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Where's the Water Coming From? A Combined Formation Saturation, Production Logging, Water Flow, and Leak Detection Diagnosis Deployed on Coiled Tubing

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Abstract

An offshore gas-producing well recently encountered an increase in water production. The well featured multiple completion zones, creating ambiguity and uncertainty in the water source and production zone. Due to the significant deviation of the well, coiled tubing (CT) provided the means of conveyance for an advanced array of well diagnostic tools selected to evaluate the multiple downhole scenarios that may lead to the increase in water production, including completion failures, saturation depletion, and flow from unexpected sources.

This paper discusses the integrated analysis and methodology behind the successful determination of the water source in an offshore gas-producing well. The deployed tools include a multi-detector pulsed-neutron tool (MDPNT), an advanced acoustic array leak detection tool (ALDT), and a suite of production logging tools. The logging suite was tailored to address the wealth of possible scenarios for the increase in water production. Logging was performed in shut-in and flowing environments to understand the behavior of the well in dynamic conditions. Following the acquisition, the data sets were integrated and analyzed, leading to the successful determination of the problem zone.

The well featured two perforated reservoirs, each separated by packers and sliding sleeves. The deeper zone was determined to be water-saturated and should have been isolated by a closed sliding sleeve beneath a packer. MDPNT oxygen activation eliminated the possibility of channeling between the water-producing zone and the gas-producing zone. The packers in the well proved to be intact based on the interpretation of the ALDT acoustic noise data and the count rate reading of the MDPNT. The investigation then focused on the completion string jewelry and involved computing a two-dimensional (2D) radial flow map from beamforming of the ALDT-recorded acoustic noise activity around the wellbore, which revealed a closed sliding sleeve within the water-producing zone was likely leaking and, therefore, ineffective. The saturation results using the MDPNT in sigma mode indicated that the perforated reservoirs contained a low remaining gas saturation. Following the diagnosis, the operator ensured the sliding sleeve was closed reducing water production by more than 50%, resulting in an improved well performance.

Compatibility with CT enabled the advanced suite of pulsed neutron, acoustic noise array, and PL wireline sensors to be deployed in a well with significant deviation. As the water production source was unknown,

many possible scenarios had to be tested. Careful job planning and interpretation of the acquired log data eliminated scenarios and led to the conclusion that the completion integrity was compromised at a sliding sleeve, therefore enabling flow from a water-saturated zone.

Logging Scenario and Data Acquisition

The studied well features deviation up to 63 degrees in the logging interval; this environment can present a challenge when attempting to convey advanced sensors on wireline or slickline without the use of mechanical tractors. The well had an increase in water production, which could be coming from the perforated interval or from other unwanted entry points. Fig. 1 shows the scenario of the well condition which shows possible entry points. Other than the perforations, water could come from leaks at the packer, plug, sliding door, or a tubing breach.

