Chair of Drilling and Completion Engineering

Master's Thesis

Design of a quality control system for logging while drilling data in horizontal wells

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May 2019

Dedicated to my mother

AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

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Abstract

It is quite common for logging while drilling (LWD) tools to be unstable and the acquired data to be of poor quality. This is why quality control of LWD data is of utmost importance. Common methods of quality control for wireline logs in vertical wells often do not show good results in horizontal wells because of vertical and horizontal heterogeneity of reservoir rocks. A quality control system and the ways to control the quality of common LWD methods are discussed in the thesis.

Two approaches to control the quality of LWD methods are considered in the thesis. One of them is cross-plot analysis and comparison of obtained logs with offset wells and core data. The other is solution of direct and inverse problem from obtained well logs. The methods are compared to a typical way of histogram analysis and normalization. Examples of poor and good quality logs are analyzed in detail. In addition, problems, which could be encountered if proper quality control is not used, are discussed.

The result of the thesis is a quality control system for processed LWD data in horizontal wells. The approach was tested in various lithological conditions: siliciclastic, salinated and carbonate reservoirs. The proposed system could be used to avoid poor decision-making during the process of geosteering and well completion.

Zusammenfassung

Es ist durchaus üblich, dass die Logging While Drilling (LWD) Werkzeuge instabil und die erfassten Daten von schlechter Qualität sind. Deshalb ist die Qualitätskontrolle von LWD-Daten von größter Bedeutung. Allgemeine Methoden zur Qualitätskontrolle von Wireline Logs bei vertikalen Bohrlöchern zeigen, aufgrund der vertikalen und horizontalen Heterogenität von Speichergesteinen, oft keine guten Ergebnisse bei horizontalen Bohrlöchern.

Ein Qualitätskontrollsystem und die Wege zur Kontrolle der Qualität der gemeinsamen LWD-Methoden werden in der Dissertation diskutiert. Zwei Methoden zur Kontrolle der Qualität von LWD-Methoden werden in dieser Arbeit betrachtet. Eine davon ist die Cross-Plot-Analyse und der Vergleich der erhaltenen Logs mit Offset-Bohrlöchern und Kerndaten. Die andere ist die Lösung des direkten und inversen Problems aus den erhaltenen Bohrlochlogs. Die Methoden werden mit einem typischen Ansatz zur Histogrammanalyse und Normalisierung verglichen. Beispiele für Logs von schlechter und guter Qualität werden im Detail analysiert. Zusätzlich werden Probleme besprochen, die auftreten können, wenn man keine richtige Qualitätskontrolle durchführt.

Das Ergebnis der Arbeit ist ein Qualitätskontrollsystem für verarbeitete LWD-Daten bei horizontalen Bohrlöchern. Die Methode wurde bei siliziklastischen, salzhaltigen und Karbonatspeichern unter verschiedenen lithologischen Bedingungen getestet.

Das vorgeschlagene System kann dazu verwendet werden, eine schlechte Entscheidungsfindung bei Geonavigation und Bohrlochkomplettierung zu vermeiden.

Contents

Chapter 1 Introduction

1.1 Relevance

The percentage of horizontal wells in production drilling has raised in the past decade worldwide, including Russia (Figure 1).

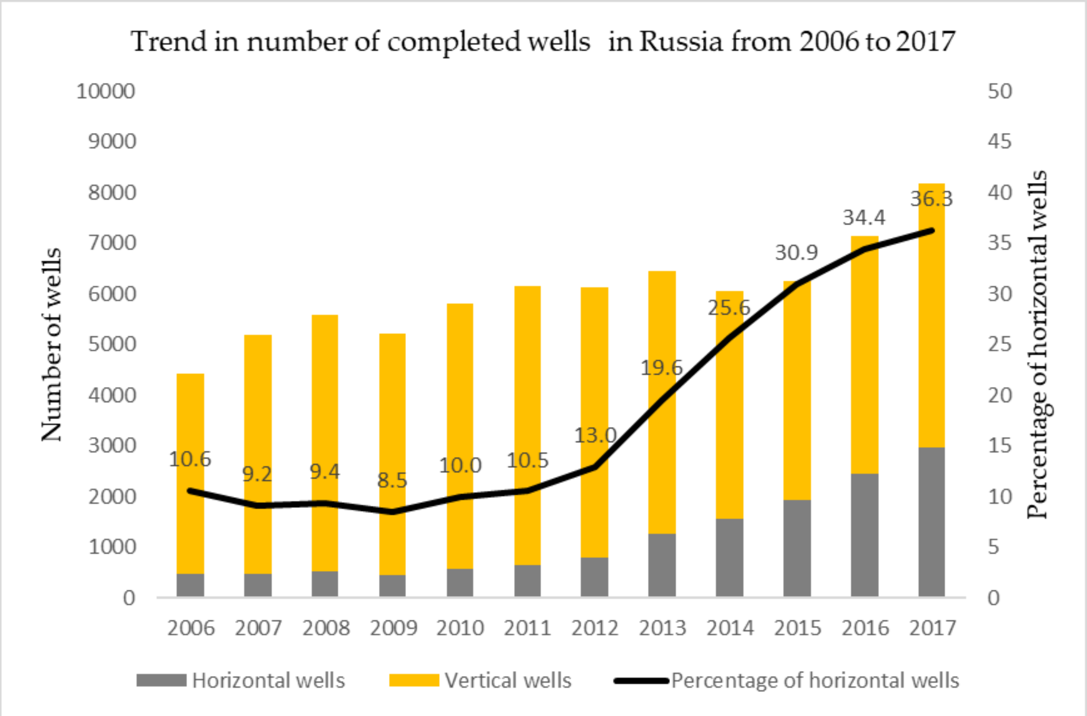


Figure 1. Trend in a number of completed wells in Russia from 2006 to 2017. (modified after V. Kravec 2018)

From the Figure 1 it is seen that in the past 10 years percentage of horizontal wells in production rose from 10.6 to 36.3 percent. The advantages of horizontal wells include:

- Reduction of water and gas coning.
- Greater wellbore length exposure to the pay zone.
- Increase in production rate with lower pressure drawdown.
- Reduction in sand production.
- Increased overall reserves recovery.

Unfortunately, most of these wells are drilled in complex geological conditions, where correct well placement in the reservoir plays the most significant role. The process of geosteering mainly relies on the logging while drilling (LWD) data, obtained in real-time. It is quite common for LWD tools to be unstable and the acquired data to be of poor quality. Existing LWD tools process data automatically downhole and do not transmit raw logs in real time, because of the limitations in the volume of information, which can be transferred through a communication link. Moreover, it is quite common for service companies not to provide raw logs even after the data from tool memory is extracted. So, most of the time geosteering engineers and petrophysicists have to assess the quality of logs in physical properties of rocks (e.g. neutron porosity, density, resistivity, gamma ray activity, etc.) and not the real tools response to the environment in counts of radiation detectors and potential differences (these data is always recorded in raw logs). The fact that common methods of quality control of physical properties, obtained from wireline logging in most cases are not applicable, adds complexity to the problem. This is the case because of vertical and horizontal heterogeneity of reservoir rocks.

Ignoring the quality control of LWD methods from the side of oil and gas producing companies could lead to various problems:

- The most crucial is incorrect calculation of porosity and permeability, and thus, incorrect assessment of the estimated flowrate of a well before completion.
- This leads to non-optimum completion (wrong placement of frac ports, problems in calculation of excess cement volume, etc.).
- Physical properties, obtained from LWD data could be later used in geomechanics for calculation of rocks elastic properties and stresses around the wellbore. If the input data is of poor quality, 1D geomechanical models will not be able to predict wellbore failures correctly.
- Non-centralized wellbore imaging tools deliver images, which cannot be used to determine dip angles of formations.

In general, ill-conditioned logging while drilling data lead to incorrect decision during the process of geosteering, especially when physical properties are slightly overestimated or underestimated and without special techniques it is hard to tell whether there is something wrong with the data.

Keeping all of the above-mentioned challenges in mind, a quality control system for the most widespread LWD methods in horizontal wells should be designed. This thesis is devoted to finding a solution to the presented problem.

1.2 Statistics

In the process of working on the thesis, LWD data from 300 wells drilled in 11 different formations (siliciclastic, salinated and carbonate reservoir rocks) were analyzed. Four international service companies with five different models of LWD tools recorded the logs. The approaches for the quality assessment of each LWD method are presented later in the thesis. The results of the analysis are presented in Figures 2 through 7.

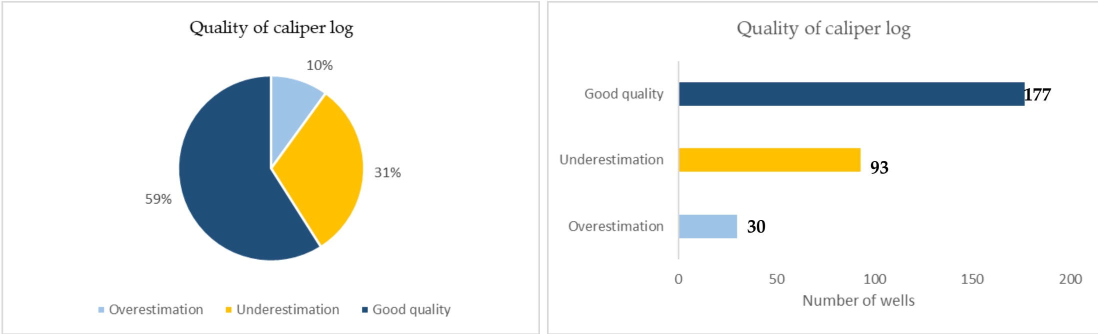


Figure 2. Quality of caliper log.

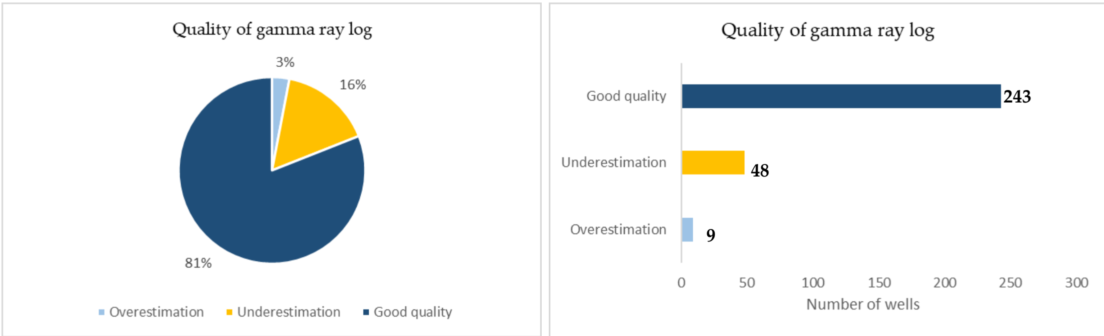


Figure 3. Quality of gamma ray.

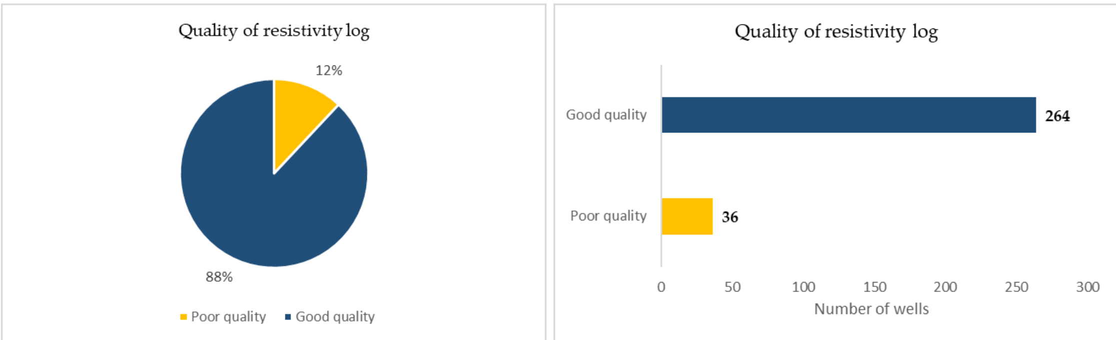


Figure 4. Quality of resistivity log.

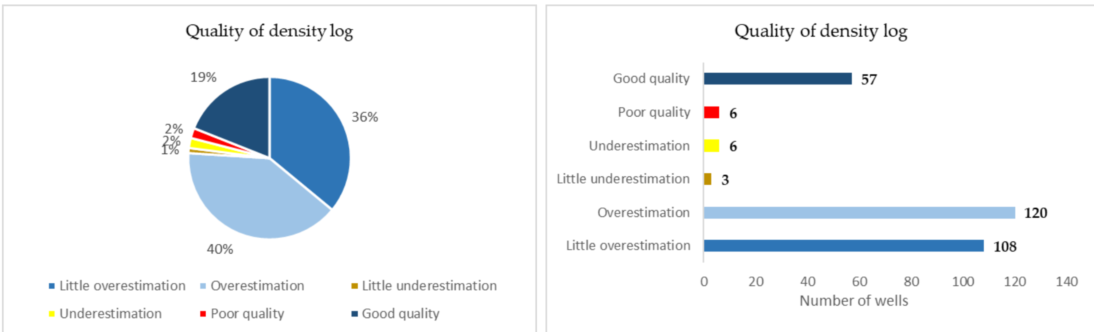


Figure 5. Quality of density log.

Figure 6. Quality of neutron log.

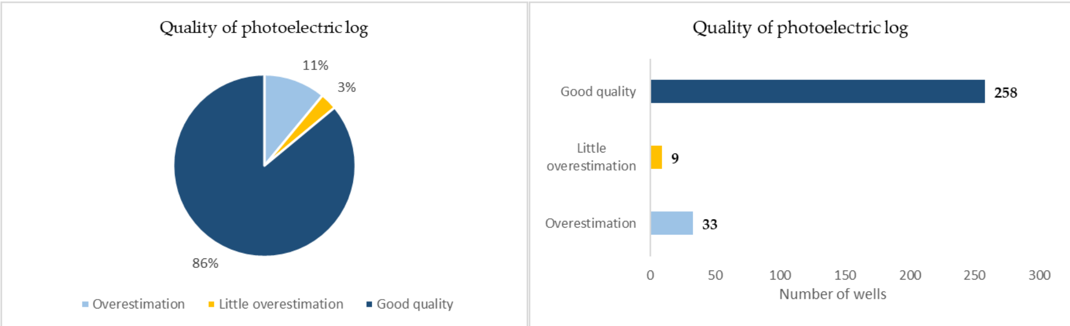


Figure 7. Quality of photoelectric log

From the conducted analysis the following conclusion are reached:

- The most common problem with caliper log is an underestimation of the wellbore diameter, which lead to false corrections to other methods, which are affected by the wellbore diameter mostly (density, neutron and photoelectric logs).
- Gamma ray log in 81% of cases shows good quality, but in 16% of the wells it was underestimated, which led to overestimation of porosity, if no other logs to estimate the porosity were available. A way to avoid that is to normalize the gamma ray log to values from zero to one, but in horizontal wells in most cases it is difficult to do so, because the shales and clean water bearing formations are not drilled through in horizontal sections of wells.
- One or more of the sondes in resistivity log in 12% of cases did not work properly, which lead to challenges in detecting the approach to contrast interface between rocks with high difference in resistivity (e.g. shale – oil bearing reservoir, shale – tight layer).
- In density log if the density was overestimated of underestimated by less than 0.1 g/cc the overestimation or underestimation was taken to be little. Nevertheless, even little inaccuracies in density lead to big mistakes in determination of porosity, especially if neutron log is also inaccurate.

In most cases density log is either overestimated by more than 0.1 g/cc (40% of wells) or overestimated by less than 0.1 g/cc (36% of wells), which lead to underestimation of porosity and permeability. In 2% of wells, quantitative analysis of a density log was not possible, which is labeled as “poor quality”.

- In case of neutron log, if neutron porosity was off by less than 3%, the overestimation or underestimation was taken to be little. In 48% of the wells neutron log was overestimated, which lead to overestimation of porosity and permeability. In 2% of wells neutron log could not be used for quantitative interpretation.
- Photoelectric log in most cases was of good quality (86 % of wells). But in 14 % of cases photoelectric factor was overestimated. It was overestimated by less than 0.2 b/elec, the overestimation was labelled as "little".

A holistic conclusion about the LWD data quality is presented in Figure 8.

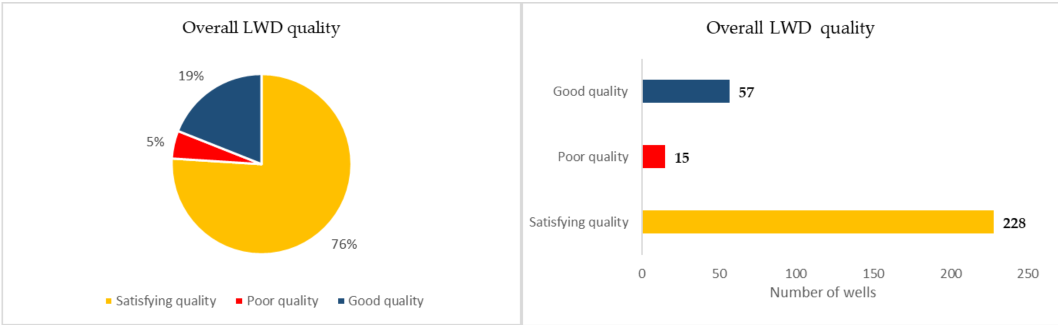


Figure 8. Overall LWD quality in the analyzed wells

Only in 19% of the wells, all of the methods worked properly and could be used for quantitative analysis without any corrections. In 5% of the wells one of more LWD methods could not be used even with corrections and normalization. In most cases (76%) the quality was decent, but additional corrections or remarks should have been used to evaluate the necessary parameters properly.

1.3 Purpose and objectives

The main purpose of the thesis is to create a quality control system for assessing the quality of the most widespread LWD methods registered in horizontal wells. Since in most cases raw data is not accessible while drilling and sometimes even after the tools are extracted, the thesis mostly deals with the processed physical parameters, which are obtained from the service companies either in real-time or after the data from the tool memory is extracted. From the statistics in 1.2 it could be inferred that even the biggest and most advance service companies could provide data of poor quality. The proposed QC system could be used by geosteering departments in oil and gas companies to control the quality of incoming LWD data from contractors.

To reach the main purpose, the following objectives are fulfilled:

- Analysis of logging while drilling quality in a number of wells in order to understand the extent of the problem and figure out which malfunctions are the most widespread.
- Comparison of logging while drilling data and wireline data as well as comparison of logging in horizontal and vertical wells is made to understand the aspects of LWD data in horizontal wells.

- Applicability of approaches to assess the quality of logs in vertical wells in relation to LWD data in horizontal wells is analyzed.
- The QC methods of the following LWD methods are discussed:
  - Gamma ray log.
  - Resistivity log.
  - Neutron log.
  - Density log.
  - Photoelectric factor log.
  - Caliper log.
  - Sonic log.
- Two approaches to assess the quality of LWD data are mentioned.
  - Application of cross-plot and histogram analysis for a QC quick-look.
  - Solution of direct and inverse problem (only applicable if a good petrophysical model of the formation exists).
- Risks and consequences of poor quality LWD data are described.
- A case study of incorrect decision to continue drilling because of poor quality LWD data is examined.
- In order to use data of satisfying quality in a quantitative analysis, methods of data normalization are discussed and a new method is proposed.

Chapter 2 Difference between LWD and wireline logs

2.1 Features of logging while drilling data

With the growing percentage of horizontal wells in production drilling and LWD tools approaching wireline quality and variety of methods, logging while drilling became a standard practice in horizontal wells worldwide for two main reasons:

- Ability to receive data in real-time and adjust the well path based on this data.
- Cost optimization with reduced rig time.

LWD data analysis with a wireline mindset could lead to erroneous conclusion, that is why this chapter is devoted to discussion of differences in LWD and wireline tool design and response.

The differences are mainly combined in the following three topics:

- Sensor and tool design.
- Reference depth in both logs.
- Influence of drilling dynamics, wellbore environment and dynamic invasion on LWD and wireline data.

The main differences in sensor design come from the fact that LWD tools must primary function as drill collars and only then as logging tools, because the cost of failure in the former is far greater than in the latter. (Jackson et al. 1994) Differences in the most widespread sensors are discussed below.

Wireline calipers measure borehole diameter by two, four or six mechanical arms. On the other hand, LWD calipers use ultrasonic waves or azimuthal variation in density. Unless the wellbore is round, LWD calipers are supposed to detect the geometry of the wellbore with a greater resolution compared to wireline calipers. This is the case because, for example, most of the density LWD calipers measures the distance from the tool to the wellbore wall in 16 sectors (ultrasonic caliper has even higher resolution) compared to four standard mechanical arms in a wireline caliper. Even though, density and ultrasonic caliper have the advantage of detecting some wellbore features, which are not seem on the mechanical calipers, these tools have some drawbacks too. Since the measurement is not mechanical, reading rely a lot on the calibration of tools, so the fluid, with which the wellbore is filled should be known, but since sometimes during drilling mud properties could vary a lot, it is difficult to select correct calibration coefficients. Another problem with LWD calipers is that ultrasonic waves and emitted gamma rays have certain depth of penetration into the mud. If a washout is larger than this depth, the caliper will not read a correct value. In Figure 9 an ultrasonic caliper started showing large overgauge hole (red log) from the depth marked with red horizontal line, because the drilling mud was changed and calibration factors did not account for that. The green log represents the real borehole diameter after a proper correction was implemented.

