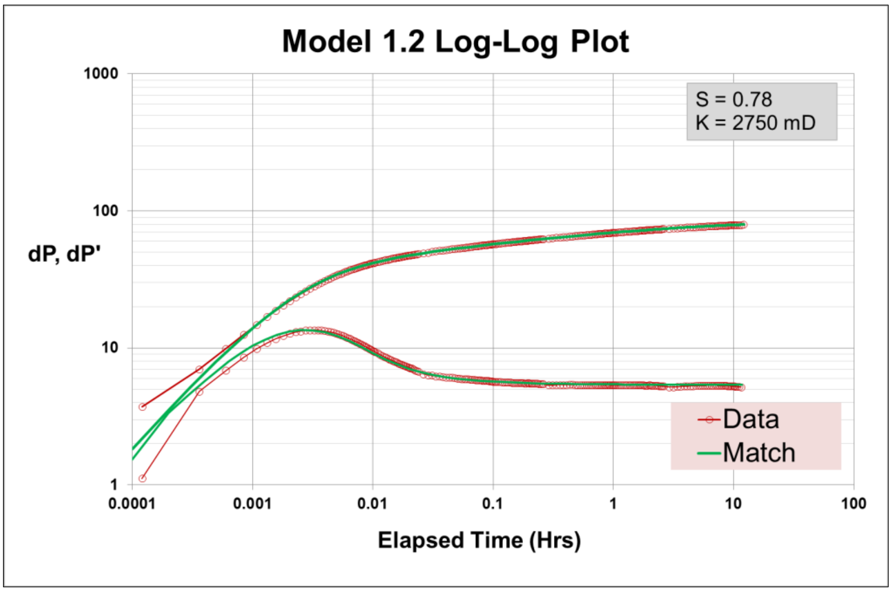


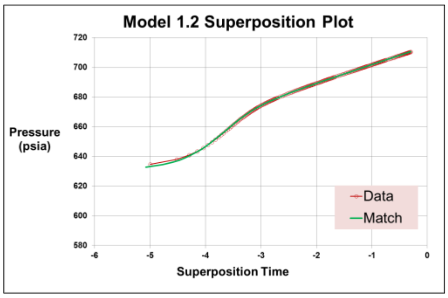
Fig. C 2: Variation of interpreted skin and $(kh)_t$ with input layer 2 skin for model 1 cases

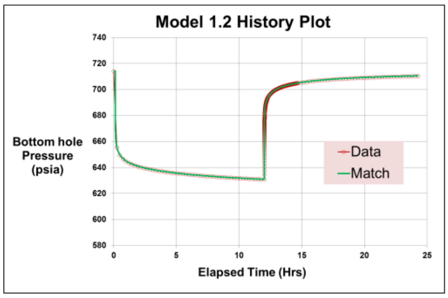


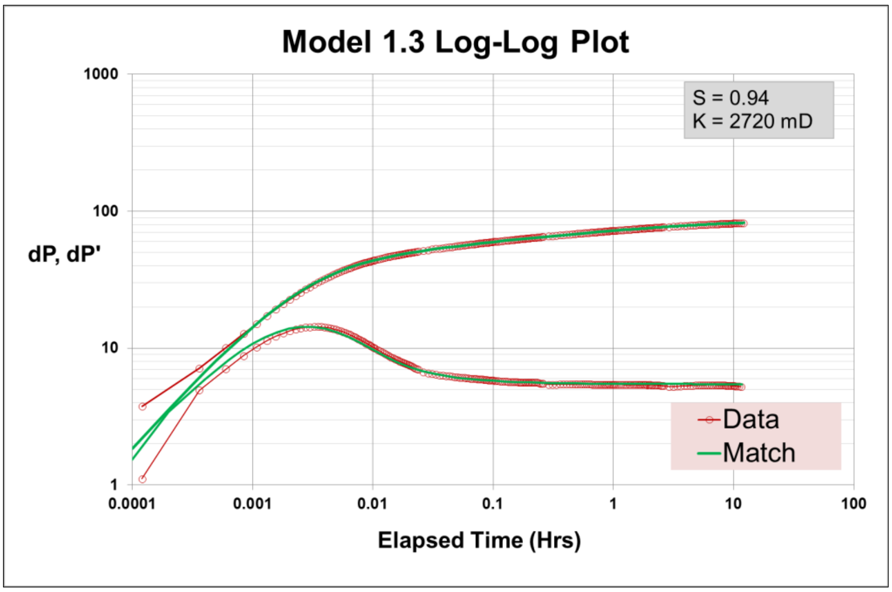


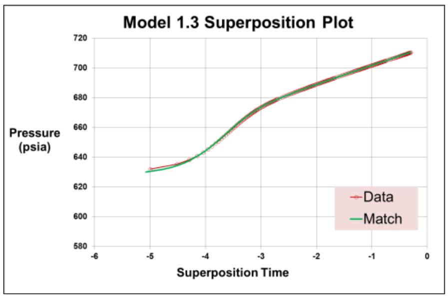


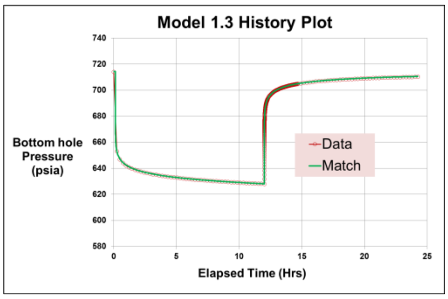

Model 1.2 Log-Log Plot
S = 0.78
K = 2750 mD
1000
100
10
1
dP, dP'
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

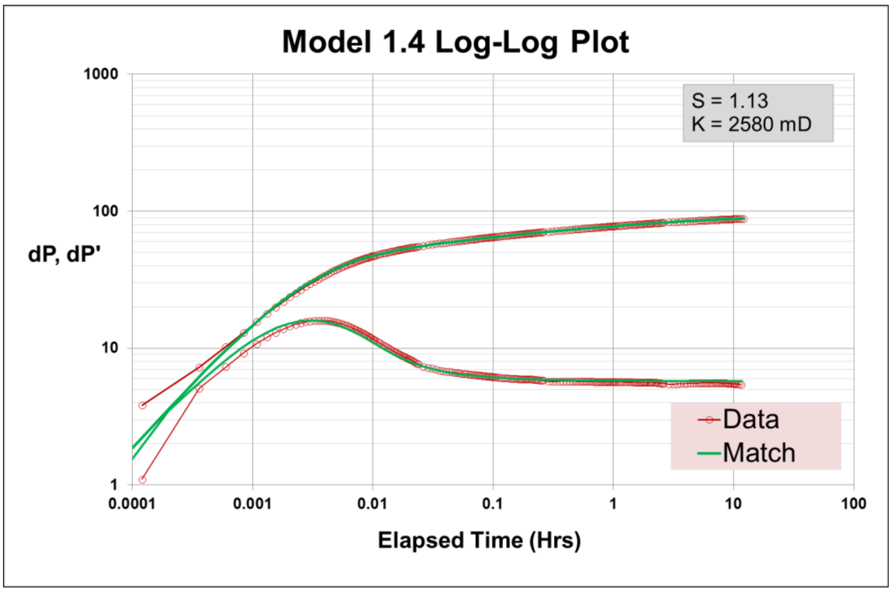

Model 1.2 Superposition Plot
720
700
680
660
640
620
600
580
Pressure (psia)
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

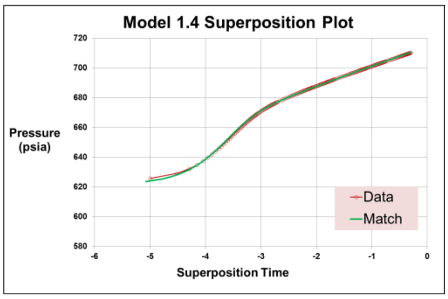

Model 1.2 History Plot
740
720
700
680
660
640
620
600
580
Bottom hole Pressure (psia)
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

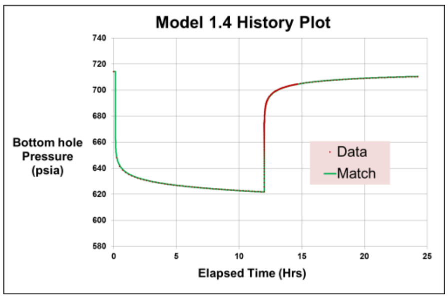

Model 1.3 Log-Log Plot
S = 0.94
K = 2720 mD
1000
100
10
1
dP, dP'
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

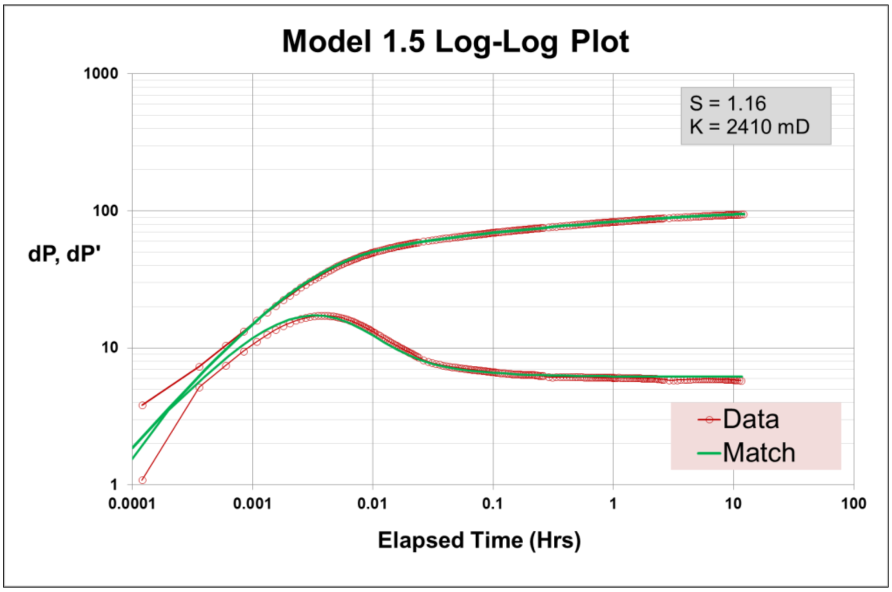

Model 1.3 Superposition Plot
720
700
680
660
640
620
600
580
Pressure (psia)
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

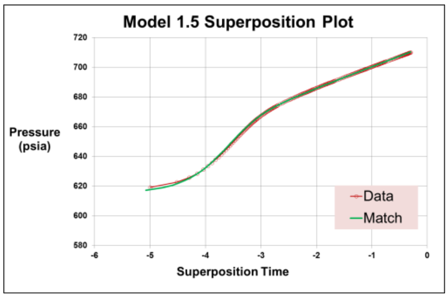

Model 1.3 History Plot
740
720
700
680
660
640
620
600
580
Bottom hole Pressure (psia)
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

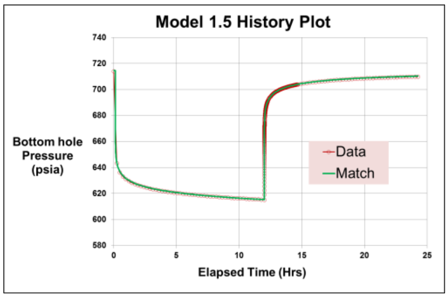

Model 1.4 Log-Log Plot
S = 1.13
K = 2580 mD
1000
100
10
1
dP, dP'
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