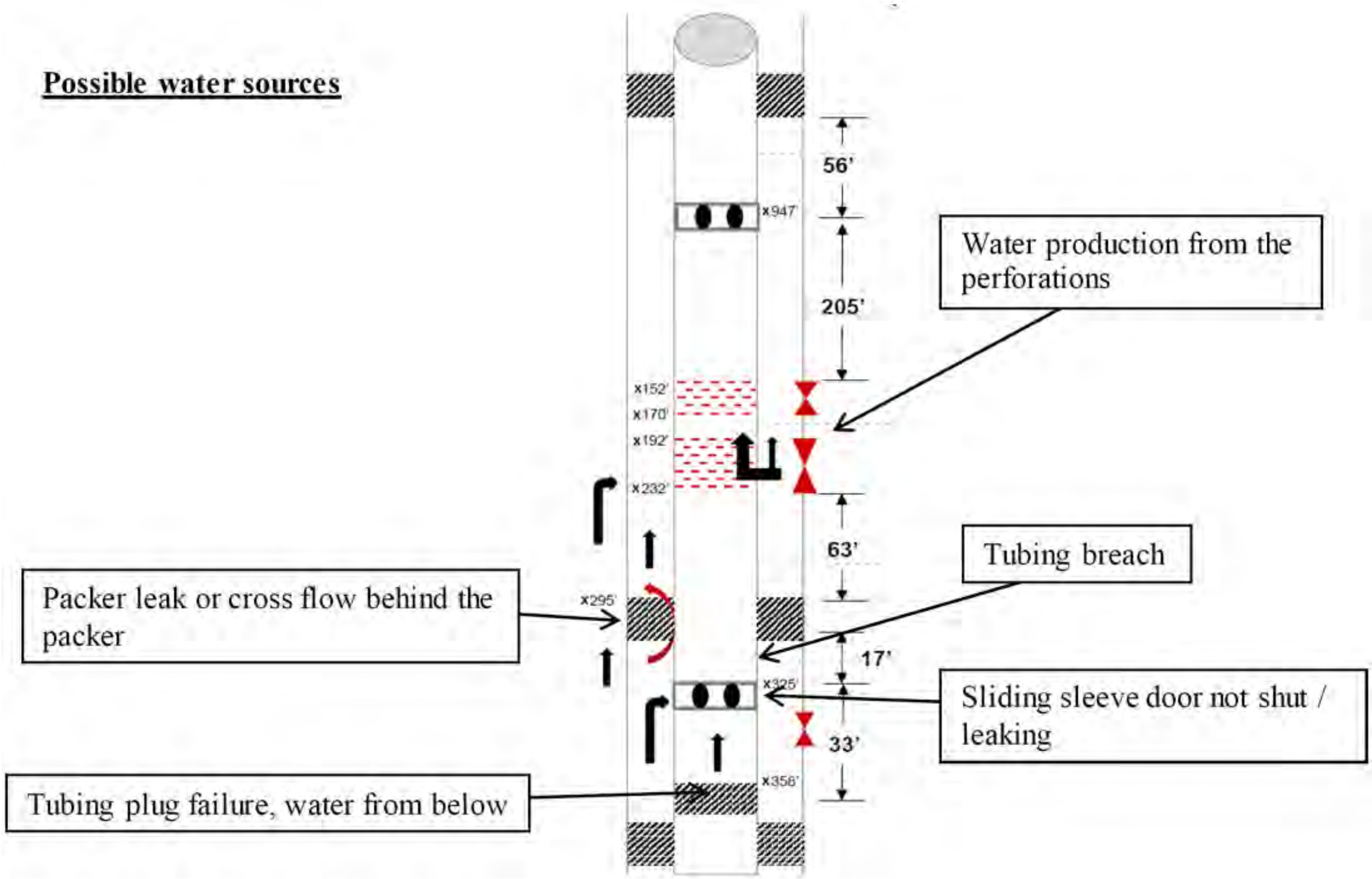


Figure 1—Possible scenario of the water entry points in the studied well

Coiled tubing combined with memory and a battery package was utilized in this scenario to carry the logging tools to the zone of interest and complete the data acquisition runs. Multiple types of sensors were used in the data acquisition, including:

- Conventional production logging tools: temperature, pressure, and capacitance
- Advanced array leak detection tool
- Multi-detector pulsed neutron tool

Data was recorded under two environments – with the well shut in at surface, and then with the well flowing through the production tubing. A combination of moving passes and stationary measurements were performed as part of the data acquisition.

Theory of Operation

Array Leak Detection Tool

Eight sensitive hydrophones arranged in a 28-in. vertical array make up the advanced array leak detection tool. The hydrophones respond to compressional waves generated from acoustic sources in the well such as tubing leaks, jewelry leaks, and flow behind the casing.

Data recorded by the ALDT can be divided into two categories based on the listening time, 5ms and 100ms. The 5ms data is compressed for telemetry and used to provide a real-time result in the field, whereas the 100ms data (uncompressed lossless memory) is recorded to a memory chip and analyzed in the processing center, then can be used for further analysis with improved resolution. This memory data is required for advanced applications, such as determining flow rates and phase types (Lu et al. 2016, Imrie et al. 2019).

The outputs of the tool include the acoustic amplitude (Pascals) for each of the eight hydrophones, a Power Spectral Density (PSD) showing signal power changes with frequency, and a 2D flow map. The 2D flow map uses a beamforming technique unique to the tool whereby the position of the noise source is triangulated radially and vertically by studying the phase shifts of the signal received at each of the eight hydrophones. This is performed using a completion model based on the acoustic and material properties of the well architecture (for example, casing wall thickness and cement density). As illustrated in this case study, it is common that the complexity of sound propagation in the well environment means that using a PSD and amplitude alone for interpretation cannot always precisely indicate the position of the noise source.

Multi-Detector Pulsed Neutron Tool (MDPNT)

A pulsed neutron tool has a mini-particle accelerator that shoots high-energy (14MeV) neutrons that pulse through a specific time interval. The emitted neutron then goes from the tool, through the casing, and through the formation. The neutron interacts with the atoms from the borehole, casing, cement, and then formation. The results from such interaction produce gamma ray particles. The gamma ray read by the detectors consists of background, inelastic, capture, and activation process. Inelastic and capture gamma rays are mainly used to determine formation properties and fluid saturation, while activation gamma rays are used to detect water flow. There are three modes that are generally used in a pulsed neutron tool: i) Carbon-Oxygen mode, ii) capture (sigma) mode, and iii) activation logging.

A Carbon-Oxygen (C/O) mode measures the energy and count rates of the inelastic and capture gamma rays. It then measures several elements based on their specific energy, in particular Carbon, Oxygen, Calcium, and Silica which is well described in a paper published by Eyvazzadeh et. al. (2004). The ratio of Carbon-Oxygen (C/O) and Calcium-Silica (Ca/Si) are used to calculate the oil saturation after some correction has been made for borehole fluids and environments.

Sigma (capture) mode detects gamma rays that were emitted by the neutron capture process and have decaying characteristics. In a pulsed neutron, each cycle started with a neutron burst. Shortly after the end of the neutron burst, the measured gamma ray count rate is mainly affected by the borehole decay. After several hundred microseconds, the formation component becomes the main contributor to the decay and shortly after it will return to the background rate. The result of the capture mode is the decay curve where it shows a plot between gamma ray counts over time (Fig. 2).