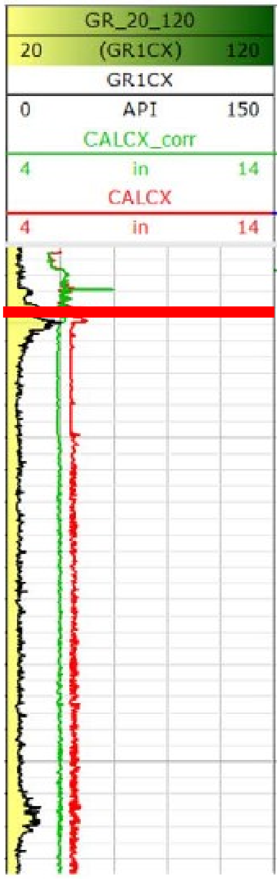


Figure 9. Recalibration of acoustic caliper after the mud was replaced. (Thakur et al. 2018)

Calipers are crucial not only for understanding the quality of the wellbore in real-time and calculation of excess cement volume. Data from caliper log is later used to add environmental correction to all other logs, since their readings are subjected to the properties and volume of drilling fluid in a zone of investigation of each method (Table 1).

Table 1. Depth of investigation of some LWD tools (Griffiths 2009)

Method	**Depth of investigation up to (cm)**
Gamma ray	50
Neutron log	75
Density log	40
Sonic log	20
Resistivity log	170 cm in LWD Schlumberger tools (Bond et al. 2010)

Gamma ray log measures the naturally emitted radiation coming from a formation. Even though, used gamma ray sensors in wireline and logging while drilling tools are basically the same, due to the fact that detectors in LWD tools are surrounded by thick drill collars, the receivers may not be able to detect low energy gamma rays, possibly causing the differences in readings up to 15%. (Jackson et al. 1994). This effect should be accounted for prior to design of the GR tool. One way to overcome that could be usage of more sensitive detectors. Another problem with GR reading while drilling could be the excitation of the formation by density log tools, if for some reasons they are located in from of a gamma ray tool (e.g. in carbonate rocks, where shale volume is minimal and GR readings in the reservoir is a straight line. In this case the knowledge of density is of far greater importance and consequently, density tool should be located nearer to the bit).

Apart from that, it was shown in (Mendoza et al. 2006) that differences in tool configuration and geometry is not a cause to significant differences in tool response. The most significant difference comes from incorrect environmental corrections to the data. Figure 10 illustrates the differences in corrections depending on the borehole diameter and density of the fluid.

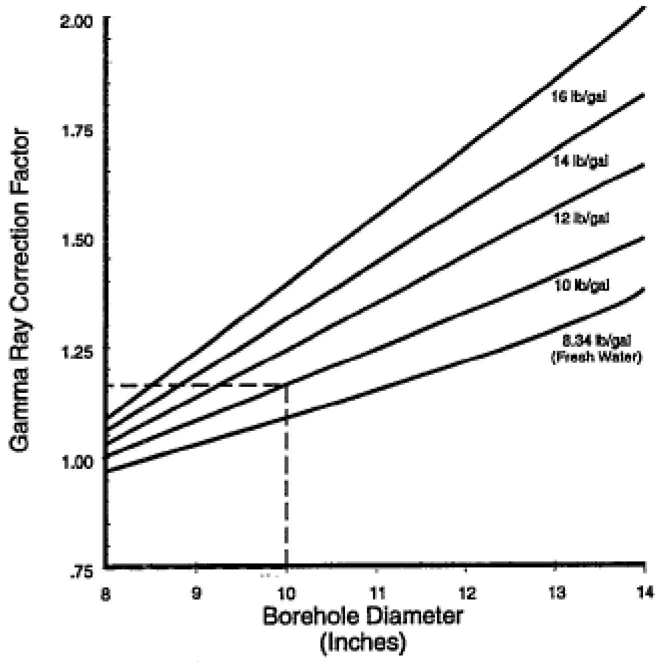


Figure 10. Effect of borehole diameter and fluid density on LWD gamma ray. (Jackson et al. 1994).

Most of the modern LWD resistivity tool are electromagnetic. This means that they are sensitive to dielectric effects. Phase-resistivity and attenuation-resistivity transforms are based on the assumption that the dialectic factor of a formation is constant and equal to 10 (Jackson et al. 1994). If formation dielectric constant is greater than 10, phase-resistivity would be lower and attenuation resistivity would be higher than true resistivity of a rock (Figure 11). The assumption that dielectric factor is equal to 10 is good-working in clean-sandstones, but constants of most common clay mineral could vary from 20-200. So the change in dielectric factor mostly correlates with shale content.

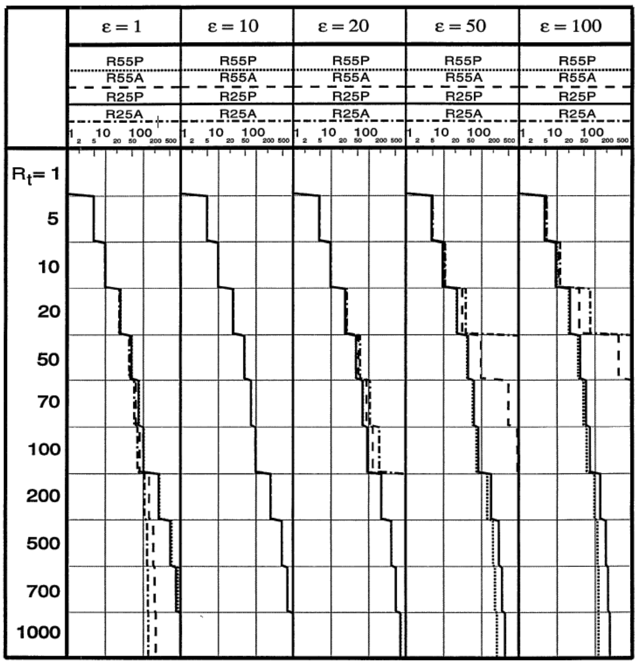


Figure 11. Dielectric effect on the LWD resistivity (Jackson et al. 1994).

Since the resistivity tools are electromagnetic, the depth of investigation varies considerably with the change in formation resistivity. Figure 12 shows that with the increase in formation resistivity, the depth of investigation could change from 20 inches to 65 inches for 40 inch attenuation resistivity sonde.

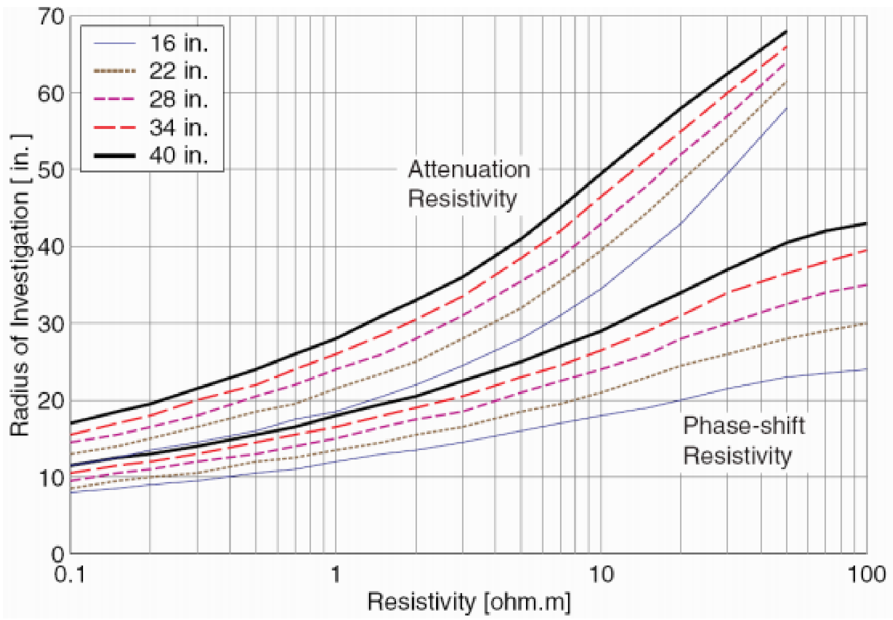


Figure 12. The radius of investigation of phase and attenuation measurements for 6 ¾′′ tool at 2 MHz (Griffiths 2009)

Neutron log in wireline and LWD modification may not read the same values because of the following reasons:

- Source-detector spacing (influence of depth of investigation).
- Which neutrons or gamma rays are detected (thermal, epithermal neutrons or neutron induced gamma rays).

The most important difference in density logs obtained while drilling and on a wireline is that pads of wireline density tools contact the formation, minimizing the wellbore fluid effects on the readings. This is not the case in case of LWD density tools, these tools cannot ensure physical connection of formation and tool pads. This is why environmental corrections applied to the density measured while drilling is of utmost importance. Another feature of LWD density tool is that while rotating the tool could measure the parameter over 360 degrees, thus creating wellbore images.

Bottom-hole assemblies could get stuck. This would impose additional problems if the BHA include sources of radioactive emissions. This is why some service companies try to introduce sourceless LWD density tools. (Alakeely 2014) discusses problems and challenges arising with these tools. These tools use pulsed neutron generator instead of a chemical source. In the paper, it was concluded that sourceless LWD density showed higher values of density in comparison to a conventional wireline log with a chemical source. The problem, which the sourceless tools face now is accounting for fast neutron cross-section (Alakeely 2014). This is why in formations with varying amounts of shale and heavy elements, tool response should be modelled thoroughly and corrections should be calculated more precisely. The comparison between sourceless density tool (neutron-gamma) and tools with a source (gamma-gamma) are presented in Table 2. It is clearly seen that sourceless density tools provide poorer quality of logs. In my opinion, with the improvements in how to add the environmental corrections, sourceless tools could be used in logging while drilling assemblies, because of safety reasons.

Table 2. Comparison between NGD and GGD specifications (Alakeely 2014)

	Neutron-Gamma density (NGD)	**Gamma-gamma Density (GGD)**
Range:	1.7 to 2.9 g/cc	1.7 to 3.05 g/cc
Precision: ROP	0.018 g/cc at 2.4 g/cc at 61 m/h ROP	0.006 g/cc at 2.5 g/cc at 61 m/h ROP
Accuracy: Clean sandstone, limestone Shale	 0.025 g/cc 0.045 g/cc	 0.015 g/cc 0.015 g/cc
Axial resolution	89 cm	38 cm

The overall comparison in sensor design for LWD and wireline methods are presented in Table 3.

Table 3. Overall comparison of sensor and tool design between wireline and LWD

Method	**Wireline**	**LWD**	**Outcome**
Caliper	Mechanical arms	Ultrasonic or density calipers	Drilling fluid impact on the LWD caliper data
Gamma ray	-	Problems in detection of low energy gamma-rays	Lower readings of GR in LWD
Resistivity	Usage of electrodes or coils	Coils are mains used (electromagnetic method)	Dependence of the readings on the resistivity of formation in LWD

Density	The tool is always in contact with the formation	The tool is not in contact with the formation, sourceless modification could be used	Lower readings in LWD density (in case of gamma-gamma density), if proper environmental corrections are not applied. Higher readings in case of sourceless tools usage
Neutron	Source-detector spacing, detected particles		Different readings

Depth measurement is of great importance, because it shows where all of the rest parameters have been measured. Errors in depth could lead to target missing while drilling. In the industry wireline depth is considered as reference as it is supposedly of better quality, because of better techniques used to correct for stretches in wireline.

LWD depth is referenced to drillers's depth, which is a plain measurement of quantity and length of the drilling pipes lowered into the well. To acquire continuous depth data a geolograph or draw works encoder is used. For each movement of the travelling block it is assumed that bit has travelled the same distance. The depth is updated only when the pipe is out of slips, which is determined by software. With time, LWD depth starts to deviate from the drillers depth. So, in practice, LWD depth is periodically adjusted to drillers depth (Chia et al. 2006).

The factors, affecting drillers depth are described in table 4.

Table 4. Factors affecting drillers depth (Alakeely 2014)

Factor	Description	Effect on string length
Weight	Weight of the string	Increase
Temperature	Thermal expansion of metal	Increase
Axial pressure	Pressure drop across the string at the bit	Vary
Ballooning	Differential pressure across the walls of the drill pipe	Decrease
Friction	Drag against the side of the borehole	Increase or decrease depending on direction of travel
Buckling	Compression effects	Vary
Weight on bit	Weight application on the bit	Decrease
Twists	Stored revolutions within the pipe	Vary

Drill pipe stretch and thermal expansion are accounted for the largest errors in driller's depth (Alakeely 2014), this is why LWD depth is usually shallower rather than wireline depth. Another problem that the shift in depth is not linear, since the factors, affecting the driller's depth vary with the depth.

Poor wellbore conditions, such as hourglasses, washouts, rippling, spiraling wellbores affect log quality a lot. These wellbore profiles could be a result of usage of different steering systems. Rotary steerable systems provide much smoother wellbore compared to steerable mud motors.

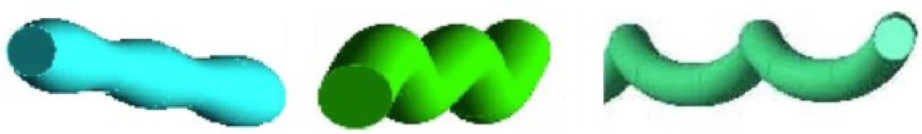


Figure 13. Hourglass, rippling and spiraling wellbore (Thakur et al. 2018).

Figure 14 shows how much a density image log could be affected by steerable mud motor. On top of that usage of mud motors could lead to missing values on the image, associated with sliding mode of the motor, when the LWD tool is not rotating.

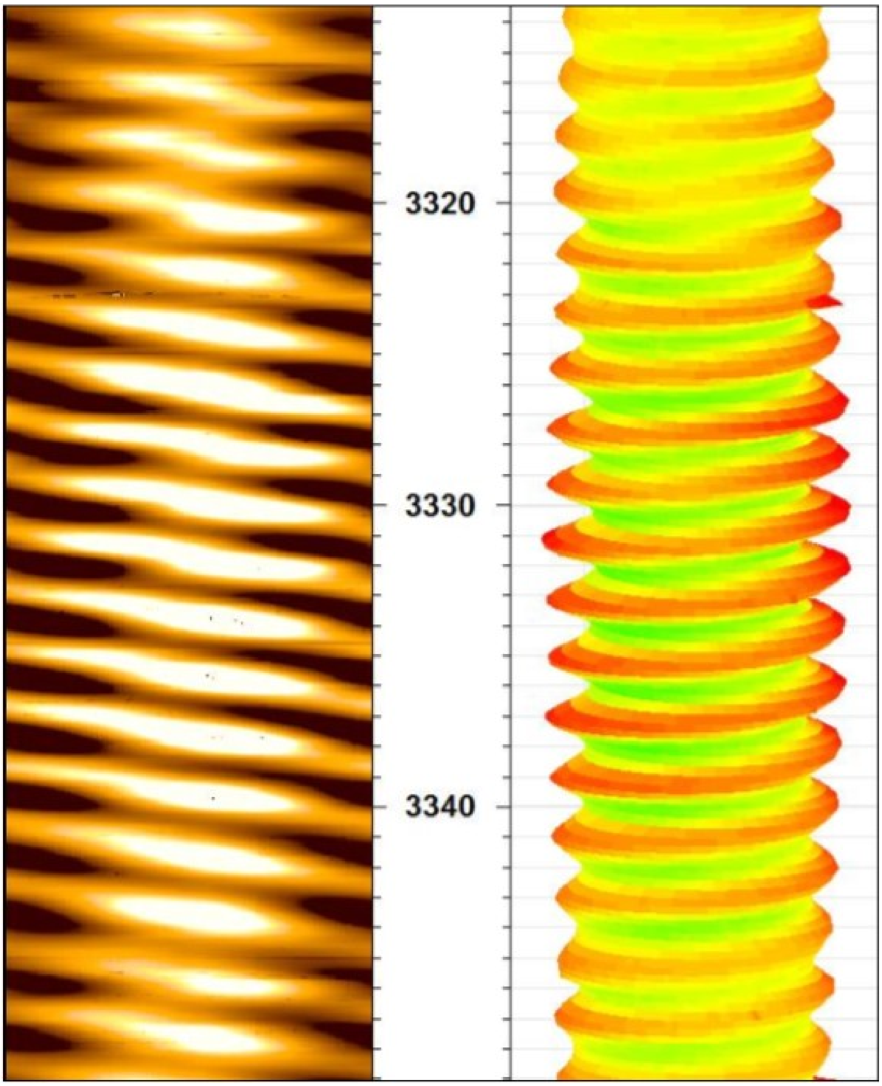


Figure 14. Density image of a well drilled with a mud motor.

Wireline logs could also be affected by borehole conditions, but since most of the affected methods could maintain a good contact with a wellbore wall, the effect is minimized.

When the logging is done minutes or even hours after the drilling, the invasion of mud filtrate and formation of mud cake is still dynamic. So, the LWD logs recorded at different times of invasion could read different values because of different connate water, hydrocarbon and mud filtrate saturation. This effect is the most severe in gas saturated reservoir, where the density of formation and drilling fluids differs quite a lot. Figure 15 shows that the invasion effect on LWD density and neutron could be even seen due to pipe connection time. On the wireline logs this effect is minimized because the invasion zone is fully developed, so neutron and density logs read the flushed zone of a formation.

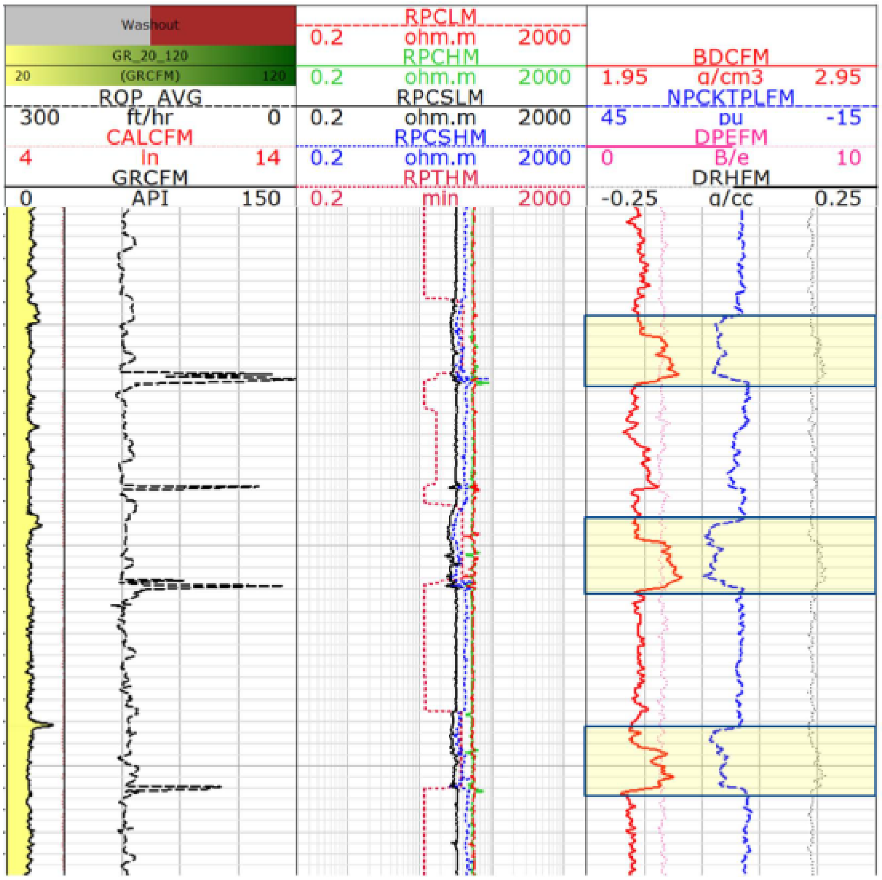


Figure 15. Change in density and neutron logs due to pipe connection (intervals are marked with yellow).

Since mud properties could change throughout the process of drilling and LWD data should be environmentally corrected to account for changes in borehole fluid properties, they should be tested at least every 6-12 hours and at every major change in the mud system. Wireline logging is mostly done when the properties of mud is static, so only one mud test is needed.

Table 5 discusses the main differences in formation conditions during wireline and logging while drilling.

Table 5. Formation conditions during logging (Jackson et al. 1994).

Parameters	LWD	Wireline
Time since drilled	Minutes-hours	Days-Weeks
Filtration	Dynamic	Static
Mud properties	Dynamic	Stabilized
Invasion	Active	Fully developed
Permeability		
High	Shallow invasion	Shallow invasion
Medium	Shallow invasion	Shallow to medium invasion
low	Shallow invasion	Deep invasion
Formation fluids	Connate formation water Oil Gas	Mud Filtrate Connate formation water Oil Gas
Mud cake	Developing, dynamic	Fully developed, static
Formation damage	Pore-bridging Pore lining clays damager	Fragile clays damaged Pore throats bridged Swelling clays

The main differences between wireline and LWD and different influences are described in Table 6. All of the discussed differences between wireline and logging while drilling should be kept in mind when assessing the quality of LWD.

