Data Mining: Caliper Prediction Based on Gamma Logging while Drilling

Shaolong Jiang*, Supervision & Consultancy Center, CNOOC, Tianjin, China; **Guoqiang Zhang**, Well Construction and Intervention Center, CNOOC, Tianjin, China; **Renguo Yuan**, **Xin Li**, and **Enlong Feng**, Supervision & Consultancy Center, CNOOC, Tianjin, China

Abstract

During offshore drilling and completion operations of production adjustment wells, logging while drilling (LWD) is often adopted to improve the timeliness of drilling. In order to provide more reliable decision-making basis under limited data conditions, a study on data mining is needed. By collecting and analyzing 55 sets of data on wells in the PL block of Bohai Oilfield, the main controlling environment factors of the gamma geophysical response were identified. And based on adjacent well interpolation prediction, a mathematical model of predicted gamma/measured gamma difference versus caliper curve was built. This model was applied to E59 well, providing a decision-making basis for its subsequent casing running operation. It is found that: (1) with increasing potassium ion concentration and mud specific gravity, the geophysical response of gamma logging while drilling (GLWD) increases gradually; potassium ions have the most significant influence on gamma, and the influence increases with increasing caliper; (2) the caliper prediction model built based on the gamma-difference scatter fitting function and measured caliper has some engineering applicability in PL Block; (3) the in-depth mining of the GLWD geophysical response data is of directive significance to field drilling and completion operations, yet various sources of data need to be utilized for comprehensive analysis. The successful application of this method provides an idea for accurately guiding drilling and completion operations, a way to increase the utilization rate of logging data, and an important technical support to increase reserve and production and promote engineer-geology integration in the Bohai Sea.

Introduction

In modern offshore drilling and completion operations, LWD is usually adopted to lower production cost and improve operational safety and quality. Due to the limitation by the features of LWD and in order to reduce the operation cost of the development adjustment well, there are generally only two curves in LWD–gamma curve and resistivity curve, which often leads to a lack of caliper curve data of the development adjustment well. Different from an exploratory well, a development adjustment well usually has a large deviation or it can even be a horizontal well, so decision making is more dependent on the understanding of the sidewall conditions. However, the missing of caliper curve data in LWD poses great challenges for understanding of the sidewall conditions and providing a decision-making basis for subsequent drilling and completion operations (Xu et al. 2019). In view of this, we hope to obtain more efficient geological engineering information only by the gamma curve and the resistivity curve, thus providing support for decision-making in subsequent operations (Shen et al. 2015). The main direction of the study is to further perform data mining

DOI: 10.14800/IOGR.1196

Received October 21, 2021; revised November 13, 2021; accepted December 29, 2021.

*Corresponding author: jiangshl3@cnooc.com.cn

based on large data analysis, to find relationships between data and data, to allow full use of existing log data and to solve the geology-engineering integration problem (Ma et al. 2014).

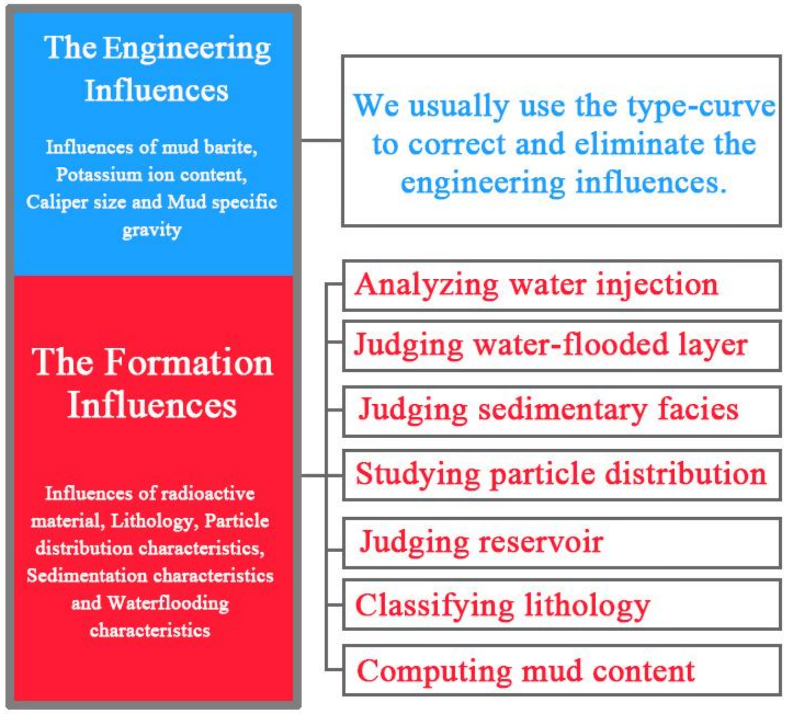


Figure 1—Gamma geophysical logging response and data application.