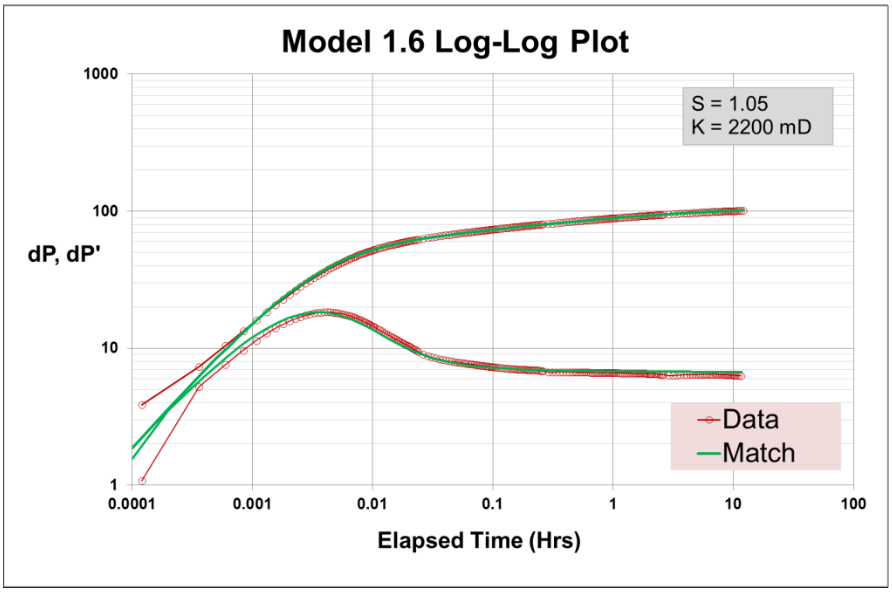

Model 1.4 Superposition Plot
720
700
680
660
640
620
600
580
Pressure (psia)
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

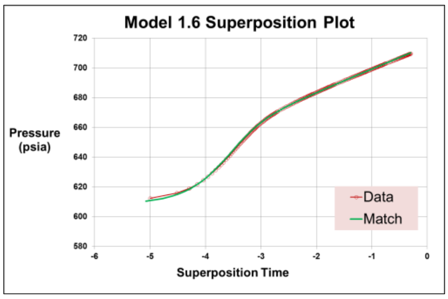

Model 1.4 History Plot
740
720
700
680
660
640
620
600
580
Bottom hole Pressure (psia)
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

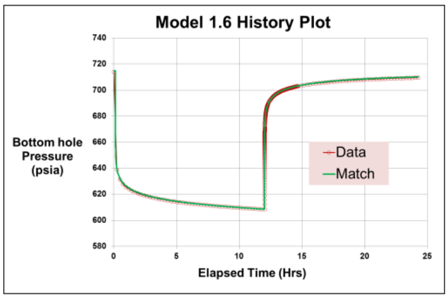

Model 1.5 Log-Log Plot
S = 1.16
K = 2410 mD
1000
100
10
1
dP, dP'
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

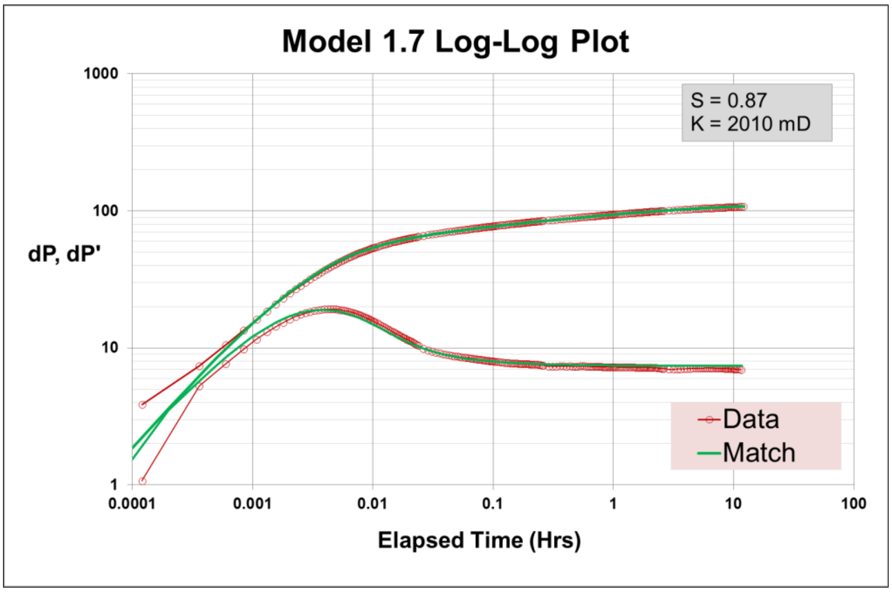

Model 1.5 Superposition Plot
720
700
680
660
640
620
600
580
Pressure (psia)
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

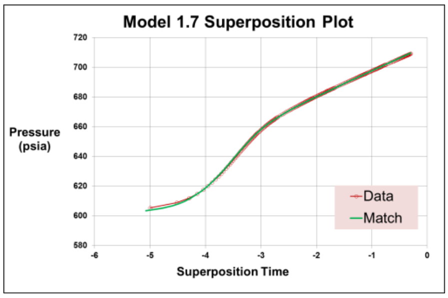

Model 1.5 History Plot
740
720
700
680
660
640
620
600
580
Bottom hole Pressure (psia)
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

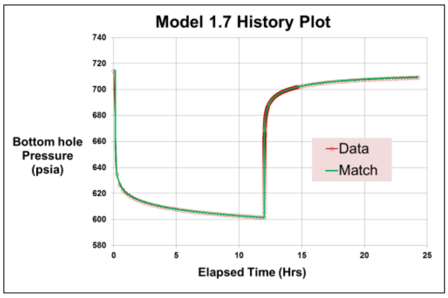

Model 1.6 Log-Log Plot
S = 1.05
K = 2200 mD
dP, dP'
1000
100
10
1
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

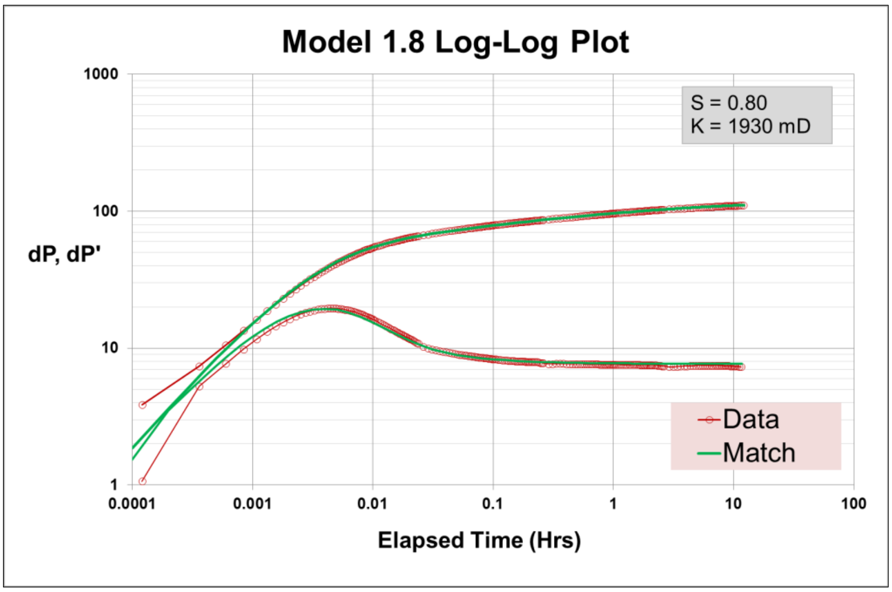

Model 1.6 Superposition Plot
Pressure (psia)
720
700
680
660
640
620
600
580
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

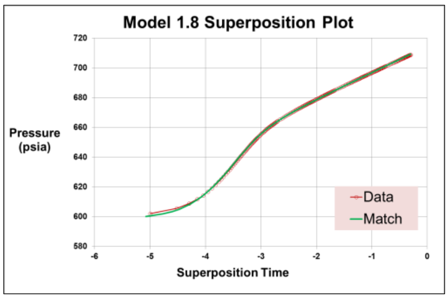

Model 1.6 History Plot
Bottom hole Pressure (psia)
740
720
700
680
660
640
620
600
580
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

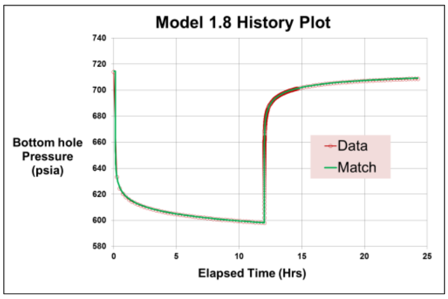

Model 1.7 Log-Log Plot
S = 0.87
K = 2010 mD
dP, dP'
1000
100
10
1
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

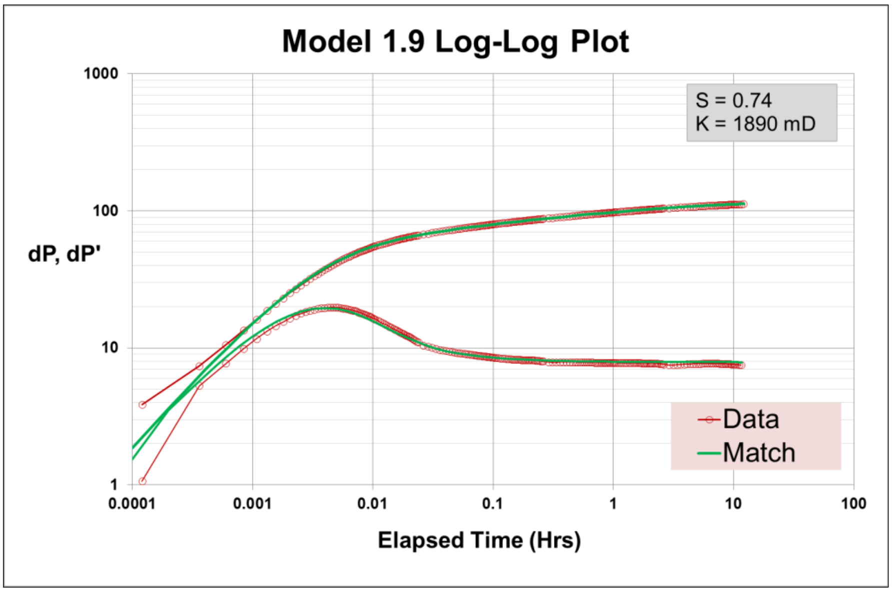

Model 1.7 Superposition Plot
Pressure (psia)
720
700
680
660
640
620
600
580
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

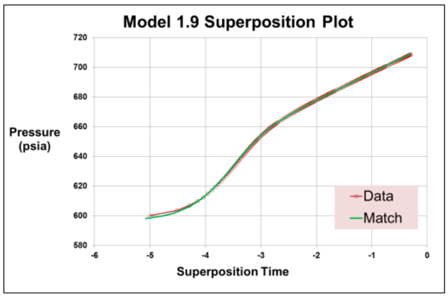

Model 1.7 History Plot
Bottom hole Pressure (psia)
740
720
700
680
660
640
620
600
580
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