Table 6. Summary of the main LWD features

	Drilling dynamics			BHA design			Wellbore Geometry			Wellbore environment		Dynamic Invasion	
	Vibration	**Uneven drill pipe compression**	**Stick-Slip**	**Position of RA source**	**Mud telemetry module**	**Tool physics**	**Anisotropy**	**Polarization horn**	**Eccentricity**	**Borehole Shape**	**Mud properties**	**ROP-controlled Invasion**	**Connecting Drill pipe**
GR	Spiky log	Slight depth mismathing between the logs	Abrupt change of logs	Possible formation excitation	Affect data density in real time	Probe tool has strong influence of drilling collar	-			Minor effect	Difficult to correct for K-40, if its colume is changing while drilling	-	When the source is below
Resistivity				-		Dielectrical attenuation resistivity reads higher than than phase resistivity	Separation of all resistivities with increasing wellbore angle	Horn in high well angle and resistivity contrast	separtion of high frequency resistivities	Separation of resistivity in order of DOI	The Rt/Rm contrast affects amplitude of eccentricity invasion and borehole effect	More separation in slow ROP, vice versa	Minor effect
Density						Stabilized vs slick density tool design	-			low readings in breakouts, spikes in rugose holes	Pf/Pm contrast affects invasion effect	More invasion in slow ROP, cice versa	Invasion is seen in light HC bearing permeable zones
Neutron						Different reading for thermal, epithermal neutrons				High readings in breakouts, spikes in rugose holes	Contrast to formation salinity affects the invasion effect		
Acoustic slowness	Strong noise					Pre-run selection of frequency to minimize noise and dispersion	Slowness decreases with well angle	-	Affect Stoneley permeability	Dispersion	Dispersion in heavy mud	Hardly seen	Minor effect
Acoustic caliper	-					-	-			Loss of accuracy in huge washouts	Mud affects caliper calibration	-	-
NMR	Artificial irreducible fluid signal on T2				Affect T2 resolution in Rt	-				High irreducible water saturation and total porosity in washouts	High noise in highly conductive mud	HC signal replaced by filtrate in T2 in slow ROP	HC signal replaced by filtrate in T2 during connection
Density Image	Minimum effect	Trunction of image			Affect Image resolution in RT	Resolution limit				Aftifacts to the mud	-	Affects the density image as density of mud	Minor change due to invasion

2.2 Features of petrophysical data in horizontal wells

In the last decade, technology has advanced to the point when horizontal drilling has become a common practice. After Passey et al. 2005, the following definition of high angle and horizontal wells will be applied:

- Vertical (near-vertical) wells is a well with apparent deviation angle with the respect to formation bedding less than 30 degrees.
- Moderately deviated well is a well with angles between 30-60 degrees.
- A high-angle (HA) well is a well with angles between 60-80 degrees.
- A horizontal well (HZ) is a well with angles higher than 80 degrees.

Historically, wireline measurements were mainly conducted in vertical and near vertical wellbores with the measuring approximately parallel to formation layering. In this environment, measurements provide optimal vertical resolution and information about the formation (Griffiths et al. 2012). On the contrast, logging data acquired in high angle and horizontal wells (HaHz) measurements are sub-perpendicular to formation layering and some of the readings (especially with high depth of investigation) may be associated with multiple layers (Figure 16).

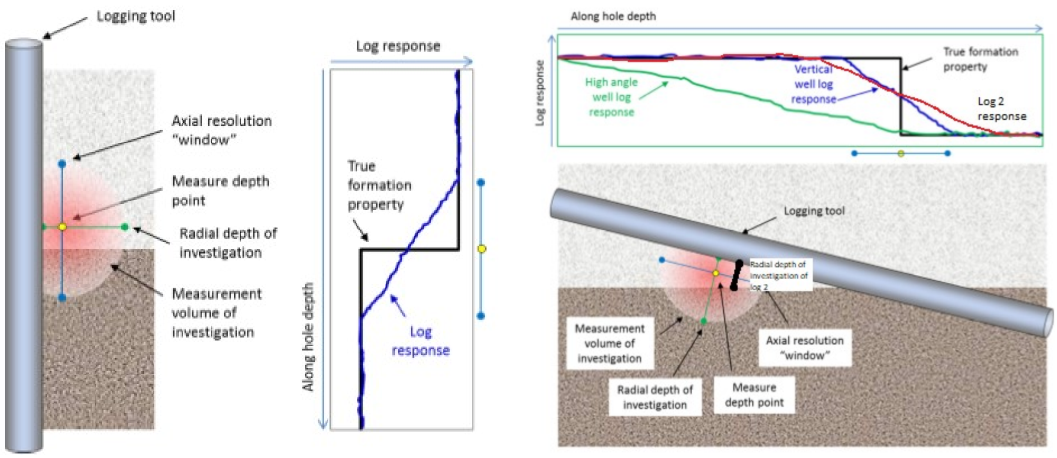


Figure 16. Logging tool response in vertical and high angle wells (modified after Griffiths et al. 2012).

The main reasons for logging in horizontal and high angle wells could be categorized into two main groups:

- Qualitative purposes (geosteering and completion).
- Quantitative purposes (formation and fluid properties).

The requirements for quality in case of quantitative purposes are much stricter than in case of qualitative purposes. With the latest improvements in approaches for petrophysical analysis in HaHz wells (3D petrophysics), the quality requirements for LWD data became very strict to allow correct quantitative interpretation of the data.

The differences in petrophysical properties between vertical and horizontal wells for the following methods are described below:

- Resistivity log.

- Density log.
- Acoustic log

This methods are chosen because the type of a well (vertical or Hz) influences these logs the most.

One of the first anomalies noticed as holes started to deviated was the development of polarization horns on resistivity tool response. Polarization horns start to show at the apparent deviation angles of 60-70 degrees and are quite useful for determining the bed boundaries. The example of polarization horns on the resistivity log is shown in Figure 17. What also could be noted from the Figure is how gamma ray log develops shoulder bed, which appear at bed boundaries, the mechanism of its formation could be clearly seem from Figure 16.

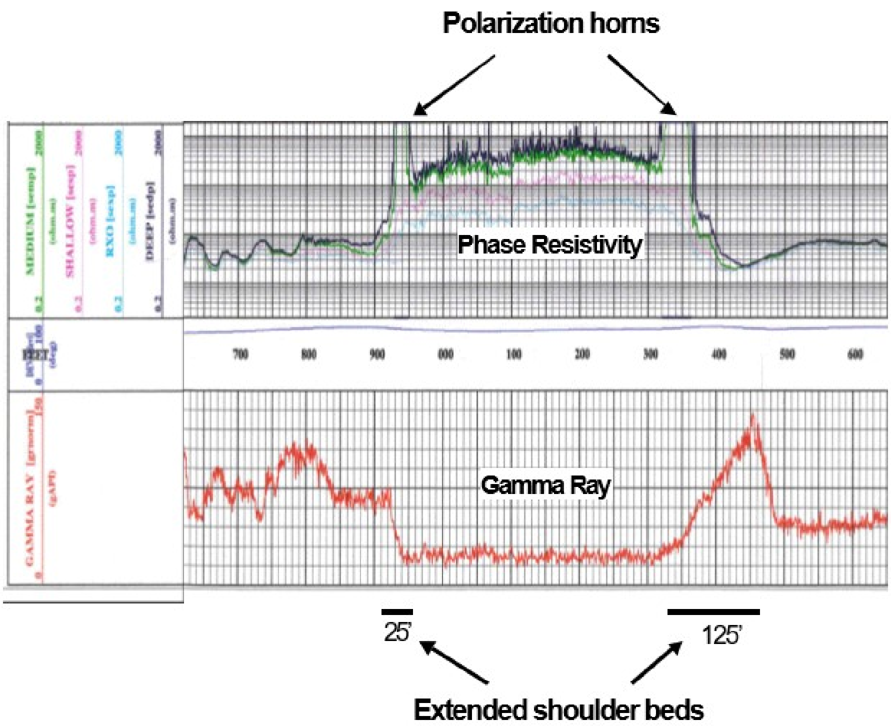


Figure 17. Example of polarization horns on a resistivity log and extended shoulder bed on gamma ray log (Passey et al. 2005).

Another problem with the resistivity is its high depth of investigation. Since the bedding is parallel to the tool, the resistivity tool readings could be influenced by layers, which are above and below the bed in which the well is drilled.

In general, density and neutron response in horizontal wells should be similar to the response in vertical wells. However, since LWD density tools are not in direct contact with the formation, density obtained from a horizontal well could show different values compared to vertical wells. This could happen for a number of reasons, which include asymmetric invasion, gravity segregation of drilling fluid, incorrect pad alignment or/and presence of low-density cuttings on the lower part of the wellbore, if the cleaning is not sufficient. Same effects could influence the readings of neutron logs in horizontal wells.

Because of anisotropy in acoustic properties in most rocks, velocities measured in different directions (vertical and horizontal wells) could differ a lot. The problem become more severe when the tool is inclined and measures combination of two velocities (in horizontal and vertical directions). Figure 18 shows slowness and gamma ray in three wells with different deviations through the same formation. It could be seen that the effect is the most severe in shales, while sandstones show more isotropic behavior.

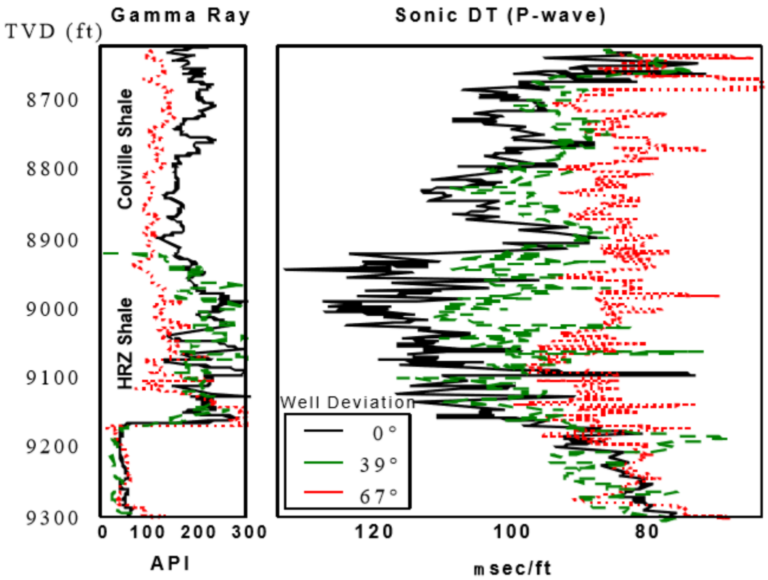
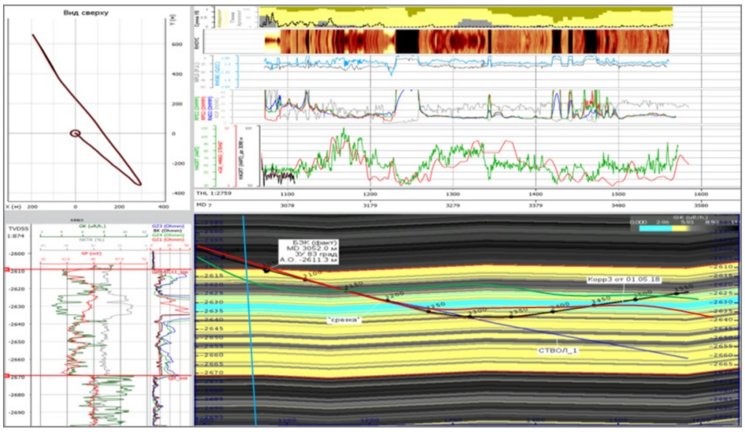


Figure 18. P-wave responses in a sand and shale in wellbores of various deviation (Passey et al. 2005).

The proposed quality control methods of the most LWD methods in the thesis are connected with comparison of data obtained from offset vertical or horizontal wells and core studies with the data received from a horizontal well in question. This is why all of the above-mentioned features of LWD data in horizontal well should be kept in mind when comparing.

Since the methods of QC discussed in the following chapter include comparison of data in horizontal and vertical wells, a common way of histogram analysis, used in QC of physical properties in vertical wells, applied to HaHz wells is described in Figure 19. In the Figure a geological cross-section is presented. Four wells penetrating the same formation but in different zones are described. The blue line is a near-vertical wellbore, which penetrates all of the layers. “Green” well was drilled mainly though shales and a little through sandstone at the end. “Red” well was drilled mostly through tight layer with high values of density. On the histogram a modelled distribution of density is presented. It is clearly seen that even though this method for QC works rather well in vertical wellbores, it cannot be applied straightforward to horizontal ones, because of huge differences in distribution of physical parameters (in this example, density). That adds complexity is the fact that open hole LWD data in horizontal wells rarely include data about penetrated layers with known physical properties, since they are located above the casing shoe of the previous casing or at the depths below the horizontal section.



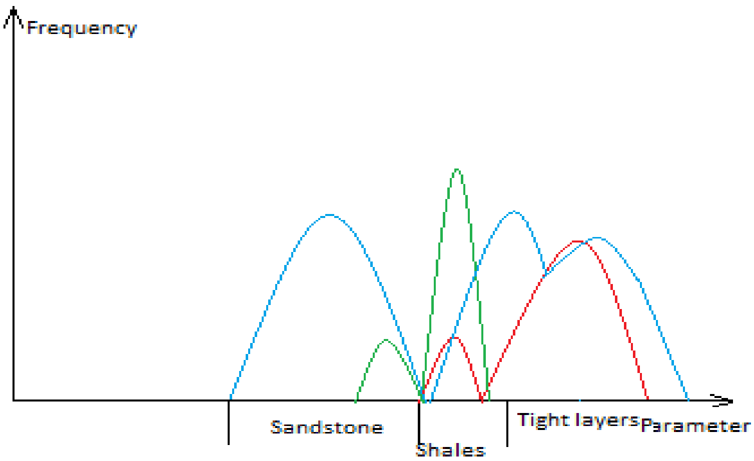


Figure 19. Distribution of density in three horizontal wells drilled through the same formation.

To compare, the distributions of GR in three adjacent wells are presented in Figure 20. One could conclude pretty easily that gamma ray in the "red" well is underestimated.

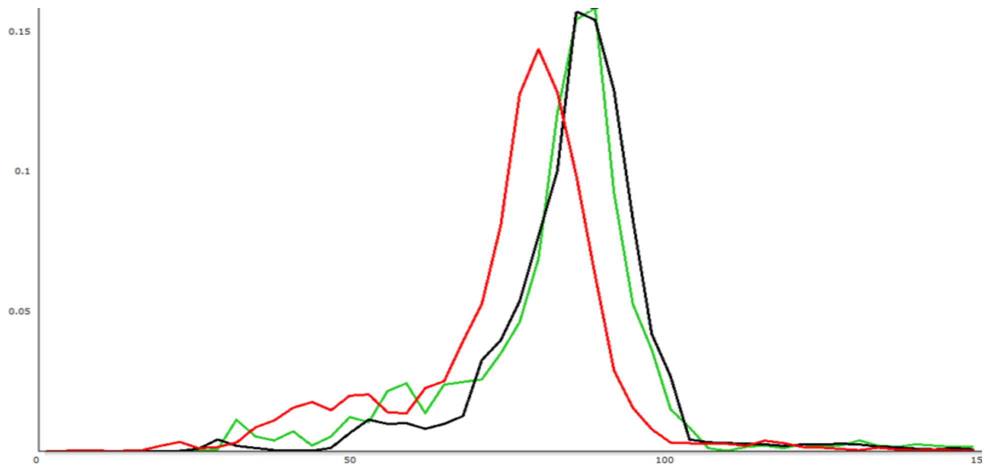


Figure 20. Distribution of GR in three adjacent vertical wells.

Chapter 3 Quality control of main LWD methods

Most of the papers and manuals dedicated to the quality control of LWD data (Gonfalini et al. 1995, Theys et al. 2014, Storey 2016, Hutchinson 1994, Jackson 2013, Hanes 2011) are dedicated to assurance of quality on the stage of acquiring of the logs. Unfortunately, representatives of oil and gas producing companies and people, who interpret the data, cannot be involved in data acquisition in the field most of the time. In addition, raw data is usually not transmitted in real-time, so it is impossible to access the correctness of tool responses. Moreover, petrophysicist and geosteering engineers rarely have access to raw logs even from a tool memory long after a borehole is completed. For three reasons, techniques of quality control for the most widespread LWD methods in physical values are discussed in this chapter.

The techniques are implemented on the obtained output data in horizontal wells (Figure 21). The first four stages of information received are usually done on the rig site by service companies, which provide LWD surveying.

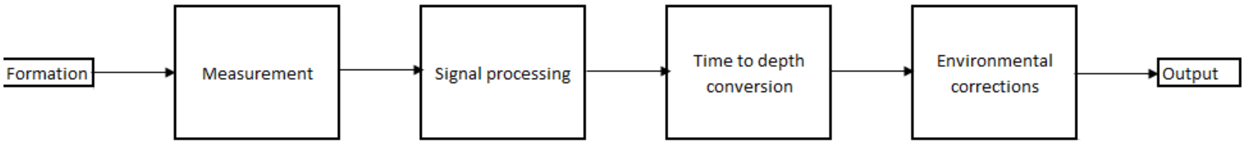


Figure 21. Stages of obtaining the LWD data (modified after Theys et al. 2014).

Before talking about the quality control, quality assurance should be discussed briefly.

3.1 Quality assurance

Quality management system consists of three main elements (Figure 22) (Jackson 2013):

- Quality control.
- Quality assurance.
- Quality improvement.

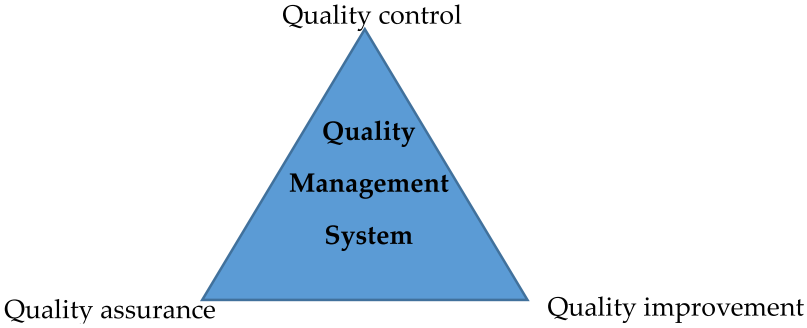


Figure 22. Quality management system.

Quality control (QC) activities usually occur after the data has been acquired and are aimed to evaluate the correctness of measurement.

Quality improvement is the process of changing standards to improve the quality.

Quality assurance (QA) comes before the measurements and includes planned and systematic actions necessary to assure that a tool will fulfill all of the requirements. QA include sensors calibration, wellsite verification, downhole instrument configuration and surface system configuration (Jackson 2013).

Quality assurance is done during the following operations:

- Pre-job planning
- On-site pre-planning
- Operation while logging (Hanes 2011)

Service companies usually do all of the quality assurance operations. Prior to the logging job itself, a service company should coordinate methods to be used, tool requirements, expected drilling parameters and so on. This is done to prepare all of the necessary equipment in time for a job. All sensors should be properly calibrated and verified in a shop prior to the job. The information about calibration should be provided with LWD data. Usually, before the job a Pre-Job Logging Program is established for each well with the necessary information for field engineers. (Hanes 2011)

During on-site preparation phase workability of all the sensors is checked once again before running in hole. Calibration check is conducted once again, since it influences the acquired logging data a lot. Parameters of sampling for telemetry system and memory mode are calculated according to memory and real-time data requirements (density of data points per unit of depth) and expected ROP. Each LWD tool location in a BHA is verified.

During logging while drilling data is monitored constantly to prevent anomalies in log information. In addition, environments, in which the tools are functioning (doglegs, vibrations, mud properties, temperature, pressure, etc.), are monitored to ensure that the tools are working in its designed conditions. Moreover, during drilling depth measurements are checked with driller's depth and corrected if necessary.

Before discussing common problems occurring with different LWD methods, two categories of well data should be identified:

- Raw (original) data, which is received prior to post-acquisition processing in sensor responses. For example, gamma ray log is the measurement of number of counts in scintillation detectors of gamma ray.
- After raw data is processed, derived (or processed) data is received. Processed data is physical properties of the penetrated formation (gamma ray activity in API, density, neutron porosity, resistivity, etc.)

Most of the time modern LWD tools process data automatically downhole and transmit processed data.

3.2 Common processed LWD data problems

The most widespread problems, which could be seen in all of the LWD methods include:

- Unstable tool and/or communication link.
- Low sampling rate.
- Non-centralized tools.
- Binnig in some of the methods.
- Depth mismatch between different methods.
- Absence of image data in sliding sections of a well, unless there were no relog.
- Mismatch between real time and memory data.

The problem of an unstable tool or sonde could be identified by the fact that only one method would show anomalies. Figure 23 shows an example of inconsistency of attenuation resistivity (blue line). It is clearly seen, that all other methods, including phase-shift resistivity show good match and only attenuation resistivity is affected. This could happen because the attenuation resistivity receiver is malfunctioning.