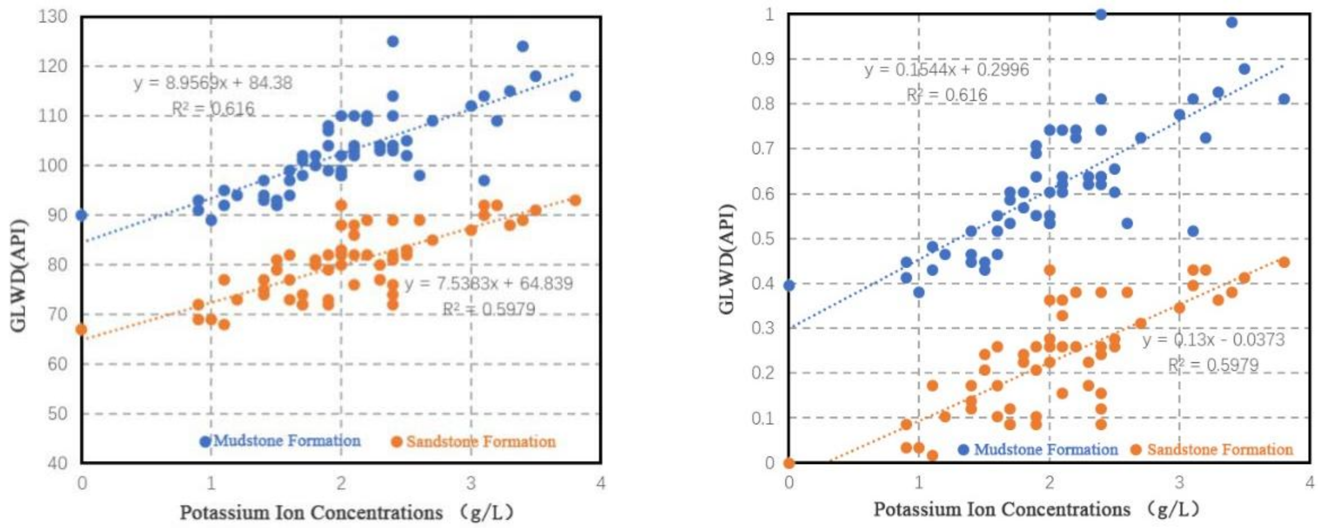
In the field, the gamma geophysical logging response is affected by two aspects - the formation and the engineering, as shown in **Figure 1**. The formation influences include radioactive material, lithology, particle distribution characteristics, sedimentation characteristics, and waterflooding characteristics. The response rule in this aspect can be used to interpret the GLWD data, such as the calculation of the mud content, the classification of the lithology, the evaluation of the reservoir, the study of the characteristics of the particle distribution, the evaluation of sedimentary facies, the evaluation of the water flooded layer and the analysis of the injectivity of water injectors (Cripps and Mccann 2000). The engineering influences include mud barite, potassium ion content, caliper size, and mud specific gravity (Wang 2011). Since our study focuses on formation, we usually use the type curve to correct and eliminate engineering influences, to ensure that the gamma geophysical logging response merely contains formation information without interference from engineering information (Liu 2006).

In the main direction of the geology-engineering integration study, the main technical challenge is how to explore more values of existing data and how to provide more reliable decision-making for subsequent drilling and completion operations (Frahm and Lemke 2010). For this purpose, we studied the main factors influencing GLWD, tried to make an interpolation prediction for the target well data based on the existing adjacent well data, used the difference between the gamma value and the measurement gamma value to fit the measured caliper, and built a model (Klaus 2010). We studied GLWD data mining and found a method to predict the caliper and to understand the stability status of the sidewall through GLWD. This method can provide efficient technical support and a decision-making basis for subsequent drilling and completion operations.

Influence Factors in GLWD

Influence of Potassium Ions on GLWD Curve. To identify the environmental influence factors and the main controlling factors during field operation of GLWD, we collected 55 sets of logging data of 40 development adjustment wells operating in PL Block of Bohai Oilfield from 2018 to 2019, and analyzed the

GLWD distribution of sandstone and mudstone formation under different potassium ion concentrations, as shown in **Figure 2**.

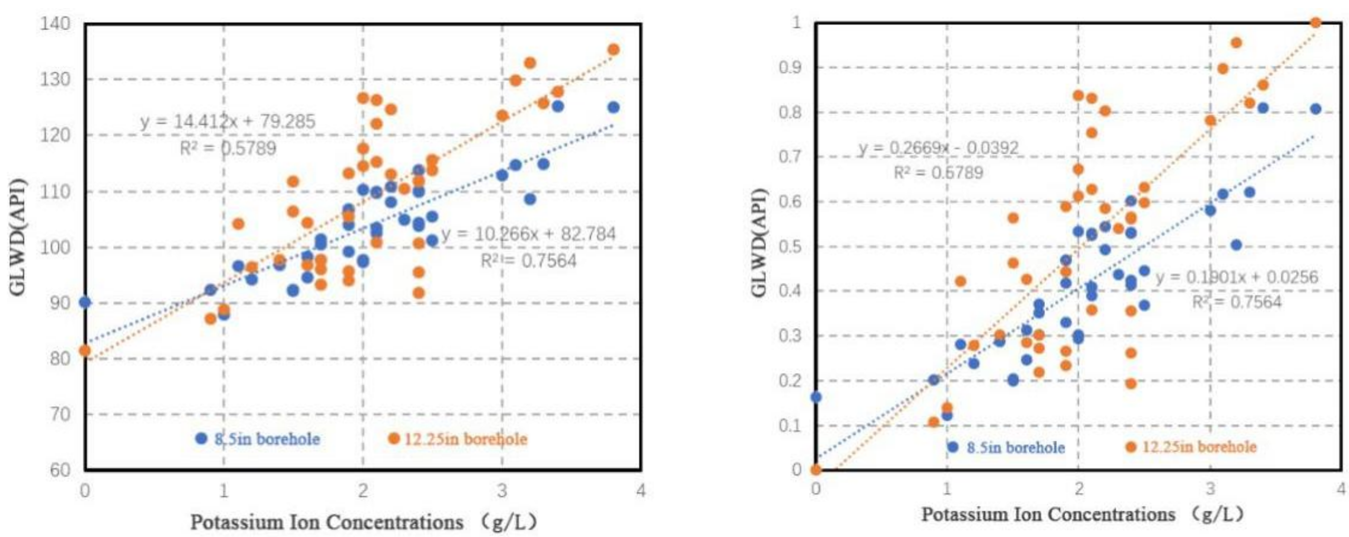


(a) (b)

Figure 2—Distribution of the mean GLWD of sandstone and mudstone formation under different concentrations of potassium ions.

Figure 2a shows the distribution of GLWD mean values in dimensions of sandstone formation and mudstone formation at different potassium ion concentrations. Figure 2b is the dimensionless relationship diagram. As can be seen in the figure, with the increase in potassium ion concentration, the GLWD response value exhibits a gradual increase trend and the trend is almost the same for sandstone and mudstone (we can see from Figure 2a that the slope adjusted for the formation of mudstone is 8.95, while that of sandstone is 7.53), indicating that potassium ions have the same influence on the sandstone formation and mudstone formation, which is in agreement with the phenomena we usually observe in field operation. The fitted R-squared ranges from 0.59-0.62, indicating that such fitting relationship is significant, in other words, potassium ions have a significant influence on gamma geophysical response.

