

Making the most of production logging information

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Abstract

Although the basics of production logging are reasonably straightforward we often do not make the most of the data we acquire. This paper will show a couple of examples, illustrating how extra information can be obtained from basic PLT data. Some of the extra uses are:

CCL: The CCL can give a good indication of where the perforated interval is and how successfully it has been perforated.

Temperature: As well as using basic temperature profiles to indicate gas or water flow and behind-pipe movement, the temperature curve can also be differentiated to more accurately pinpoint sources of fluid entry. This temperature gradient log also shows excellent correlation with lithologies, due to the difference in thermal capacity of different rock types.

The paper will also discuss the value of combining PLT information with other logs (open hole and CBL) as well as core data etc. to optimise the analysis of the well in question.

Introduction

Production logging tools are traditionally run to determine the nature of inflow into a wellbore. Although the basics of production logging are reasonably straightforward, the data obtained is often not used to its maximum extent. The following case histories give examples of how PLT data has been used in combination with log, core and pressure build-up data to better understand well performance.

Case 1

Background information

The well in question had two zones open to flow, however, using Flowing Tube Head Pressure (FTHP) as the key performance indicator, it had been concluded that the majority of the flow was coming from the lower zone (Zone B). All pressure welltest analyses had assumed that the whole of the Zone B perforated interval was contributing to flow. The objective of the flowing production log was to determine the extent of the productive interval and identify if there was any cross-flow between Zones A and B. Cross-flow was detected on the initial PLT. A second log was run approximately 6 weeks after shut in to determine the extent of the cross-flow.

Initial PLT results

Shut-in passes were performed over the perforated intervals in order to calibrate the spinner response and monitor cross-

flow. The well was then opened up and flowed at approximately 16 mmscf/day. Flowing passes were performed to determine the well's flow profile.

Note: The nomenclature used in the plots is as follows:

sensor_logging direction wellstatus logging speed.

Therefore, CCL_DF10 would correspond to the CCL response, for the Down pass, of the Flowing survey, at a speed of 10 metres/minute.

The calibration passes have a C rather than an F.

The individual sensor naming convention is:

FLDN = spinner response detecting downward flow (a % symbol after the cable speed indicates the response has been normalised to 100%).

FLUP = spinner response detecting upward flow.

RHO = gradiomanometer measurements.

TEMP = temperature.

PRES = pressure.

GR = gamma ray.

CCL = casing collar locator.

SPD = tool speed.

TGRAD = differentiated temperature.

Individual sensor responses

Spinner

Calibration passes

Shut-in passes were carried out approximately three and a half hours after initial shut-in of the well. Cross-flow was detected at all logging speeds and in both the upward and downward passes. Figure 1 shows the spinner responses for the calibration passes.

This plot clearly identifies that flow is coming out of an interval at or above 3703 mAHBKB (top Zone B) and entering an interval of approximately 1 metre at 3595 mAHBKB (top Zone A). There is also a slight decrease in spinner speed at a depth of 3606 mAHBKB.

From the spinner information a rough estimate of the flow into the Zone A perforations can be made and, using estimated pressures, the productivity and kh of the zone can be inferred.

The increase in spinner speed between Zones B and A was approximately 0.55 rps, which corresponded to a flow rate of about 1 mmscf/day. The pressure at the Zone A perforations was 5967 psig and at the Zone B perforations was 6003 psig (based on the same down pass).

Combining this data with the results of the flowing passes an estimate of the flow capacity of Zone A could be made. This is discussed later in this report in the interpretation section.

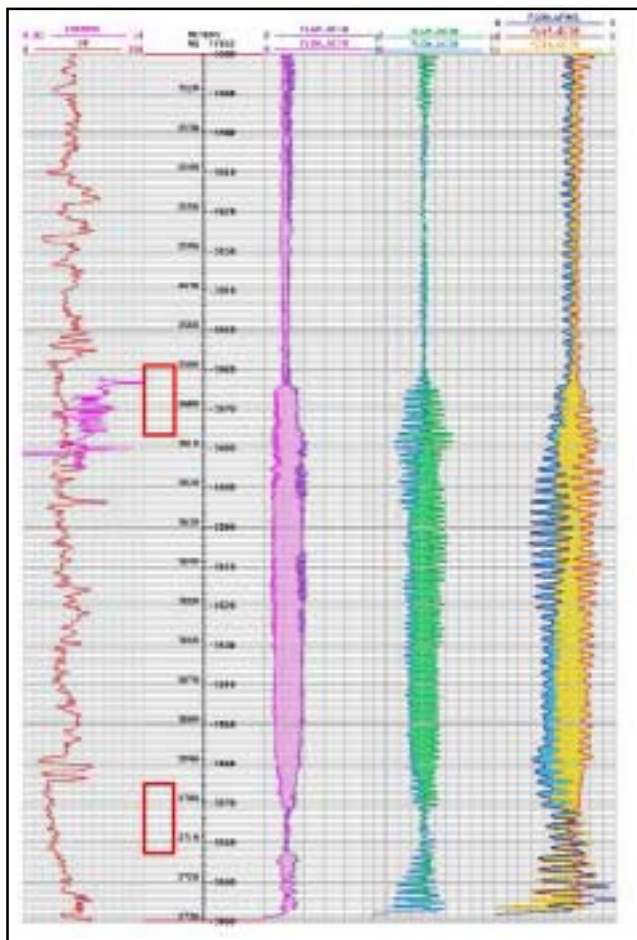


Figure 1: Summary of calibration passes spinner data.

At the end of the flowing passes an extra shut-in pass was made (FLDN_UFWEL) to evaluate the extent of cross-flow immediately after shut in. There is a greater cross-flow shown for this logging pass which was carried out approximately 5 minutes after shutting-in the well.

Flowing passes

Flowing passes were carried out once the well had stabilised, approximately 70 minutes after reopening the well. Figure 2 shows the spinner responses for the flowing passes. It was clearly demonstrated that only a small interval within Zone B was actually contributing to flow. The interval from 3701 to 3703 mAHBKB was contributing approximately 65% of the flow and the interval from 3694 to 3696 mAHBKB was contributing the remaining 35%. The most significant anomaly of the latter interval is that it is above the perforated interval and in a section of the reservoir identified as a coal zone. This will be discussed in the interpretation section. There was also a very small dip in the spinner response over the Zone A perforations indicating that there may still be a minute amount of cross-flow from Zone B into Zone A even while the well is flowing. What is absolutely certain is that Zone A is not contributing to flow at this particular drawn down condition.

Temperature

Calibration passes

Figure 3 shows the temperature response from the calibration passes. The raw temperature data has been differentiated and is also shown on the plot (TGRAD). Both curves show the interval of the well over which gas is cross-flowing, as this manifests itself in a constant gas gradient. The depth interval

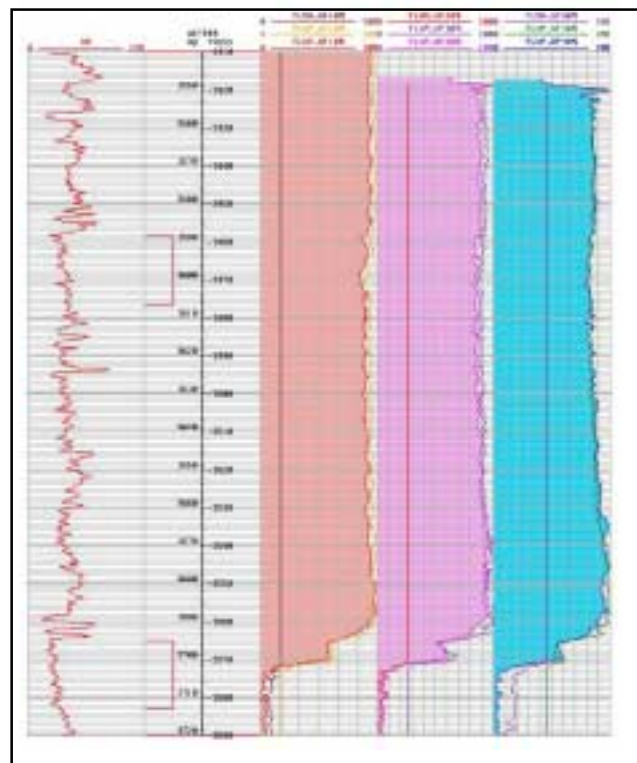


Figure 2: Summary of flowing passes spinner data.

over which the cross-flow is occurring ties in with the spinner analysis i.e. gas flowing from 3701 mAHBKB into 3595 mAHBKB. There is also a slight blip in the temperature gradient at 3696 mAHBKB, which corresponds to the upper Zone B flowing interval. The temperature curves overlay exactly below 3714 mAHBKB, which corresponds to the base of the Zone C perforations. There is also a sharp gradient change at this point. However, there is also a gradient spike at 3711 mAHBKB, which could correspond to a slight change in fluid composition (for example condensate overlying water in the sump).