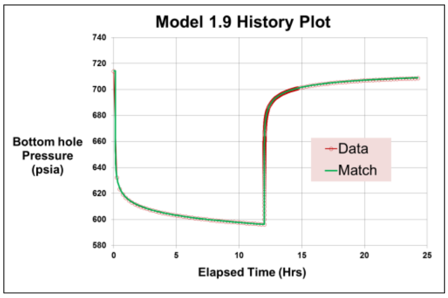

Model 1.8 Log-Log Plot
S = 0.80
K = 1930 mD
dP, dP'
1000
100
10
1
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match

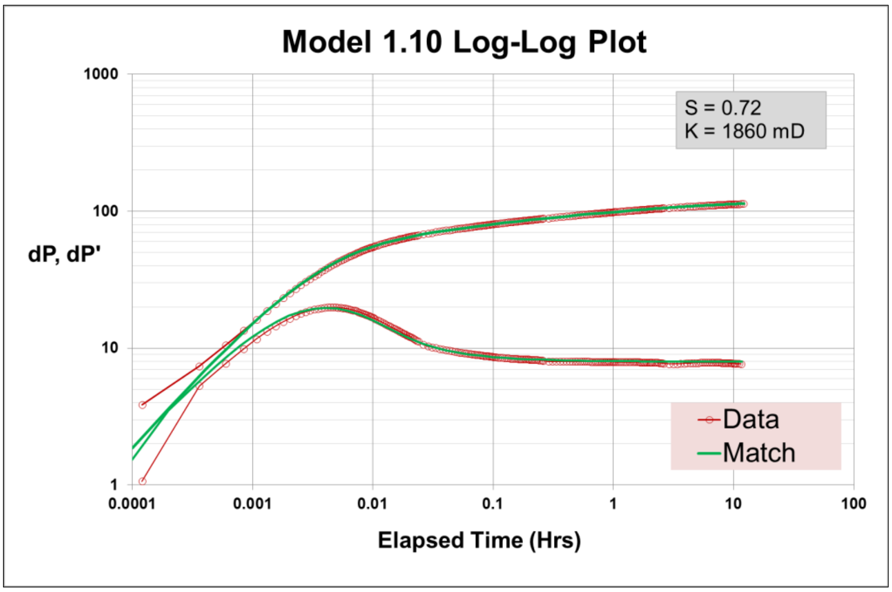

Model 1.8 Superposition Plot
Pressure (psia)
720
700
680
660
640
620
600
580
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match

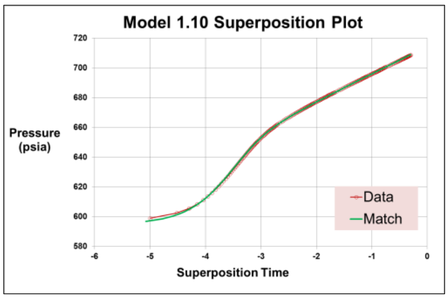

Model 1.8 History Plot
Bottom hole Pressure (psia)
740
720
700
680
660
640
620
600
580
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

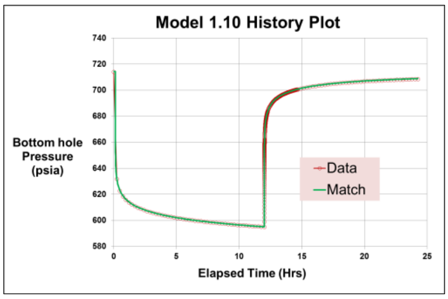

Model 1.9 Log-Log Plot
S = 0.74
K = 1890 mD
dP, dP'
1000
100
10
1
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match


Model 1.9 Superposition Plot
Pressure (psia)
720
700
680
660
640
620
600
580
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match


Model 1.9 History Plot
Bottom hole Pressure (psia)
740
720
700
680
660
640
620
600
580
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match


Model 1.10 Log-Log Plot
S = 0.72
K = 1860 mD
1000
100
10
1
dP, dP'
0.0001
0.001
0.01
0.1
1
10
100
Elapsed Time (Hrs)
Data
Match


Model 1.10 Superposition Plot
Pressure (psia)
720
700
680
660
640
620
600
580
-6
-5
-4
-3
-2
-1
0
Superposition Time
Data
Match


Model 1.10 History Plot
Bottom hole Pressure (psia)
740
720
700
680
660
640
620
600
580
0
5
10
15
20
25
Elapsed Time (Hrs)
Data
Match

Appendix D: Radial Model 2 Cases, Interpretation using stabilized layer flowrates