To better understand the influence of potassium ions on the GLWD curve, we collected logging data from 40 development adjustment wells and analyzed the distribution of GLWD of 8.5-inch and 12.25-inch borehole sizes under different concentrations of potassium ions, as shown in **Figure 3**.

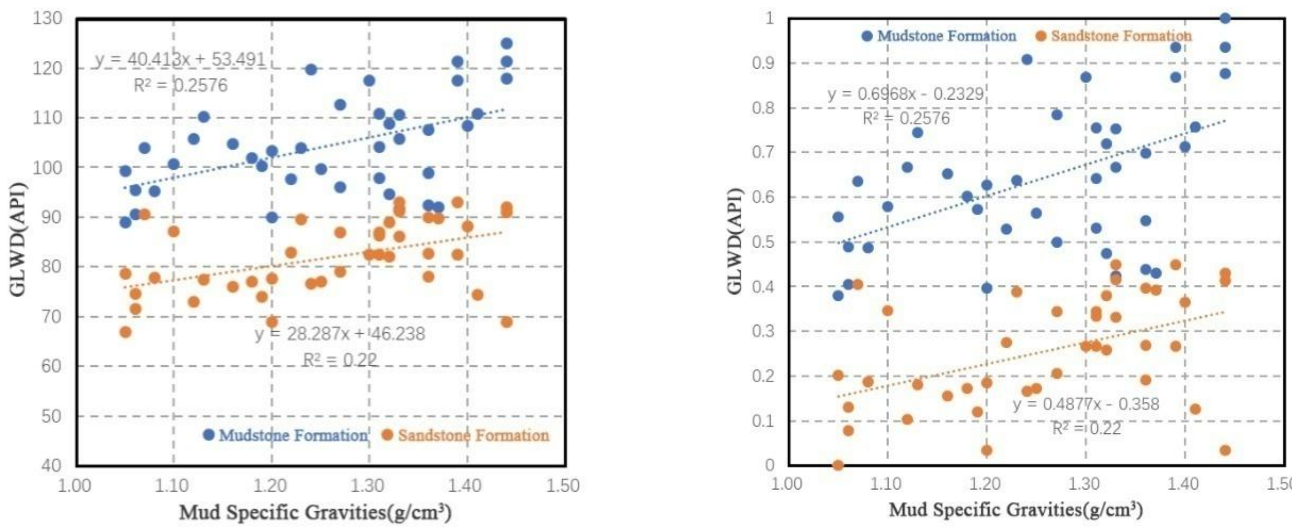


(a) (b)

Figure 3—Distribution of the mean GLWD of different borehole sizes at different concentrations of potassium ions.

Figure 3a shows the distribution of GLWD mean values of different borehole sizes in dimensions under different concentrations of potassium ion; Figure 3b is the dimensionless relationship diagram. As can be seen in the figure, with the increase in potassium ion concentration, the geophysical response of GLWD increases gradually. From the fitted curve (Figure 3a), we can see that the fitted slope of the 8.5-inch borehole is 10.27, while that of the 12.25-inch borehole is 14.41, indicating that the rate of increase in gamma response of the 8.5-inch borehole with increasing potassium ion concentration is smaller than that of 12.25-inch. This is because the increase of the caliper causes an increase of the response of the logging instrument to the mud in the wellbore.

Influence of Mud Specific Gravity on GLWD Curve. Through literature research, we have known that the geophysical response of GLWD is influenced by the specific gravity of the mud. To understand the degree of such influence on logging data of the study area, we collected 55 sets of logging data of 40 development adjustment wells operating in PL Block of Bohai Oilfield from 2018 to 2019, and analyzed the GLWD distribution rule of sandstone formation and mudstone formation under different mud specific gravities, as shown in **Figure 4**.

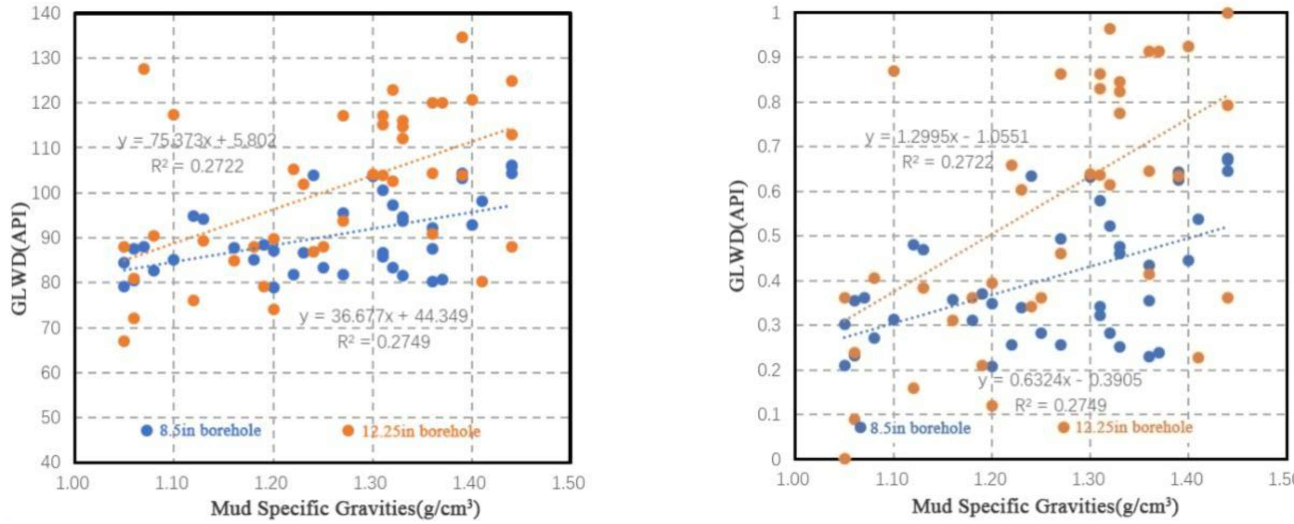


(a) (b)

Figure 4—Distribution of the mean values of GLWD of the sandstone formation and mudstone formation under different mud specific gravities.