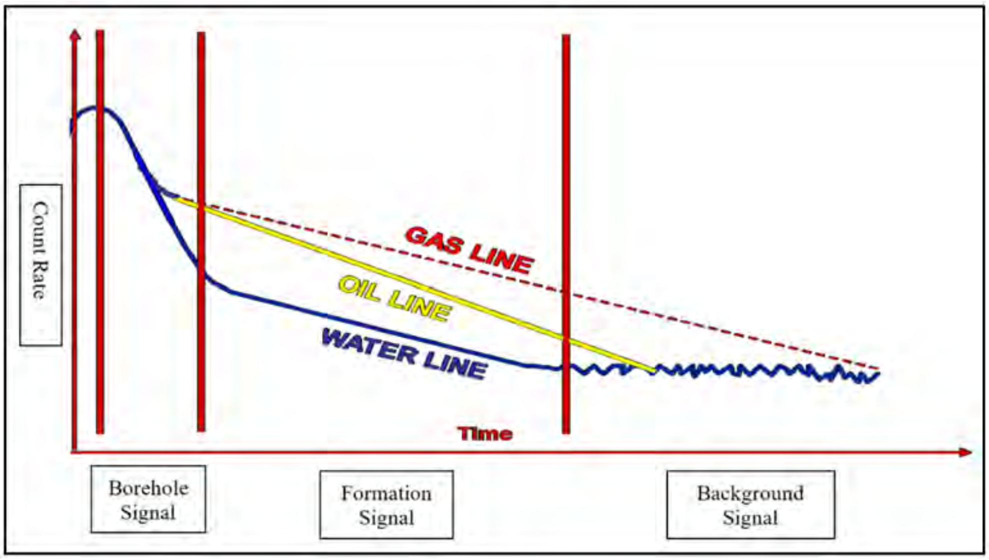


Figure 2—Decay curve showing count rates vs time with different formation fluids

Each element has different capacities to absorb neutrons and will emit different rates of gamma rays (Smith et. al., 1983). These rates of gamma rays are described as sigma (Σ) values, and Fig. 3 shows typical values for common minerals, rocks, and fluids.

TYPICAL Σ VALUES

MINERAL/FLUID	Σ VALUE	MINERAL/FLUID	Σ VALUE
SANDSTONE	4.6	SALT WATER (240 kppm NaCl)	118
LIMESTONE	7.5	OIL	18.2-22 **
DOLOMITE	4.7	GAS	UP TO 14 *
ANHYDRITE	12.6	QUARTZ	4.6
GYPSUM	18.6	CHALK	7.5
FRESH WATER	22	SHALE	20-50
SALT WATER (100 KPPM NaCl)	59	HALITE	761

* THE Σ VALUE IS DEPENDS UPON RESERVOIR PRESSURE, TEMPERATURE, GAS GRAVITY AND CONDENSATE RATIO.

** THE Σ VALUE DEPENDS UPON THE GAS OIL RATIO (GOR).

THE Σ VALUE FOR THE COMMON MINERALS IS SHOWN FOR PURE MATRIX. THE VALUE WILL VARY IN REALITY DEPENDING ON THE FORMATION CONDITION, i.e. TRACE IMPURITIES, CONNATE WATER SALINITY, ETC.

Figure 3—Typical sigma values for common minerals, rocks, and fluids

Sigma values are different between specific elements and minerals which can be used to compute gas saturation. Sigma pass measures the formation intrinsic sigma, which consists of sigma matrix, sigma, sigma shale, sigma water, and sigma hydrocarbon and water saturation can be expressed in Eq. 1 below:

$$\sum_{log} = \sum_{Ma*} V_{Ma} + \sum_{W*} S_{W*}\Phi_e + \sum_{Sh*} V_{Sh} + \sum_{Hc*} S_{Hc*}\Phi e \quad (1)$$

Where:

Σ_{LOG} : Measured formation Σ

Σ_{MA} : Σ matrix

Σ_{SH} : Σ shale

Σ_{HC} : Σ hydrocarbon

Σ_{W} : Σ water

Φ_e : Effective porosity
V_{SH} : Shale volume
S_W : Water saturation

Activation logging measures the gamma rays emitted by activated elements due to absorbance of neutrons. These gamma rays have specific half-life and energies such as 7.35 seconds and 10MeV for oxygen, 2.24 minutes and 1.78 MeV for silica (Simpson, et. al,. 1998). These delayed gamma rays can be used for water flow logging (oxygen activation) and gravel pack evaluation (silica and iron activation).

Water flow logging can be run in continuous mode or stationary mode. In both modes, the tool can only read activation gamma rays from oxygen only if the water is flowing by the generator and then the detector. Hence, the tools need to be configured in such a way to detect the oxygen gamma rays. In continuous logging mode, the water velocity needs to be faster compared to the wireline speed to be detected by the tool. Meanwhile in stationary mode, the speed of the water flow should at least cover the distance between the generator and the detector. The count rate of the gamma rays is equal to the volume of the water passing the generator and then the detector, so this can be used to determine the velocity of the water. The stationary mode consists of generator on and generator off sequence. Oxygen's gamma ray counts are then compared between the two sequences to provide velocity and the accuracy of the measurements.

Multiple passes in shut-in and flowing conditions are recommended to see changes of fluid column in/behind borehole (annulus fluid). Additional data such as temperature, capacitance, and pressure can be used for support in pulsed neutron interpretation.