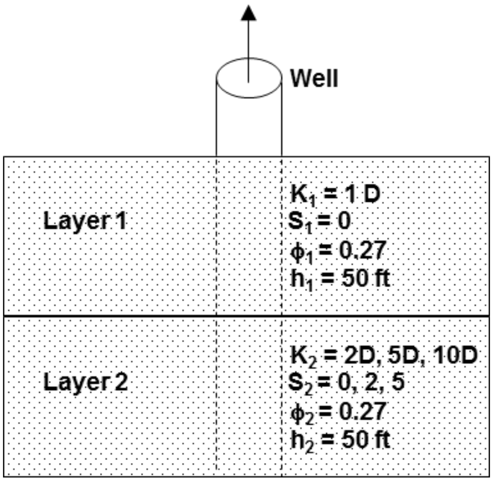


Fig. D 1: Radial model 2

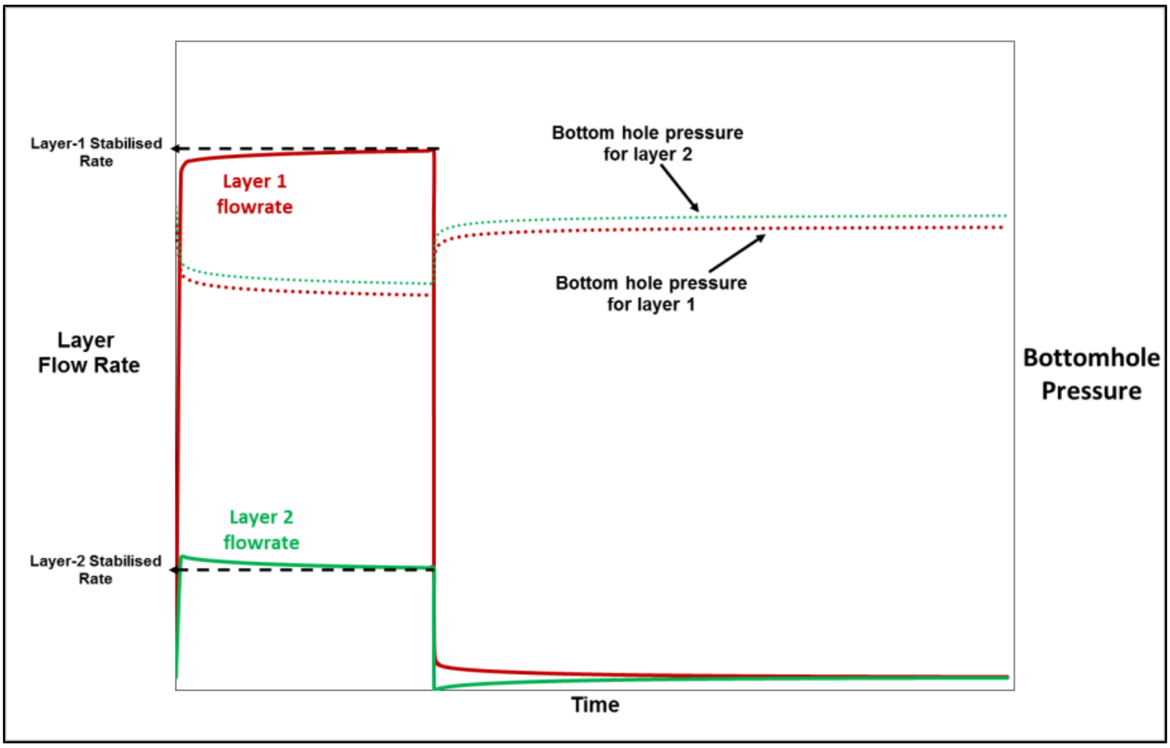


Fig. D 2: Layer pressure and flowrate used for analysis

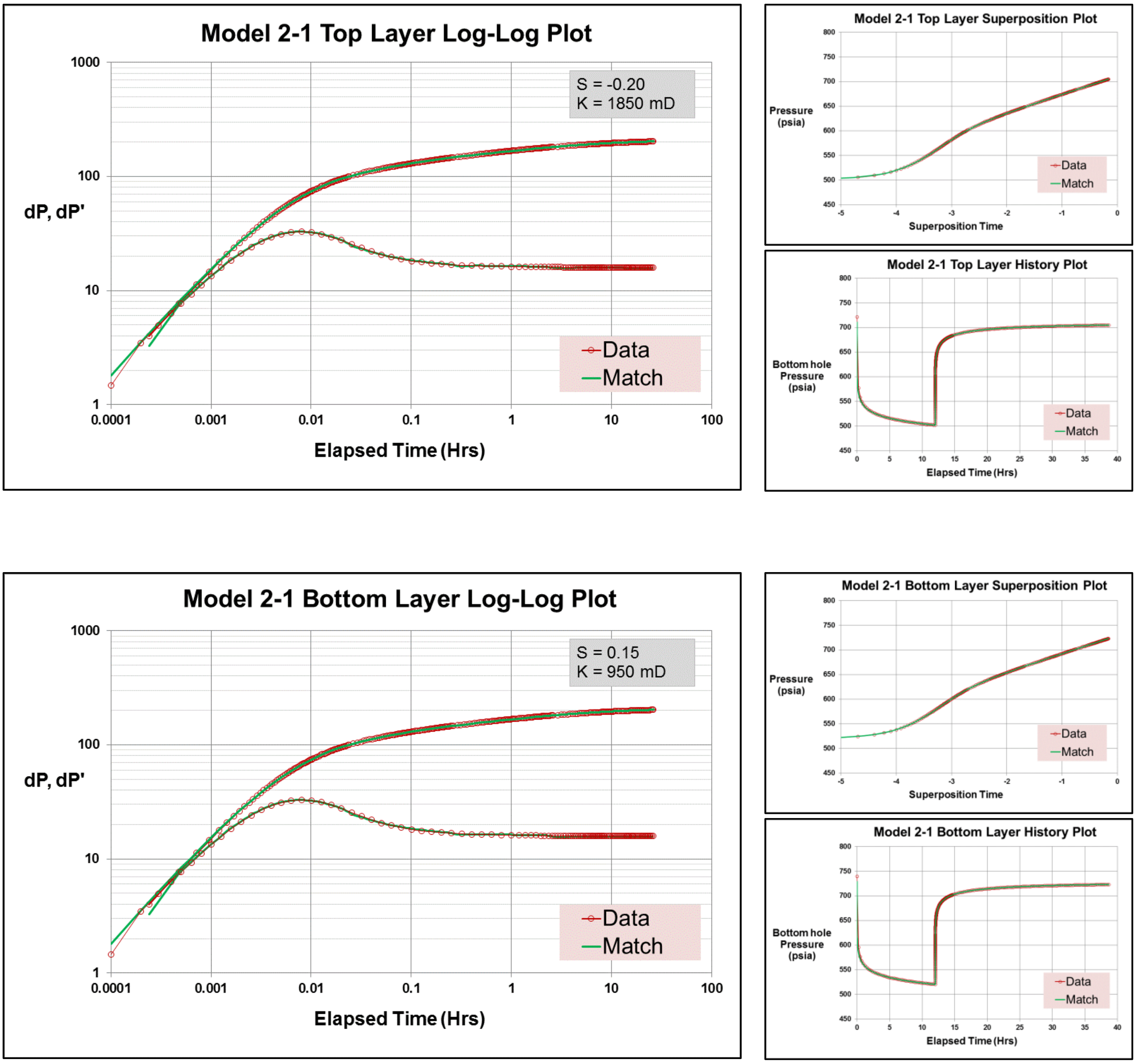


Fig. D 3: Model 2-1 analysis plots

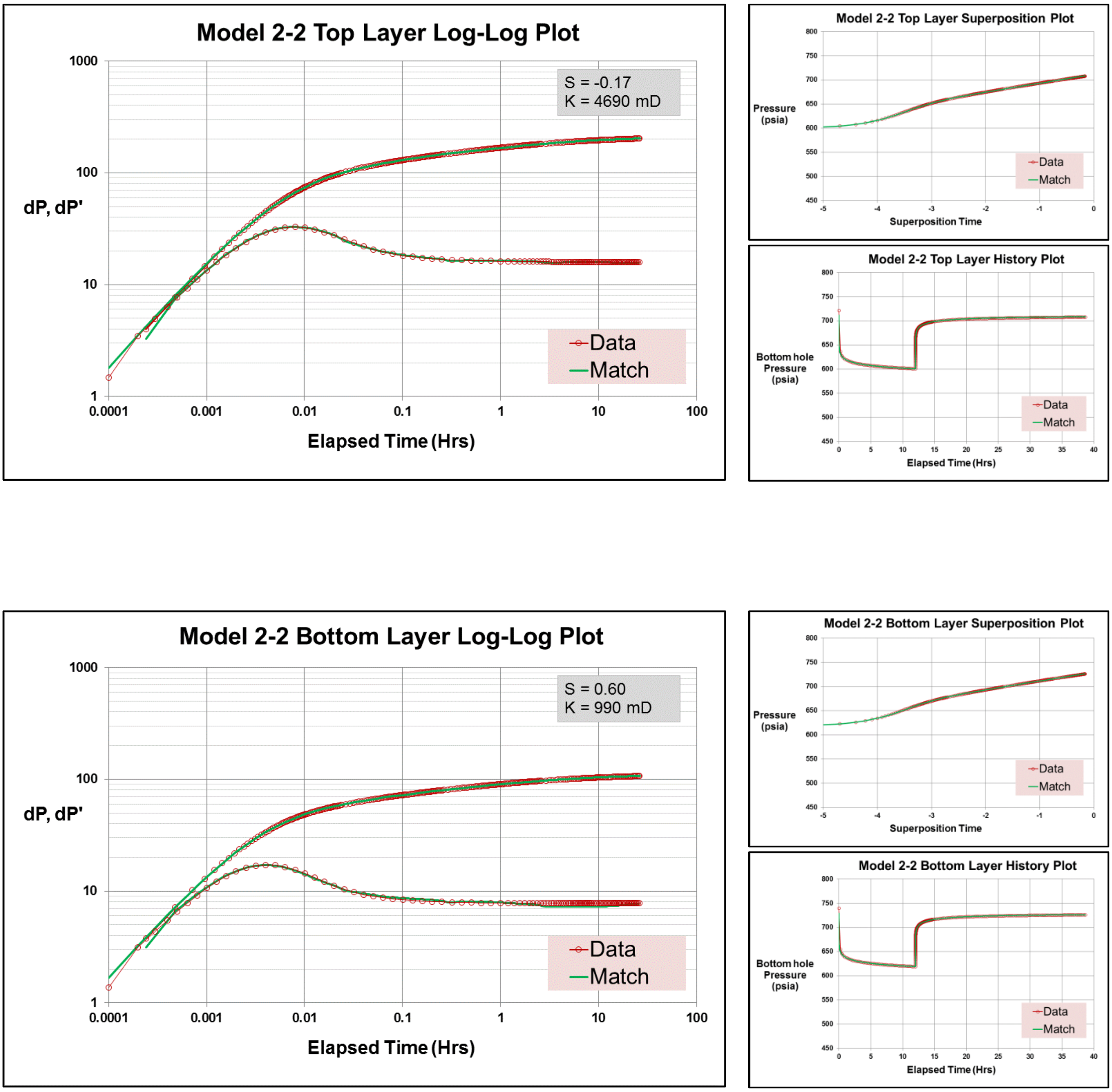