Figure 4a shows the distribution of the mean GLWD of sandstone formation and mudstone formation in dimensions under different mud specific gravities; Figure 4b is the dimensionless relationship diagram. As can be seen in the figure, with the increase in mud specific gravity, the geophysical response of GLWD gradually increases. However, compared to the influence of potassium ion concentration, the influence of mud specific gravity is relatively small. This can be seen from the fitted R-squared. The R-squared of the mudstone formation and sandstone formation is between 0.22 and 0.25, slightly lower than the fitted value in the case of potassium ion concentration, indicating that the change in mud specific gravity has a relatively weak influence on the geophysical response of GLWD. It can be seen from the distribution rule of mudstone and sandstone that the rate of change in the influence of different mud specific gravities on the geophysical response of GLWD under different lithologies is the same, indicating that the influence of mud specific gravity on the geophysical response of GLWD formations with different lithologies is the same.

To better understand the influence of mud specific gravity on the GLWD curve, we collected logging data from the 40 development adjustment wells and analyzed the geophysical response distribution of the GLWD of 8.5-inch and 12.25-inch borehole sizes under different mud specific gravities, as shown in **Figure 5**.



(a) (b)

Figure 5—GLWD mean value distribution of different borehole sizes under different mud specific gravities.

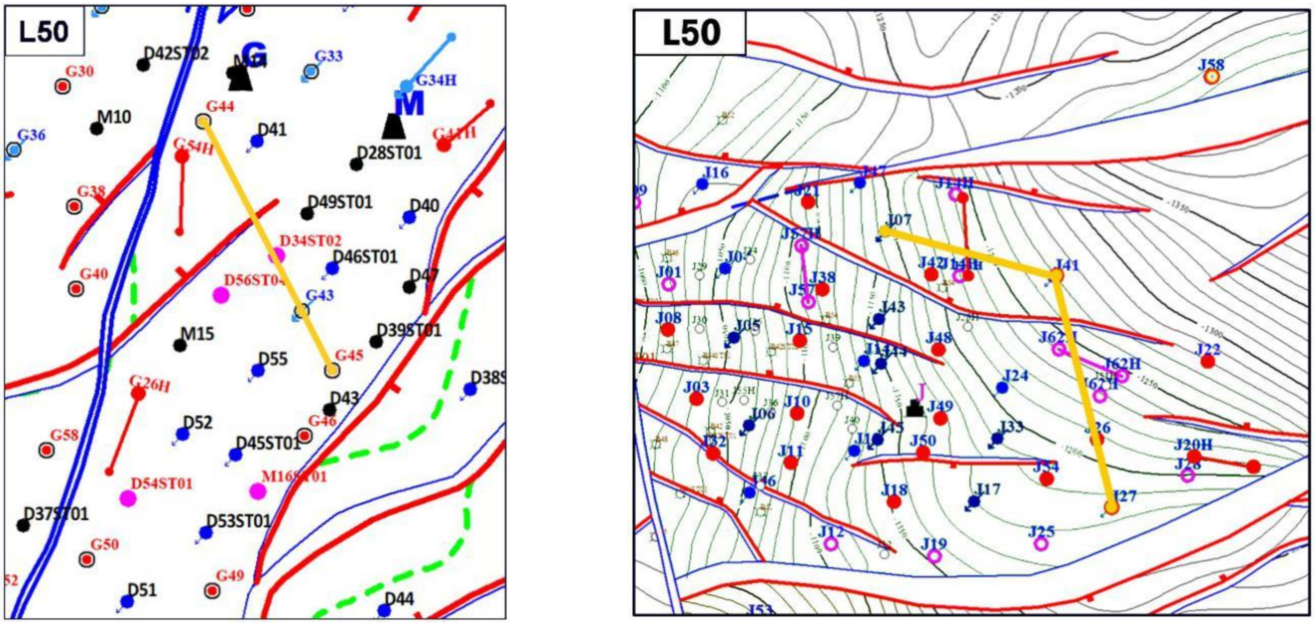
Figure 5a shows the distribution of the mean GLWD in dimensions of different borehole sizes under different mud specific gravities; Figure 5b is the dimensionless relationship diagram. As can be seen in the figure, with the increase in mud specific gravity, the geophysical response of GLWD gradually increases. The fitted R-squared indicates a significant fitting effect (the fitted R-squared of both 8.5in borehole and 12.25-inch borehole is 0.27). The influence of mud specific gravity on the gamma curve is relatively weak compared to potassium ions. By comparing the influences of mud specific gravity on GLWD geophysical response in different boreholes, we can see that the slope of 12.25-inch borehole is high (Figure 5 b), the slope of 12.25-inch borehole is 1.3, while that of 8.5-inch borehole is 0.6). This indicates that the gamma value is more susceptible to mud specific gravity in 12.25-inch borehole. The reason is that the larger the radius of a well, the more contributions the mud in the well makes to the logging instrument.

Based on the statistics of the 55 sets of logging data, we analyzed the influence of four groups of different influence factors on GLWD geophysical response. By conducting comparison and analysis, we found that with the rise of potassium ion concentration and mud specific gravity, the GLWD geophysical response increases gradually; potassium ions have the most significant influence on gamma; and the bigger the caliper, the greater the influence of potassium ions on GLWD geophysical response.

Building a Caliper Prediction Model

By statistical analysis and analysis of regional data, we found that the larger the caliper, the greater the influence of potassium ions on the geophysical response of GLWD. Based on this study result as well as the existing logging data and geological data for PL Block, we built a caliper prediction model.

We used the data of two groups of wells selected from 40 development adjustment wells operating in PL Block from 2018 to 2019 for modeling. **Figure 6** is the regional tectonic map of the data from the two groups of wells at layer L50. Figure 6a shows the data for the first group of wells, that is, three directional wells G45, G43 and G44 completed at the beginning of 2019. Figure 6b shows the data of the second group of wells, that is, J07, J41, and J27. These wells penetrate the formation, with full coverage and complete logging data (including GLWD and caliper data), and are representatives of all the development adjustment wells in the block.



(a)G45, G44 and G43 Wells (b)J07, J41, and J27 Wells

Figure 6—Regional tectonic map of the data from the two groups of wells at layer L50.