Unwanted Water Production

In general, especially in the later stage of a well, water will be produced alongside hydrocarbon. As the oil/gas saturation decreases, the relative permeability of water will be increased, therefore more water is being produced. According to Bailey et al. (2000), the unwanted water production is when the produced water-to-oil ratio or WOR exceeds the economic level of the well. In a strong water-drive mechanism, the high water cut is inevitable; unwanted water production is when the water cut exceeds economic value.

Unwanted water production can be related to mechanical aspects of the well integrity (e.g. packer, gas lift mandrel, cement bond channeling etc.) or reservoir aspects of the well (e.g. coning, formation channeling, fractures, etc.) (Fig. 4). Unwanted water production has also proved to be very costly, as it not only reduces the hydrocarbon production, but also is environmentally difficult to dispose of safely. Table 1 contain the estimated cost to dispose of water (Rabiei, 2011).

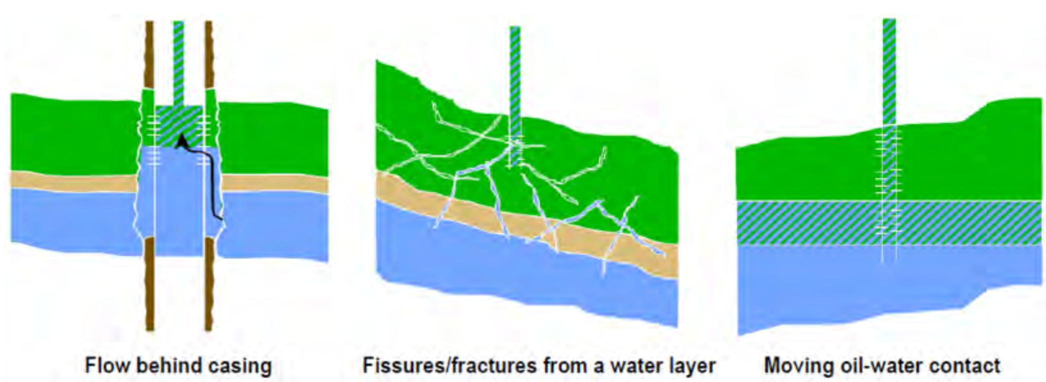


Figure 4—Cause of excessive water production from mechanical/completion-related problems (Elphick and Seright, 1997)

Table 1—Example of estimated cost for water management.Produced water management costs (After Jackson and Myers 2003)

Management Option	Estimated Cost ($/bbl)
Surface discharge	0.01-0.8
Secondary recovery	0.05-1.25
Shallow reinjection	0.1-1.33
Evaporation pits	0.01-0.8
Commercial water hauling	1-5.5
Disposal wells	0.05-2.65
Freeze-thaw evaporation	2.65-5
Evaporation pits and flow lines	1-1.75
Constructed wetlands	0.001-2
Electrodialysis	0.02-0.64
Induced air flotation for de-oiling	0.05
Anoxic/aerobic granular activated carbon	0.083

Results

Array Leak Detection Tool

A moving pass was made at 15 feet per minute over the zone of interest, first in shut in and then again with the well flowing. With the tubing plugged at x356 ft MD and the Sliding Sleeve Door (SSD) at x325 ft MD in the closed position, it was expected that aside from tool conveyance noise, there should be no detectable difference between shut in and flowing passes over this zone because there should be no flow deeper than the packer at x295 ft MD.

Contrary to this, the dataset showed that an increase in acoustic amplitude was apparent when the hydrophones were opposite the supposedly closed SSD at x325 ft MD. The signal observed was in the range of 8 – 15 KHz. As summarized in Fig. 5, there is a clear increase in power when the zone of interest is logged during a flowing environment with around 800 pa^2/Hz observed during flowing compared to less than 100 pa^2/Hz during shut in. This indicates that the SSD could be allowing a flow of fluid into the 3.5-inch tubing and either be in the open position or not properly closed. It is inferred from the acoustic data that during shut-in logging that the leak may still be active at a lesser flow rate than during flowing conditions.