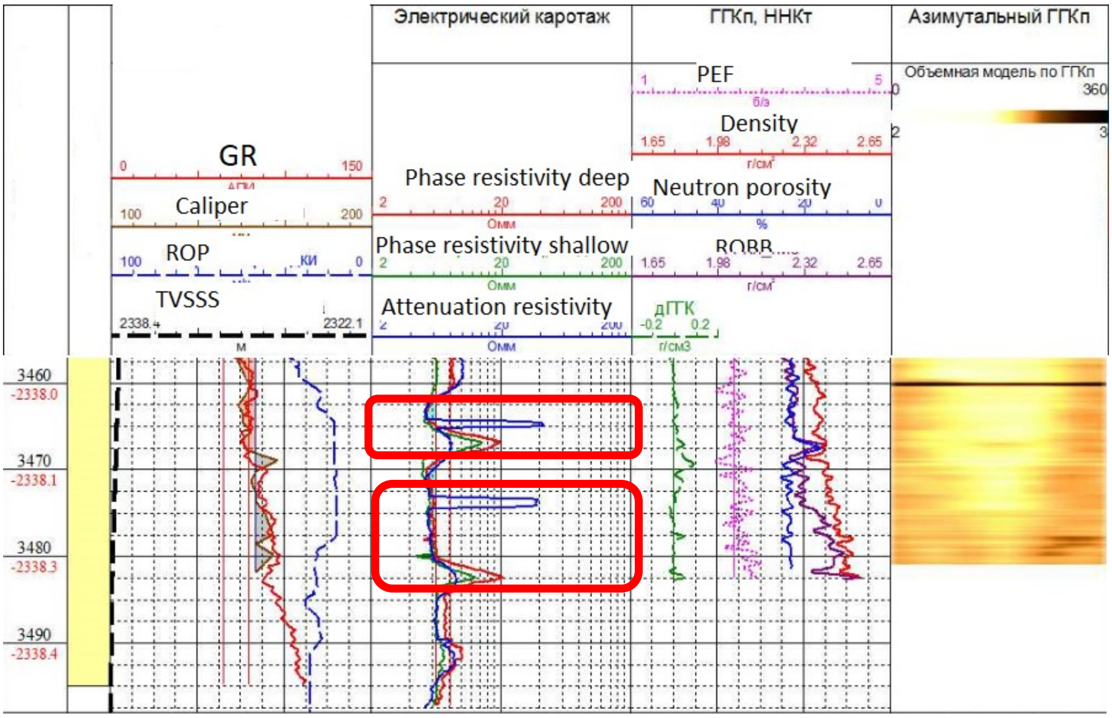


Figure 23. Example of unstable attenuation resistivity sonde. Note that phase-shift resistivity is of good quality.

If the communication link is malfunctioning, all of the LWD curves would show absence of data and the points on the log would be connected with a straight line. Figure 24 shows section of a well with an example of malfunctioning in a communication link. The red line is synthetic gamma-ray and the green line is a GR obtained while drilling. Long intervals of “straight lines” can be observed.

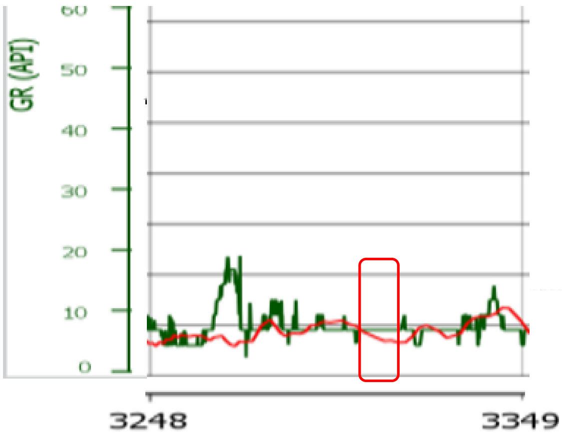


Figure 24. Example of a communication link malfunctioning.

Low sampling rate is usually either a combination of the above discussed problems, but it also could happen because of high ROP when the communication link is not able to transmit the required volume of information. In this case, a decision should be made. Either lower the ROP and receive data with low sampling rate or drill with high ROP and access sampling rate only from memory data. The latter decision is usually made if the geological uncertainties are minimal and it is clear how to drill a well even with low density of data.

Non-centralized tools could lead to poor quality images of a wellbore, which cannot be used to accurately calculate dip angles. Also, some of the methods with small depth of investigation will read incorrect values, since the response is much affected by mud in case of non-centralized tools and it is difficult to correct for that. Figure 25 shows an example of good (upper image) and poor (lower image) quality wellbore images. In the lower image, in some intervals washouts in the upper part of the wellbore are clearly seen (indicated with red squares). On the images the darker the color, the higher the density.

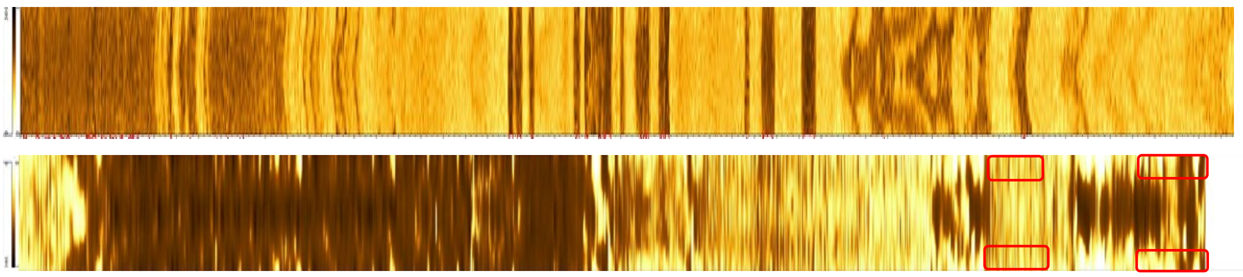


Figure 25. Example of good and poor quality density images.

The idea is binning is that if the measurement is azimuthal, the sector with lowest possible error in a measurement will be identified as a resulting reading. For example, in case of density – the density in a sector with lowest difference between near and far detector (DRHO) will be taken as a resulting density. This approach may work better compared to a standard approach of associating the resulting parameter with a mean value around a wellbore in most cases. However, there are some cases when this technique could lead to erroneous conclusions. In figure 26 an example of coal seems between shale layers is displayed. In the zone highlighted with a red rectangle the resulting density (black line) was taken from the sector, which have smaller washout (shales, since coals are washed faster), and the resulting neutron porosity was taken as a mean around the wellbore (shale and coal combined). This lead to a density-neutron crossover, which was interpreted as a reservoir rock and almost lead to incorrect decision while geosteering.

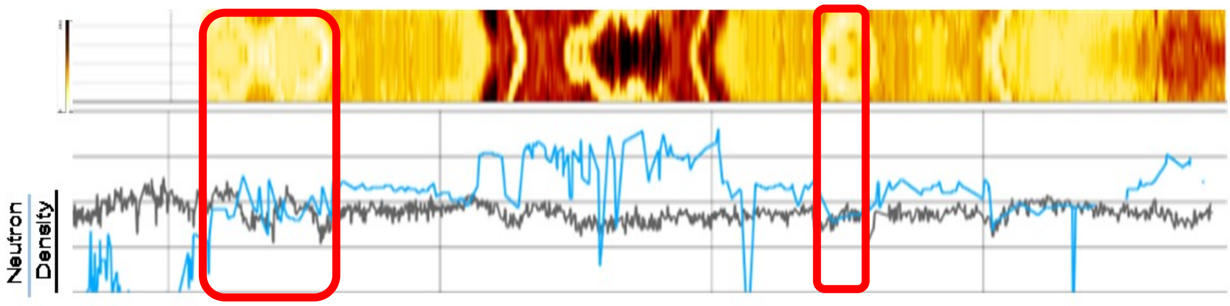


Figure 26. Example of bining.

Depth mismatch between two methods could happen if a LWD engineers incorrectly calculate values of distance from a bit to a sensor. Figure 27 show a depth mismatch between neutron and density logs. It is clearly seen that bed boundaries are seemingly lower on a neutron log compared to density and gamma ray logs. The lower picture show how depth mismatch log on a neutron-density cross-plot.

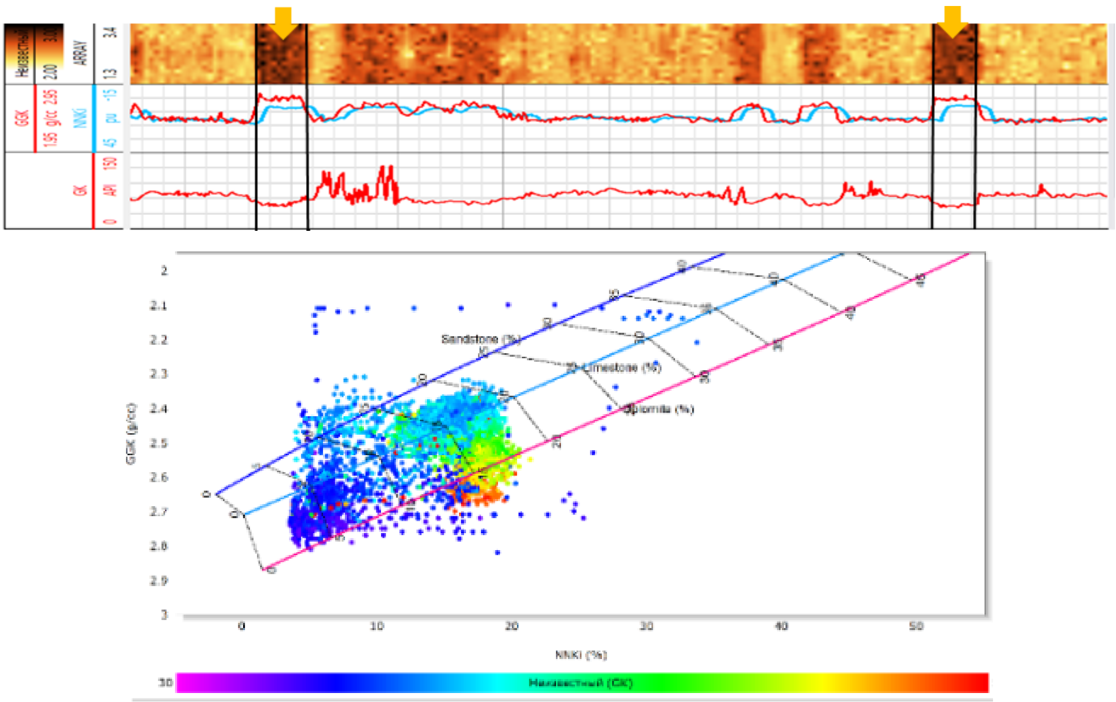


Figure 27. Example of depth mismatch.

Since azimuthal measurement are only possible when the tool is rotating, in a sliding mode no images of a wellbore are produced, since the tool detects formation only in one (sometimes three) directions.

Mismatch between real time and memory data is possible if after the tool has been pulled out of hole, new corrections and calibration coefficients were applied, indicating that the data in real time was not corrected properly.

3.3 Resistivity logs

When analyzing the quality of resistivity logs one should keep in mind than most of the existing LWD resistivity tools use electromagnetic variation of resistivity log (analog to induction log in wireline).

The curve separation in resistivity logs with different depths of investigation is caused by:

- Adjacent beds (since the bedding in horizontal wells is usually parallel to the wellbore, methods with different depth of investigation are affected by different layers).
- Invasion (only in case of highly permeable formations and ROPs or some operations, which was long enough to induce invasion zones deep enough to cause curve separation).
- Dielectric constant variations (discussed in Chapter 2).
- Eccentricity (caused when the tool is not centered in the borehole and there is a large contrast between resistivity of mud and formation).
- Anisotropy.
- Range and accuracy (every tool has its working range of parameter in which it could work).
- Calibration/human error. (when one of tools was not calibrated properly).

The indication of data quality in resistivity is relative position of curves with different depth of investigation in terms of absolute values in resistivity. Figure 28 shows two charts for radius of investigation calculation for a Schlumberger LWD resistivity tool (2 MHz and 400 kHz).

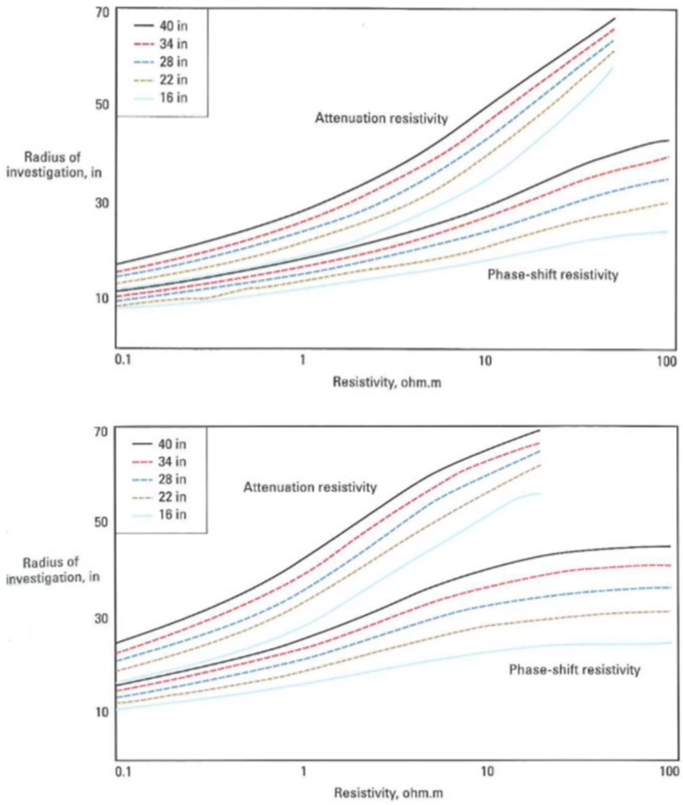


Figure 28. Radius of investigation.

From the Figure 28 it is clearly seen that radius of investigation of attenuation resistivity sonde is always higher than of phase-shift resistivity sonde. In addition, with increase in sonde length, the radius of investigation also increases, moreover 400 kHz tools have higher radius of investigation compared to the 2 MHz tools of the same dimensions.

Good quality LWD resistivity curves should be positioned in relation to each other according to their depths of investigation. If the deepest method read the highest resistivity and shallowest reads the lowest, all of the other methods should be located between the deepest and shallowest sondes according to their depth of investigation, and vice versa. If the attenuation resistivity 40 inch reads the highest value and phase-shift resistivity 16 inch reads the lowest, all of the other resistivity curves should related as follows (in absolute resistivity): 22 – 28 – 34 – 40 inch phase resistivity – 16 – 22 – 28 – 34 inch attenuation resistivity. In my opinion, this is a good method for quality controlling, because 400 kHz and 2 MHz resistivity have different transmitters, also phase-shift and attenuation resistivity are calculated differently using different calibration factors. This is why they are independent of each other and if one method fails, it will be clearly seen. Figure 29 illustrates an example of failure in attenuation resistivity. On the left layout attenuation has gone off-scale (more than 200 ohmm), even though there are no overlaying or underlying high resistivity layers (on the right a well drilled from the same pad into the same formation is displayed).

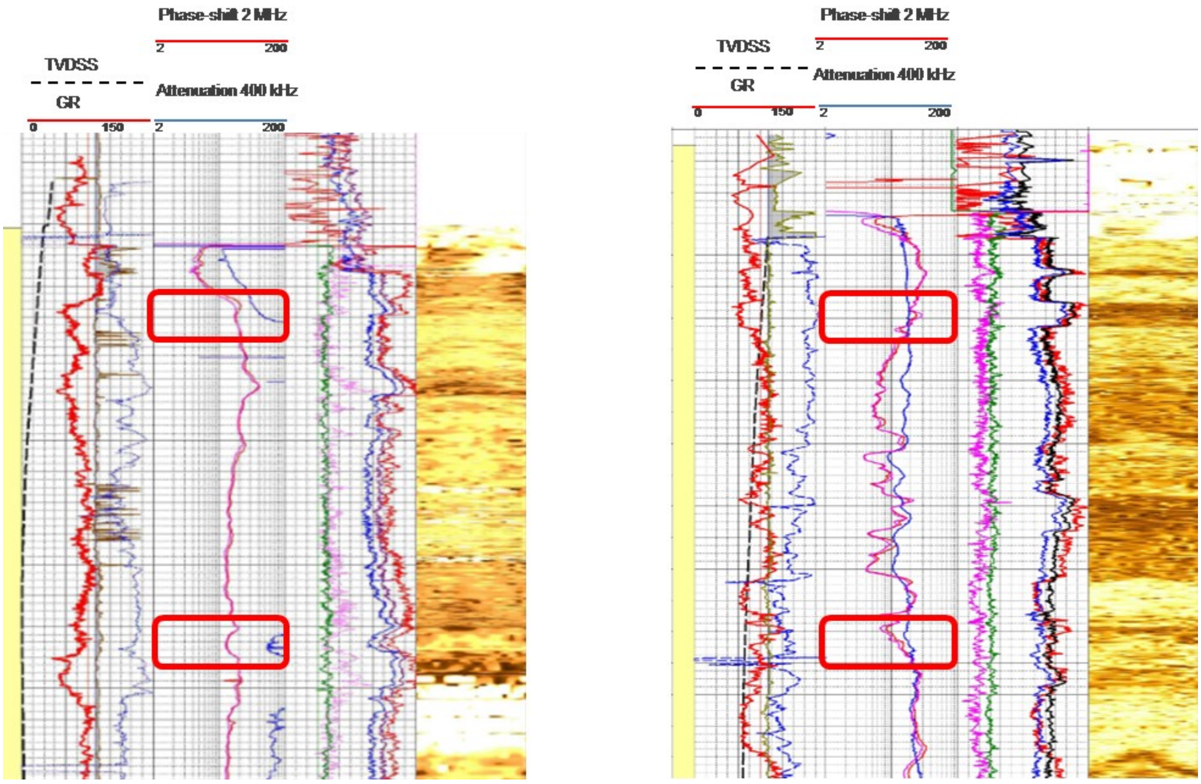


Figure 29. Example of a failure in attenuation resistivity.

3.4 Gamma Ray-Neutron log-Density log

The unit of measurement in gamma ray is API gamma ray, which is taken from an artificially created concrete block at the University of Houston, USA (Jackson 2013). This block has a radioactivity of 200 API units, this is considered to be twice the value of typical shale.

Calibration of gamma ray tools should ensure that tools read identical response in the same conditions regardless of tool type/detector type. Corrections for the following factors are applied to gamma ray logs:

- Hole size (if diameter of a tool is the same, with increased hole diameter, fewer gamma rays will reach a detector).
- Mud weight (increased mud weight reduce the gamma counts).
- Potassium content of the mud.

As in gamma ray log, count rate of gamma rays is measured in density log. The difference is that the registered gamma rays are not naturally occurring, Emitted gamma rays interact with a formation and only then are registered with a receiver.

The calibration of the tools establish a relationship between count rates of a detector with density. Modern tools provide the density correction curve (delta-rho) along with the acquired density. Density correction is directly proportional to a difference between short and long-spaced density sondes. Variation in delta-rho is closely connected with tool standoff and the quality of acquired data. It is taken that if delta-rho exceed 0.1 g/cc, the density readings are of poor quality. Density, obtained from the tool should be corrected for the following factors:

- Borehole size.
- Mud weight.
- Tool standoff.

In neutron log the neutrons emitted by a source are considered to be fast. After scattering in a formation either epithermal or thermal neutrons are detected. Most of neutron tools are calibrated in apparent limestone unites. Obtained neutron porosity is corrected for the following factors:

- Borehole size.
- Standoff.
- Mud weight.
- Composition of the mud (oil-based or water-based, salinity).
- Mud pressure and temperature.

It is quite difficult to access the quality of neutron porosity, density and gamma ray separately using common techniques for vertical wells in case of horizontal wellbores for the reasons discussed in chapter 2.2. This is why a complex method of neutron-density cross-plot usage is proposed and discussed below.

Although, density tools provide correction curve, which is connected with the quality of acquired data, it could show values under the tolerance limits even if the tool is not calibrated properly and density is over- or underestimated.

Although, it should be noted that in some cases only GR log is available in logging while drilling data and no cross-plots could be plotted. In this case, only conventional histogram analysis (comparison of received data with the data acquired from offset wells) could be performed, but it may not be able to show little overestimation or underestimation of GR in the well. A problem could be more severe in some cases in Russia, because Russian GR logging tools read natural radioactivity in micro Roentgen per hour compared to API in international service companies' tools. Sometimes, it is a challenge to correctly convert uR/h to API units.

On a neutron-density cross-plot neutron porosity is located on an X axis in a direct scale and density in plotted in reverse scale on a Y axis. The coloring is done in gamma ray. The cross-plot is presented in Figure 30. Decrease in fluid density or increase in salinity decrease the density and neutron porosity, shifting the points to upper-left part of the cross-plot. Increase in shaliness increase the density and neutron porosity, shifting the points to the lower-right part of the cross-plot. Increase in porosity decrease density and increase neutron porosity, shifting the points to the upper-right part of the cross-plot. One should keep in mind that all of these effect usually occur at the same time. The chart on the cross-plot is unique for every LWD and wireline tool and is usually provided by a tool manufacturer. In this particular case the chart is for a Weatherford LWD neutron-density tool TNP 675.