In the section above Zone A, the temperature log indicates that the gas in the wellbore is gradually being cooled by the formation, until it reaches the geothermal equilibrium. The rate at which the gas is cooled is dependent upon the thermal properties of the rocks themselves. Clean sandstone for example will absorb heat more readily than a dirtier sandstone. Coals have a very low thermal capacity and will take the longest time to reach equilibrium. The differentiated

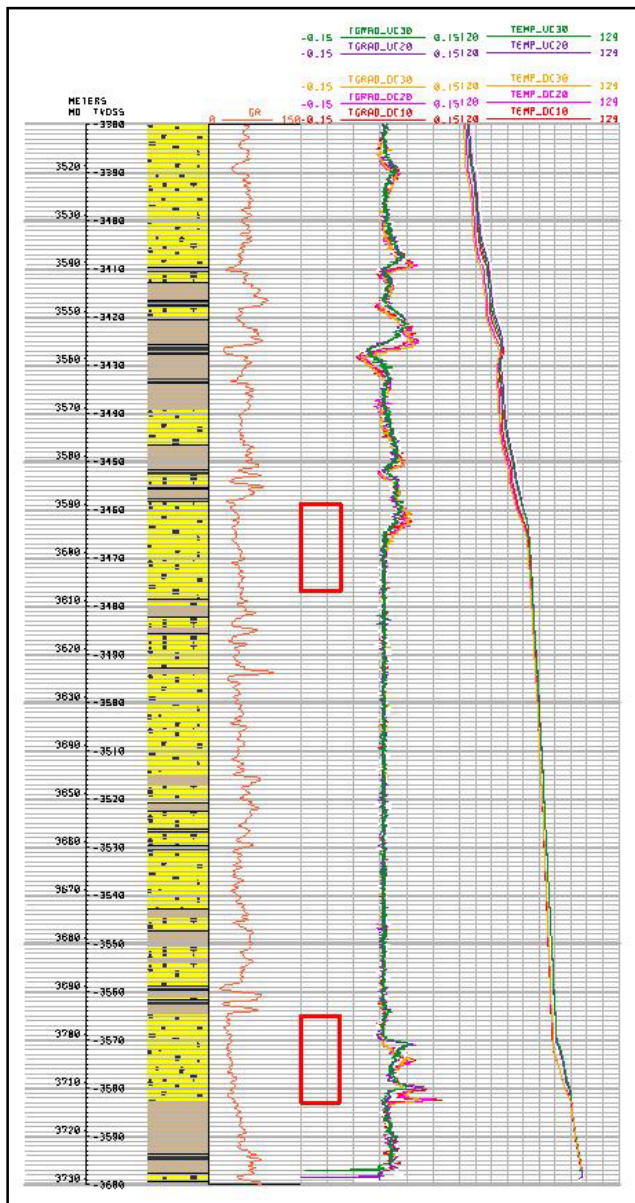


Figure 3: Summary of calibration passes temperature data.

temperature log can therefore be closely correlated to the gamma ray response, with low GR rocks giving a larger temperature gradient than a higher GR rock. The notable exceptions to this rule are coals, which have a low GR and low gradient. Therefore, it is possible to use the GR and temperature gradient, in conjunction, to distinguish good sand from a coal.

Flowing passes

The flowing temperature shows a constant gradient above 3701 mAHBKB indicating flow of gas above this level (see Figure 4). Below 3710 mAHBKB there is also a constant gradient indicating the presence of water below this level. It is possible that there could be some influx of water from the perforations between 3710 and 3714 mAHBKB, but the response is not large enough to detect with the spinner.

The alternative view is that the water level could rise due to expansion when the pressure is lowered during flowing conditions. Considering the low compressibility of water this would not be expected.

Gradiomanometer

The gradiomanometer shows a clear liquid level at the base of the perforations during the static passes. This level appears to rise to 3710 mAHBKB during flowing conditions with a slight change at 3712 mAHBKB which could correspond to a condensate layer (see Figure 4).

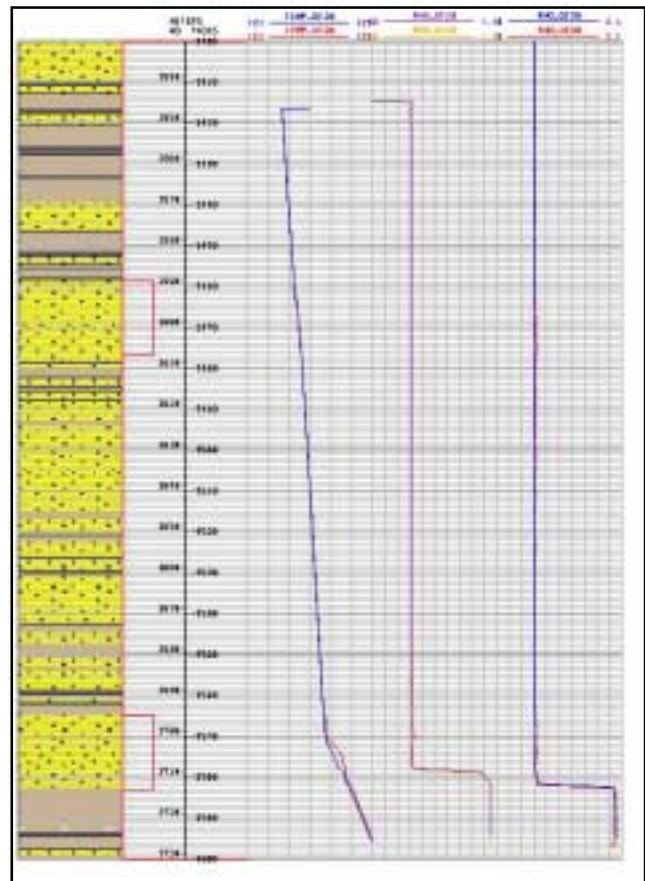


Figure 4: Summary of temperature and gradio data.

During the flowing passes there is also a slight kink at 3702 mAHBKB. This occurs predominantly during the up passes and could be due to fluid being lifted up with the tool (perhaps in the centraliser section which is immediately above the gradiometer), and then getting blown out at the first point of gas entry.