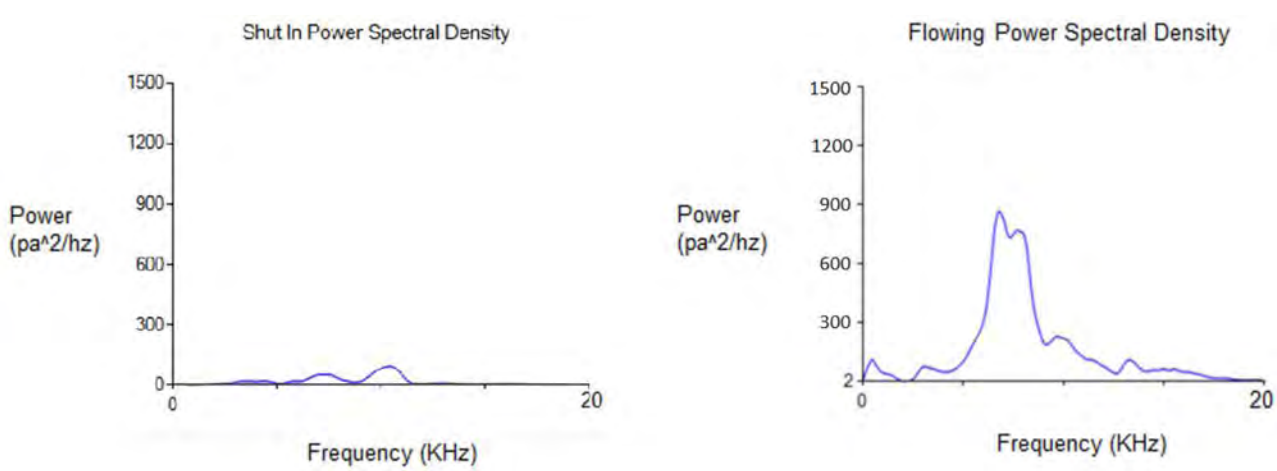
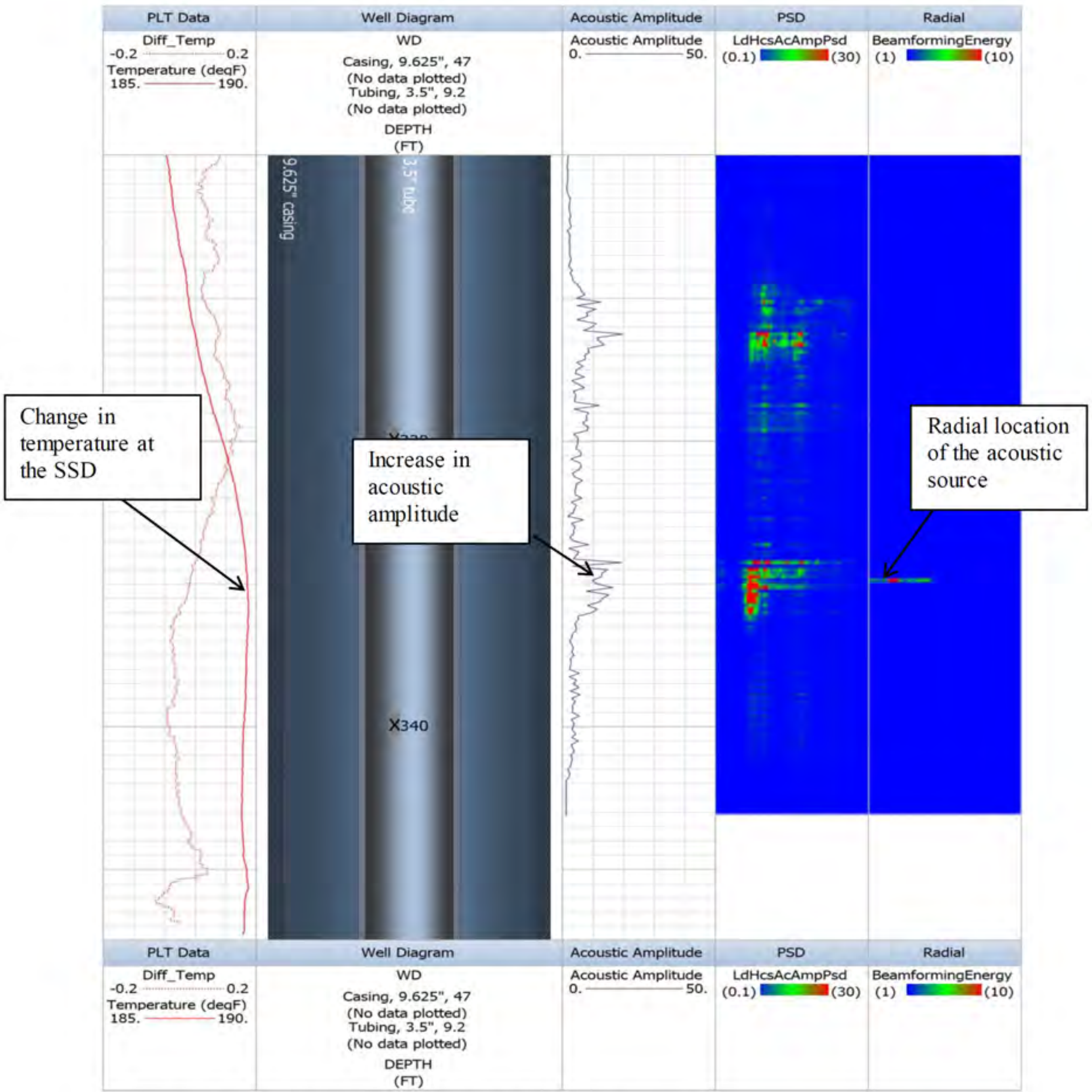


Figure 5—Power Spectral Density (PSD) data extracted from the SSD depth (left – shut-in, right – flowing)

Beamforming processing on the flowing pass data computed the radial position of the noise to be approximately 2 inches from the tool and at a depth x329 ft MD, at part of the SSD (Fig. 6).



- Track 1 – Temperature profile recorded during flowing conditons.
- Track 2 – Well diagram showing the logging environment (3.5-in. tubing inside 9.625-in. casing)
- Track 3 – Acoustic Amplitude (Pa)
- Track 4 – Power Spectral Density image 100 Hz to 30 KHz (bandpass filtered to remove road noise)
- Track 5 – Radial location image showing 1-in. to 10-in. from the tool. Indicating a focus of energy at circa 2-in. from the tool.

