Correcting Hole Enlargement Impacts on Density Logs for Coalbed Methane Reservoirs

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Abstract: Density logging is an effective method in the evaluation of coalbed methane (CBM) reservoirs. Whether density log values effectively represent true density of coal will directly determine precision of evaluating coalbed methane parameter logs. In this paper, a statistical method is used to analyze density log response characteristics and hole enlargement rate for three main coal beds in the study area in order to determine the internal relation between hole enlargement rate and density response. Analytical results show that distortion of density log response values is caused mainly by hole enlargement impacts. Based on the apparent geometric factor theory, a model suitable for correcting hole enlargement impacts density logs for coalbed methane reservoirs has been deduced. To correct density logs for hole enlargement influences, it is key to determine a mud apparent geometric factor. Using measured apparent relative density, density log values and caliper logs for coal rock, the least squares fitting method was adopted to obtain computation model constants for the mud apparent geometric factor applicable to the study area. When this model was applied in a computer auto-correcting process for evaluating enlargement impacts on density logs for coalbed methane reservoirs of the Hancheng gas field in the eastern section of Ordos Basin, China, the correction results were very close to measured relative density, indicating that this method can improve precision of correcting hole enlargement impacts on density logs.

Keywords: Coalbed methane, correction, density log, hole enlargement impact.

INTRODUCTION

Compared with other types of rock, coal rock is characterized by low density; thus, a coal bed and its thickness can be determined using only density logs [1]. Of all logging methods, the density log is the most effective geophysical method to detect coalbed gas content [2]. Coalbed methane (CBM) scientists often consider use of a density log in their industry as an electric log that is used to determine the saturation levels of oil and gas in the petroleum industry. Therefore, use of the density log is an indispensable part of the methodology necessary for evaluating CBM reservoir logging.

With shallow burial depth, full development of microporosity and cleats and low mechanical strength, coal beds collapse easily during the drilling process and there appears to be a noticeable enlargement of the borehole [3]. An expanding borehole may give rise to various degrees of distortion in the density log curve for coal rock because the measured density log value is the sum of true density of mud and coal rock as well as other factors [4]. This will result in an inaccurate representation of the geologic features of the CBM reservoir based on the measured density value. The required correction of significantly distorted original logging data to address the impacts of the hole enlargement will reduce the precision of evaluating the CBM reservoir parameter logs. Consequently, reservoir-quality evaluation of the density log will be meaningless. For this reason, it is necessary to define the density log response characteristics for the CBM reservoir, characterize the hole enlargement pattern, implement correction of density log data to account for hole enlargement impacts, restore the true density log information for the encountered coal rock as much as possible to increase the precision of evaluating the density log reservoir, reduce the risk of CBM exploration and achieve high-quality and efficient production of coalbed methane.

ANALYZING HOLE ENLARGEMENT IMPACTS ON DENSITY LOGS FOR CBM RESERVOIRS

Coal beds resemble other types of sedimentary rock in their responses on log curves and vary in their physical-chemical constituents. Coal mainly consists of organic matter evolved from plants and small portions of inorganic matter [5, 6], and its chemical composition includes high molecular hydrocarbon compounds that are composed of carbon (C), hydrogen (H) and oxygen (O). Compared with other minerals (excluding water and petroleum), the minerals that compose coal have a small average atomic number that is manifested in a lower volume density for coal rock than volume densities for sandstone and mudstone. Compared to strata that may have different lithologic characteristics, coal rock has distinct density log response features.

Hole enlargement rate, which is introduced to provide a quantitative representation of hole enlargement, is the ratio of the difference between borehole diameter and bit diameter against bit diameter. The formula for calculating the hole enlargement ratio is:

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$$k = (CAL - BITS)/BITS \quad (1)$$

where k is hole enlargement rate (%); CAL is caliper logging value (cm); and $BITS$ is bit diameter (cm).

An expanded borehole or an irregular borehole wall may affect the density log curve so markedly that the curve drops precipitously, and the measured density value is much lower than the true density value [7]. Fig. (**1**) shows the response characteristic chart of a density log. The figure shows that the hole enlargement rate of the coal bed in the 1083~1086.5 m section of the well is as high as 92% and the average enlargement rate is 83.6%, indicating a discernable collapse of the borehole.