Fig. D 4: Model 2-2 analysis plots

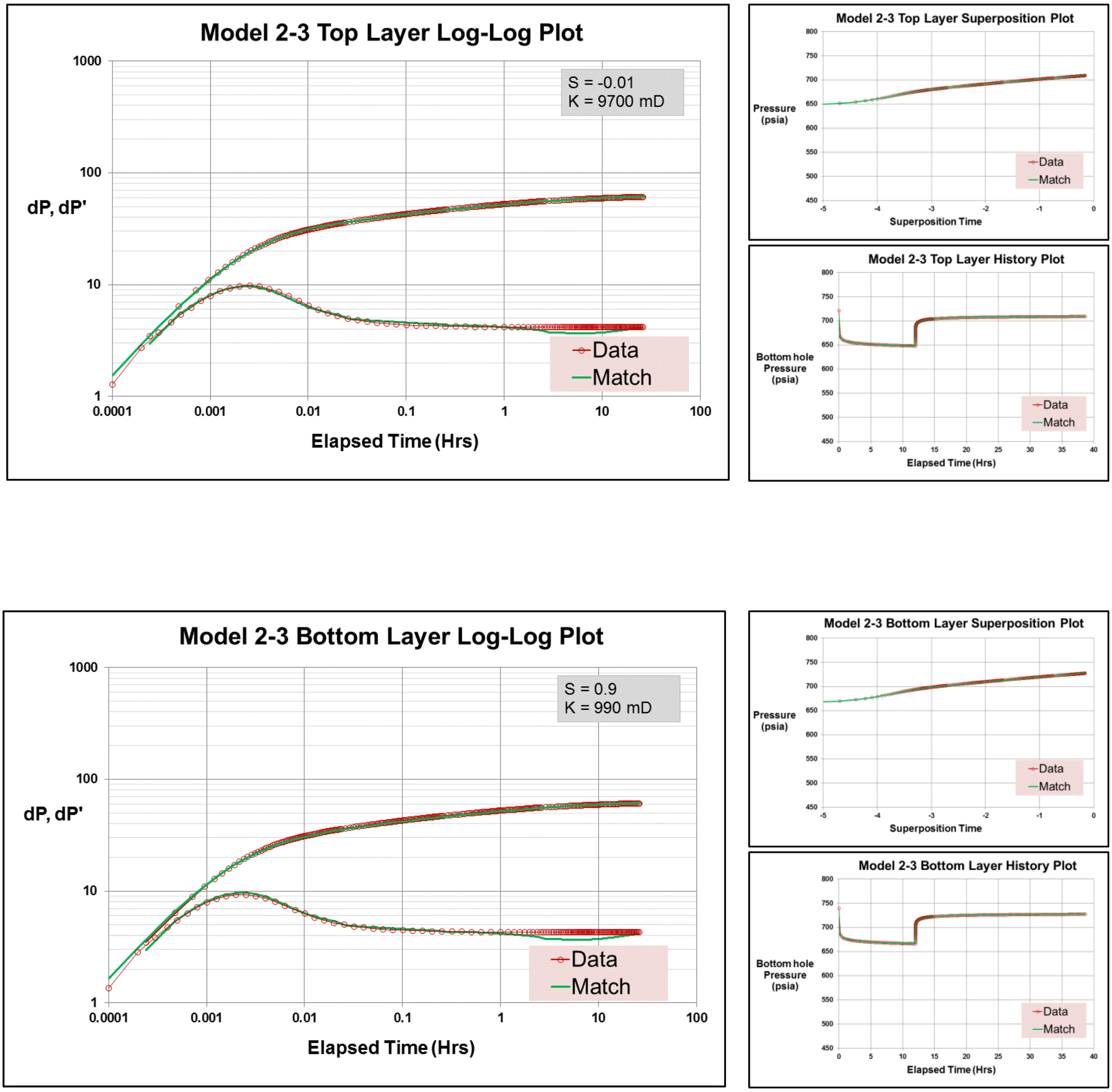


Fig. D 5: Model 2-3 analysis plots

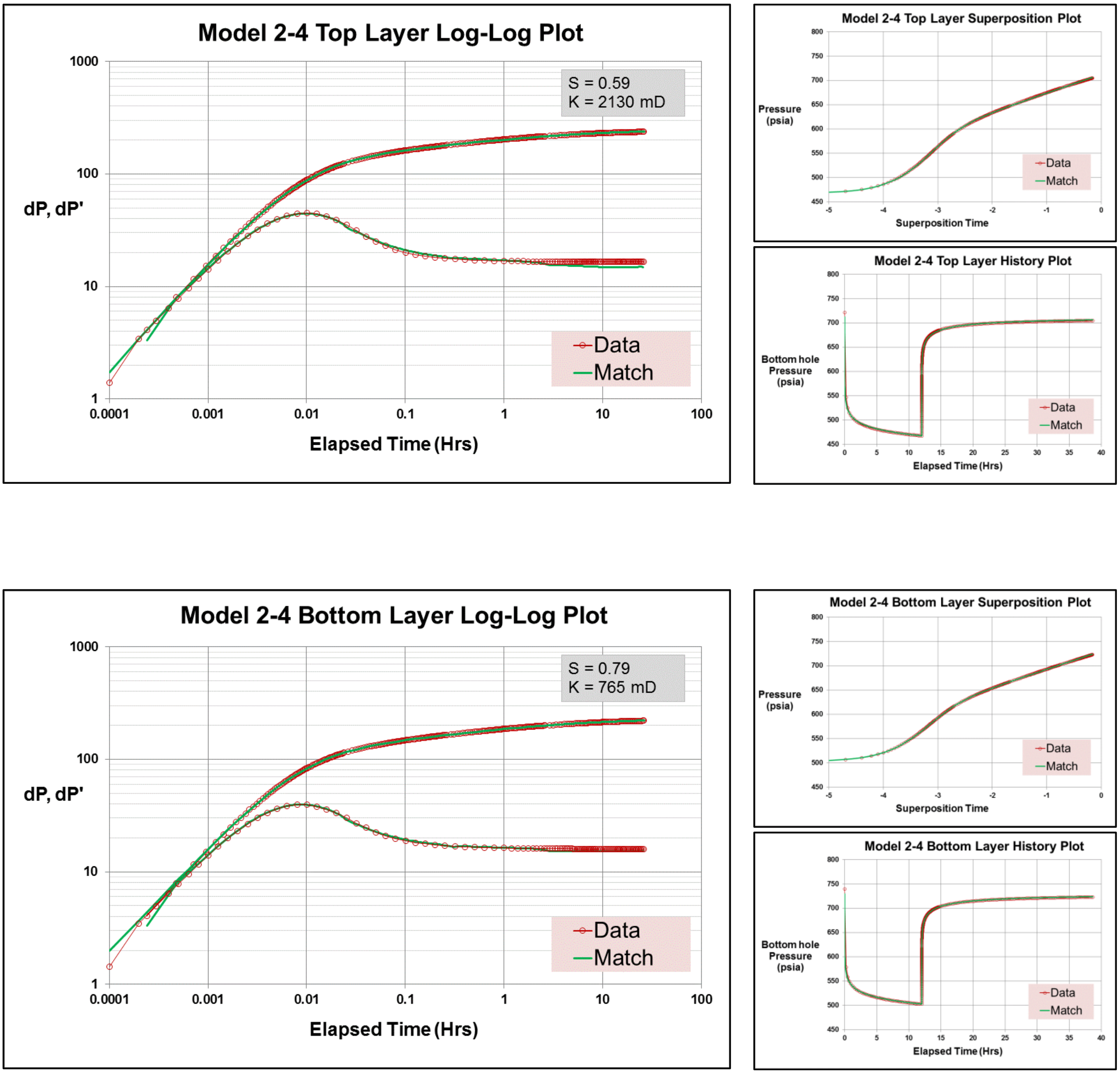


Fig. D 6: Model 2-4 analysis plots

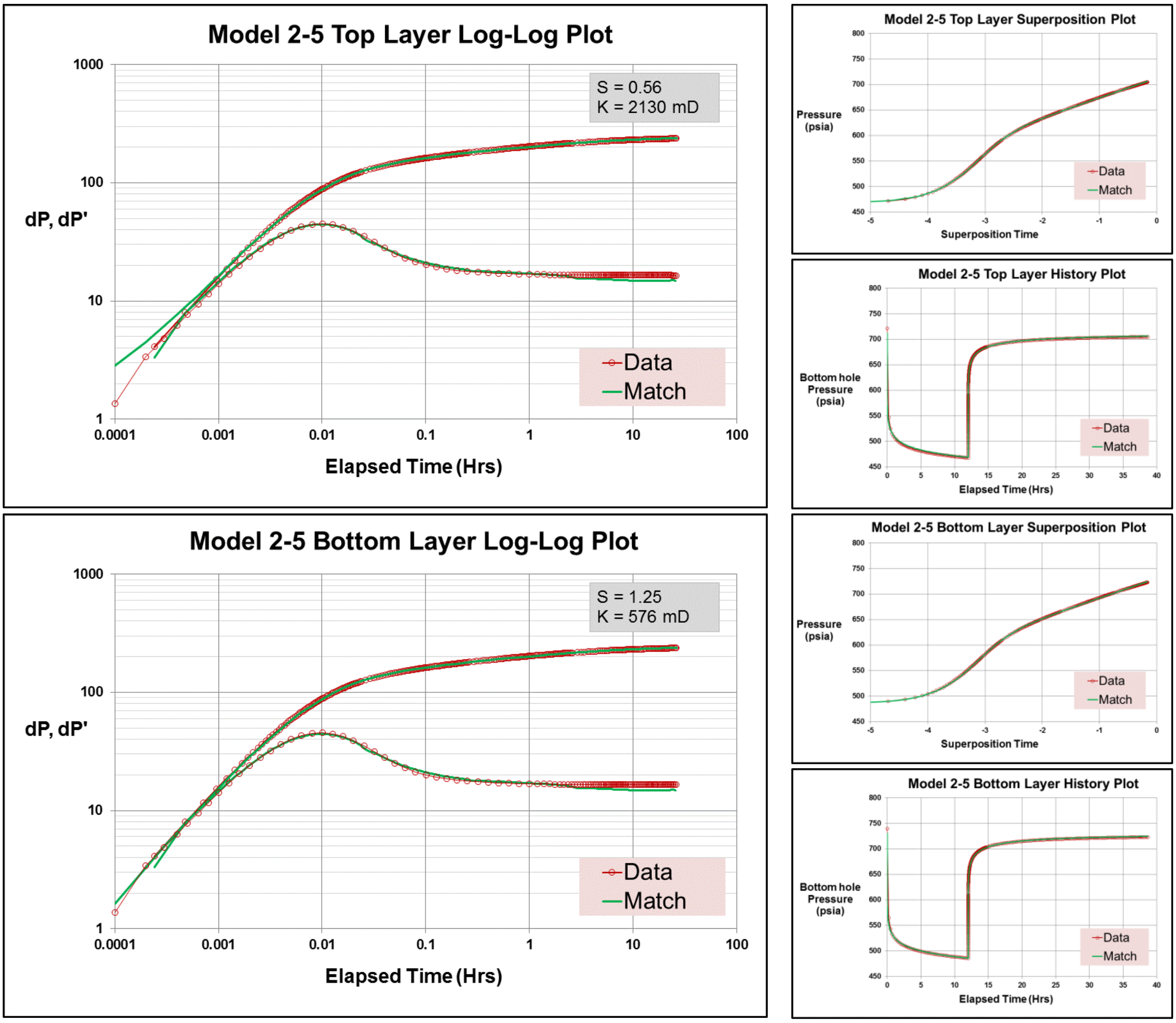
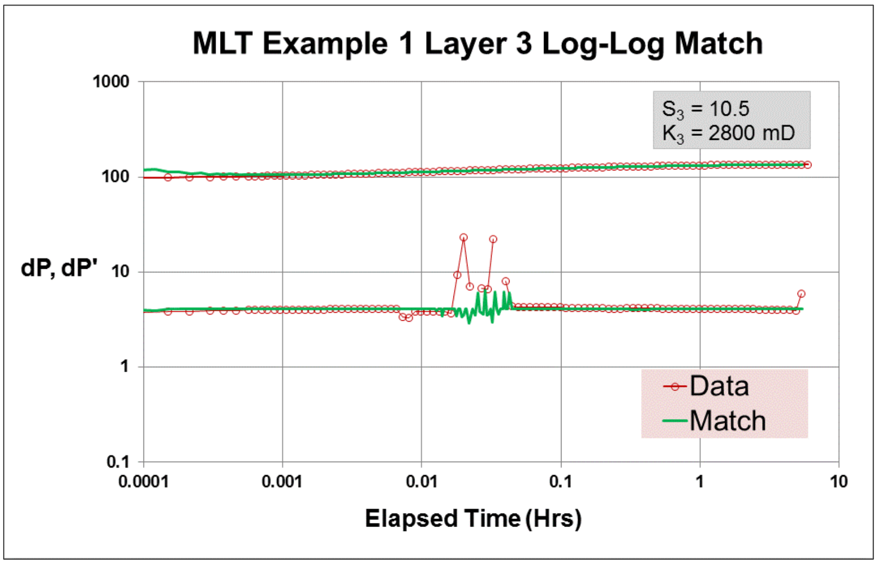