Figure 6—Processed ALDT log across the SSD zone of interest

Reservoir Saturation

Sigma mode was used during this acquisition. The field product of the sigma mode is sigma formation, which in diffusion is corrected formation sigma (SGFF). The final product of the sigma mode is sigma intrinsic (SGIN), which can be used to calculate reservoir fluids of the formation porosity, lithology, and shale volume. Formation porosity data uses open hole density and neutron. Supporting lithology information was used and shale volume was computed using open hole gamma ray data. Besides the sigma, there are several curves that can be used to determine formation liquid, especialy gas. The count rates from the near (NCAP) detector and the far (FCAP) detector would show crossover after they are stacked between each other in a shale or water-bearing formation. Additionally, the ratio of capture gamma ray counts from the near and far detectors (RNF) and the ratio of inelastic gamma ray counts (RIN) can also be used as pseudo open hole density and neutron. The inelastic count rates from the far detector (FSIN) is a curve that is sensitive to the changes in borehole fluids. The values of these curves can be used relatively to determine whether the fluid in the borehole is gas, oil, or water.

Two sigma passes (main and repeat) were performed in memory mode for repeatability purposes. Fig. 7 shows that the two passes show very good repeatability and interpretation of the borehole fluids were also included to justify the changes in the count rates. Above the packer, the fluid in the annulus between the tubing and the casing is filled with water, meanwhile below the packer down to the SSD, the annulus is filled with gas.

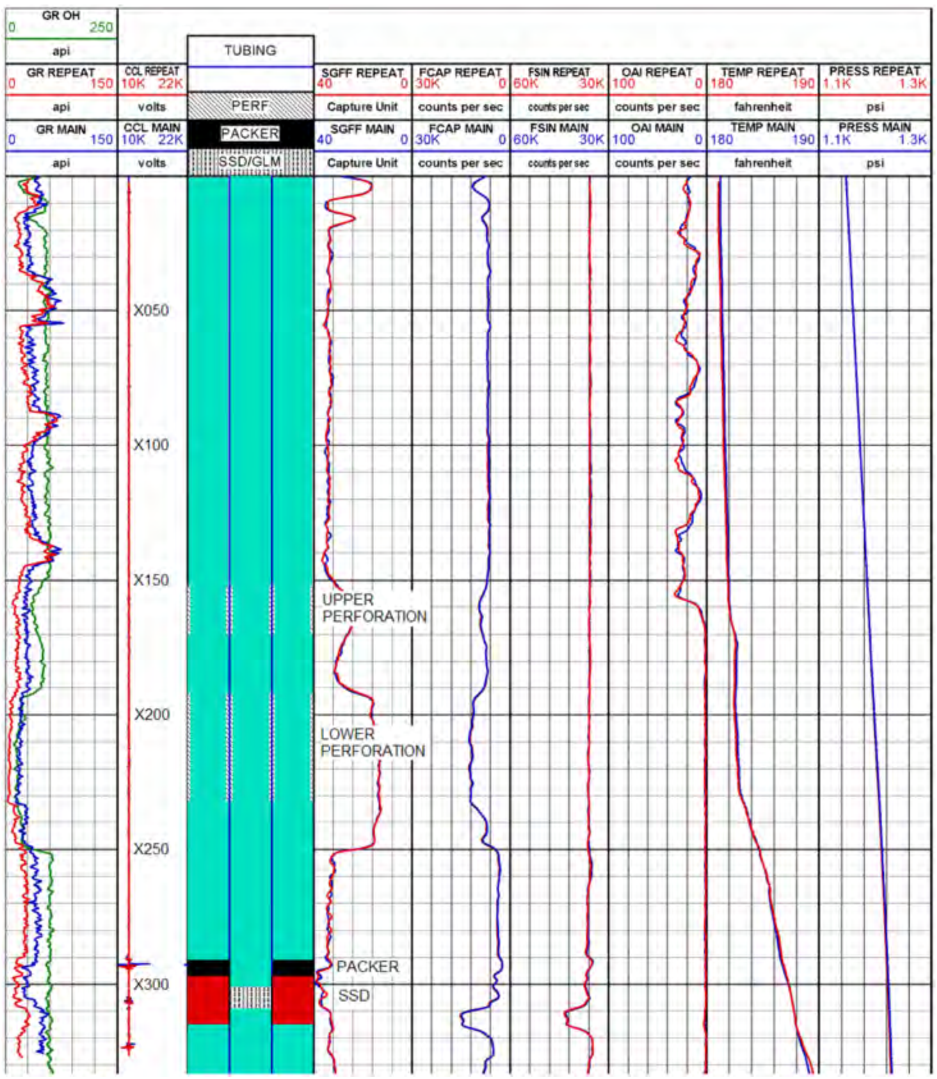


Figure 7—Repeatibility of the pulsed neutron data along with borehole fluids interpretation

The sigma saturation results show that there is approximately 10% gas saturation at the top perforation and 25% of gas saturation at the bottom perforation. The gas saturation also can be seen from the FCAP-NCAP and RIN-RNF crossovers. The saturation plots are shown in Fig. 8.