CCL

The CCL tool is normally just used as a correlation tool in conjunction with the gamma ray. In this well however, where there is some uncertainty as to the perforated interval, the CCL was more intensively scrutinised to see whether the actual perforations themselves could be detected. Figure 5 shows all the calibration passes, together with an enlargement of a couple of the runs. Also shown on the plot are two curves, highlighting the flow profile of the well, a cumulative flow curve (solid green fill) and a differentiated flow curve (red line). The Zone A perforations seem to be detectable from the CCL response. There is some uncertainty however, about the location of the Zone B perforations. The initial Zone B perforating job was carried out in three runs, each run consisting of a 6-metre gun length. These three runs are marked individually on Figure 8. The correlation runs that were carried out during perforating operations show both the depth correlation pass and the shot pass for each gun run. There is no hard or digital copy of the final (run #3) shot pass. This makes it difficult to double check that the zone was perforated. Also, the correlation pass for run #3, shown in the log, is over an interval higher than the supposed

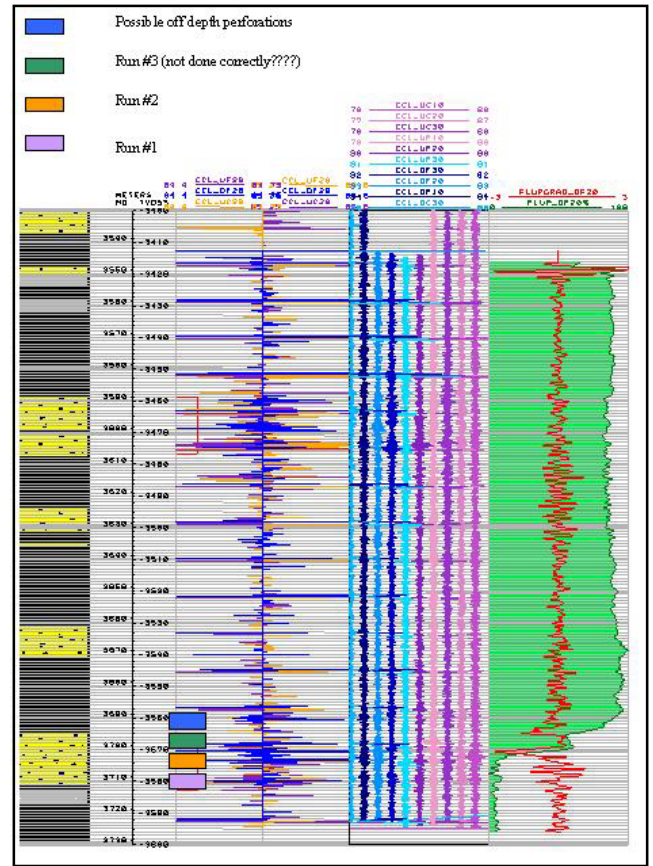


Figure 5: Summary of CCL data with flowing spinner data.

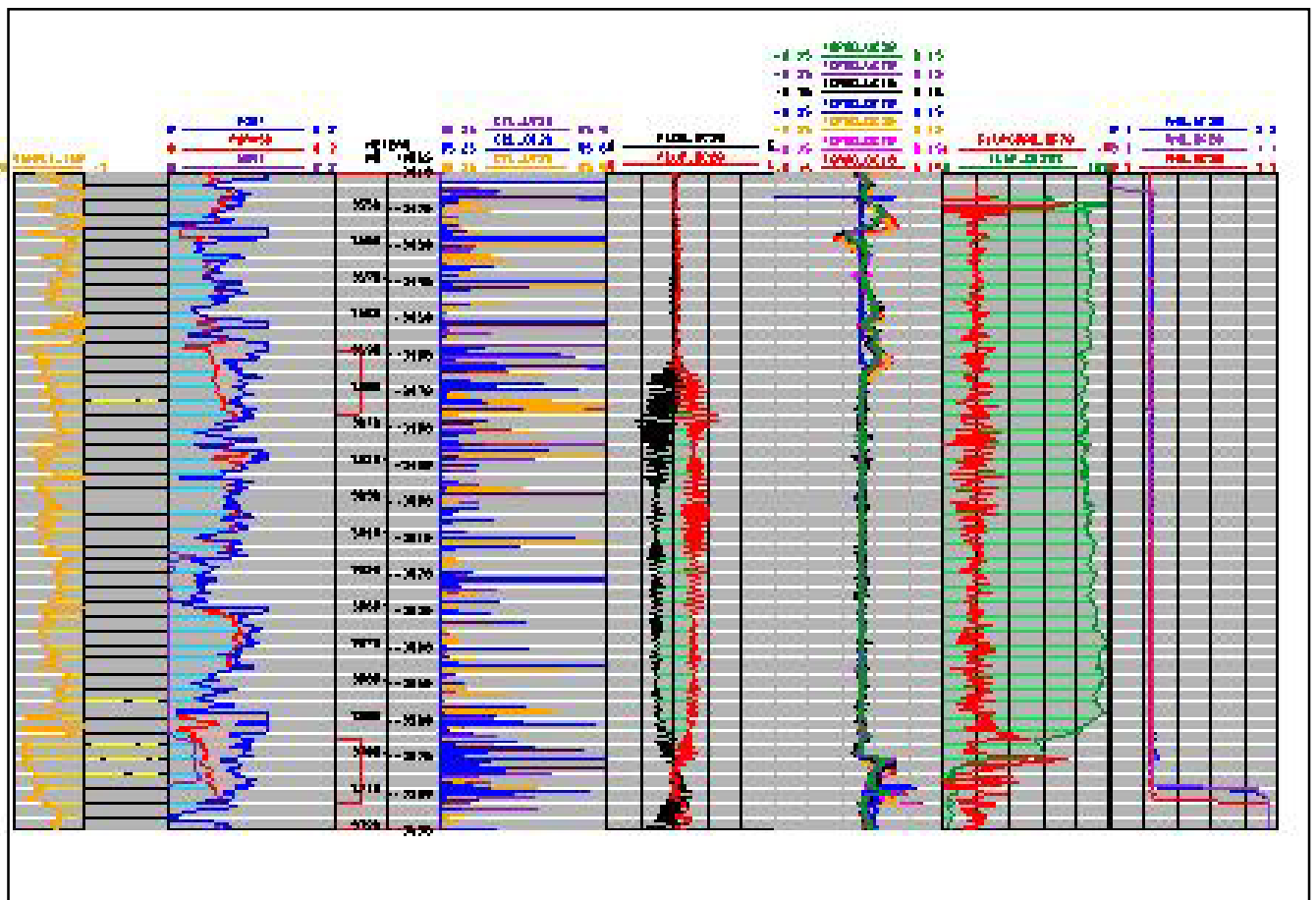


Figure 6: Overall summary of PLT information for Case 1 - First PLT.

perforated interval. This does not instil much confidence that the correct interval was actually perforated on run #3! It is therefore possible that a higher zone (3690 to 3696 mAHBKB) was perforated (and is producing gas).

Interpretation of results

Figure 6 is a summary plot of all the pertinent sensor data.

Zone B

All of the gas flow is coming from Zone B. It appears that a section above the top of Zone B itself may have been perforated. Approximately 4 m of formation is contributing to flow in two distinct sections. The interval from 3701 to 3703 mAHBKB is contributing approximately 65% of the flow and the interval from 3694 to 3696 mAHBKB is contributing the remaining 35%. The water level appears to be at the base of the perforated zone (3714 mAHBKB) but there could be a small amount of water production from the interval 3710 to 3714 mAHBKB. Cross-flow is occurring from Zone B to Zone A when the well is shut-in. How long this cross-flow actually lasts before the pressures are stabilised is unknown.

It is difficult to use the data from the PLT to evaluate the productivity index of Zone B as the reservoir pressure is an unknown. However, using the rock properties calculated from welltest analysis (skin of -4.4 and kh of 270 mDft), the flow rates obtained tie in to the pressure response seen. This would mean that the calculated permeabilities would be 27 mD for the interval from 3701 to 3703 mAHBKB and 14 mD for the interval from 3694 to 3696 mAHBKB.

Zone A

There is no flow coming from Zone A.