Fig. D 7: Model 2-5 analysis plots

Appendix E: MLT Example 1 Analysis Plots

MLT Example 1 Layer 3 Analysis Plots



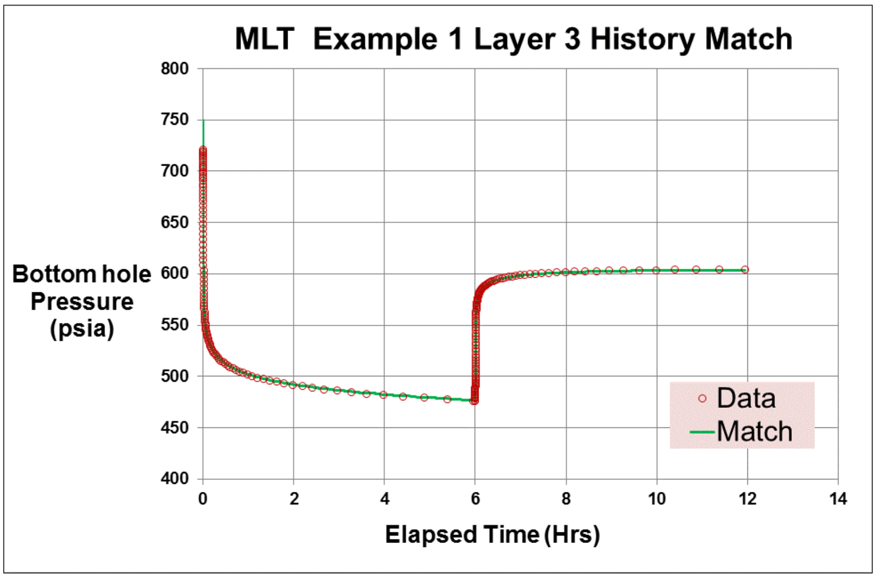


Fig. E 1: MLT Example 1 Layer 3 analysis plots

MLT Example 1 Layer 2 Analysis Plots

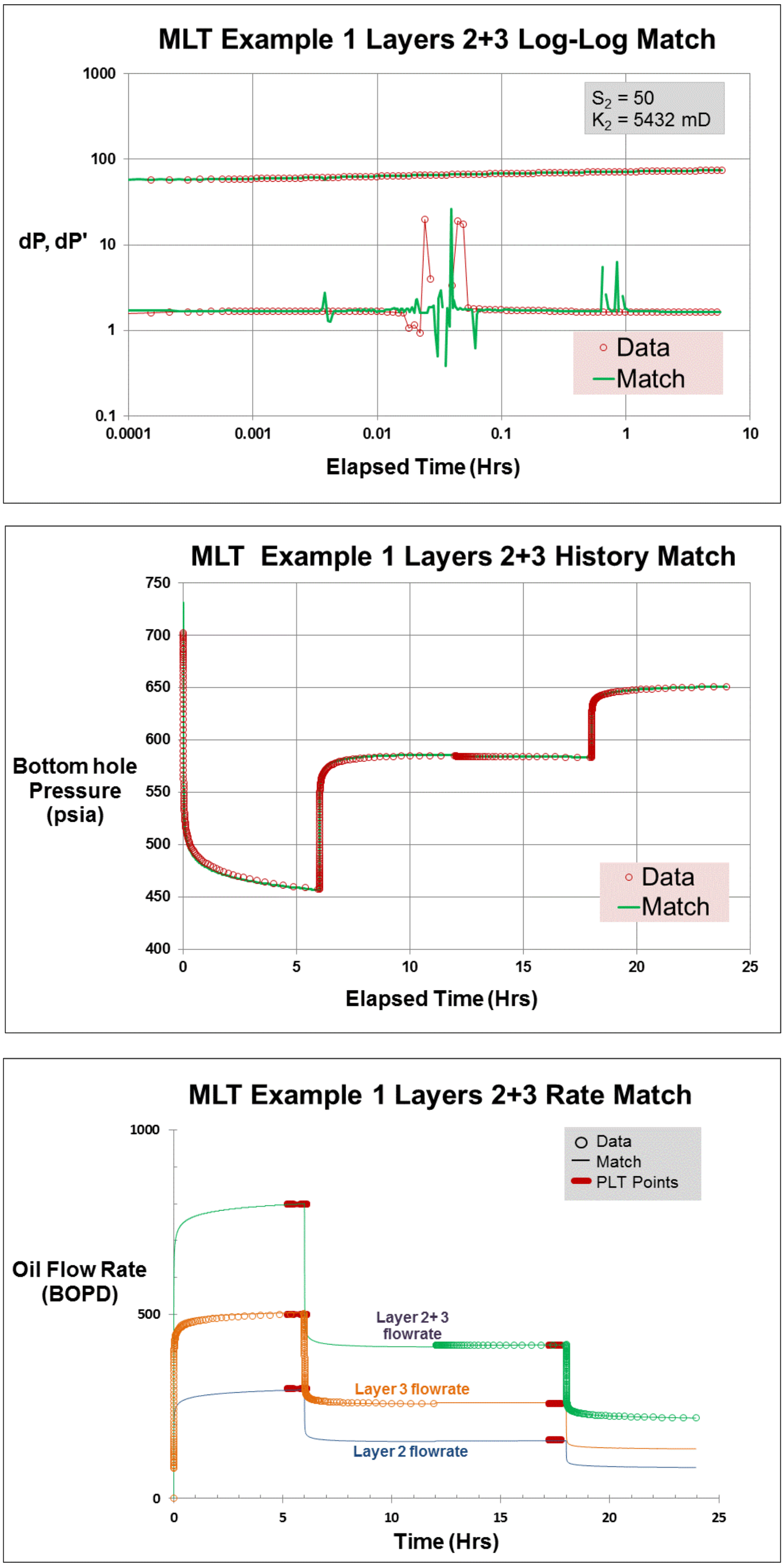


Fig. E 2: MLT Example 1 Layer 2 analysis plots

MLT Example 1 Layer 1 Analysis Plots

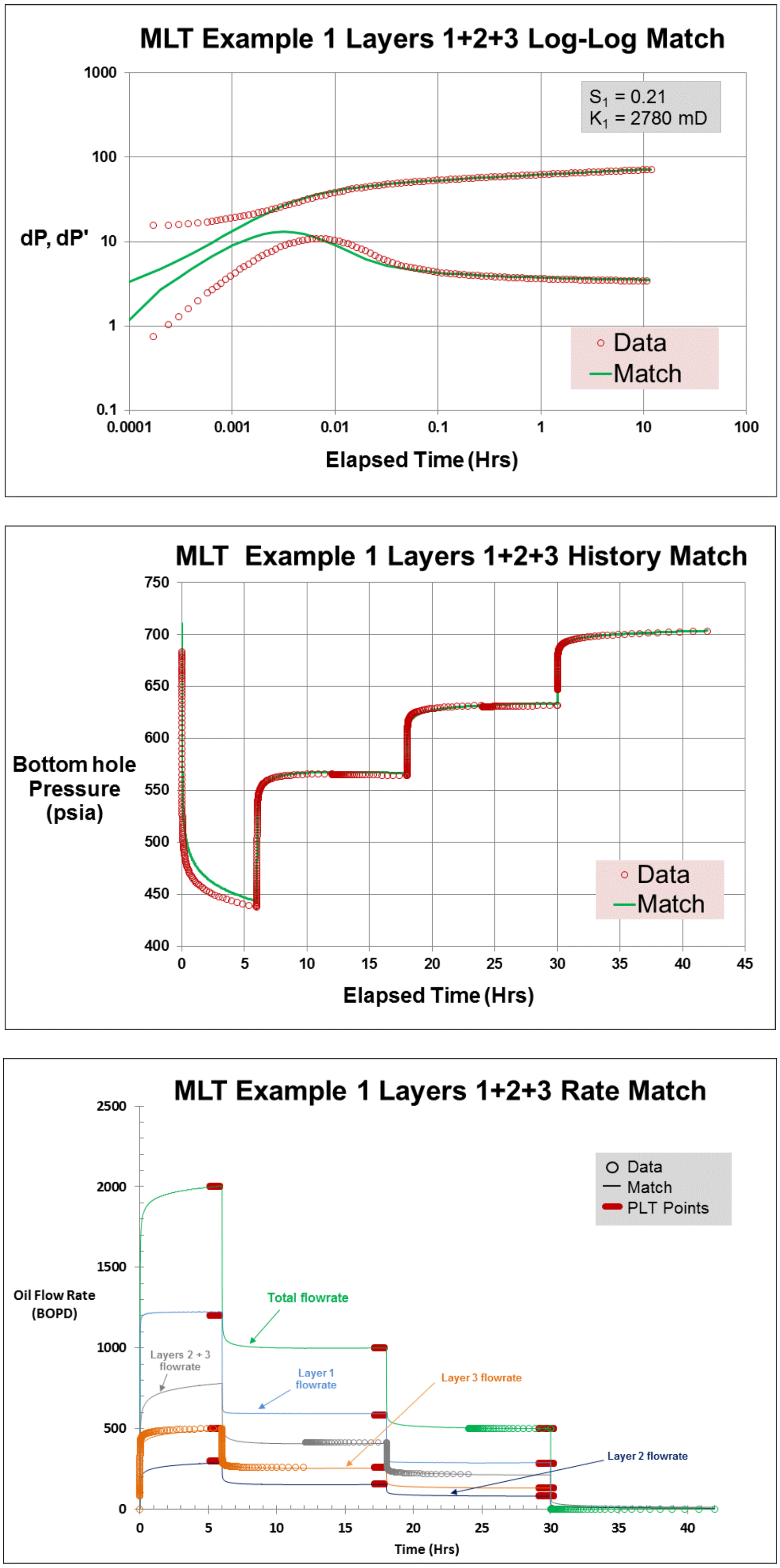
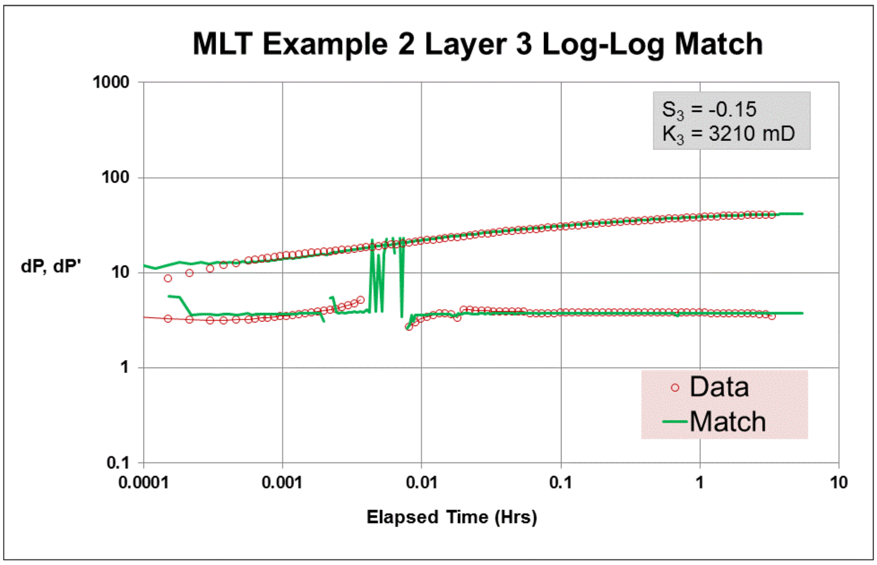


Fig. E 3: MLT Example 1 Layer 1 analysis plots

Appendix F: MLT Example 2 Analysis Plots

MLT Example 2 Layer 3 Analysis Plots



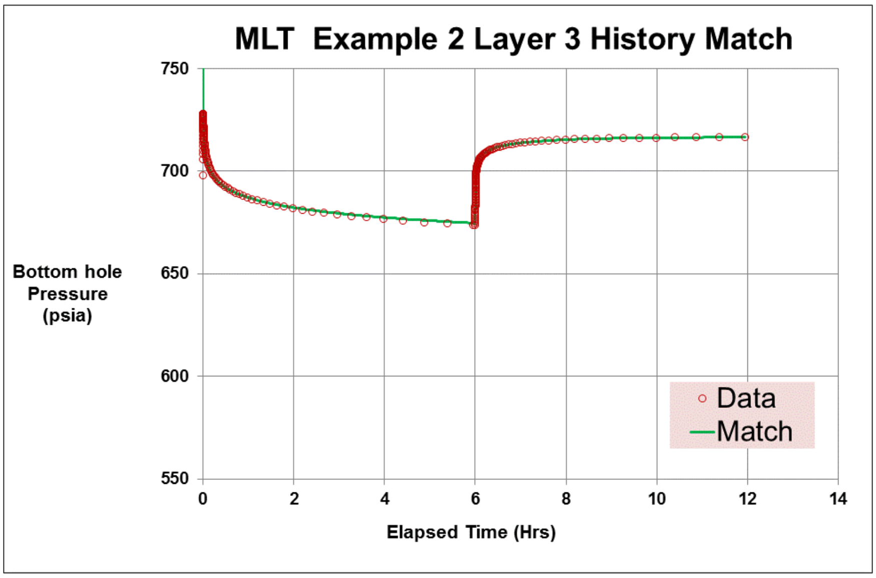
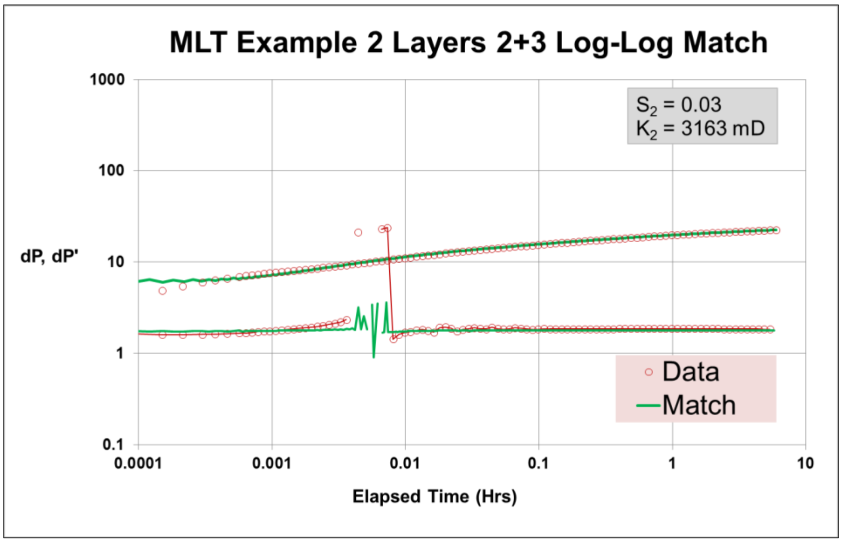
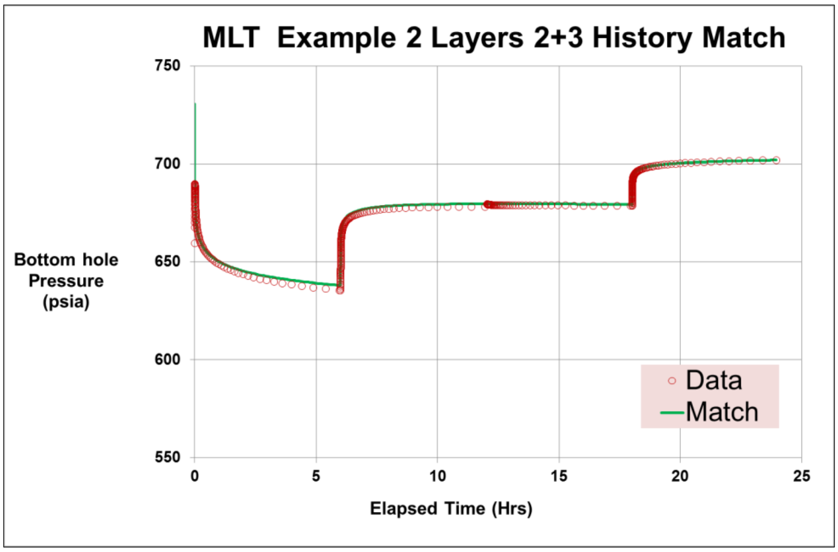