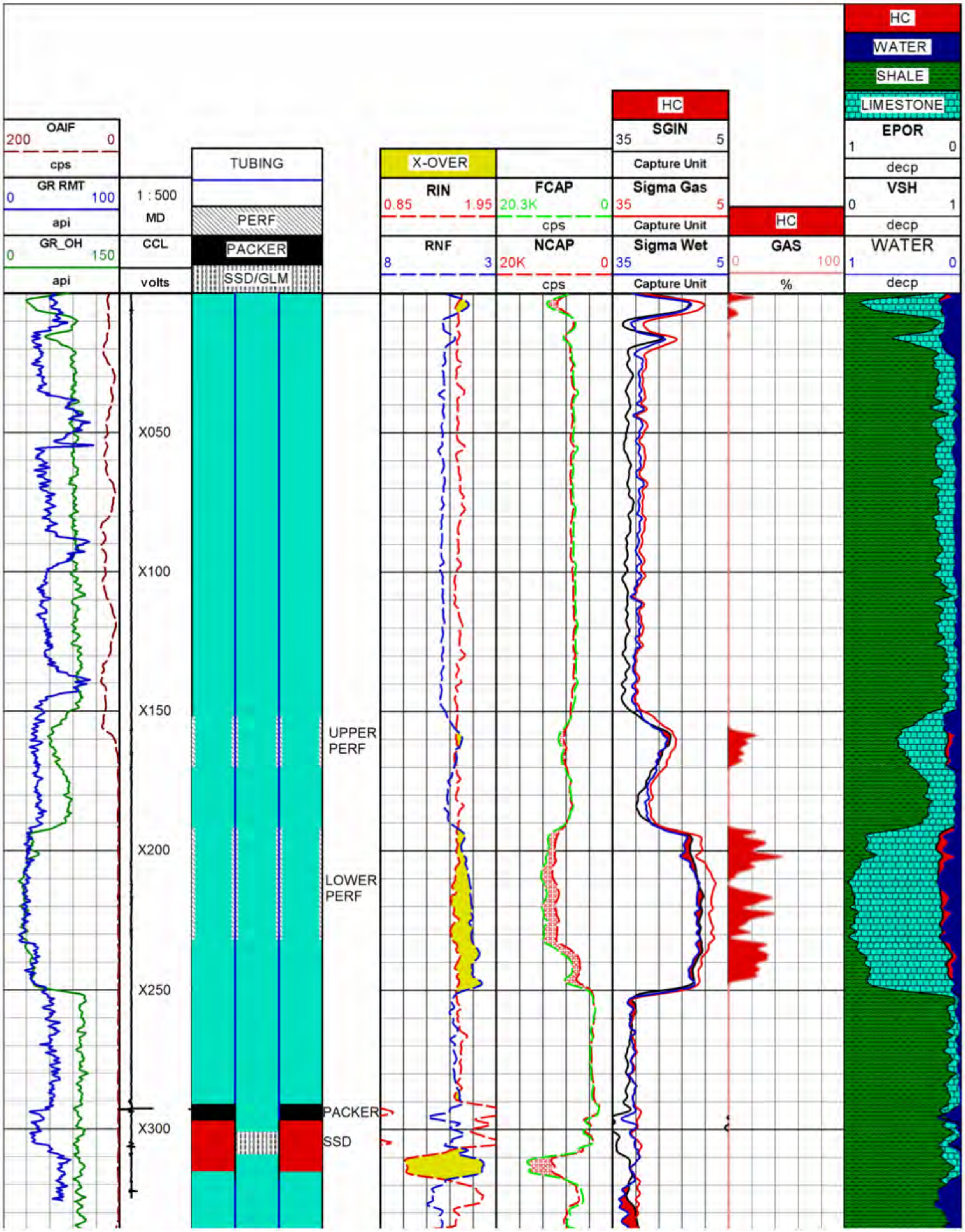


Figure 8—Saturation result using the sigma iIntrinsic value from the pulsed neutron tool

Water Flow-Logging

Oxygen activation logging was done in continous and stationary modes. The stationary mode was done in conjunction with the sigma mode and produced the oxygen activation (OAI) curve which can be used to determine whether there is any water movement upwards. Stationary measurements were performed to determine fluid velocity of the water.

As discussed, inelastic count rates from the far detector (FSIN) can be used relatively to determine the fluid in the borehole because of its sensitivity to fluid changes. Combined with the production logging data such as capacitance, temperature, and pressure, water flow-logging and count rates can provide good insight on the borehole dynamics.

Fig. 9 shows the flowing and shut-in passes. In general, it can be concluded that the SD is leaking, and the packer is intact. There are several differences seen from the log:

1. SGFF shows small changes from X010 to X150 because of the gas inside the borehole.
2. FSIN shows that from X150 upward, the fluid inside the tubing and casing changed between water in shut-in and gas while flowing. From X150 downward, the change in counts are smaller, because the borehole fluids are mixed between water and gas. Below the packer at X290, there is a high count rate, suggesting that there is gas below the packer and showing that the packer is intact.
3. OAI does not show any changes from the bottom up to the bottom of the lower perforation from both shut-in and flowing. This is because of slow water movement and the water cannot reach the detector before all the activated oxygen decays. While on shut-in, there are no OAI until the top of the upper perforation, suggesting that there is water movement from there upward.
4. Temperature shows fluid movement throughout the interval during flowing from bottom to top. During shut-in, the flow was seen from the lower perforation to the top of the interval.
5. Pressure shows a drop because of the flowing of the well.
6. The capacitance measurement while shut-in shows the tubing is filled with water. While in flowing, it shows changing fluid inside the tubing from gas and water. This could be a sign that there is slug movement between the fluids