Creation of Prediction Curve Based on Adjacent Well Data. To create the prediction curve, we need to rely on the logging data of the target well's adjacent wells, including GLWD curve and caliper curve. Here we take three wells (G45, G43 and G44) for example. Note that they are all highly-deviated wells, so we first need to make the true vertical depth (TVD) conversion for the data of G45 and G44 wells, that is, the TVD coordinate system rather than the along-hole depth coordinate system is to be used. By interpolation between G45 and G44 wells, the predicted gamma curve and predicted caliper curve of G43 well can be obtained. The calculation **Eq. 1** to **4** are as follows:

$$CAL_{43}^{'} = a_1 CAL_{45} + a_2 CAL_{44}, \quad (1)$$

$$GR_{43}^{'} = a_1 GR_{45} + a_2 GR_{44}, \quad (2)$$

$$a_1 = \frac{D_{4345}}{D_{4445}} = \frac{\sqrt{(X_{43}-X_{45})^2+(Y_{43}-Y_{45})^2}}{\sqrt{(X_{44}-X_{45})^2+(Y_{44}-Y_{45})^2}}, \quad (3)$$

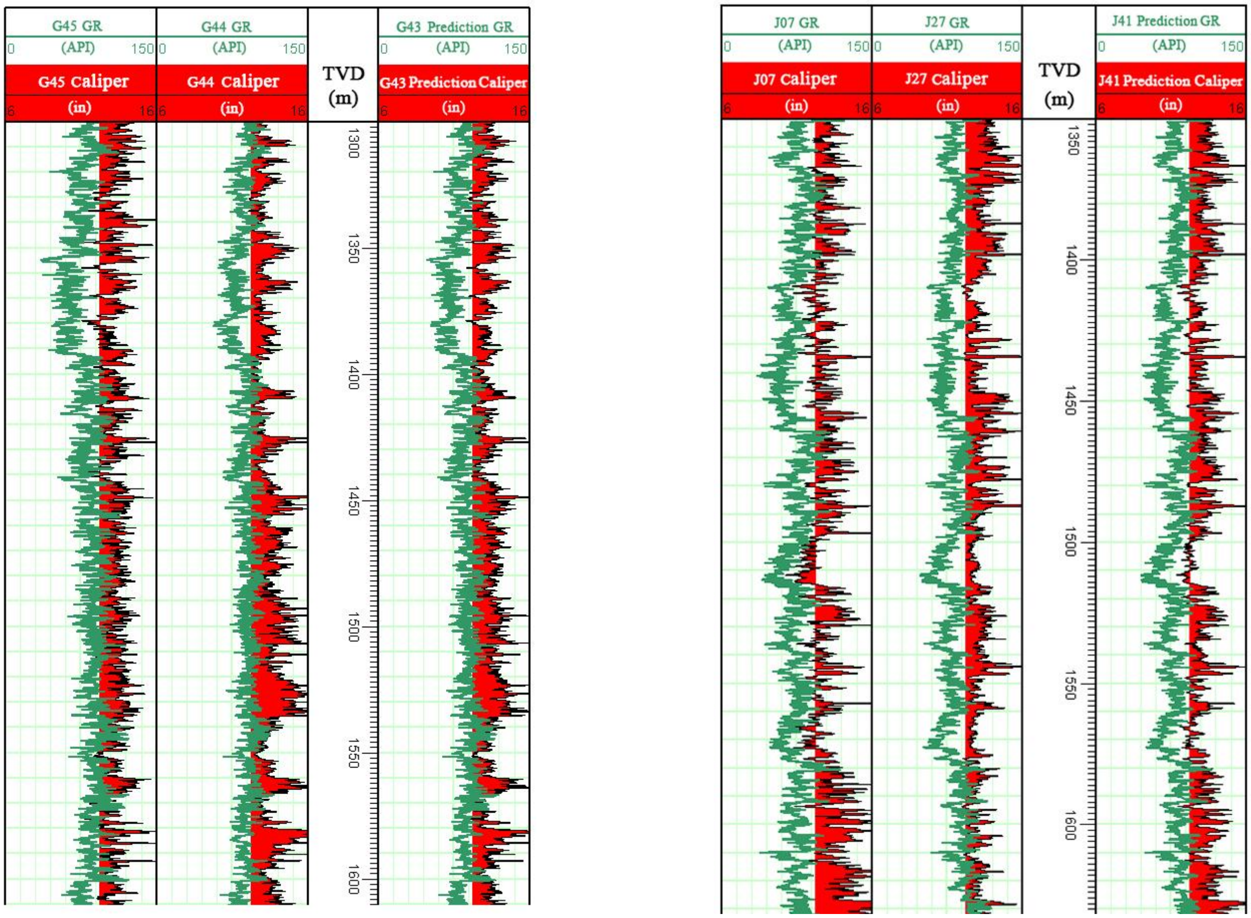
$$a_2 = 1 - a_1, \quad (4)$$

Where CAL is the caliper, in; GR is gamma, API; $a_1,\ a_2$ are interpolation coefficients, related to geographic location; D is distance between two wells (m); X, Y are X and Y coordinates of wellhead, m.

Using the interpolation calculation method, we can get the predicted gamma curve and predicted caliper curve of G43 well (expressed with $GR_{43}^{'}$ and $CAL_{43}^{'}$ respectively). **Figure 7a** shows the predicted gamma curve and predicted caliper curve of G43 well at TVD 1300-1600m, and **Figure 7b** shows the predicted gamma curve and predicted caliper curve of J41 well at TVD 1350-1650m.

As can be seen in Figure 7a, since G45 well and G44 well penetrate the same formation, these gamma curves and caliper curves at TVD show a similar fluctuation rule. It is worth noting that the selected gamma curves of G45 and G44 wells are logging data subject to potassium ion and caliper corrections, which only reflect the formation characteristics, without considering the wellbore influence. Therefore, the gamma curve and caliper curve of G43 well predicted on this basis are not influenced by the wellbore.