Fig. F 1: MLT Example 2 Layer 3 analysis plots

MLT Example 2 Layer 2 Analysis Plots





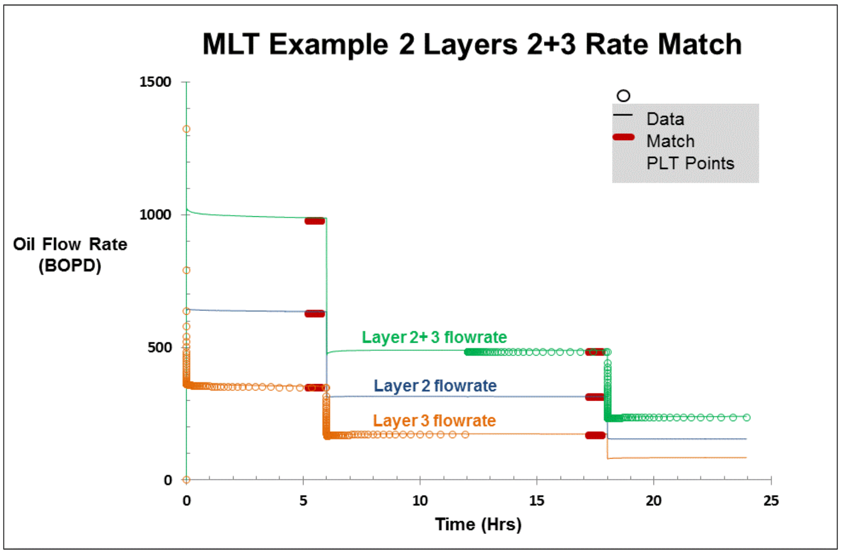


Fig. F 2: MLT Example 2 Layer 2 analysis plots

MLT Example 2 Layer 1 Analysis Plots

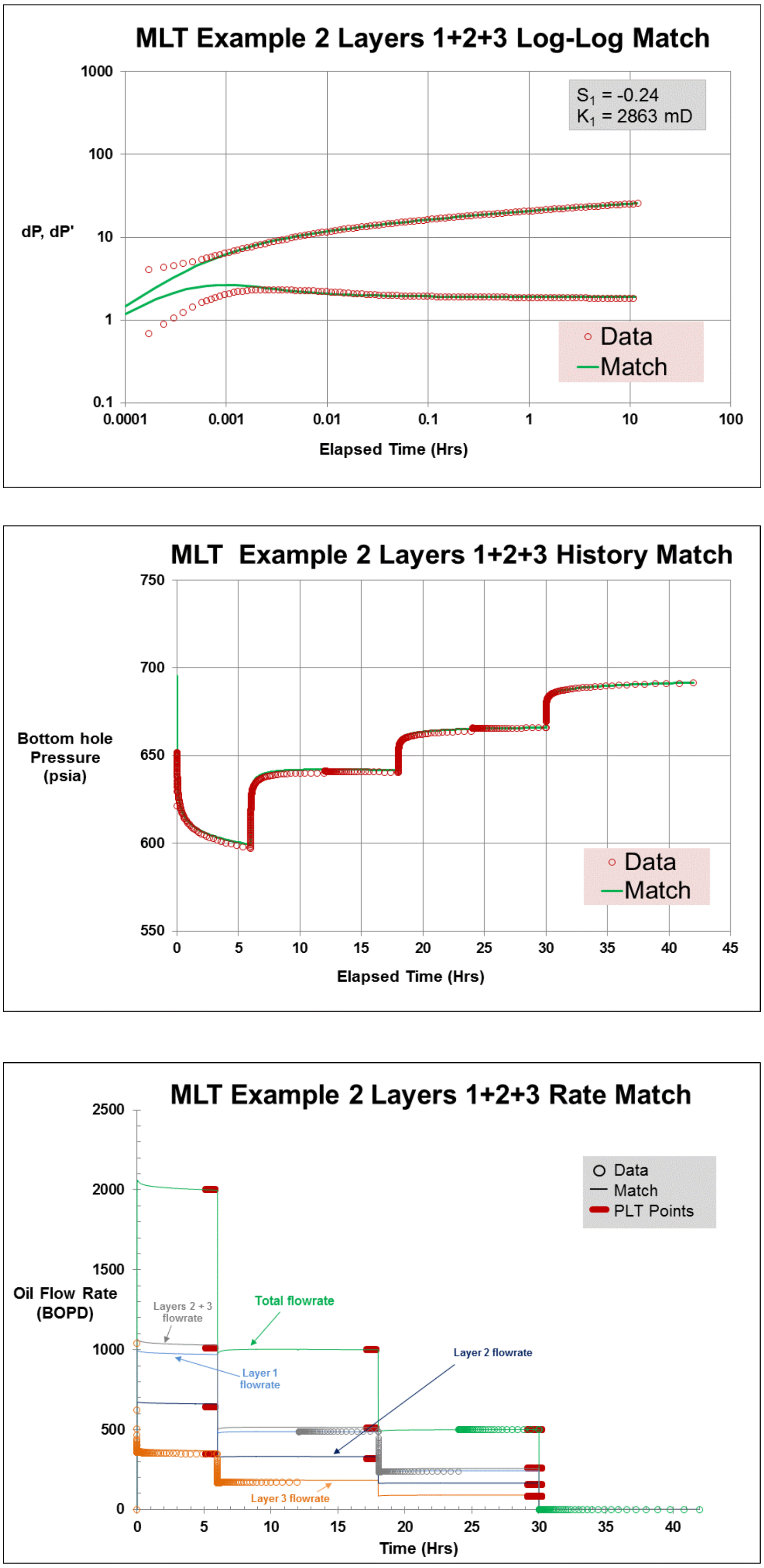
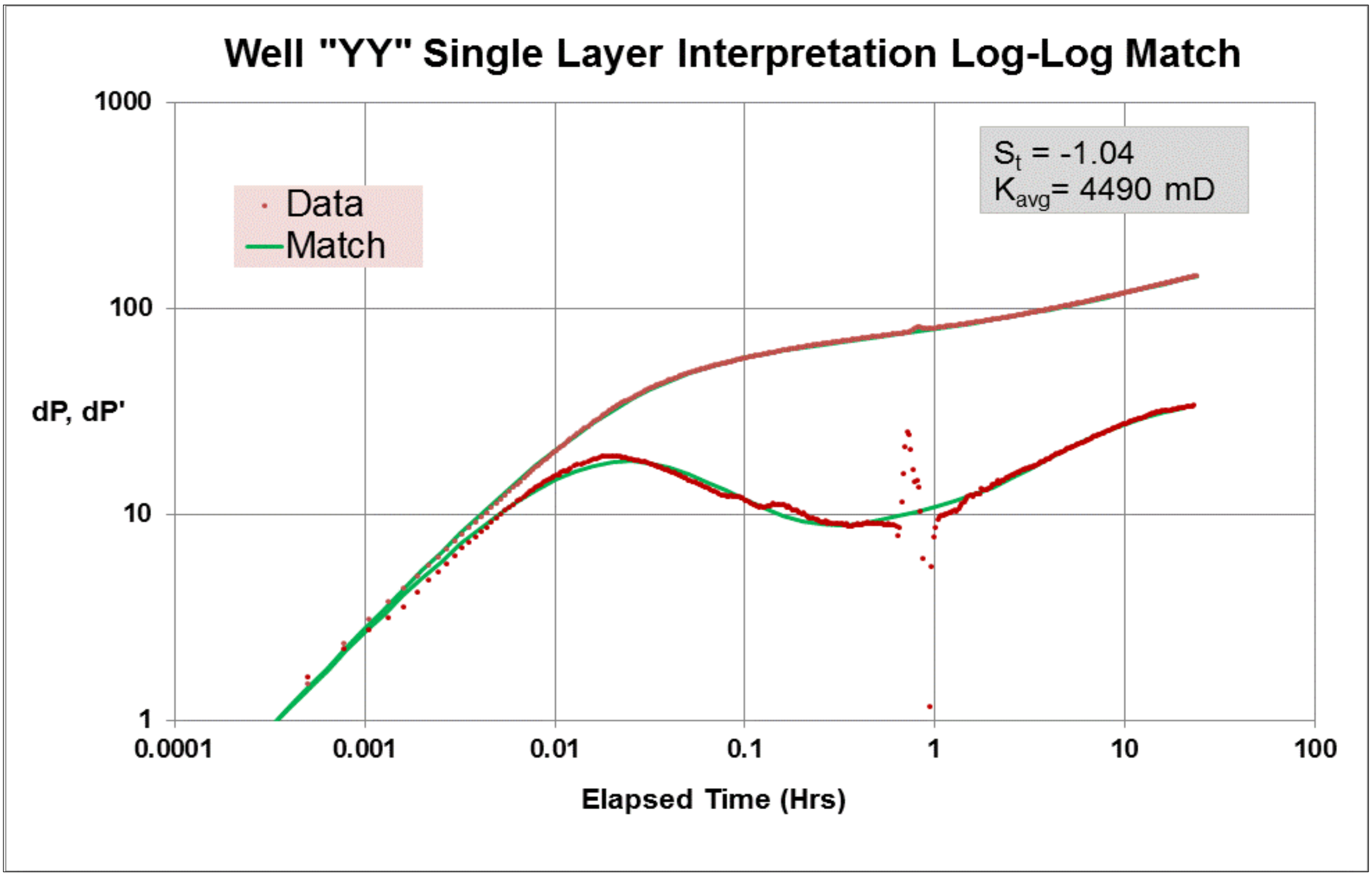