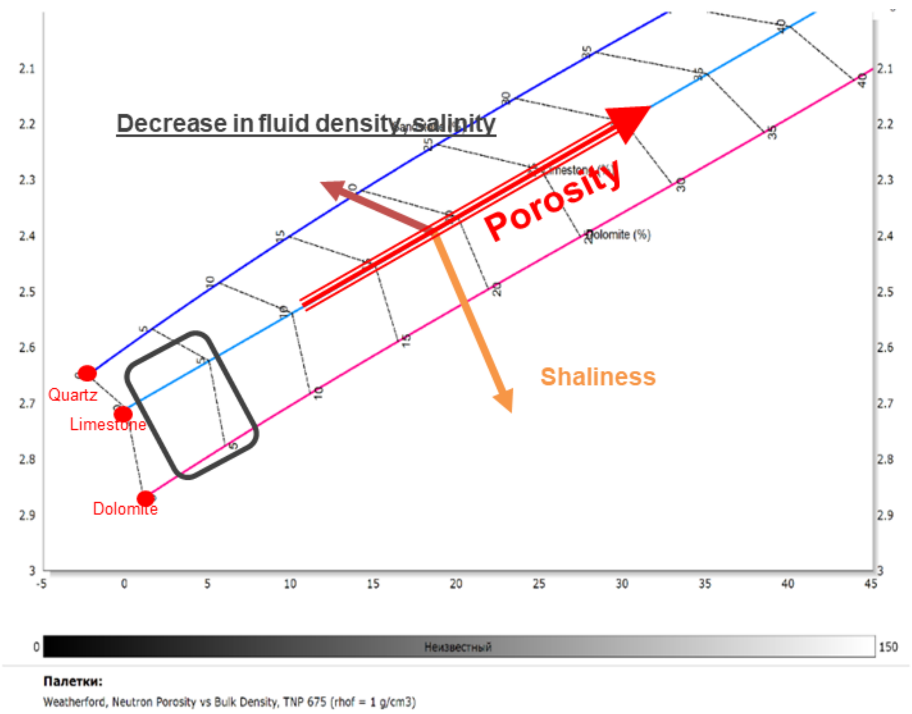


Figure 30. Neutron-density cross-plot.

Figure 31 shows an example of good quality LWD data, obtained in a horizontal well in siliciclastic reservoir. While assessing the quality, attention should be focused on the region of tight layers with low values of porosity and shale region. This is because properties of reservoir rocks could change considerably across the reservoir (different shaliness, density of fluids in pore volume, porosity, etc.), while the properties of shales and tight layers are considered to be more or less constant in one reservoir. On the figure 31 we can see that increase in GR (green and yellow points) is associated with increase in density and neutron porosity. Tight layers on the cross plot are characterized as sandstones with carbonate cement. The points, which lie above the sandstone line, are associated with low shale volume sandstones with the density of pore fluid less than 1 g/cc. With the increase in shale volume, points shift to the region below the sandstone line.

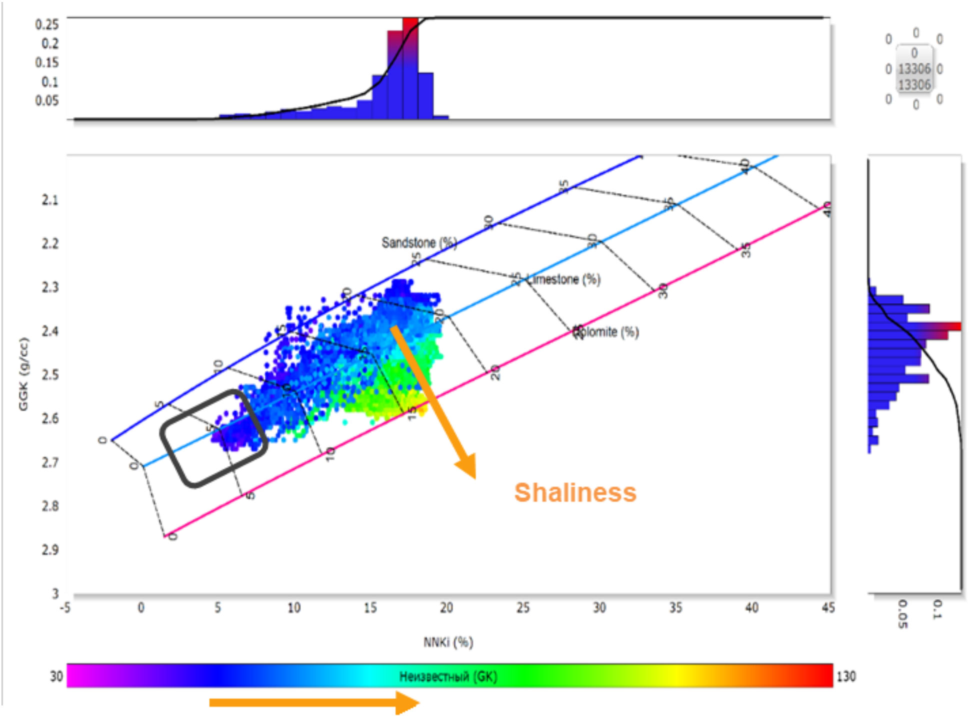


Figure 31. Example of a cross-plot with good quality gamma ray-neutron-density LWD data.

So, to access the quality of data in adjacent wells drilled through the same formation, a reference well or a couple of wells should be established to allow the comparison of the acquired data. The method could be used to identify overestimation or underestimation of gamma ray, density and neutron porosity readings.

In the Figures 32, examples of different problems in data quality could be seen. It could be noted that the charts on cross plots are different. This is because the tools were different, but the logged formation and the oil field was the same. These cross-plots should be compared with Figure 31 to visually understand the problems with methods, since in this case, data from cross-plot 31 considered to be as reference to assess the quality of LWD in other wells. As it has already been stated, the focus should be made on the region of shales and tight layers with low porosity. To simplify the analysis, the red arrow on each cross-plot indicates the shift in points compared to the reference data.

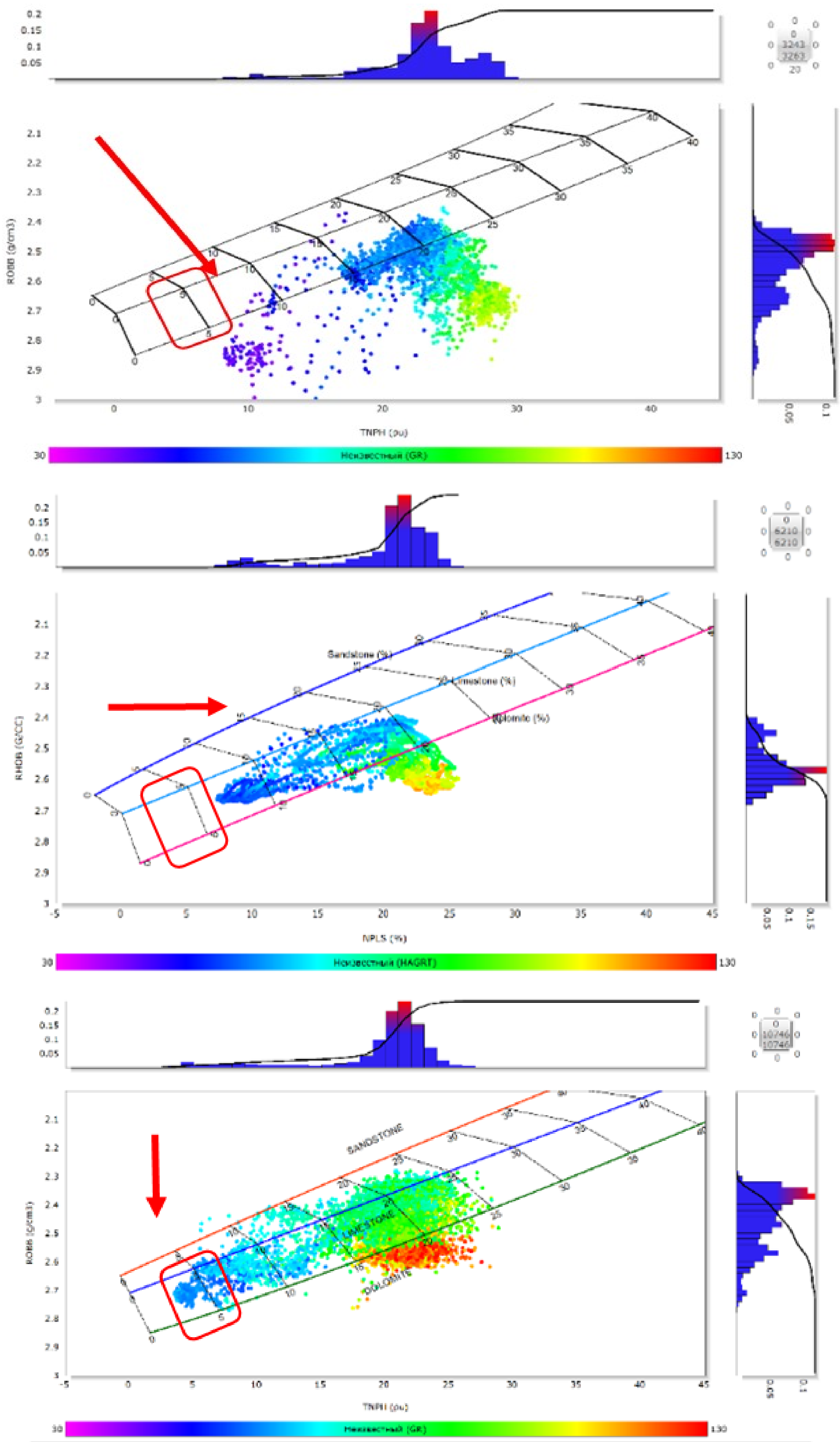


Figure 32. Examples of different problems occurring with density, neutron porosity and gamma ray, which could be identified with a cross-plot.

The data on the upper cross-plot have three problems at the same time. Density and neutron porosity are overestimated. Note how the region of shales and tight layers is shifted to the lower-right part of the cross plot. Moreover, the color of points in tight layers zone is more violet compared to reference data, which could indicate that gamma ray is underestimated. This kind of data cannot be used in quantitative analysis.

Using the same procedure on the middle cross-plot one could identify than neutron porosity is overestimated, since the tight layers region and shales region are seemingly shifted to the right. Usage of this data for quantitative analysis can lead to underestimation of porosity and permeability as well as overestimation of shale volume.

Lower cross plot shows an example of density and gamma ray overestimation, which lead to underestimation of porosity and permeability. On this cross plot it could be seen, that the wellbore was placed in reservoirs with higher porosities, but regions of tight layers and shales should still be in the same part of the cross plot.

The above mentioned problems usually occur because no proper calibration was done or incorrect or insufficient environmental corrections were applied. Figure 33 shows a pair of wells drilled from the same pads into the sane formation. The serial number of a LWD tool was the same. The only difference was that the well presented below was drilled a couple months after the well presented above.

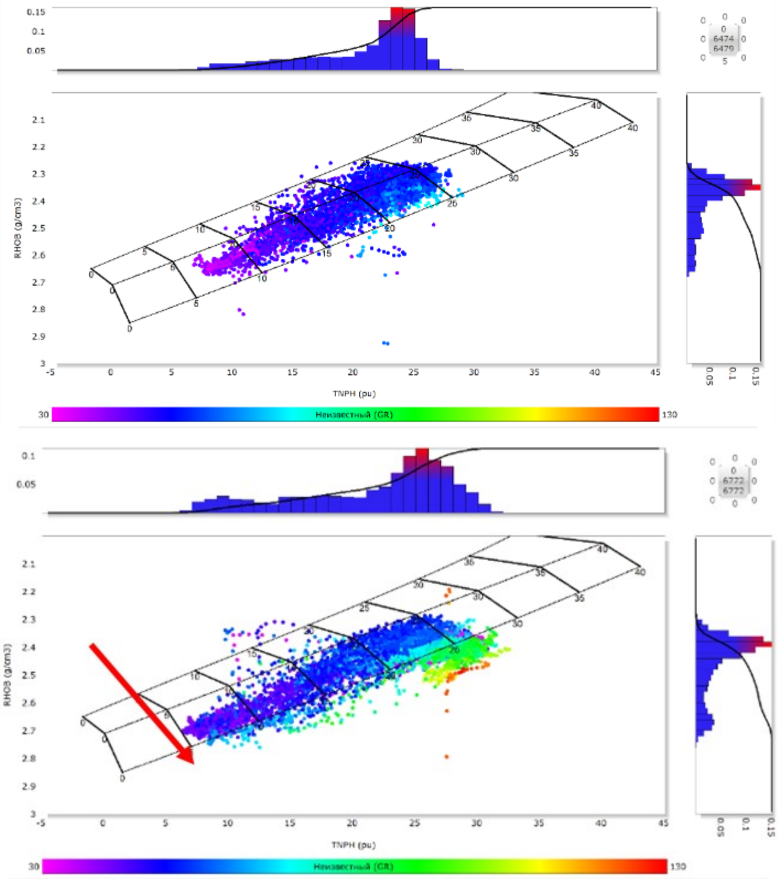


Figure 33. Data from two wells with the same LWD tool.

3.5 Photoelectric factor log

Photoelectric factor is usually obtained from a density tool. The difference between density and photoelectric factor is that in the latter the energy of registered gamma rays is lower (Figure 34).

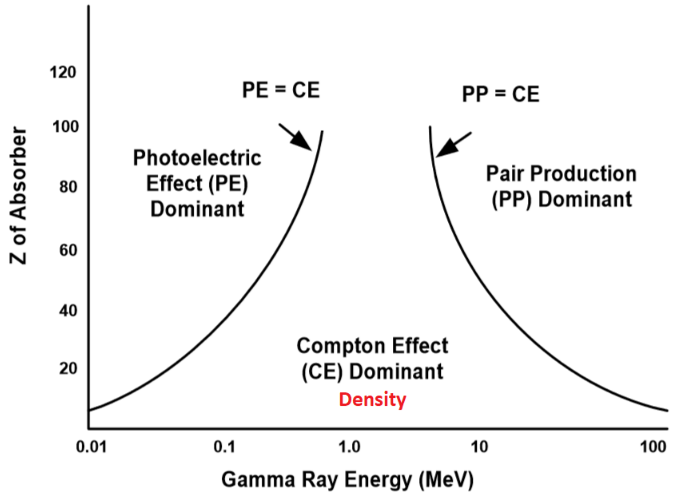


Figure 34. Gamma ray energy vs. the physical effect which is happening.

Photoelectric factor is calculated from the short-spaced detectors only (Jackson 2013).

The approach for assessing the quality of photoelectric factor is the same as described for gamma ray-neutron-density logs. The cross plot used is photoelectric factor vs. density in reverse scale with the coloring from gamma ray values. The problem with photoelectric factor is that mud-weighting agent influences PEF a lot. Table 7 shows values of photoelectric factor for the most widespread minerals and barite. When the mud is weighted with barite it is almost impossible to correct for that, thus photoelectric factor cannot be used for quantitative analysis.

Table 7. Photoelectric factor of some minerals (Crain's petrophysical handbook).

Mineral	**PEF, b/elec**
Quartz	1.82
Calcite	5.09
Dolomite	3.13
Kaolinite	1.47
Illite	3.03
Chlorite	4.77
Water	0.36
Barite	**226**

Figure 35 shows the influence of the barite on the acquired data (the lower cross plot). The data is shifted to the right due to strong influence of the barite on photoelectric factor.

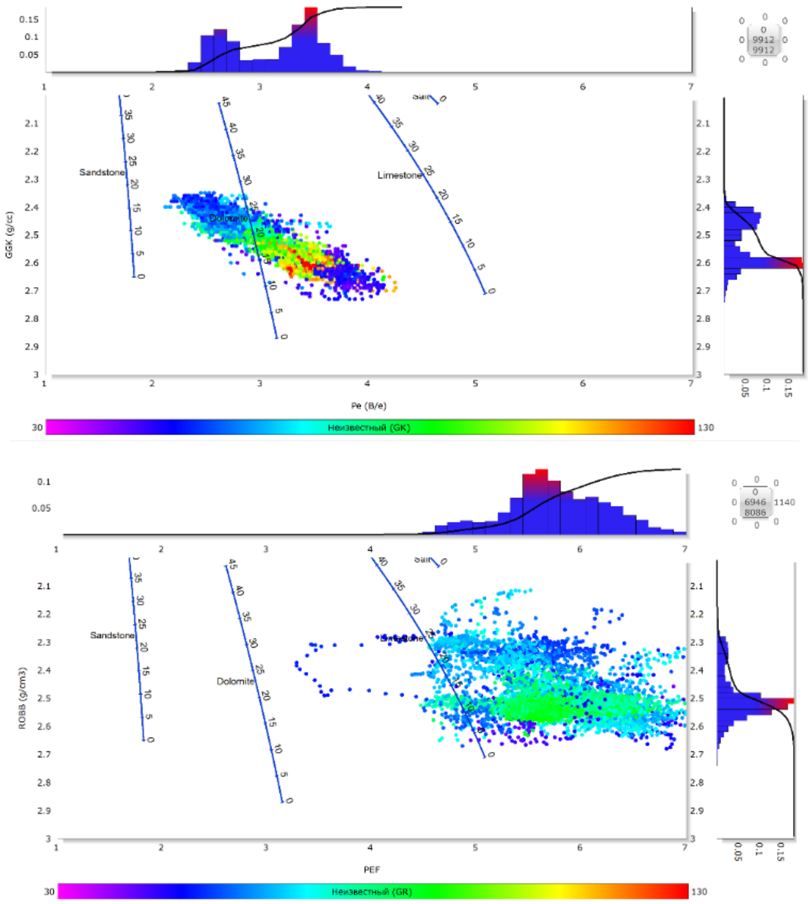


Figure 35. Influence of barite on the photoelectric factor.

3.6 Caliper log

Logging while drilling caliper could either be density or ultrasonic. Density caliper calculates the diameter of the wellbore based on delta-rho parameter (chapter 3.4). In order to acquire density caliper data, azimuthal variation of density log should be run in hole. Ultrasonic caliper calculates the diameter by measuring the transit time of a sonic wave through the mud.

In order to access the quality of caliper, histograms of diameter should be plotted. Distribution of the diameter is compared to the bit size.

If there is no indications of excessive washouts in the wellbore and the distribution of diameter shows larger values, the diameter is overestimated (figure 36, distribution in the middle).

Since the mud cake is not yet formed during LWD data acquisition (Boonen 2003), the diameter of the wellbore cannot be less than the bit size. If there are many data points with the diameter less than bit size, the diameter is underestimated (figure 36, the lowest distribution).

The distribution on the top of Figure 36 displays a good quality caliper.

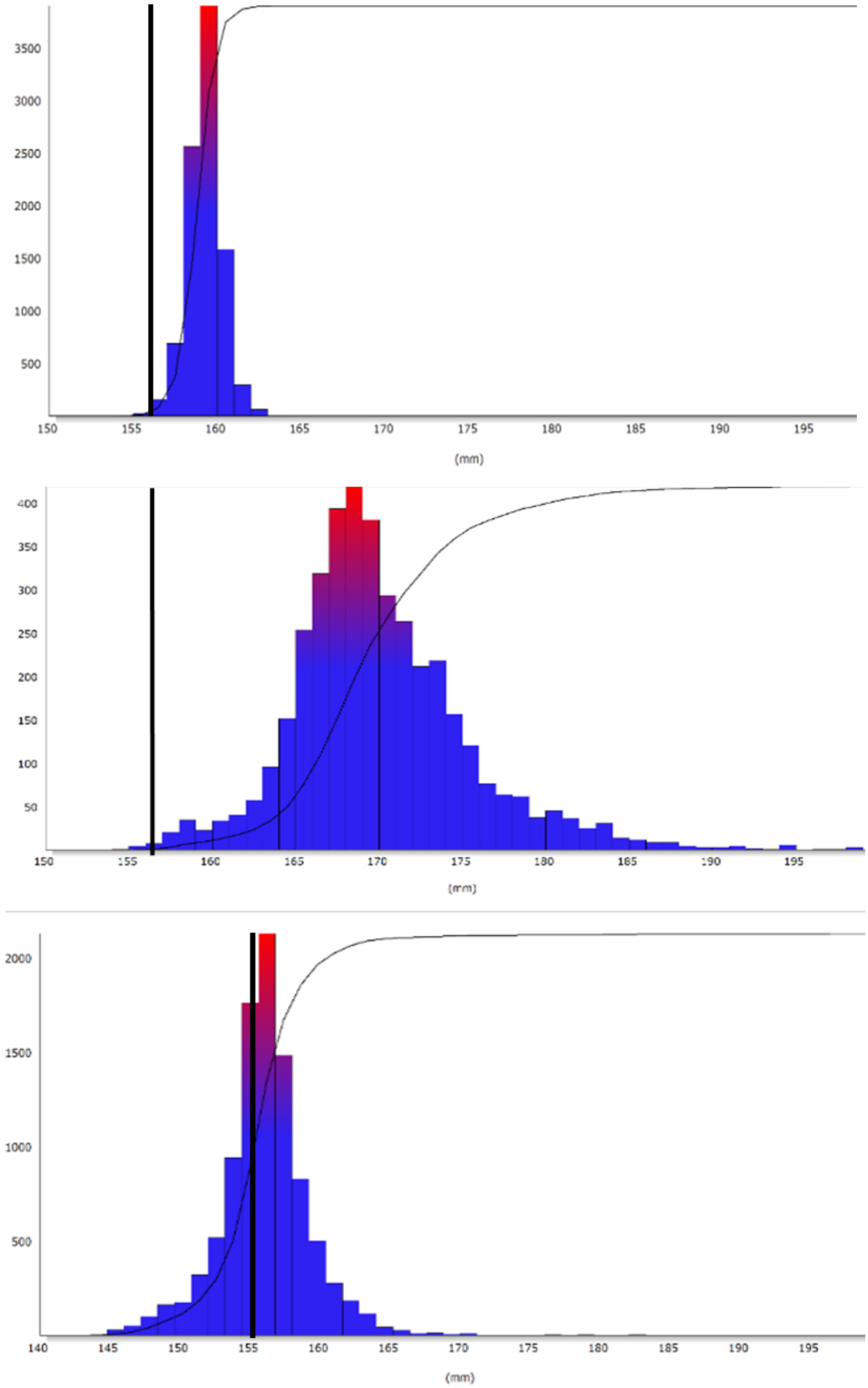


Figure 36. Examples of good quality overestimated and underestimated caliper. The black vertical line represents the bit size.