It can be seen from Figure 7b that J07 well and J27 well penetrate the same formation, so the gamma curves and the caliper curves in TVD exhibit a similar fluctuation rule. Compared with the formation shown in Figure 7a, J07 and J27 wells present an obvious difference on their caliper curves (TVD 1580-1650m), this may be associated with the engineering problem encountered in drilling of J07 well.

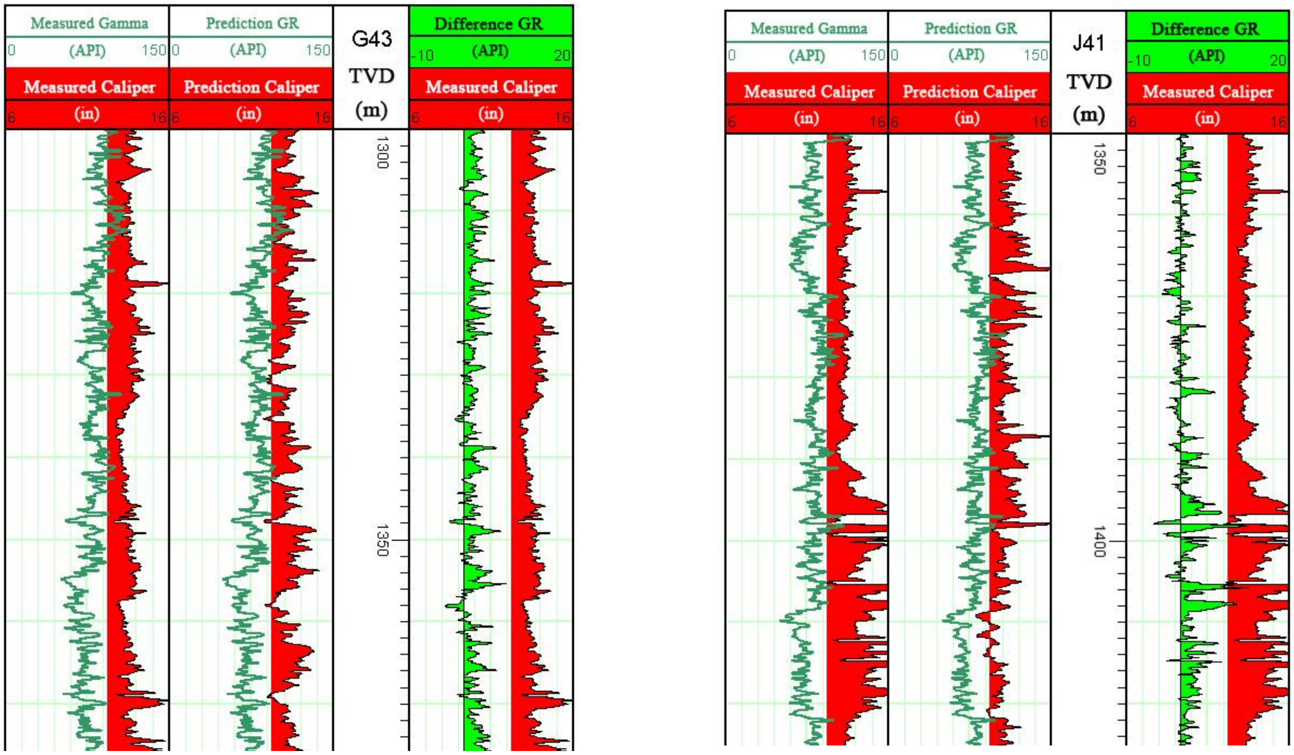


(a) (b)

Figure 7—Prediction of the gamma curve and the caliper curve of the G43 and J41 wells based on the interpolation method.

Calculation of Difference Based on Measured Gamma and Predicted Gamma. Based on the study results above, we can get the predicted gamma curve and predicted caliper curve of G43 well. In actual drilling process, the measured gamma geophysical response of G43 well considers the influence of environmental factors in wellbore, so we calculate the difference between the measured geophysical response and the predicted gamma and obtain a difference gamma curve. **Figure 8** shows the difference gamma curves obtained based on the difference between the predicted gamma and the measured gamma. Figure 8a shows the difference gamma curve and measured caliper curve (TVD 1300-1370m) of the G43 well, and Figure 8b shows the difference gamma curve and measured caliper curve (TVD 1350-1420m) of the J41 well.

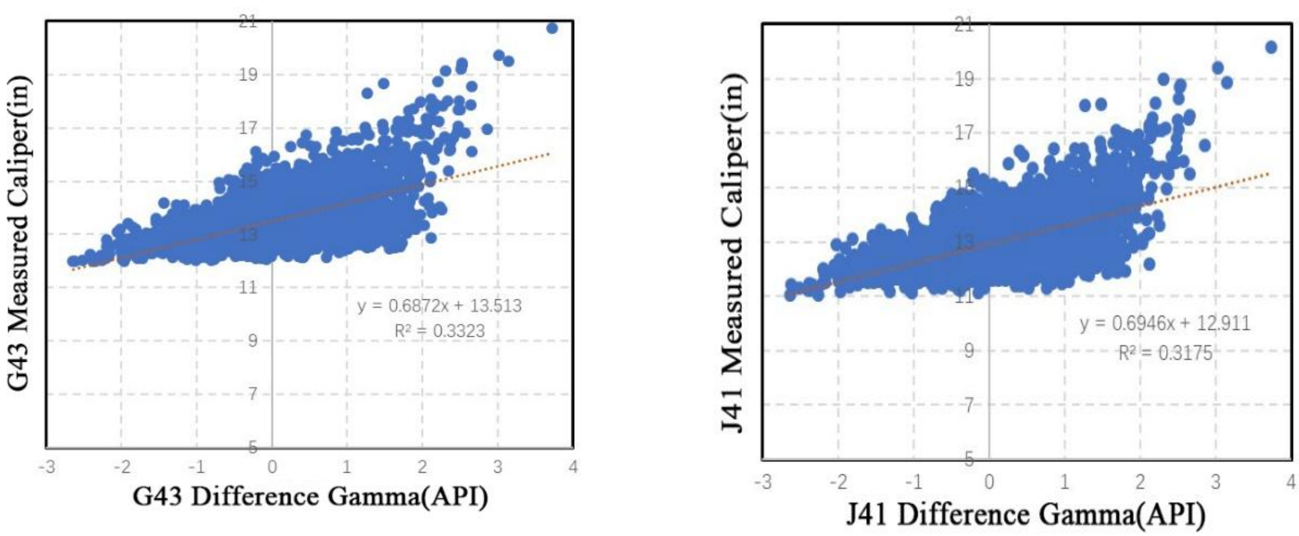
According to the analysis, we can know that difference gamma actually reflects the response of potassium ions in wellbore and caliper to the logging instrument. This response, under a given potassium ion concentration, shall have a certain functional relationship with the caliper. It is easy to see from the comparison of the two wells in Figure 8 that there is a correlation between the difference gamma and the measured caliper.