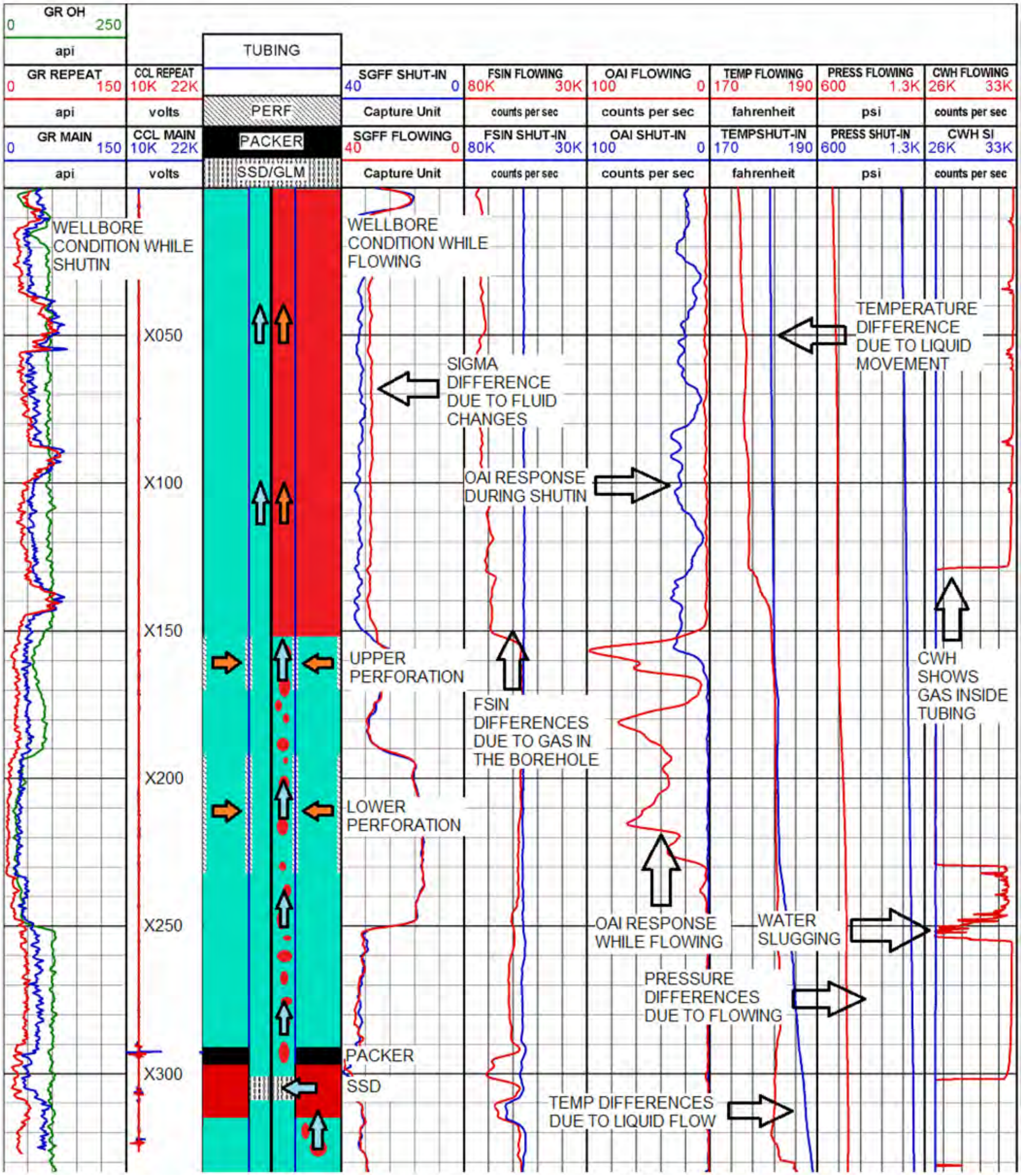


Figure 9—Borehole condition plot with pulsed neutron and production logging data

Conclusion

An integrated interpretation of multiple independent measurements revealed an anomaly at the deeper SD, suggesting that its integrity was compromised and was a likely source of water flowing into the system. A change in temperature gradient was seen opposite the SSD along with a signal detected by the ALDT in the range of 8 to 12 KHz. The fact that acoustic amplitude was seen to increase upon application of leak stimulation gave confidence to the result.

The pulsed neutron runs prove that the packer is intact as seen from the gas below the packer. The leaking SSD was also proven by the gas inside the tubing while flowing the well and the temperature tool showing fluid movement. The sigma saturation computation shows approximately 10% gas saturation in the upper perforation and 25% gas saturation in the lower perforation. Both perforations still have some gas but it can also contribute to water production.

Following logging, the operator performed an operation to ensure the deep SSD was properly closed. This resulted in a reduction in water production at surface and demonstrated the value of the use of the technology discussed in this paper.

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