During shut-in there is cross-flow occurring from Zone B into Zone A. Approximately five hours after shutting the well in the magnitude of the cross-flow was around 1 mmscf/day signifying a lower reservoir pressure at Zone A. During the flowing passes, Zone A was either at pressure equilibrium, or there was still a small amount of cross-flow occurring. Using the assumption that there was pressure equilibrium during the flowing passes, an estimate of reservoir pressure can be made (ie: flowing bottom hole pressure at the Zone A perforations is equivalent to Zone A reservoir pressure). Using the bottom hole pressure during the shut in passes gives us a minimum delta pressure causing the flow of 1 mmscf/day. The calculated delta pressure is 200 psi giving a kh of 42 mDft (assuming a skin of -4.4, similar to Zone B, as Zone A was fracture stimulated.) The flow appears to be entering a 1-metre interval (3595 mAHBKB) giving a calculated permeability of 13 mD. Coincidentally, the core permeability of a sample taken at this depth is 14 mD, and is the highest permeability seen over the Zone A interval (see Figure 1, CORPRM = core permeability).

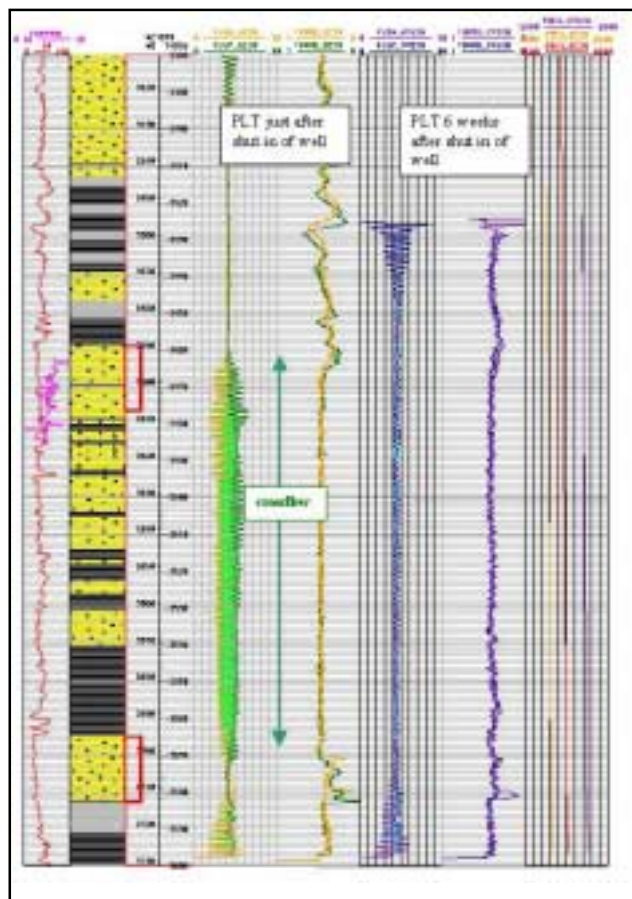


Figure 7: Comparison of first and second PLT spinner and temperature data.

Second PLT after 6 weeks shut-in

Individual sensor responses

Figure 7 shows a comparison of the TGRAD and spinner data for the two PLTs.

Spinner

There is no evidence of cross-flow occurring from the spinner data.

Temperature

The raw temperature data has been differentiated and is also shown on the plot (TGRAD). Unlike the previous log, there is no evidence of cross-flow (constant TGRAD) from the temperature data.

Interpretation of results

Estimate of GIIP

During the initial PLT a cross-flow of approximately 1 mmscf/day was seen entering the Zone A interval. Six weeks later, no cross-flow was detected. Therefore, assuming a constant decline, the maximum amount of gas entering the interval was 21 mmscf. The pressure build-up associated with this amount of gas entering Zone A is 235 psi. Using straight material balance the maximum GIIP is calculated as 0.9 bscf. Data from the initial well test of Zone A had previously estimated the GIIP as 0.45 bscf.

Overall conclusions from both production logs

- Less than 20% of the perforated interval in Zone B is contributing to flow.
- Zone A is not contributing to flow.
- Cross-flow is occurring from Zone B to Zone A when the well is shut-in (and possibly when the well is flowing). Reserves are currently being lost to Zone A unless it can be proved that they can be recovered.
- There may be perforations producing gas above the top of Zone B (in the coal section).
- Zone A has an extremely limited volume (less than 1 bscf).

Case 2

The reservoir interval in well X was perforated, tested and stimulated (with a ballout treatment) during November and December 1998. Pressure and production logging (PLT) information was collected during this time as well as samples of the produced fluids. The following summary details the analysis of the PLT in conjunction with pressure build-up (pbu) welltest analysis in order to gain a better understanding of the well performance.

Production summary

The reservoir interval was perforated with an overbalance of approximately 3000 psi. The reason this occurred was: the well was displaced with nitrogen to create a 4000 psi underbalance (expected reservoir pressure was 7100 psi). The well was then pressured up to activate the delayed TCP firing

and release mechanism. The well was then bled off but the guns failed to fire. The next day the procedure was repeated but the intended pressure of 11000 psi was never reached. It became apparent that the guns had fired without a delay thus resulting in an overbalanced perforating operation.

The well then flowed low volumes of water (approximately 40 bbls/day), thought to be predominantly formation water. A memory pressure/temperature/CCL log run identified a warmer 2 m interval at the base of the perforations, indicating formation water entering the wellbore. The CCL combined with the fluid levels indicated that the whole section had probably been perforated, but the question still remained as to why the uppermost 15 m of perforations do not show flow. Welltest pbu analysis concluded that there was minimal formation damage with a permeability thickness consistent with a 2 m interval of 1mD rock open to flow. Petrophysical analysis using water resistivity obtained from well samples indicated there should be gas production from this zone.

Based on all this information it was decided to carry out a ballout treatment to open up the perforations and obtain gas communication with the reservoir. An injectivity test was carried out prior to the ballout, which confirmed that only a small number of perforations were open. The ballout was carried out, with a total of approximately 600 barrels of liquid pumped into the reservoir. After the ballout treatment the well was flowed for four days. The initial rate was approximately 600 bbls/day with small gas shows however, this declined to a rate of 70 bbls/day with no significant gas being produced. A second (post-ballout) memory pressure/temperature/CCL/flowmeter log was run and the well was shut in for a pbu.