(a) (b)

Figure 8—Comparison between the difference curve based on the predicted gamma & measured gamma and the measured caliper.

Establishment of Function Relationship between Difference Gamma and Caliper. By statistics, analysis and fitting of the difference gamma curve and measured caliper curve data in above section, we can obtain the scatter fitting relationship between the difference gamma and measured caliper, as shown in **Figure 9**. Figure 9a shows the scatter fitting data of difference gamma and measured caliper of G43 well at TVD 1300-1370m, and Figure 9b shows the scatter fitting data of difference gamma and measured caliper of J41 well at TVD 1350-1420m. Through comparison between difference gamma curve and caliper curves of 26 wells, it is found that there is linear correlation between them. The function relationship between the difference gamma and the caliper can be obtained by statistics and fitting, which is expressed by **Eq. 5** and **Eq. 6**.



(a) (b)

Figure 9—Scatter fitting relationship between the difference gamma and the measured caliper.

$$CAL_{G43} = 0.6872\Delta GR_{G43} + 13.513 \ \ (R = 0.5765), \qquad (5)$$

$$CAL_{J41} = 0.6946\Delta GR_{J41} + 12.911 \ \ (R = 0.5635), \qquad (6)$$

The scatter fitting relationship between difference gamma and measured caliper is obtained by fitting. From the perspective of fitting results, this method can be used for caliper prediction, and the prediction results have good performance. In PL Block, the mathematical model Eq.7 can be used to predict the caliper by difference gamma, to understand the conditions of the sidewall, and to provide technical support and a decision-making basis for subsequent drilling and completion operations.

$$CAL^{'} = 0.69\Delta GR + 13.1, \qquad (7)$$

Where $CAL^{'}$ is the predicted caliper, in; ΔGR is the difference of gamma ray, API.

Model Verification and Analysis. We got a mathematic model (Eq. 7) of gamma-based predicted caliper curve by a series of mathematic methods. To verify this model and to perform an analysis of stability and significance, we compared the measured calipers with predicted calipers between two other wells (J04 and J56) in PL Block, and the results are shown in **Table 1**.

Table 1—Comparison between the measured and predicted caliper.

Well Name	TVD (m)	R	Remarks
PLG43	1300~1370	0.4931	Modelling
PLJ41	1350~1420	0.4421	Modelling
PLJ04	1325~1395	0.3901	Verification
PLJ56	1330~1400	0.2980	Verification

As can be seen in the table, this model has certain effects when applied to other wells in the same block, and the high correlation (R 0.30-0.40) between the measured caliper and the predicted caliper indicates that the model is significant and stable.

Application and Decision-making for E59

Basic Information on the Operation of E59. PL Oilfield is located in central south of Bohai Sea, with its structure lying at the northeast end of the middle section of Bonan Uplift Zone and developing on Tanlu Fault Zone. E59 is a highly-deviated well and its maximum well deviation is 68°@2000.49m. The design well depth is 2578.00 ⊥ 1554.57m and the actual completed well depth is 2533.00 ⊥ 1544.50m. Spud-in started on June 20, 2019, the second spud-in was completed on October 21, 2019, and the completion operation was finished on October 27, 2019.

The main revealed formations include: the Pingyuan Formation, the Minghuazhen Formation, the Guantao Formation and the Dongying Formation. For more details, refer to **Table 2**.

Table 2—Stratigraphic division datasheet for E59 well.

Erathem	System	Formation	Member	MD (m)	TVD (m)	Elevation (m)
Cenozoic	Quaternary	Pingyuan	-	-	-	-
	Neogene	Minghuazhen	N_2m^u	1357.0	903.0	-862.0
			N_1m^l	2288.2	1318.2	-1277.6
		Guantao	N_2g^u	2473.7	1482.6	-1442.1
			N_1g^l	2818.0▽	1792.0	-1751.5
	Paleogene	Dongying	Ed	-	-	-
Completion depth (m)				2818.0	1792.0	-1751.5
Kelly bushing (m)				40.5		

Logging Operation Design. From the initial depth of the well 311.15mm to elevation -800 m, the LWD is adopted, with log items that include gamma and resistivity; from -800m to the bottom, the LWD is adopted, with log items that include gamma, resistivity, neutron and density.

During the completion operation, when the casing was run to 2018m, the normal lowering weight was 52t, but the actual lowering weight was 36t, 30% lower than the normal value, indicating that resistance was encountered. This might be caused by sticking of the upper casing or thrust of the lower casing into the length of the enlargement of the well. In the first case, the discharge can be increased to wash off the cuttings stuck on the casing wall, while in the latter case the casing must be lifted out and then lowered again. Considering the timeliness of field drilling operation, the drilling supervisor is required to find out the reason and make the decision promptly.

Figure 10 shows the geophysical response of E59 well at 2000-2100m(MD), from which we can see that at the depth of 2009-2015m, the resistivity is increased to 20-25Ω·m, gamma is a bit low, and neutron-density crossing happens (porosity about 6-12). By analyzing the logging and geochemical data, it is believed that this interval is an oil horizon and therefore will be the main perforation interval in subsequent completion operations.