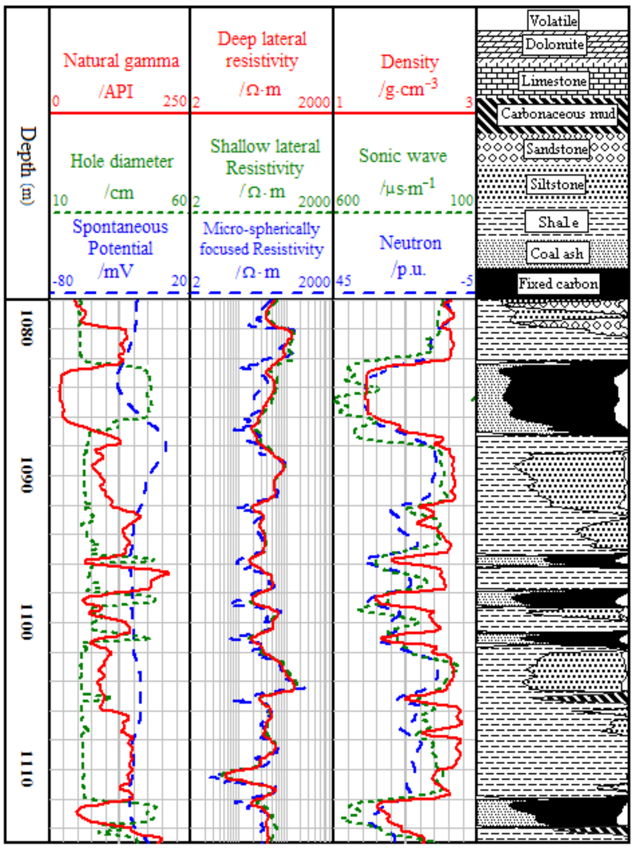

Fig. (1). Chart for well H4 density log response characteristics.

Despite the large measuring ranges and extensive radial investigation depths of present-day density log instruments, such as Baker Atlas's 2228 density well log instrument for measuring boreholes, which measures in the range of 15.24 cm~55.88 cm with a probing depth of 20.32 cm [8], hole enlargement is a very serious problem in the study area (Fig. **1**) and causes appreciable distortion of density logging data. The minimum density of coal beds shown in Fig. (**1**) is only 1.414 g•cm^{-3}. The density log response value goes beyond the true density range of coal beds. Hole enlargement impacts of varying degrees are evident in sections 1095.1~1095.9 m, 1098~1099.1 m, 1100.5~1101.4 m and 1112~1114.1 m of this well. Density log responses in affected sections indicate density log values that decline in sections where hole enlargement has occurred.

Table **1** provides a comparison between density log and borehole enlargement rate for three main coal beds (3$^{\#}$, 5$^{\#}$ and 11$^{\#}$) encountered in six key wells within the study area. According to this table, when the 3$^{\#}$, 5$^{\#}$ and 11$^{\#}$ coal beds are compared, the 3$^{\#}$ coal bed has a small average enlargement rate, while the average enlargement rates indicated for the 5$^{\#}$ and 11$^{\#}$ coal beds are significantly greater and increase with declining density log value. In the study area, face and end cleats have been fairly developed in the coal beds and are characterized by weak cementation, slackness, brittleness and softness. The coal beds collapse easily to form expanding boreholes during the drilling process. Because the coal beds have less variance in burial depth and coal rock contains meager amounts of coal, there are fewer impacts from geologic factors indicated by density log values. Based on the above analysis, hole enlargement impacts are the main cause of distorted density logs in coal rock.

For sedimentary rock, the count rate of scattered gamma rays can be expressed as Equation (2) from the principle of density logging [9].

$$N = N_0 e^{-\frac{\sigma_e N_A}{2}\rho_b L} \quad (2)$$

where N is the measured count rate for density logging; N_0 is zero distance from source to the count rate; σ_e is atomic microscopic scattering cross section; ρ_b is the density of formation; and L is the distance between the probe and gamma ray source.

Equation (3) below is derived when logarithmic values for both sides of Equation (2) are combined:

$$\rho_b = \frac{2 \cdot (\ln N_0 - \ln N)}{\sigma_e N_A L} \quad (3)$$

Based on a hypothesis of $A = -\frac{\sigma_e N_A L}{2}$, $B = \ln N_0$, Equation (3) can be converted to

$$\rho_b = \frac{1}{A}(\ln N - B) \quad (4)$$

Table 1. Comparison between coalbed density log and borehole enlargement rate.