3.7 Acoustic log

An acoustic transmitter produces energy in the form of compressional wave, which travels through the mud to the formation, where it is either reflected or refracted at the borehole wall. Energy is retransmitted and arrives at the receiver as a composite wave that consists of:

- Compressional wave (P-wave).
- Shear wave (S-wave).
- Stoneley wave.
- Pseudo-Rayleigh wave. (Jackson 2013)

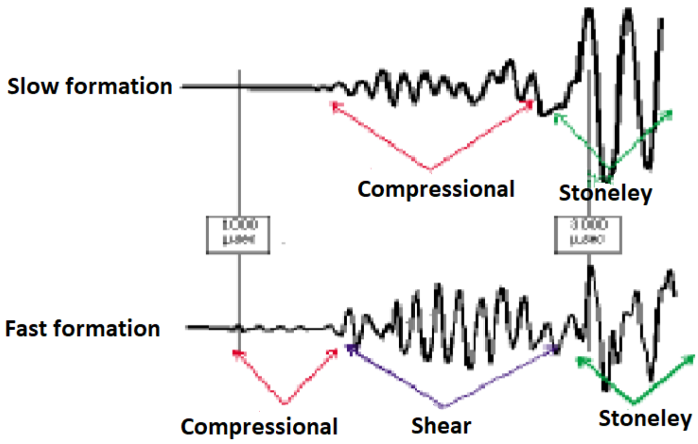


Figure 37. Typical waveforms arriving at the receiver (with the use of monopole devices).

Formations could be categorized into fast and slow.

Fast formations:

- Shear slowness < compressional slowness of the borehole fluid
- Refracted energy will propagate along the borehole

Slow formations:

- Shear slowness > compressional slowness of the borehole fluid
- No refracted energy will propagate along the borehole
- Shear slowness cannot be measured by monopole devices – can only use dipole (or quadrapole) (Jackson 2013).

Since full waveform is stored only in the tool memory and is not transmitted in real-time (Market et al. 2002), it is hard to construct a quick-look method for accessing the quality in real time. The problem is complicated by the fact than acoustic parameters are not only affected by formation lithological composition, but also by the type of porosity (primary or secondary), angle of formation dipping, anisotropy of the rocks, etc.

Modern acoustic tools have not one, but several receiving arrays. The arrival is computed for each receiver array separately and the correlation value is calculated, the nearer the correlation factors to one, the better the received data.

Figure 38 shows a QC display for the compressional wave. On the first track gamma ray is presented. On the second track compressional slowness calculated from front and back receiver arrays. Black line with black filling is the coherence (correlation). It is seen that coherence is high and close to one, meaning that the data is of good quality.

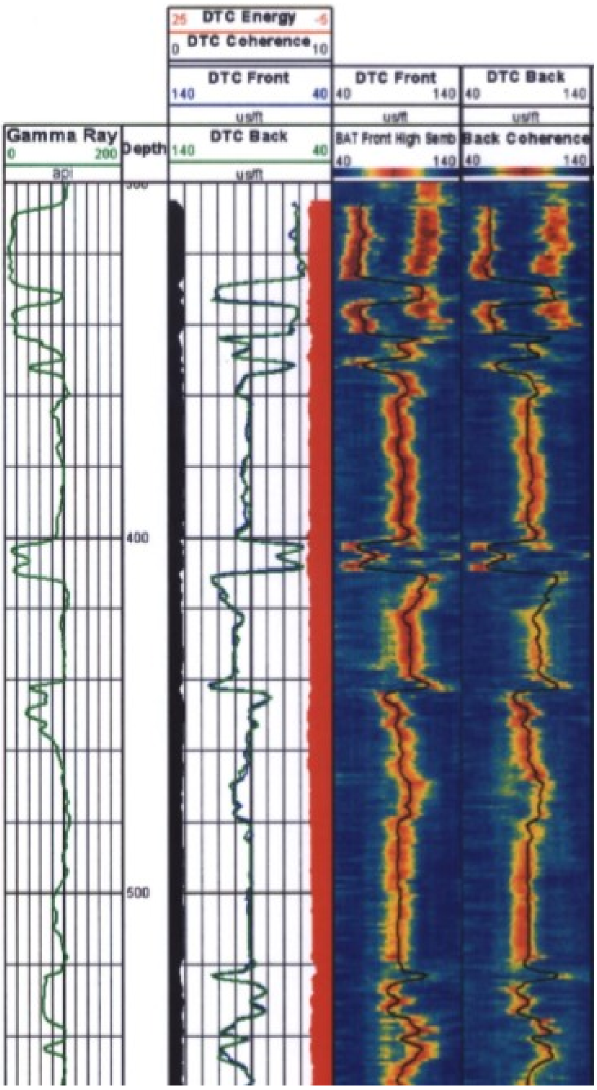


Figure 38. Compressional QC log (Market et al. 2002).

The following points could indicate a good quality acoustic data:

- Logging in the previous casing should be implemented with the slowness values of the compressional wave of 187 ± 7 us/m.
- No travel times less than 131 us/m should be observer.
- Correlation factor (coherence) should be always high and close to 1.
- If the marker bed are penetrated, they should read the values presented in Table 8.

Table 8. Average log values for marker beds (Jackson 1994).

Material	us/m
Anhydrite	164
Halite	220
Coal	328-394

3.8 Solution of direct and inverse problem in petrophysics

Solution of inverse problem in petrophysics is a determination of volumetric content of each component in a formation by solution of a system of equation (the properties of each element and values in the left side of an equation are known).

$$\begin{cases} \delta = \delta_{fl} * \varphi + \delta_{sh} * V_{sh} + \delta_{qz} * V_{qz} + \delta_{fs} * V_{fs} + \cdots \\ w = w_{fl} * \varphi + w_{sh} * V_{sh} + w_{qz} * V_{qz} + w_{fs} * V_{fs} + \cdots \\ PE = PE_{fl} * \varphi + PE_{sh} * V_{sh} + PE_{qz} * V_{qz} + PE_{fs} * V_{fs} + \cdots \\ \ldots \\ \varphi + V_{sh} + V_{qz} + V_{fl} + \cdots = 1 \end{cases}$$

Where V_{sh}, V_{qz}, V_{fs} – volumetric content of shale, quartz and feldspar respectively. φ is porosity of a formation, w-neutron porosity, PE-photoelectric factor and δ – density.

Any number of logs could be used in the system. The more the number of input value, the better. Although, some logs (e.g. acoustic, resistivity logs) could show non-linear relationship between the read value and the components. There could be any number of elements in the system. The only limitation is number of used logs for modelling. If the number of logs is less than the number of elements by more than one, the system becomes indefinite. In this case, it cannot be solved definitely, creating additional error in the output. If this method is used as a part of QC, the number of input logs should be equal or exceed the number of elements in the system, so the solution of the system becomes statistical and not deterministic, because the quality of the logs will be assessed by solution of direct problem.

The solution of direct problem is a calculation of the modelled response of each log with the known volumetric factor of each element. After that, the modelled log responses are compared with the acquired data and a conclusion about the quality is made.

For the usage of this technique for quality control a correct petrophysical model of a formation should be build. The number and properties of each element in the system should be measured on the core samples. If an incorrect petrophysical model is used, the technique will not show good results, since the inverse problem will not be calculated properly.

In the case of LWD data the following uncertainties could be encountered:

- Unknown properties of the formation fluid, because the invasion zone is not formed yet and the fluid in the logged volume of rock is a mixture of formation fluid and mud filtrate.
- Unknown properties of shales, since because of the mud influence they could change their properties (Jackson 1994).
- In horizontal wells in case of either angles between the wellbore and the formation being less than 5 degrees or thin layers in the formation, shoulder beds influence the response of the tools. The problem becomes more severe, because different logging methods have different depths of investigation and shoulder beds influence the methods differently.

Additional research should be carried out to build a correct petrophysical model for LWD data.

Figure 39 shows an example of direct problem solution. The black line on each track are modelled logs based on the acquired volumetric model of the formation, which was obtained by a statical solution of an inverse problem. On the tracks photoelectric factor, gamma-ray, neutron porosity and density are plotted. It is seen that neutron porosity and density are overestimated. The same conclusion could be made by looking on the neutron-density cross-plot (the reference data is presented in Figure 31). Neutron porosity is overestimated by 3-4% (cross plot in the lower left part of the figure). Density is overestimated by 0.07-0.1 g/cc.

This method cannot be considered to be a quick-look analysis. Also, a good petrophysical model of the reservoir with the consideration for differences between LWD and wireline data (most of the petrophysical models are build and analyzed withthe use of wireline data in vertical wells) should be available.

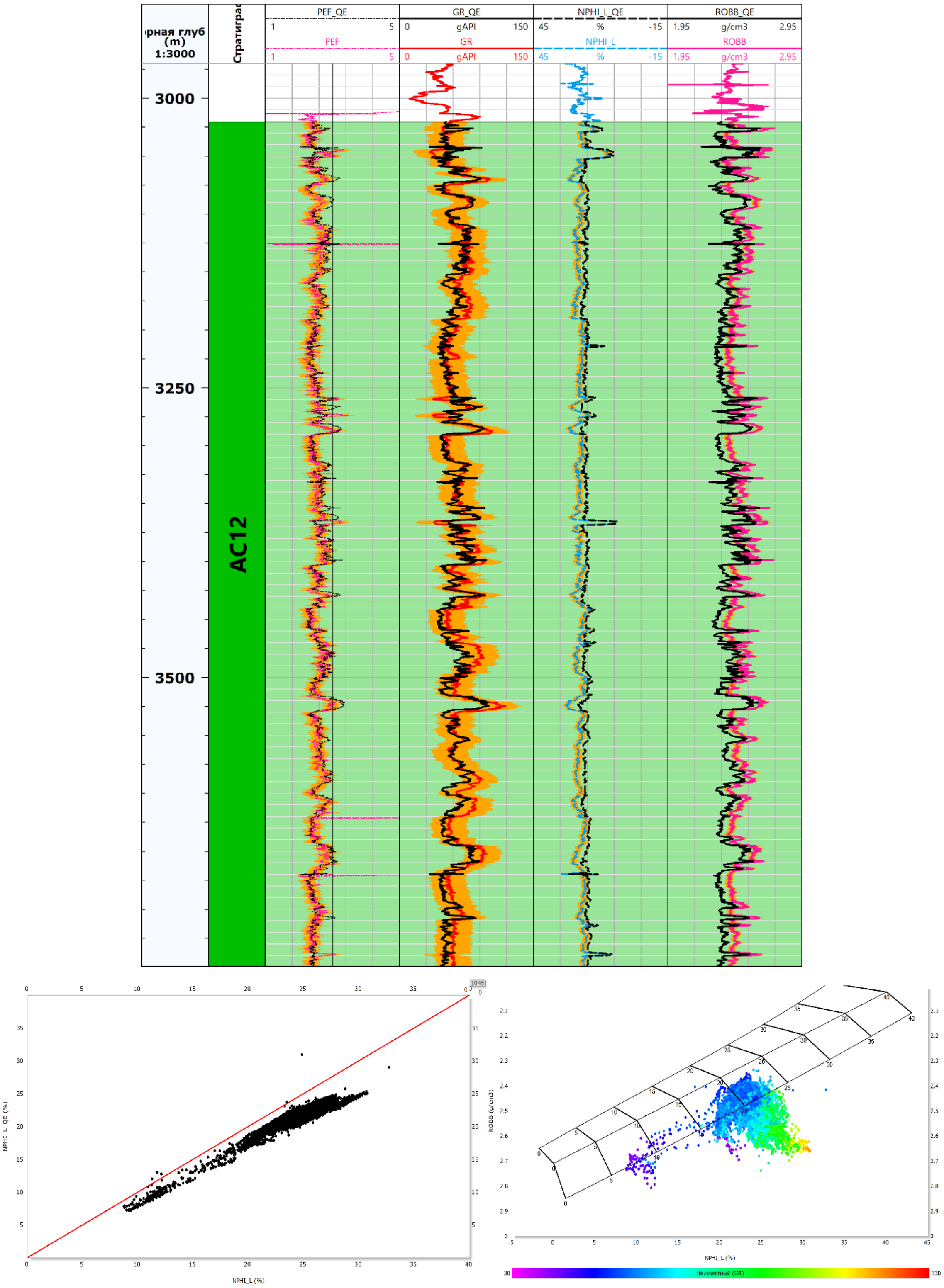


Figure 39. Example of solution of direct problem for quality control of the acquired data.

Chapter 4 System of LWD data quality control

It is quite common for physical parameters obtained from logging while drilling to be overestimated or underestimated; this is why this chapter is devoted to discussion of a proposed system of LWD data quality control in the form of a flowchart.

The first step of assessing the quality of data is to perform the following checks:

- Range check.
- Logic check.
- Continuity check.
- Spike check.
- Depth match check.

Range check is needed to control the units of the obtained data, adequacy of the physical values and the correspondence of the acquired data with the tool specification. For example, some of the attenuation resistivity tools have an upper limit for the measured resistivity of 200 ohmm, if the readings are consistently higher than 200, this means that the tool does not function properly. Another example is density of rocks. Density of siliciclastic rocks cannot be higher than 3 g/cc and less than 2 g/cc, if a tool read densities less/equal to 2 g/cc, or more/equal to 3 g/cc, it does not work properly. The same logic could be applied for almost any log. The data may not pass the range check because the units are mixed up. For example, in most cases GR reading cannot be less than 10 API, but in most cases in uR/h the readings will be in the order of 10.

Logic check is the check of inconsistencies between a number of logs. For example, it is known that the shale content generally increase density, neutron porosity and gamma ray readings, as well as decrease resistivity. If all of the logs indicate increase in shale content and one of them does not, there could be a problem with that log. Although, it should be noted that in complex geologies some of the logic check procedures may not work properly.

Continuity check is a verification that the data is obtained constantly without any interruptions. This check should always be done to real-time data, since problems with the telemetry systems are quite common. An indication that the continuity is poor is the presence of straight lines on the logs, which basically connect two data points, received at large distance between each other.

Spike check is needed to make sure that the tools work properly and there are no problems with the communication line. If the tool is unstable, there will be a lot of spikes on the acquired log.

Depth match check is needed to make sure that different log respond to changes in the formation and/or wellbore at the same depth. This is crucial, because modern well log analysis represents a holistic approach to all available logs.

Usually, a LWD field engineer performs all of the above-mentioned checks and it is quite unusual for the processed data to have these problems, but sometimes they are encountered.

After the above-mentioned checks passed, the quality of the main methods is accessed. Depending on the logs included, the quality of each method is controlled using the techniques described in Chapter 3.

Figure 40 describes the workflow of quality control.

Let us consider an example. The following LWD methods were registered while drilling:

- Caliper log.
- Density log.
- Neutron log.
- Gamma ray log.
- Photoelectric factor log.
- Resistivity log.

After the processed data is obtained, the following procedure should be implemented to assess the quality.

- Step 1: Range check, logic check, continuity check, spike check, depth match check. If the checks pass, move on to the next step.
- Step 2: Assess the quality of caliper using comparison of borehole diameter distribution with the actual bit size (additional information about excessive volume of cuttings is needed). If the resulting conclusion is poor quality caliper data, it could indicate the problems with all of the other logs, since environmental corrections to each log are applied based on the borehole diameter obtained from the caliper log.
- Step 3: Control the quality of neutron, density and gamma ray log with the cross-plot analysis.
- Step 4: To complete this step information about mud weighting materials is needed. If the mud was not weighted with barite, a cross-plot could indicate the problems in photoelectric factor. If the mud is weighted with barite, photoelectric factor log cannot be quality controlled and the data cannot be used in future analysis,
- Step 5: Since tools for obtaining borehole images are not included, the tool centralization cannot be checked.
- Step 6: Assess the quality of resistivity logs by checking relative position of sondes with different depths of investigation and by checking the regions with off-scaling values.

- Step 7: If all of the checks pass, the conclusion is that the obtained data is of could quality and can be later used in the analysis without any limitation. If not all of the checks pass, a geosteering engineer and/or petrophysicist working with the data should immediately contact the field engineer to understand why the acquired data is of poor quality. After the problem was identified and solved, the data could be used for future analysis without limitations. If the problem cannot be solved, the data should be used with some limitations and understanding that there are some problems.

Let us consider another example, where only the following logs have been registered:

- Gamma ray log.
- Resistivity log.

This combination of logs is usually used in simple geological conditions, where gamma ray log certainly indicate reservoir/non-reservoir rock and resistivity log indicate the hydrocarbon/water bearing formations.

To assess the quality of the logs the following procedure should be implemented:

- Step 1: Range check, logic check, continuity check, spike check, depth match check. If the checks pass, move on to the next step.
- Step 2: Since only GR log is available, it is not possible to use complex cross-plot analysis, this is why only comparison with gamma ray readings in adjacent well is possible. Even though it is quite hard to tell whether or not the readings are overestimated or underestimated by a small degree, it could generally show if the over-/underestimation is large.
- Step 3: Assess the quality of resistivity logs by checking relative position of sondes with different depths of investigation and by checking the regions with off-scaling values.
- Step 4: Step is similar to step 7 from the previous example.

Depending on the number of logs, number of steps of quality control could vary (from three in case only GR is obtained to eight when all of the methods presented in the flowchart are received).

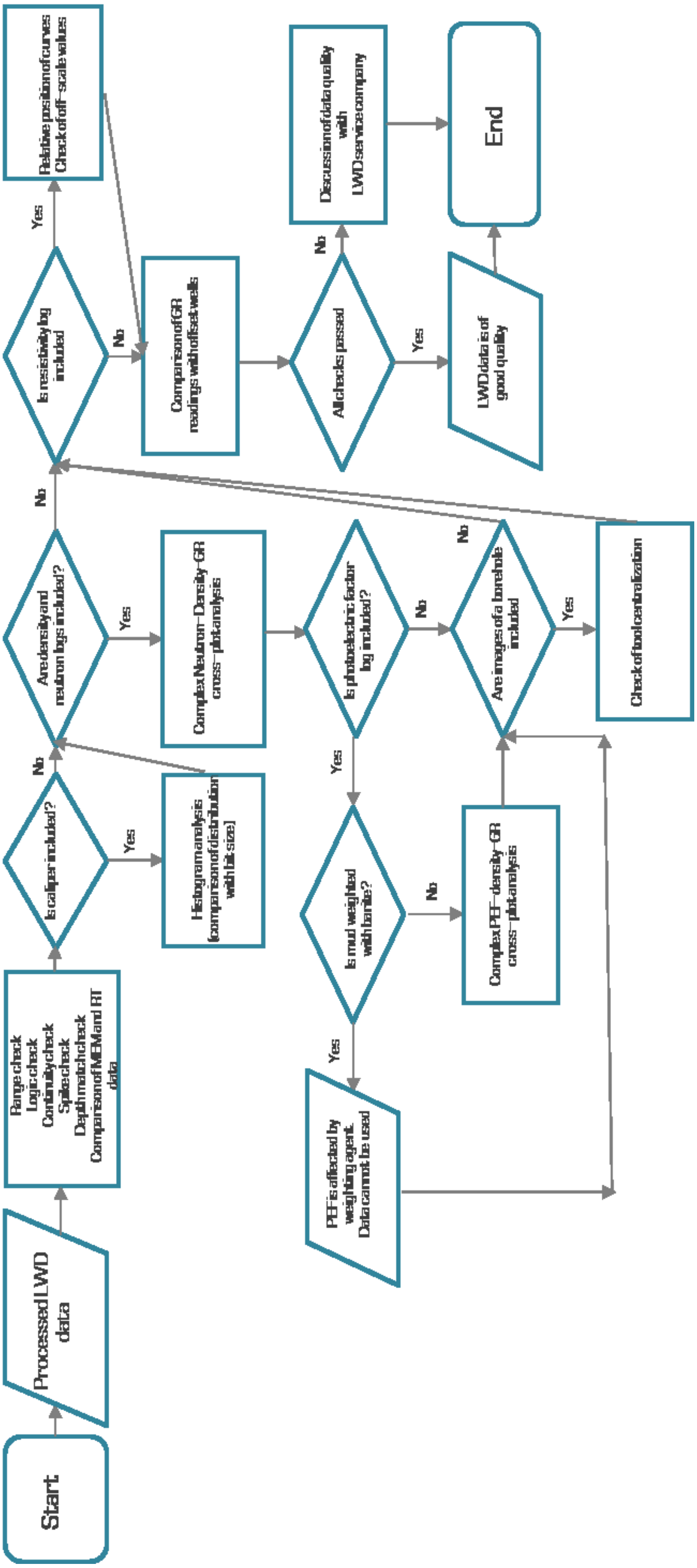


Figure 40. Flow chart of LWD quality control.