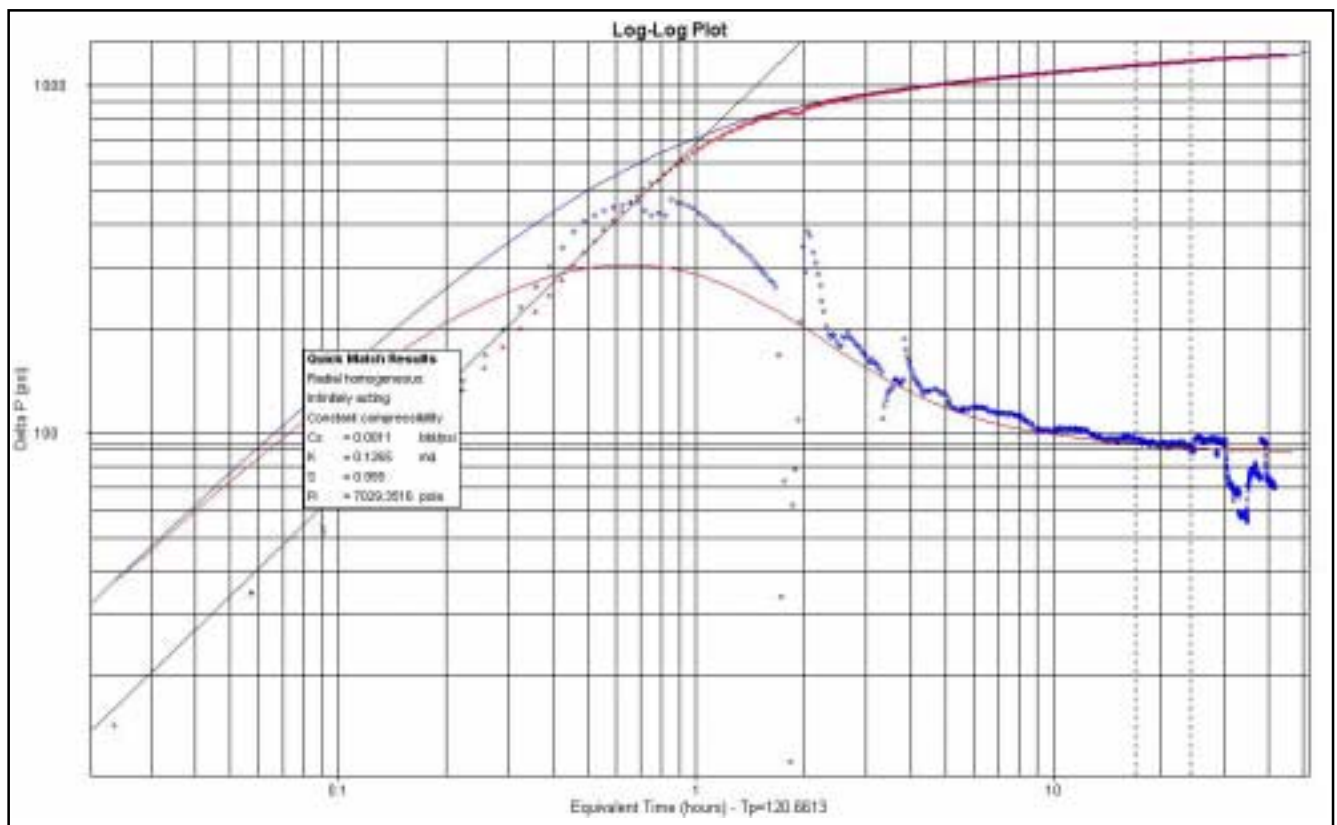


Figure 8: Initial pbu.

The following discussion section details the analysis of the PLT and pbu information.

Discussion

Initial reservoir performance

As stated in the previous section the initial performance of the reservoir interval was poorer than expected with a fairly low water rate and no significant gas being produced. There was some concern as to whether or not the entire section had been perforated due to the unplanned overbalance perforating operation.

Welltest (pbu) analysis

Figure 8 shows the analysis of the build-up assuming a water interval. The total fluid produced was estimated to be 210 barrels of water with a total flowing time of 120 hours, thus giving an average production rate of 42 bbls/day. No significant gas flows were seen and the predominant fluid appeared to be formation water (resistivity readings were taken on an hourly basis).

Although the data isn't perfect, clear flow periods can be detected including the wellbore storage region and radial flow. The interpreted radius of investigation (assuming a 17 m interval) is 75 m. Analysis of the build-up data gives the following results:

kh	7.2 mDft
k (assuming an h of 17 m)	0.1265
S	0.955
Pi	7029 psi (@ gauge depth of 4530 mAHBKB)

This analysis shows that there seems to be little formation damage. The extrapolated pressure ties in with the expected pressure and the permeability is in the right ballpark (average perm from log data was 0.44 mD for the 17 m section).

Production log (PLT) analysis

A memory production log was run incorporating CCL-GR-Pressure-Temperature sensors. The aim of the log was to try

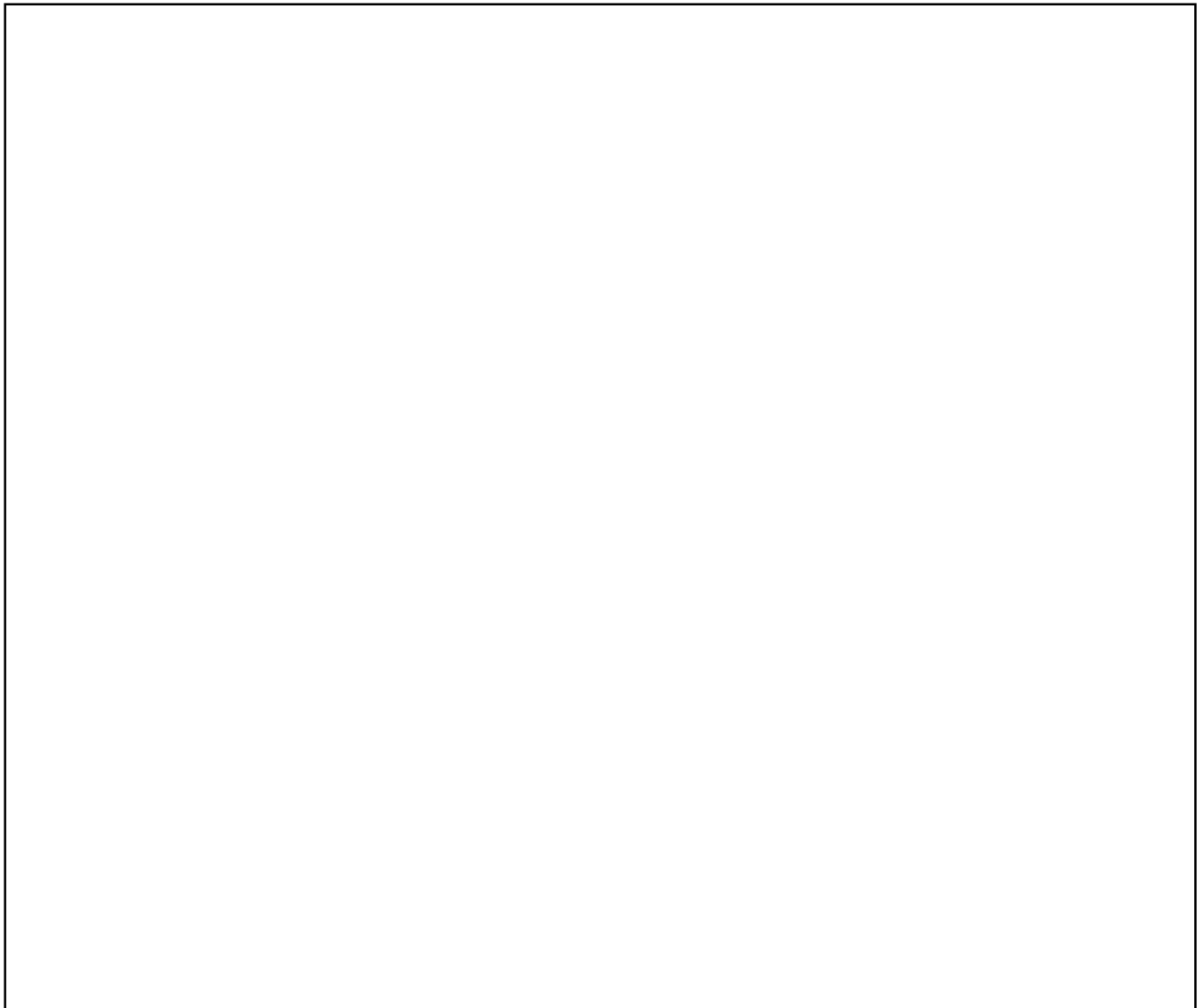


Figure 9: Summary of pre-ballout PLT data.

and determine the position of the perforated interval and see if the actual perforations could be detected after the unsuccessful perforating operations. A total of eight passes were made over from 20 m above to 20 m below the expected perforated interval (should be from 4588-4605 mAHBKB) at speeds of 10, 20, 30 and 45 metres/min in both upward and downward directions. Figure 9 shows a summary of all the sensor information for all eight passes and Figure 10 shows a more detailed look across the perforated interval. The results of the different sensors are detailed below.

Gamma ray

The GR was tied in to a radioactive pip (inserted in one of the liner collar joints) at 4618.8 mAHBKB (see Figure 9). Unfortunately there seems to be a certain amount of stretch in the cable for some of the runs and so caution must be used when looking at individual passes. There is an obvious shift in GR at 4605 mAHBKB which corresponds to the detection of completion brine sitting in the well below the lowest most perforation. This suggests that the perforations are on depth and the lowest section of the guns must have fired.