Caliper Prediction and Decision-making on Casing Operation. First, the predicted gamma curve is created based on the data of adjacent wells, and then the caliper is obtained by interpretation of the mathematical model (Eq. 7), as shown in **Figure 11**. As can be seen from the figure, there is a visible difference between predicted gamma and measured gamma at 2009-2015m, while the difference is insignificant in other well intervals. The difference gamma obtained by calculating the difference between measured gamma and predicted gamma also indicates the same phenomenon. Meanwhile, the predicted caliper obtained by interpretation of the mathematical model (Eq. 7) is obviously enlarged in this depth range. Therefore, it can be judged that the enlargement of the well takes place at a depth of 2015 m during the casing running. Based on the results of the interpretation, it is suggested that the field operation supervisor lift the casing and then lower it for reinstallation.

The results of this study provide a decision-making basis for the field drilling supervision. The casing is lowered to place successfully, demonstrating the effect of this method in field applications.

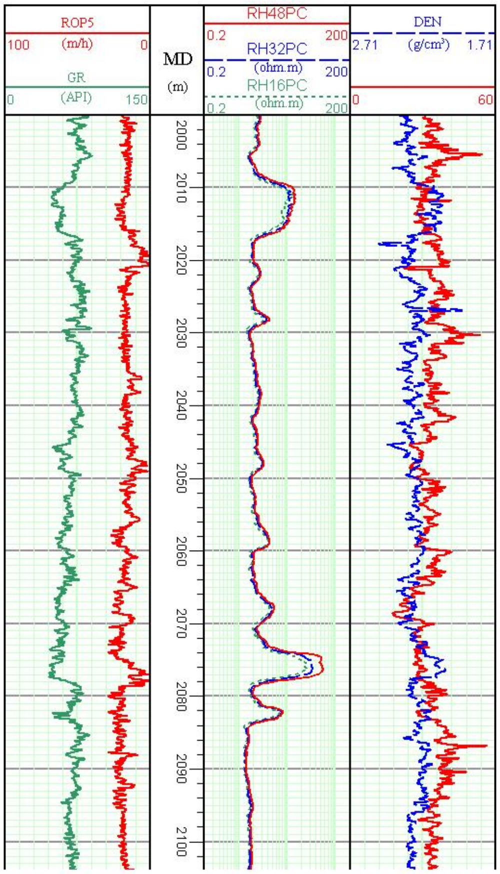


Figure 10—Field logging and geophysical response of PLE59.

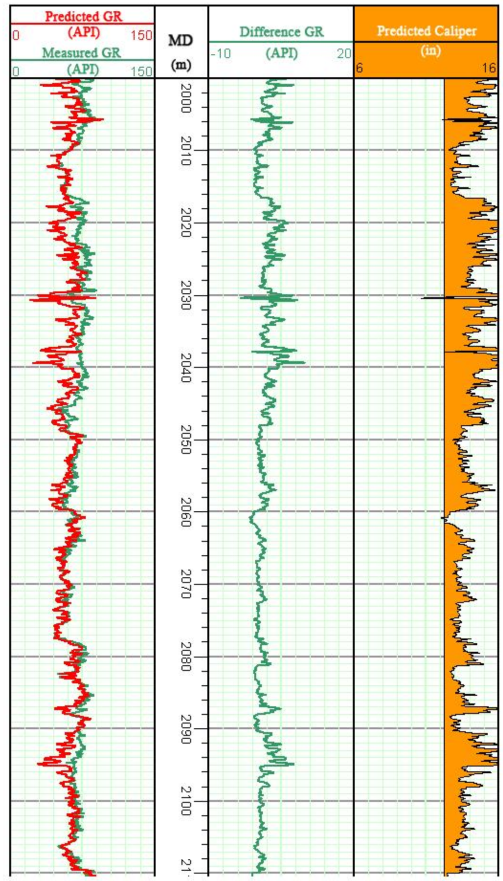


Figure 11—Results of the Caliper prediction of PLE59.

Conclusions and Suggestions

1. With increasing potassium ion concentration and mud specific gravity, the geophysical response of GLWD increases gradually; potassium ions have the most significant influence on gamma; and the larger the caliper, the greater the influence of potassium ions on the geophysical response of GLWD.
2. The caliper prediction model built based on the scatter fitting function of difference gamma and measured caliper can be applied in PL block. Its stability and significance can meet the demand for providing technical support and a decision-making basis for subsequent drilling and completion operations.
3. In-depth mining of GLWD geophysical response data is of directive significance to field drilling and completion operations, yet various sources of data need to be utilized for comprehensive analysis. At present, there is no good method that can acquire accurate caliper information indirectly without relying on the caliper logging instrument.

Conflicts of Interest

The author(s) declare that they have no conflicting interests.

References

Xu, B., Wang, Z., Li, Z., et al. 2019. Automatic Correction of Natural Gamma Logging Data Based on Environmental Influence. *Journal of Oil and Gas Technology* **10**(5):99-102.

Shen, L., Wang, Z., and Qu, X. 2015. Influence Factors And Correction Method Of Gamma Logging While Drilling. *Petrochemical Industry Technology* **23**(1):108-115.

Ma, H., Zhang, B., Kong, F., et al. 2014. Application of Natural Gamma Logging Tool In Gas Field Development. *Oil-Gas Field Surface Engineering* **14**(12):23-24.

Cripps, A.C. and Mccann, D.M. 2000. The Use of the Natural Gamma Log in Engineering Geological Investigation. *Engineering Geology* **55**(4):313-324.

Wang, Y., Liu, B., and Jia, C. 2011. Study on Sidewall Stability. The 16th Nation Exploration Engineering (Rock & Soil Drilling and Tunneling) Technical and Academic Exchange Annual Meeting, Chengdu, China, 10-12 October.

Liu, Z. 2006. Study on Inversion Method of LWD Response and Its Application. Master Thesis. Southwest Petroleum University, Chengdu, China.

Frahm, A.L. and Lemke, L.D. 2010. Comprehensive Glacial Sediment Characterization and Correlation with Natural Gamma Log Response to Identify Hydrostratigraphic Units in A Rotosonic Well Core. Paper presented at the AGU Fall Meeting, Houston, Texas, USA, 1-3 December.

Klaus, L. 2010. Environmental Corrections to Gamma-Ray Log Data: Strategies for Geophysical Logging with Geological and Technical Drilling. *Journal of Applied Geophysics* **70**(1):17-26.