Fig. F 3: MLT Example 2 Layer 1 analysis plots

Appendix G: Well “YY” Single Layer Analysis Plot



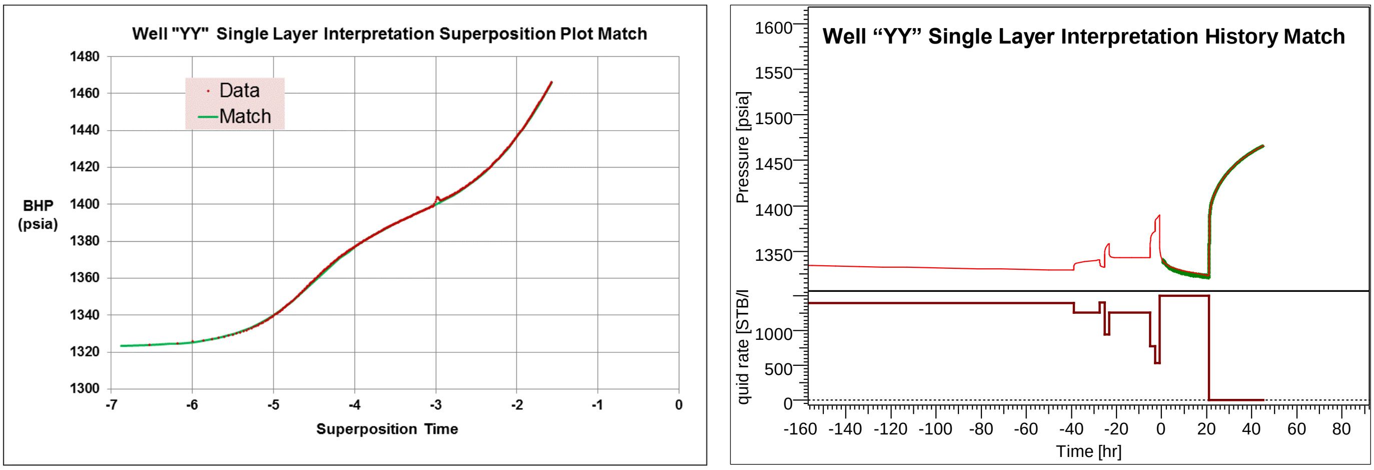


Fig. G 1: Well “YY” Single Layer analysis plots

Appendix H: Well “YY” Simultaneous Multi-Layer Analysis Plots

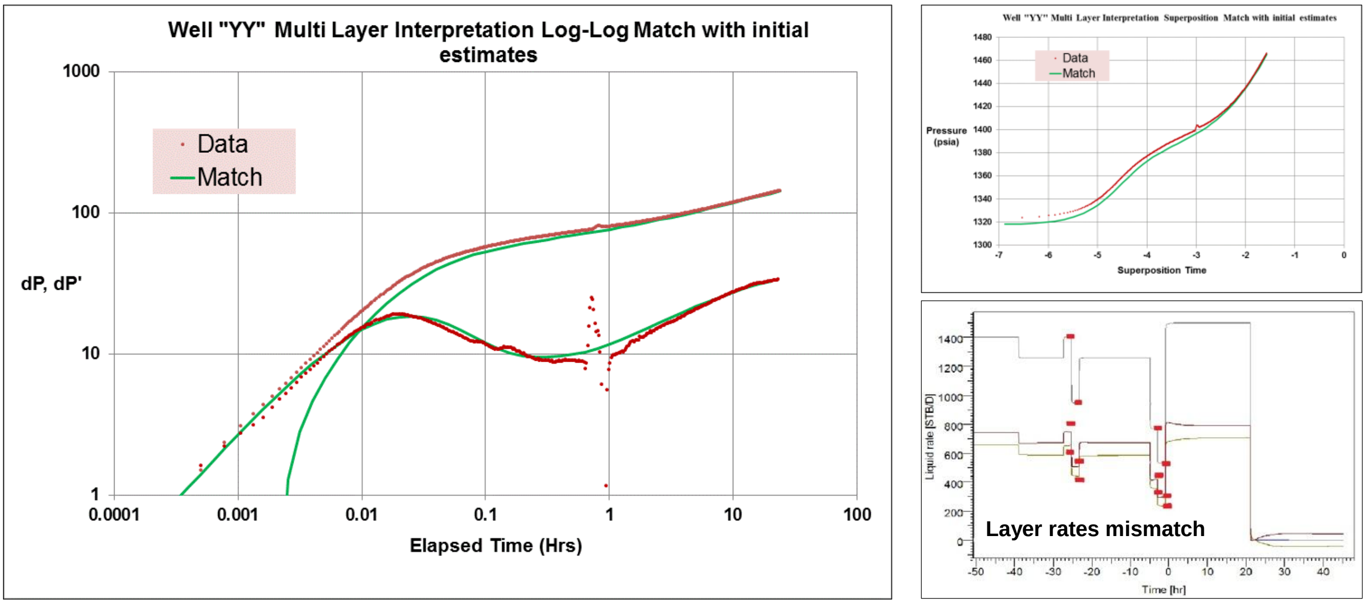


Fig. H 1: Well “YY” Simultaneous multi-layer analysis plots with initial estimates

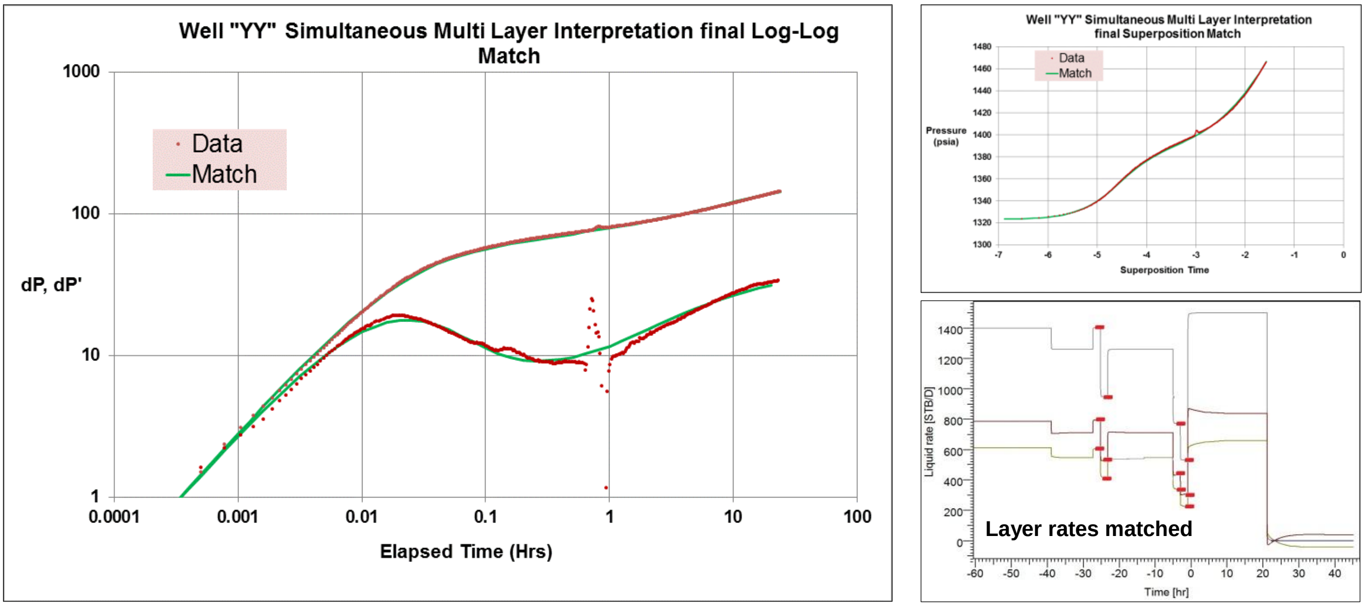


Fig. H 2: Well “YY” Simultaneous multi-layer analysis final plots

Appendix I: Well “YY” Sequential Multi-Layer Analysis Plots

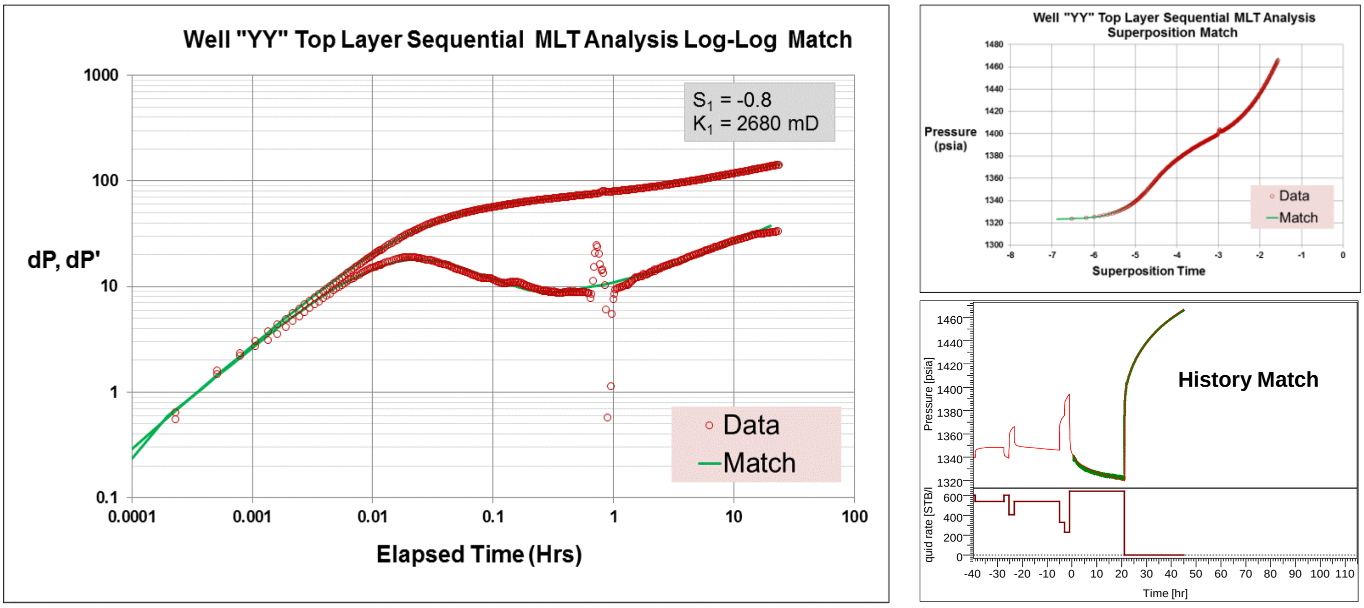


Fig. I 1: Well “YY” Top Layer sequential MLT analysis plots

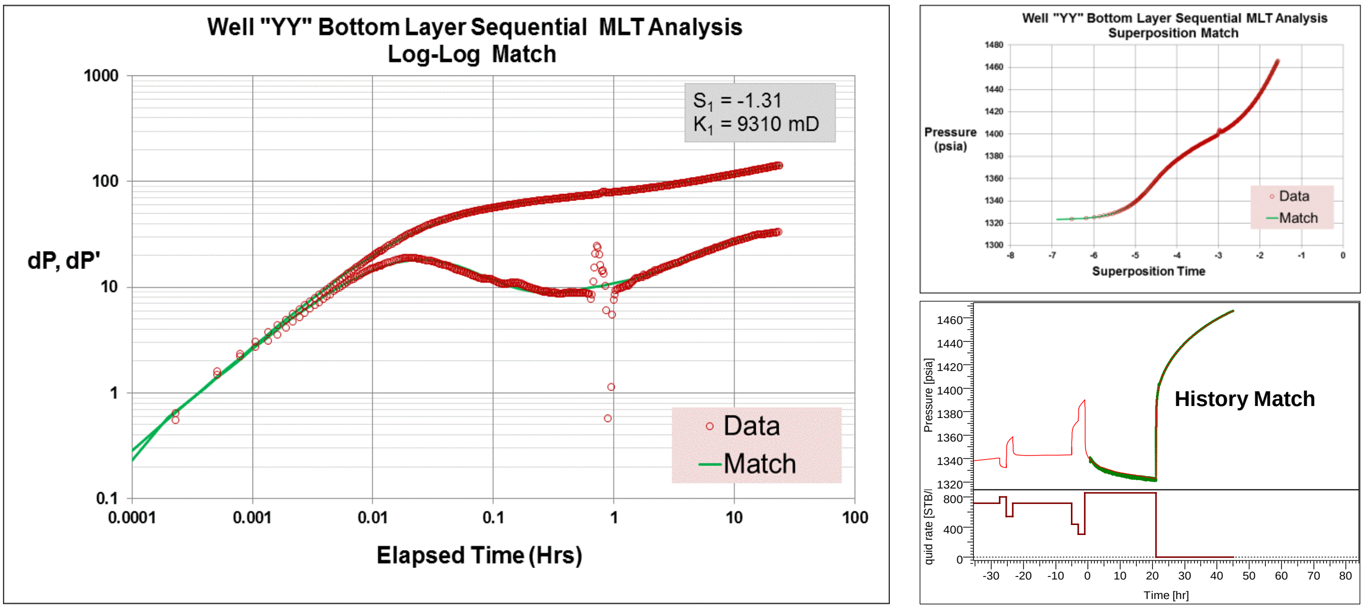


Fig. I 2: Well “YY” Bottom Layer sequential MLT analysis plots