Temperature

The temperature log (see Figure 10) shows a warm peak at 4605 mAHBKB. As the log was run approximately four days after shutting the well in it can be assumed that this warmer area corresponds to the main source of water influx into the well. The temperature gradient also gives a very pronounced spike at this depth and is reasonably constant over the remaining reservoir section.

Pressure

The pressure profile doesn't alter much over the whole section. However the pressure gradient above 4605 mAHBKB is 1.46 psi/m (equivalent to 8.6 ppg) and below 4605 mAHBKB is 1.81 psi/m (equivalent to 10.6 ppg). These densities tie in with formation fluid sitting on top of completion brine.

CCL

Although not conclusive, the CCL signals for all passes do seem to be stronger across the expected perforated interval.

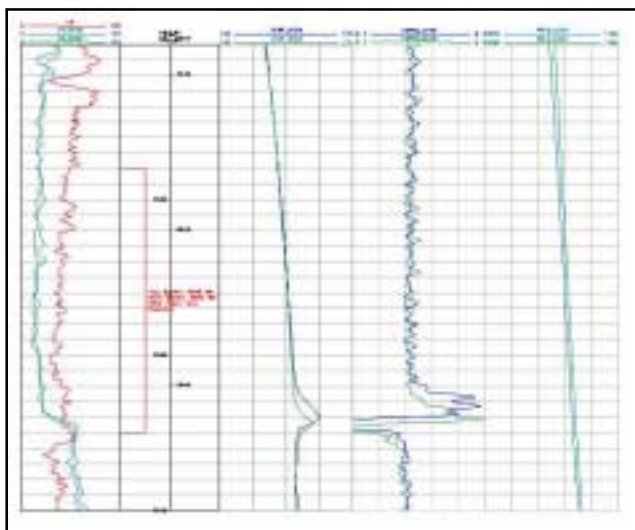


Figure 10: Zoom in over perforated interval (pre-ballout PLT).

Summary of initial well performance

- The well had been perforated in the correct place however there was concern over whether or not all the perforations were open (or plugged up due to overbalance perforating).
- The main fluid influx into the well is formation water (based on produced water resistivity and composition).
- The influx is occurring over a small interval at the base of the perforations.
- There is minimal formation damage (consistent with a small number of perforations open).
- The permeability is in the ballpark (0.1 to 1 mD).
- The reservoir pressure is as expected (around 7100 psi).

Post-ballout reservoir performance

Immediately after the ballout treatment there was a big improvement in flow rate with the water production rate estimated at 45 barrels per hour (equivalent to approximately 1000 bbls/day). However, over a four-day period this rate had reduced to approximately 70 bbls/day with no significant volumes of gas being produced.

Post-ballout PLT analysis

Following the ballout a second memory production log was run incorporating CCL-GR-Pressure-Temperature-flowmeter-radio sensors. The aim of the log was to try and determine if the ballout treatment had been successful in opening up any more perforations. Unfortunately the gradiomanometer tool malfunctioned but a summary of the other sensors for the calibration run (while the well is shut-in) is shown in Figure 11. A summary of the flowing passes can be seen in Figures 12 and 13. The details of the individual sensors are summarised below.

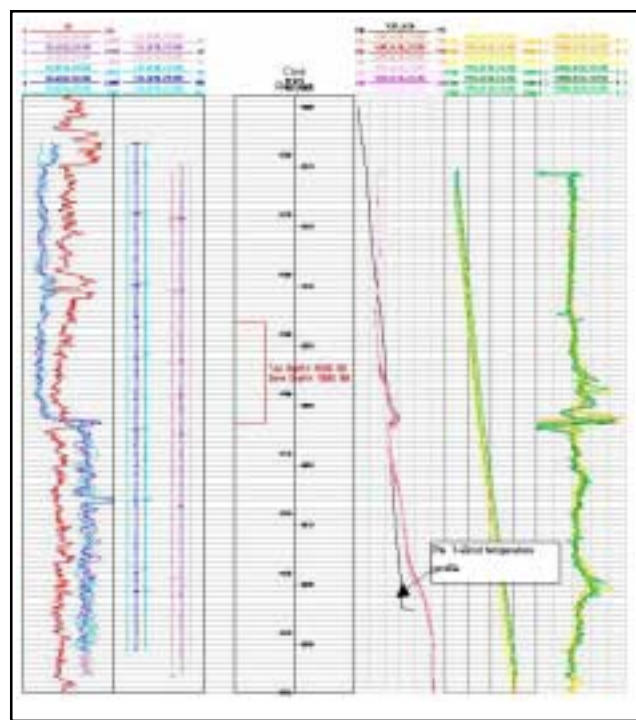


Figure 11: Summary of post-ballout calibration (shut-in) PLT data.

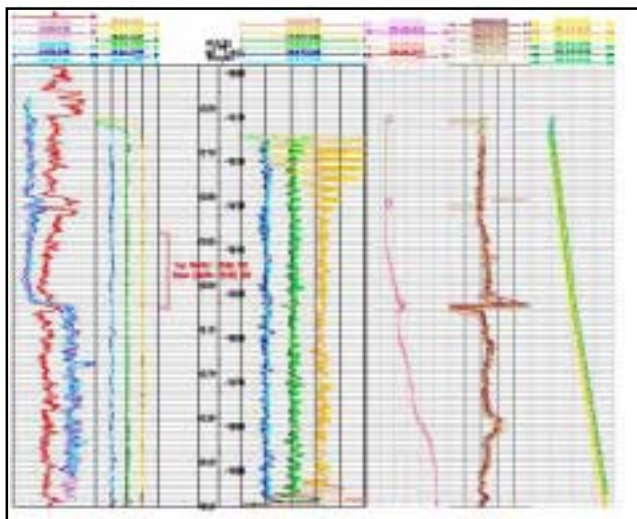


Figure 12: Summary of flowing PLT data.

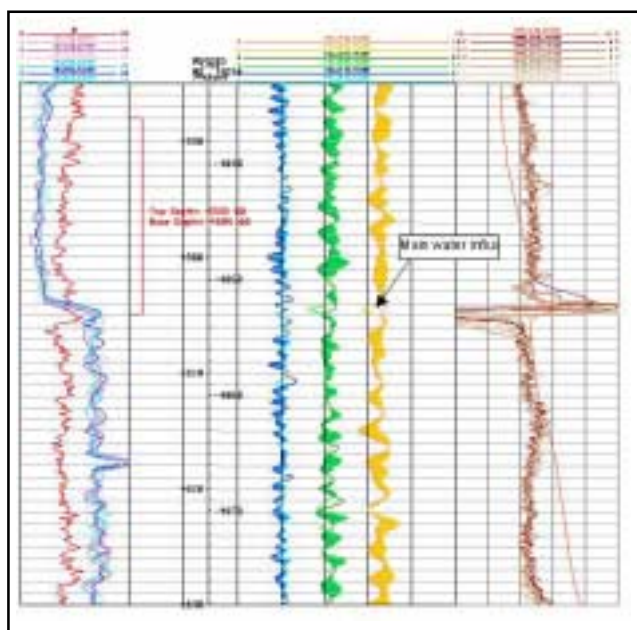


Figure 13: Zoom in of flowing PLT data over perforated interval.

Gamma ray

There is an obvious shift in GR at 4605 mAHBKB, which corresponds to the detection of completion brine sitting in the well below the lowest most perforation. This level has not changed since the previous PLT, which suggests that no movement of fluid has taken place within the sump of the well.