Table 8 could be used by the representatives of oil and gas producing companies to control the quality of each LWD method and gather more thorough statistics about each tool and service companies, which could later be used when planning which tool to run in the next wells.

Table 8. Check list for LWD data quality control.

Log	**GR**	**Neutron**	**Density**	**…**
Tool type				
Tool diameter				
Tool serial number				
Tool calibration				
Range check, units check				
Depth matching				
Spike check				
Noise				
Percentage of intervals with absence of data				
Repeating of readings in the same intervals				
Underestimation/ Overestimation of the parameter				
Other remarks				
Overall score				

Chapter 5 Consequences of poor quality LWD data

Consequences of poor LWD data usage could be categorized into two main groups:

- Incorrect calculations of parameters (porosity, permeability, elastic properties, etc.)
- Poor decision-making in geosteering.

Incorrect calculations of parameters could be further divided into the following problems:

- Calculation of porosity and permeability.
- Calculation of expected oil/gas rates from the well.
- Calculation of elastic properties.
- Uncertainties in completion

5.1 Calculation of porosity and permeability

The petrophysical model of a formation is usually built based on core and wireline logging data in vertical wellbores. When approaches from vertical wellbores are applied to horizontal wells with LWD data, it leads to a number of difficulties and uncertainties. For example, calculation of porosity from density log depends not only on the density of rock matrix, but also on the density of formation fluid. When calculating the porosity of a rock from density log, one could assume the density of formation fluid to be equal to density of mud filtrate, since the invasion zone is fully developed. Upper picture in Figure 41 shows dependence of porosity calculation on density of formation fluid. Horizontal red line divides the plot into two parts: non-reservoir rock (upper part) and reservoir rock (the porosity cutoff value is taken from the petrophysical model of this rock). Variation in density of formation fluid lead to uncertainties in porosity estimation from density log. The case is even worse with the permeability of the rock, since in most cases the only way to evaluate the permeability from logs is through porosity-permeability correlation and the correlation is usually exponent.

The above-mentioned problems add difficulty to estimation of permeability and porosity from LWD logs. If, on top of that, parameters are over- or underestimated, it could lead to completely erroneous conclusions. For example, if the actual density of a rock is 2.35 g/cc and the obtained density is 2.4 g/cc, the difference in porosity will be 3 percent and the permeability will be four times lower. Moreover, a layer with density of 2.4 g/cc is considered non-reservoir, according to porosity cut-off value, on the contrary, a layer with density of 2.35 g/cc is a reservoir rock.

The following formula for correlation of porosity-permeability was used:

$$PERM = 0.0031 * e^{0.4307*100*POR}$$

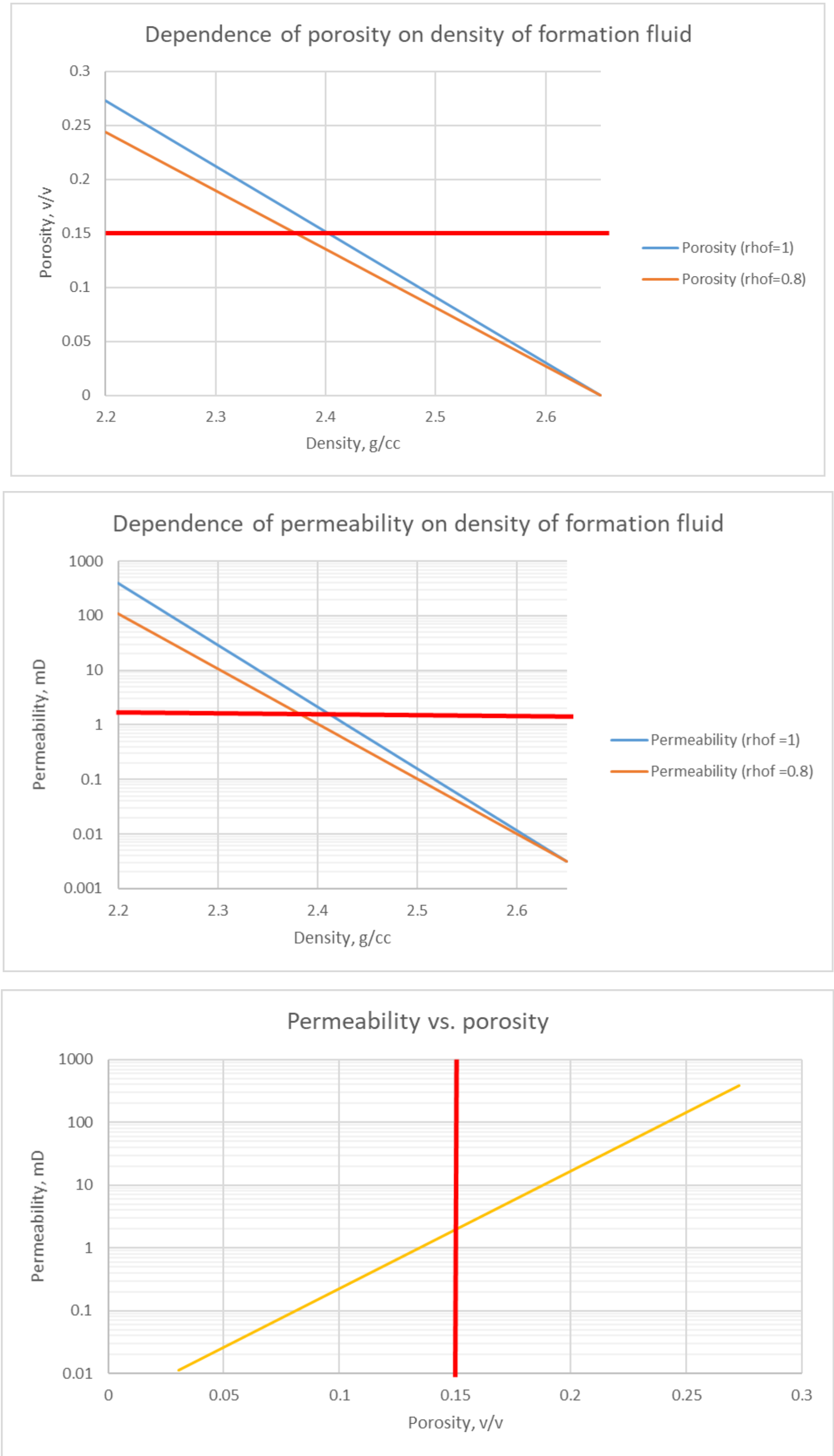


Figure 41. Dependence of porosity and permeability on density of formation and formation fluid.

5.2 Calculation of expected oil/gas rates from the well

During the well drilling at some points expected oil and gas rates from this well are calculated in order to understand whether or not the well could produce the planned amount of hydrocarbons. A formula to calculate a flow rate from a horizontal well was proposed by S. Joshi. The formula is presented below (Joshi 1988):

$$Q = \frac{2\pi kh\Delta p}{\mu\left[\ln\left(\frac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right)+\frac{h}{L}\ln\left(\frac{h}{2r_c\pi}\right)\right]}$$

Where $a = \frac{L}{2}(0.5 + \sqrt{0.25 + \left(\frac{2r_{eh}}{L}\right)^4})^{0.5}$

The formula was adapted for one of the fields in which the quality of LWD data was analyzed (Mukhametshina 2005).

$$Q = \frac{2\pi kh\Delta p}{\mu\left[\ln\left(\frac{4R_k}{L}\right)+\frac{h}{L}\ln\left(\frac{h}{2\pi r_c}\right)\right]}$$

Permeability and net pay thickness during the process of drilling can be estimated directly from the LWD data. In the previous chapter it was shown that an error in density in 0.05 g/cc could lead to mistakes in porosity up to 3%, which lead to mistakes in permeability up to 30 %. Consequently, uncertainty in flow rate could be up to 30%, because the relationship between permeability and flow rate is linear. The case can be much worse the net pay thickness is also estimated with an error.

All of that could lead to wrong decisions during gesturing of either stopping of drilling in case permeability is overestimated or continuing the drilling in case permeability is underestimated.

5.3 Calculation of elastic properties

Input LWD data for 1D geomechanical modelling in the simplest example include the following logs:

- Density log.
- Acoustic log (P-waves, S-waves).
- Gamma ray log.

The first two logs are used to estimate dynamic elastic properties, which are later converted in static ones using correlations obtained from core studies. Gamma ray log is used to calculate friction angle.

The following formulas are used to calculate dynamic elastic properties of rocks from log data (Zoback 2010):

$$E = \frac{\delta V_s^2(3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} - Young's\ modulus$$

$$\vartheta = \frac{V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} - Poisson's\ ratio$$

Where δ is density of rock, V_p and V_s are compressional and shear velocities respectively.

The correctness of input parameters influence the outcomes of geomechanical modelling quite a lot. Figure 42 is an example of how 1D model could change with only a slight change in input density (all of the other parameters are kept constant). The middle picture is the actual model, built on the accurately received density log. In the left picture, density was underestimated by 0.1 g/cc; we can clearly see that the estimated mud window became narrower. In the right picture, the density was overestimated by 0.1 g/cc; it is seen that the mud window became wider.

Inaccurate measurement of density could influence the choice of mud density and depths of casing setting. The case becomes more severe in horizontals wells, because acoustic log is rarely included in the LWD system, so the velocities are modelled.

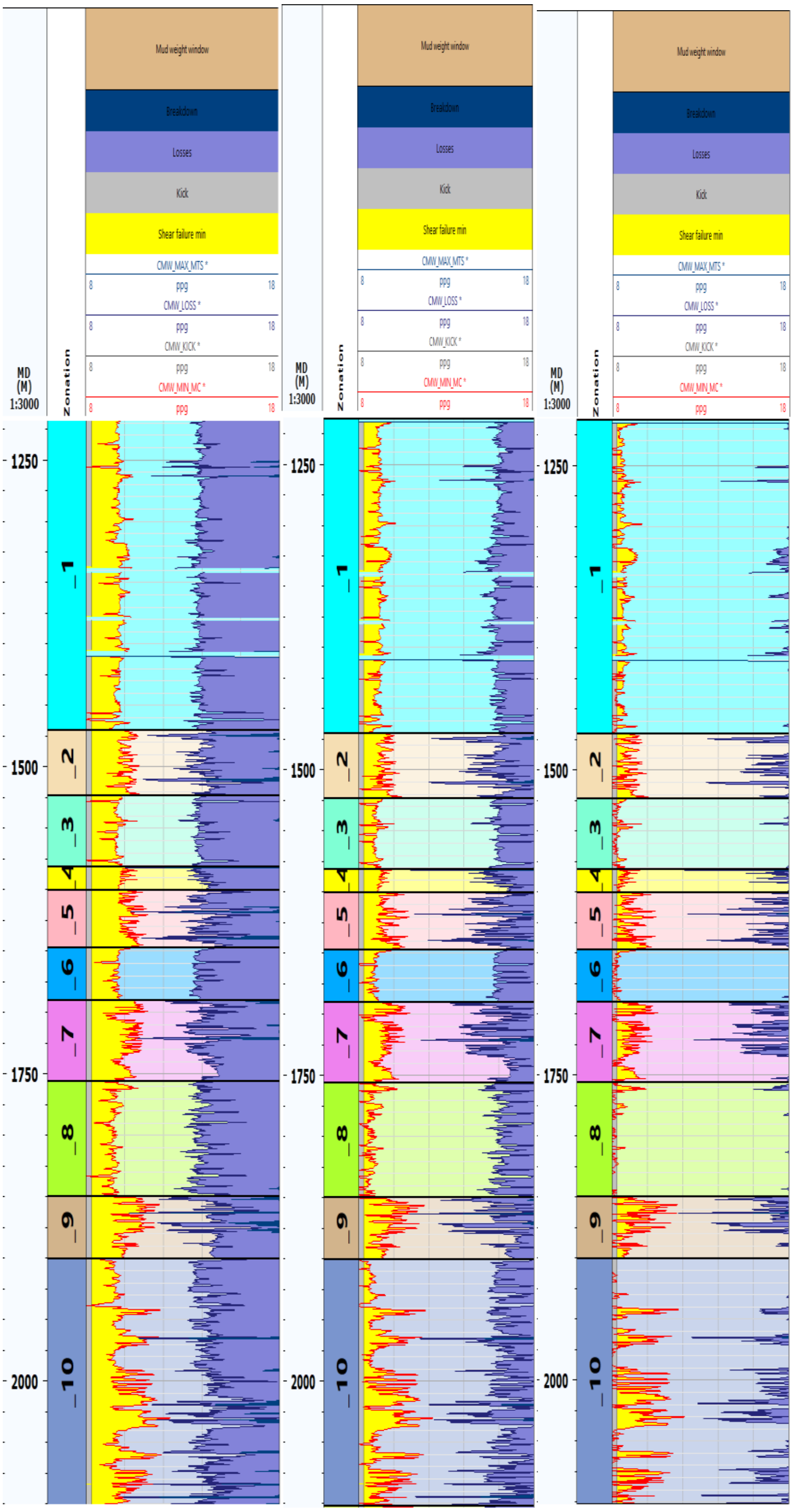


Figure 42. Examples of 1D geomechanical models with different input densities. The left model was built with the density underestimated by 0.1 g/cc, the right one – overestimated by 0.1 g/cc. The model in the middle is calculated using the actual values of density.

5.4 Uncertainties in completion

Since in most cases logging while drilling is considered as a viable alternative for wireline logging, in most of the wells LWD is the only logging survey, which will take place. So, depending on the results of this survey completion systems will be selected and adjusted.

One could encounter the following problems when making decisions about completion using poor quality LWD data:

- Incorrect assessment of the excess cement needed to cement a well. This could be because of poor quality caliper data, because the volume of cement can be calculated rather precisely, especially if there was a relog of caliper tool after the drilling of a whole section.
- Sometimes it becomes hard to understand where to put fracports if the well is supposed to be hydraulically fractured.
- The choice of perforation intervals could also be hard, because in some cases poor quality data does not give an opportunity to differentiate gas zones from oil zones.

5.5 Poor decision-making in geosteering

All of the above-mentioned problems could lead to mistakes while geosteering, this include:

- Placement of a borehole in parts of formation with low permeabilities.
- Incorrect decisions of either stopping a well prematurely or continuing drilling with risks, even though it was not needed.

An example of the latter mistake is described further.

A well was drilled to TD of 2000 meters. A decision was made to continue drilling to TD of 2200 m, even though permeability was underestimated and there were no need to do so. Problem was complicated by the fact that during landing, directional drilling engineers made a mistake, creating dogleg of 15 degrees/30 meters (Figure 43, depth 1650 m), thus creating additional torque and drag problems. A model presented in Figure 44 shows that after 2000 meters problems with torque and drag were expected. Nevertheless, the drilling was continued and stopped only at TD of 2134 meters because of T&D problems and the fact that shales were drilled through.

The drill sting components and parameters of the calculation are presented in Table 9 and Table 10.

Table 9. Drill sting components.

Drillsting component	**Diameter (OD/ID), mm**	**Weight of the element**	**Length (m)**
Drill pipe	89(80)	21.4 kg/m	2078.8
Drill collars	108(52)	51 kg/m	12.0
Non-magnetic drill collars	120 (52)	1500 kg	17.0
MWD/LWD	120(52)	2000 kg	20.0
Mud motor DR-120	120	400 kg	6.0
PDC bit	142.9	15 kg	0.2

Table 10. Parameters of the calculation

Density of mud	1.1 g/cc
Friction factor (casing)	0.3
Friction factor (open hole)	0.4
WOB	90 kN
Torque at the bit	3.1 kN*m

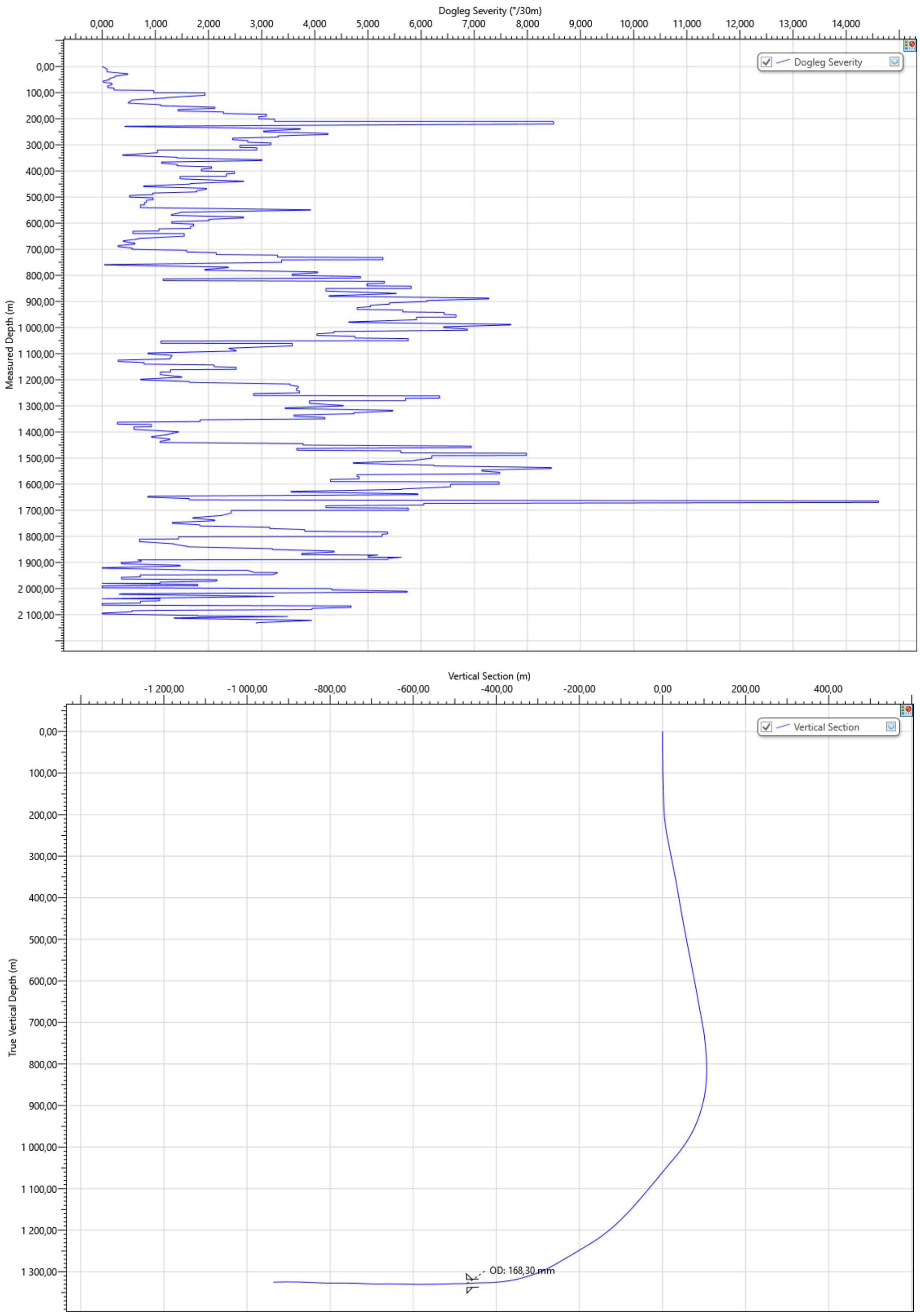


Figure 43. Dogleg along the well under discussion and its trajectory.

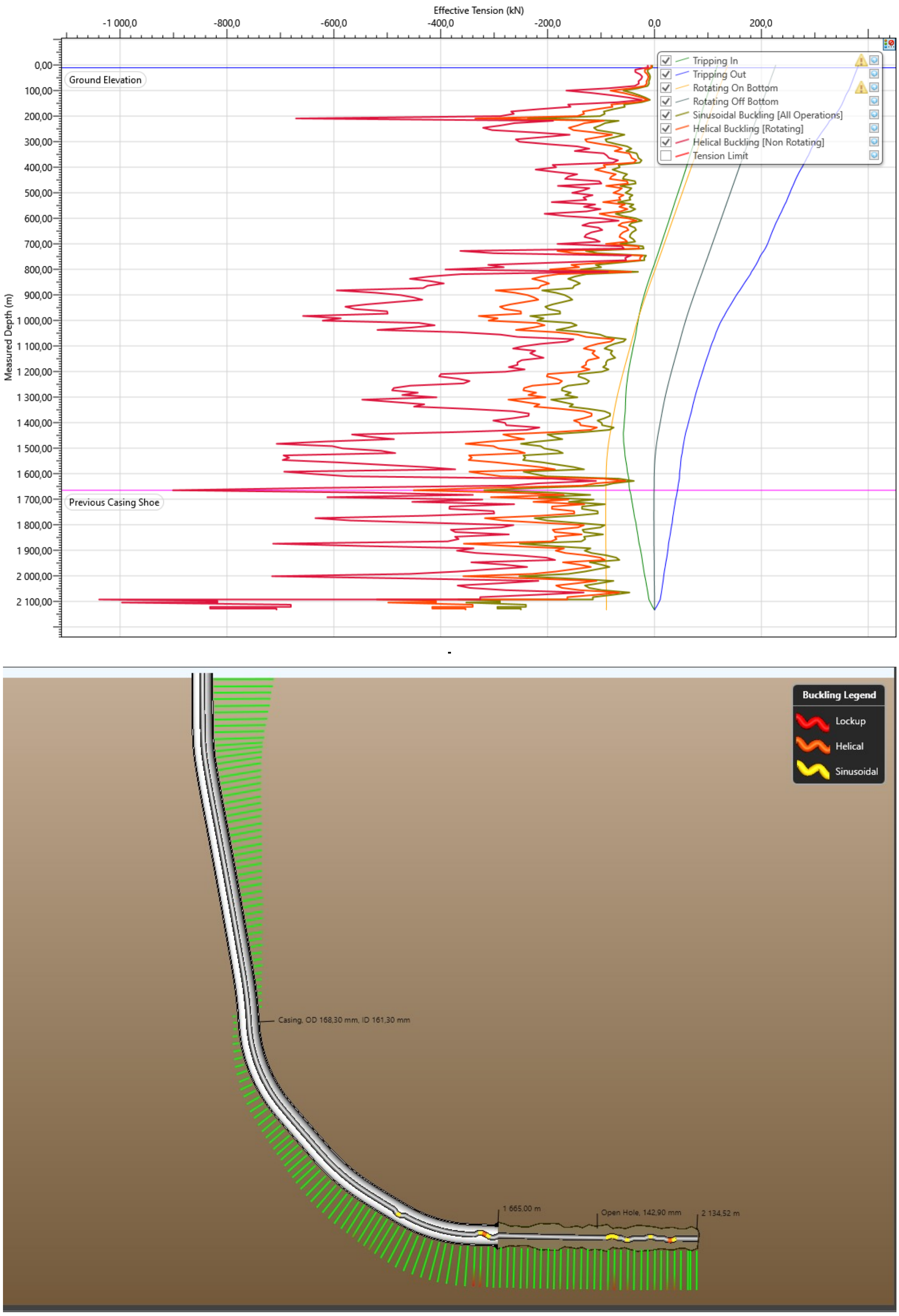


Figure 44. Torque and drag analysis.

5.6 Economic losses because of poor quality LWD data

To evaluate how much money a company could lose because of poor LWD data quality let us make the following assumptions:

- The number of horizontal wells drilled per year – 1000.
- The percentage of wells where a decision to stop drilling because of overestimation in permeability was made – 5% (corresponds with the percentage of well with the LWD data quality, which cannot be used for quantitative analysis from Chapter 1)
- Underestimation of porosity by 3%, which lead to underestimation of permeability and expected rates by 30 %.
- Mean rate of wells in the company - 500 barrels a day.

Multiplying all of the parameters one could arrive at the number of 2.7 million barrels per year. This means that only because of poor quality of LWD data a company, which drills 1000 horizontal wells, could lose 2.7 million barrels of oil yearly. Taking the oil price of 70 USD/barrel, this transforms into almost 200 million USD per year.

In order to minimize these loses, no additional money is necessary to be spent, the only thing, which needs to be done, is independent quality control of the obtained values from LWD service companies.

Chapter 6 Normalization of physical properties in horizontal wells

In most cases it is not economically viable to pull out of hole when the parameters received from LWD tools in real time are little over- or under-estimated and are sufficient for qualitative goals. In order to estimate rock properties more precisely a normalization of physical properties should be implemented.

Five techniques are discussed below. These are:

- Normalization to offset vertical wells.
- Normalization to offset horizontal wells.
- Linear shift of data.
- Normalization of data to synthetic logs acquired in pilot holes.
- Usage of 3D cross-plots for data normalization.

Normalization of LWD data to offset vertical wells usually does not show good results for the reasons discussed in Chapter 2. The main reason is reservoir heterogeneity and the fact that offset vertical wells are often located some distance from the horizontal well in question. Figure 46 shows an example of density normalization in a horizontal wellbore to the wireline data obtained from a vertical well. The normalization was done only using the data from the reservoir rock. Top picture in the Figure is obtained LWD density-neutron porosity-gamma ray. The bottom picture shows normalized density data. It is clearly seen that most of the density points shifted to the region of 2.5-2.6 g/cc, because the reservoir rock, penetrated in the offset well had this range of densities. Usage of this technique can lead to lithology information loss and erroneous estimation of rock properties.

Normalization to offset horizontal wells is a better option, especially if the wells were drilled from the same pad. This method would work better, if the wells were placed in the same parts of the reservoir, but in most cases, even wells from the same pad could be in different reservoir zones or even lithologies (see Figure 19). This is why this method is not the most optimal.

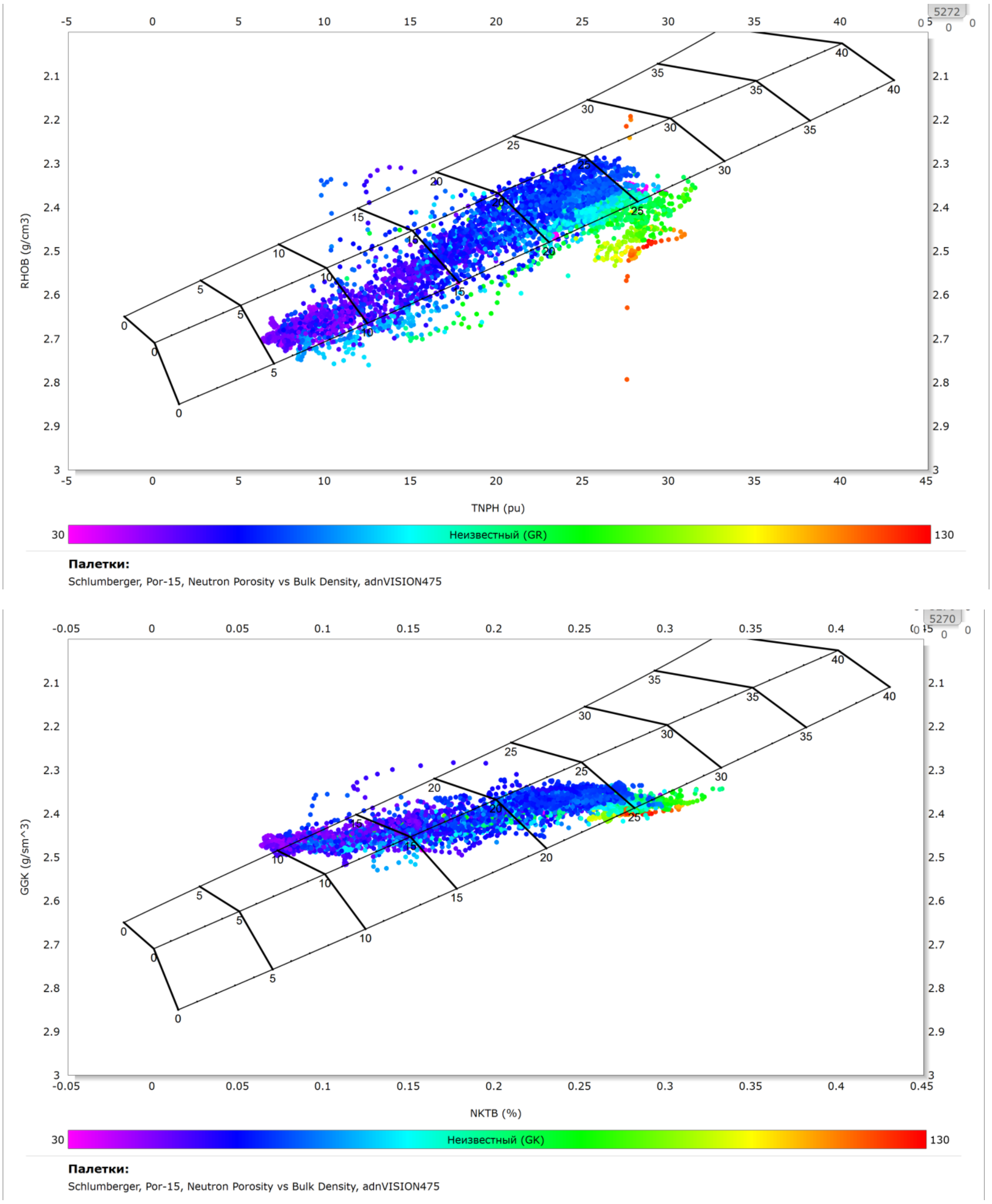


Figure 45. Example of normalization to an offset vertical well.

Linear shift of data to the point where location of data on the cross plot corresponds with the reference wells is another technique. The problem with this approach is the fact that in most of the logging tools correlation between responses to the environment and the physical properties is not linear (calibration curve is not linear). For example, when shifting gamma ray log, lower values should be shifted more compared to the higher values. Another problem is that this technique is hard to implement automatically, because each dataset requires unique value of shifting. Figure 47 shows an example of this kind of normalization. The top picture is a reference well within the same formation with good quality of data. The picture in the middle is a cross plot of original data. The on the bottom is data after a linear shift. In can be seen that even though the normalized data corresponds nicely to the tight low porosity layers, it corresponds poorly with the region of shales. This happens because of non-linear calibration curves of the LWD tools.

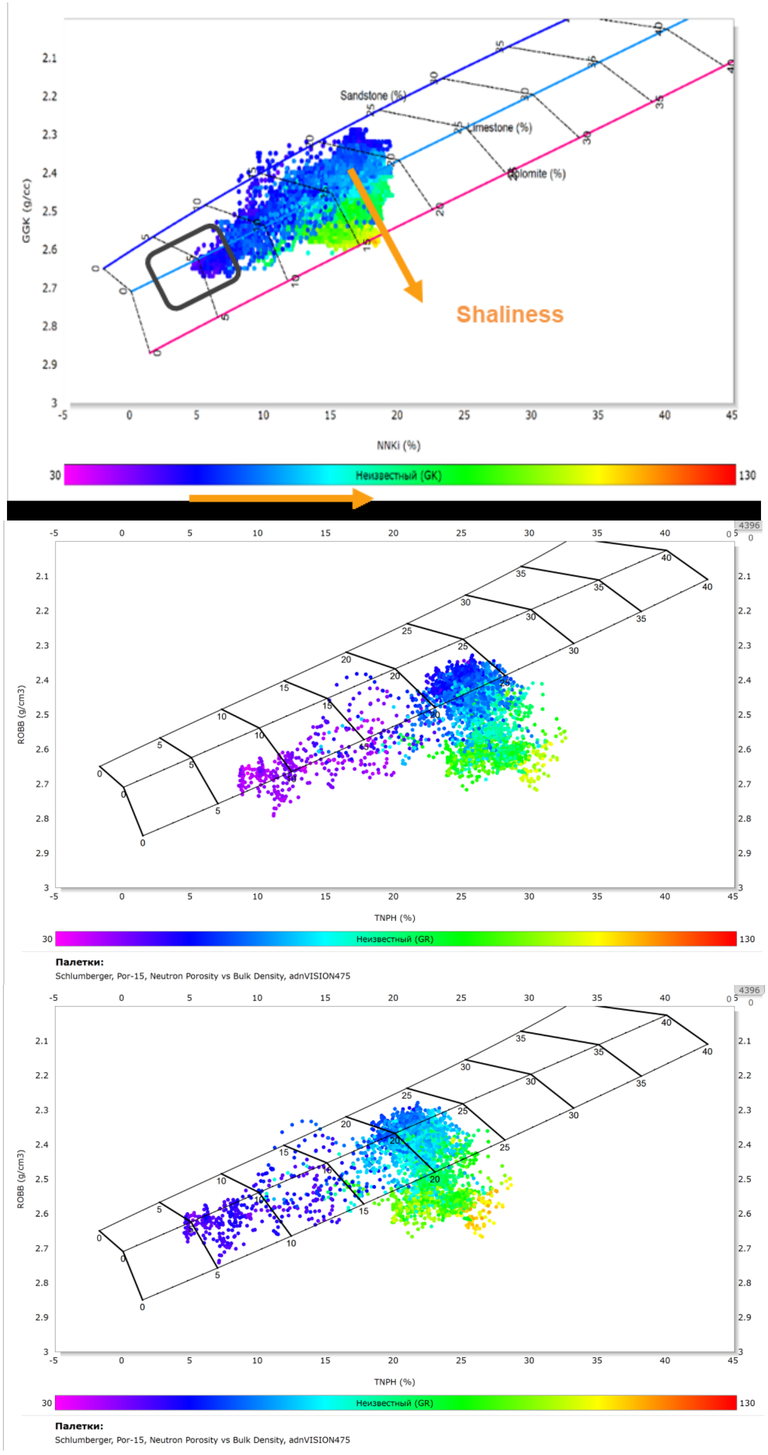


Figure 46. Example of a linear shift.

Chicheng et al. 2016 proposed a method of normalization when the GR log data is normalized to synthetic gamma ray readings, modelled along the borehole. The following steps are taken to obtain a normalized log:

1. Apply standard normalization workflow for the vertical wells.
2. Synthesize gamma ray readings from the pilot hole to the horizontal well using true stratigraphic projection method.
3. Equalize mean and standard deviation of the acquired log to the projected GR log.
4. Use normalized GR logs for analysis. (Chicheng et al. 2016)

In my opinion, this method would work rather good when a pilot hole is drilled prior to horizontal drilling to obtain the reservoir properties in a vertical section as close to the horizontal well as possible and reservoir has little heterogeneity in horizontal direction. If these conditioned are not fulfilled, we would get similar to Figure 46 results.

The proposed method for data normalization is usage of 3D cross-plots (Figure 48). They are similar to the conventional neutron-density cross plots, the only difference is that along the third axis GR readings are plotted. After that two trend lines are constructed. The first comes from the region of tight layers and the second from the region of shales. The characteristic point is the intersection of these two lines. This cross plot should be constructed for data in a reference well or a number of wells, plotted on the same plot. After that the trend lines are plotted. Then the same procedure is done to the data from the well in question. If the trend lines lie within the tolerance limit, the data well not be normalized. If the trend line from a new well does not correspond with the line from the reference wells, the data s shifted until the trend lines and their intersection lie within tolerance limit. The shortest distance from each data points to the trend lines should be kept constant. Non-linear trend lines could be used. Which kind of trend lines to use should be determined for each formation.

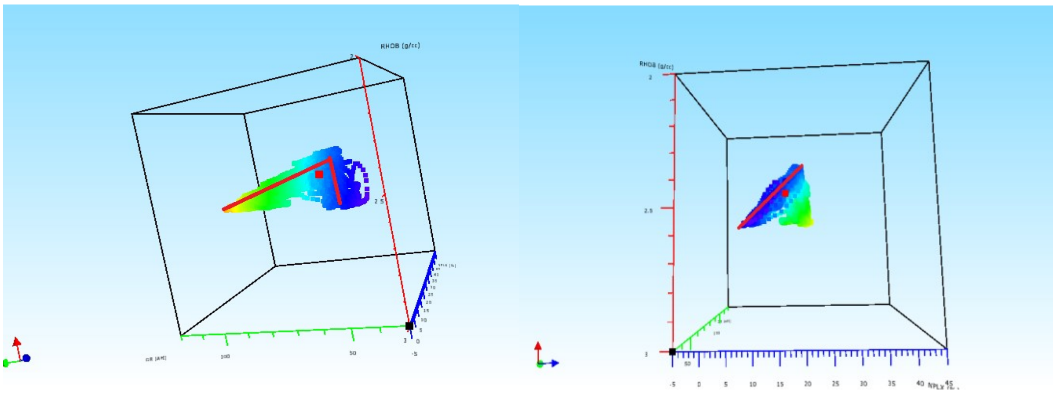


Figure 47. Example of a 3D cross plot.

Figure 48 shows an example of such normalization. The data used in normalization is the same as in figure 47. Notice how the data corresponds better for both regions of shales and tight layers. The pictures are in the same order as in Figure 47.

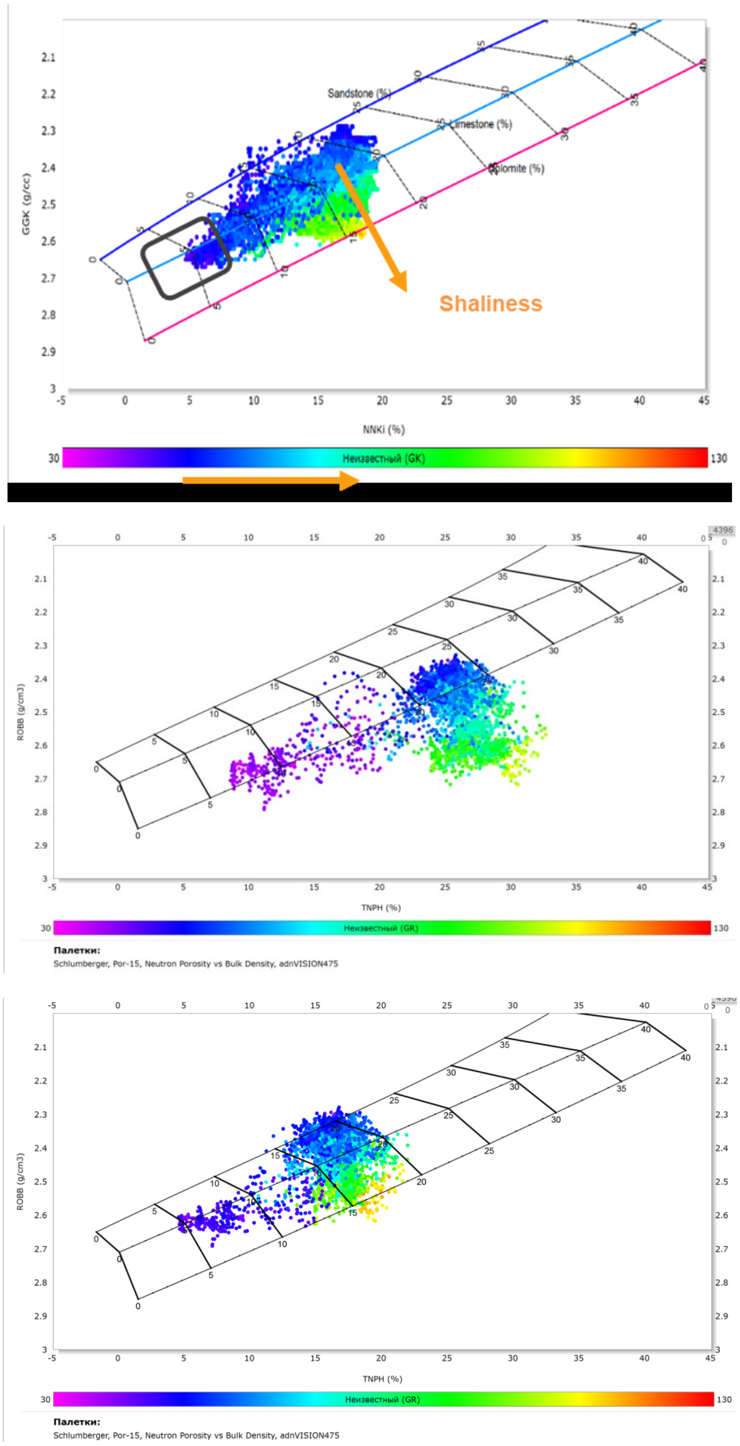


Figure 48. Example of normalization with the usage of 3D cross-plots.

Chapter 7 Conclusion

Controlling the quality of physical values obtained from logging while drilling tools in horizontal wellbores is a challenging endeavour. However, it should be done, because poor quality LWD data lead to a number of problems, described in the thesis. This is why, approaches to assess the quality of different LWD methods are discussed and a system, which could be used to control the quality of data, is presented. Since, in most cases, it is not economically viable to pull out of hole tools, which read incorrect values, to understand the reasons and solve them; approaches to normalize the data are considered in order to evaluate properties of the rocks more precisely and make reasoned decisions while geosteering.

Future work in the field could be connected with the digitalization of the proposed system and approaches of data normalization to decrease the time needed to make a decision in the process of geosteering.

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Acronyms

LWD	Logging while Drilling
GR	Gamma Ray
DOI	Depth of Investigation
TD	Total Depth
T&D	Torque and Drag
USD	United States Dollar
PEF	Photoelectric factor

Symbols

δ	density	[g/cc]
w	neutron porosity	[%, v/v]
PE	photoelectric factor	[b/elec]
V	volumetric content	[%, v/v]
ΔT	compressional slowness	[us/m]
k	permeability	[mD]
V_p	velocity of compressional wave	[m/s]
V_s	velocity of shear wave	[m/s]
φ	porosity	[%, v/v]

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