Pressure

The pressure profile doesn't alter much over the whole section. However the pressure gradient above 4605 mAHBKB is 1.42 psi/m (equivalent to 8.3 ppg) and below 4605 mAHBKB is 1.80 psi/m (equivalent to 10.6 ppg). These densities tie in with formation fluid sitting on top of completion brine although the formation fluid has slightly reduced (from 8.6 ppg) and could be a combination of formation fluid and gelled brine (pumped during the ballout job).

Temperature

The temperature log shows a warm peak at 4605 mAHBKB in both the calibration (shut-in) and flowing passes. The

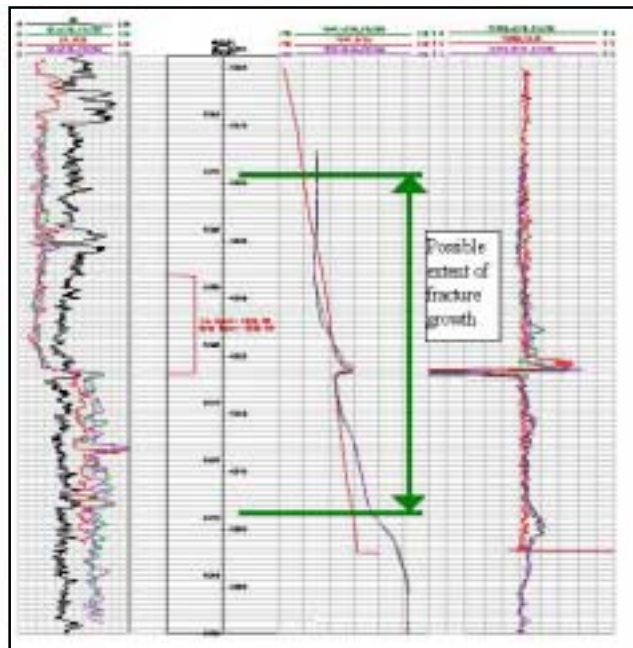


Figure 14: Comparison of pre- and post-ballout treatment temperature logs.

temperature gradient also gives a very pronounced spike at this depth.

Interestingly though, there are subtle changes between the shut-in and flowing passes and they are both very different in overall character to the pre-ballout PLT. Figure 14 plots the three different sets of temperature data.

Whereas the pre-ballout temperature log showed a fairly uniform temperature gradient, apart from the small producing interval at the base of the perforations, the post-ballout temperature profile shows a change in temperature of the formation both above and below the perforated interval.

This can be explained by the following scenario:

- Initially the formation has been cooled, uniformly, by drilling and completion operations.
- Over time the formation heats up and the temperature curve would shift (to the right in this case).
- During the ballout treatment the well is fractured and the cool injection fluid propagates in both directions leaving an altered temperature profile.
- The well starts producing again causing a heating effect from the zone that hot formation water is being produced from.

There are also subtle differences between the post-ballout shut-in and flowing passes as shown in Figure 15.

The interval from 4601 to 4603.5 mAHBKB seems to be hotter during the shut-in passes than the flowing passes. The only reasonable explanation for this is that this zone is being drawn down during production but not contributing much water, and then cross-flow is occurring with hot water entering the zone, once the well is shut-in. The interval from 4588 to 4599 mAHBKB also shows a slightly different signature between

the shut-in and flowing passes indicating possible contributing pay. The dominant flow however is from the interval 4603.5 to 4605 mAHBK. Below the perforated interval the two curves overlay, signifying that there is no flow occurring behind pipe.

Post-ballout pbu analysis

After the PLT had been run the well was shut-in for a pbu survey for two weeks using PANEX quartz gauges. A detailed rate history was input into the Pansystem welltest analysis software in order to obtain a good pressure match.

Figure 16 shows the log-log plot of the pressure data which exhibits a classic stimulated well characteristic. There is also

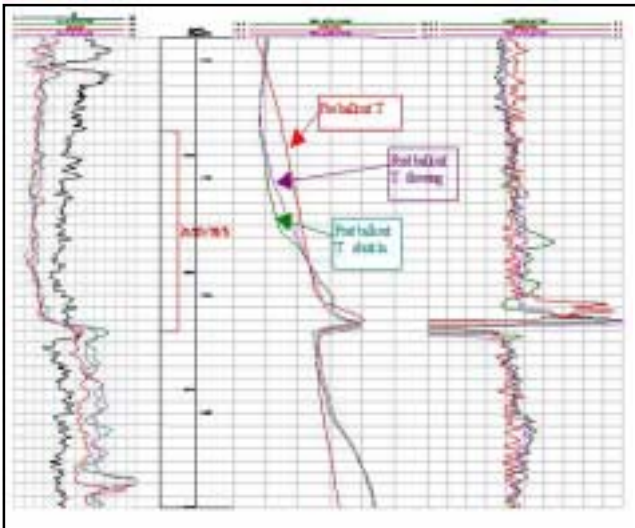


Figure 15: Zoom in of temperature data over perforated interval.

a very clear radial flow period that can be used to determine kh and pseudo radial skin. The well was analysed as a water producer with a total interval of 17 m (59 ft) with a radius of investigation of 125 m.

Analysis of the build-up data gives the following results based on the best fit to the pressure data (see Figures 16 & 17):

kh	5 mDft
k (assuming an h of 17m)	0.08
xf	83 ft
Pi (from semi log)	7114 psi (@ gauge depth of 4545 mAHBK)
Spr	-4.6

Figure 16 shows that there is a small deflection at the very end of the radial flow straight line. If this is a boundary of some sort then it would be encountered at approximately 125 m from the well.

Summary of post-ballout well performance

- The well was fractured during the stimulation treatment with height growth both above and below the perforated interval.
- The main fluid influx into the well is formation water (based on produced water resistivity and composition).
- The influx is mainly occurring over a small interval at the base of the perforations although there is some evidence (mainly from the temperature log) that the rest of the zone is open.

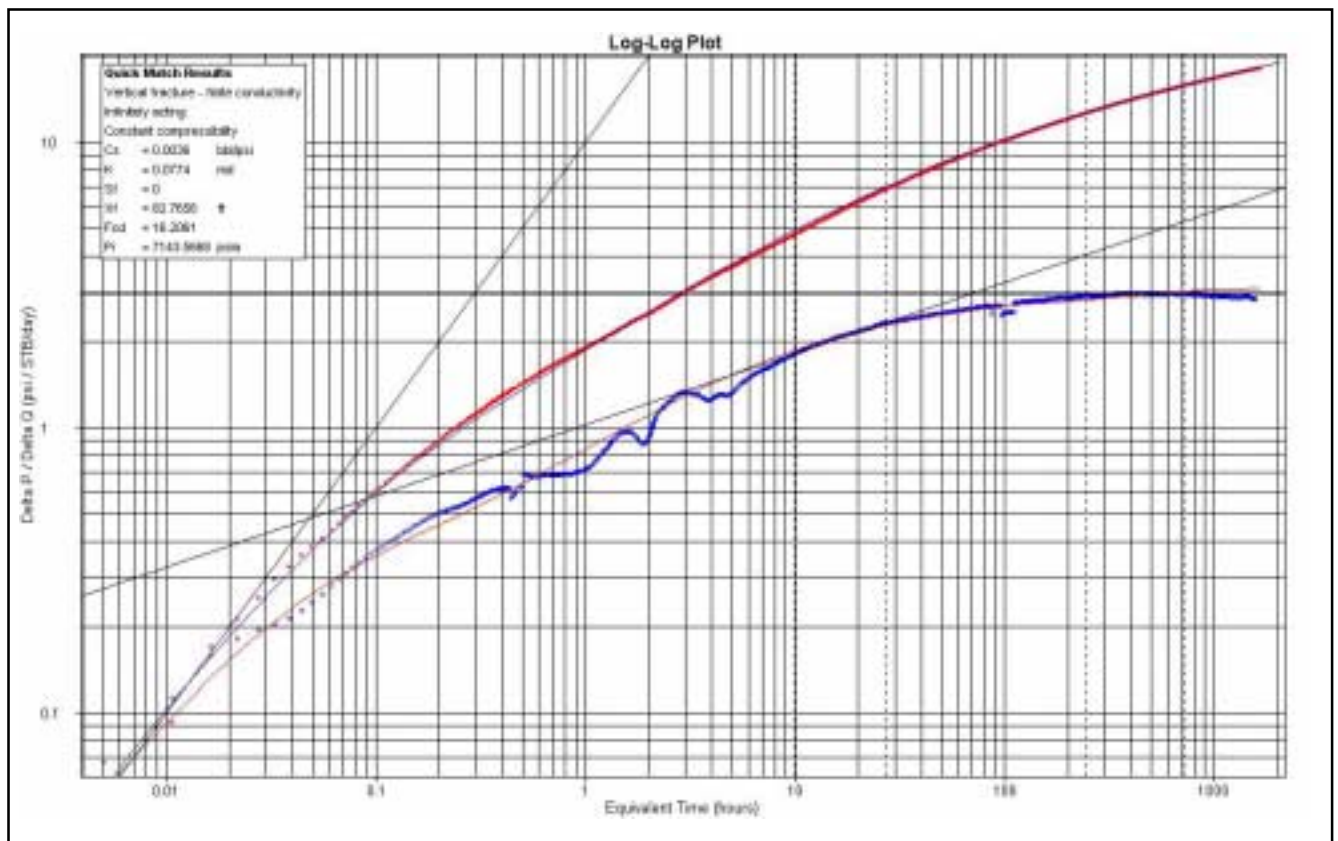


Figure 16: Log-Log plot.

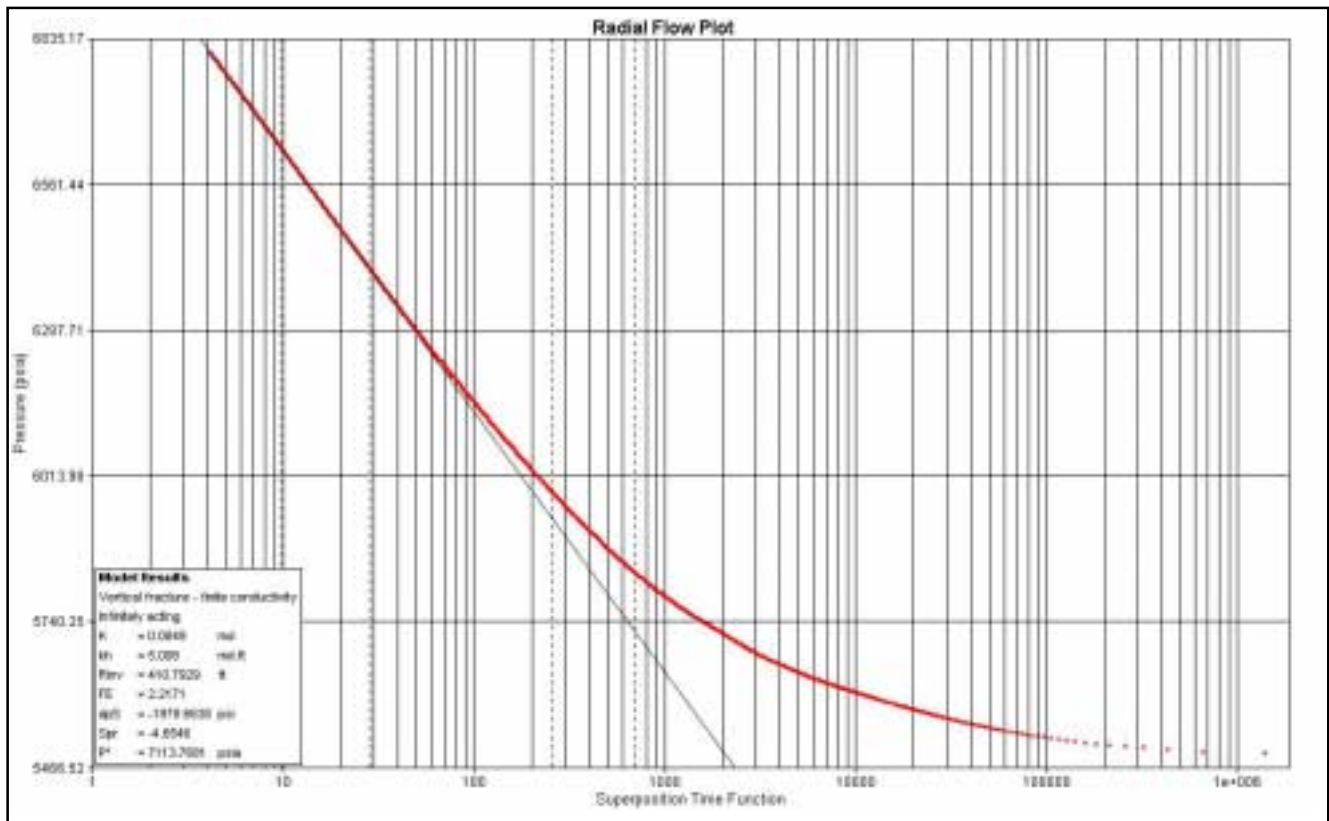


Figure 17: Horner semi-log plot.

- The reservoir pressure has increased slightly (supercharging from the ballout treatment) to 7150 psi. There is no evidence of depletion.

The overall conclusions of the PLT and welltest analysis are as follows:

- The well has been perforated in the correct place (4588 to 4605 mAHBKB).

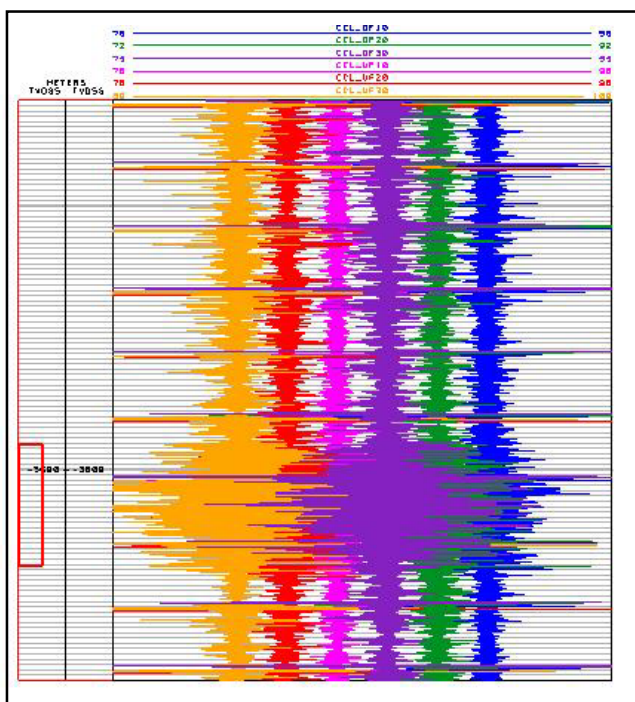


Figure 18: CCL showing position of perforations.

- The ballout treatment established communication with the reservoir and fractured the reservoir zone to a distance of 83 ft from the wellbore. The fracture also extended both above and below the perforations.
- The main fluid influx into the well is formation water (based on produced water resistivity and composition). There is no significant gas production.
- The main influx is occurring over a small interval at the base of the perforations however there is a small contribution from the rest of the zone.
- There is no channelling behind pipe.
- The calculated permeability is consistent with predicted values from log analysis (0.1 to 1 mD).
- The reservoir pressure is as predicted (around 7100 psi). No depletion was seen during the test.

Case 3

Figure 18 shows an example of a CCL log where the perforations are easily identifiable. The guns used for perforating this particular zone were 4.5 inch HSD TCP 51J UJ guns with HMX charges (i.e. big guns with big charges!!)

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