Coal Bed No.	Density log/g•cm^{-3}			Hole Enlargement rate/%		
	Min.	Max.	Average	Min.	Max.	Average
3$^{\#}$	1.24	2.05	1.49	7.0	73.3	20.7
5$^{\#}$	1.07	2.10	1.34	14.6	111.8	48.1
11$^{\#}$	1.18	2.22	1.41	6.8	121.6	36.1

Equation (3) shows that there is an exponential relationship between density log values and count rate of source spacing L. The source spacing is smaller, detecting depth is shallower and hole enlargement impacts on the density log are more prominent. The basic principle of density logging can be inferred, as well as an indication of an exponential relationship between the density log and the caliper log.

Fig. (**2**) shows the relationship between coalbed density log response and hole enlargement rate for six key wells in the study area. This figure shows that the density log value for coal rock and borehole diameter is closely related and that the relationship is exponential. As hole enlargement rate increases, the density log value decreases; on the contrary, density log values increase as borehole diameters approach normal levels.

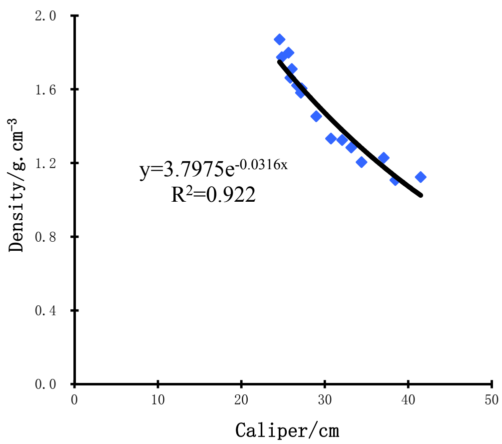

Fig. (2). Relationship between coalbed density log response and caliper.

For coal beds, hole enlargement impacts are primarily a result of the geometric shape of the borehole. The degree of impact depends largely on the detection depth of the instrument, particularly for the density logging instrument attached to the wall of the well. The ideal geometry of a borehole should be a cylinder that has a diameter similar to size of the drill bit and a smooth wall. During the actual process of drilling in coal rock, however, collapse of the wall may result in an irregular borehole. A collapsed wall may produce a large-diameter cave on the well profile. The corresponding signals recorded on the logging instrument usually are derived from drilling mud inside the well rather than formation characteristics [9]. Where borehole diameter increases, density log values tend to decrease, close to mud density, so that true density of the coal bed cannot be accurately identified using the density log data. Such unfavorable borehole conditions are common in the study area; therefore, the hole enlargement impact must be corrected when the density log curve is used for evaluating CBM reservoir logging.

NEW METHOD OF CORRECTING HOLE ENLARGEMENT IMPACTS ON DENSITY LOGS

The geometric factor theory was first introduced by Doll to describe the contribution of all formation sections to measurement signal [10]. Density log correction for hole enlargement impact is commonly addressed by using a dual detector principle and the geometric factor theory during measurement [11, 12]. However, if hole enlargement is severe, the borehole enlargement will still affect the density log value. If coal bed data are impacted by more by hole enlargement than by other environmental factors, it can be assumed that media within the range of detection by density logging are composed of mud and coal bed and that the measured value of density in coal rock is mainly the contribution of coal rock density and mud density. Hence, a measured density logging value can be considered as a concentrated expression of mud density and formation density:

$$\rho_a = G_{coal} \cdot \rho_{coal} + G_{mud} \cdot \rho_{mud} \tag{5}$$

An apparent geometric factor of coal rock and mud will correspondingly satisfy the following condition:

$$G_{coal} + G_{mud} = 1 \tag{6}$$

where ρ_a is the density log value in the case of hole enlargement (g•cm^{-3}); ρ_{mud} is mud density (g•cm^{-3}); ρ_{coal} is true volume density of coal rock (g•cm^{-3}); G_{coal} is the weight coefficient for true volume density in coal rock used in density logging, also called the apparent geometric factor of coal rock, $0 \le G_{coal} \le 1$; G_{mud} is the weight coefficient of mud density used in density logging, also called apparent geometric factor of mud, $0 \le G_{mud} \le 1$.

Equation (5) shows that all measured values of coal density are represented by mud density if the borehole diameter is expanded beyond the detection range the of density log, i.e., $G_{mud} = 1$, $G_{coal} = 0$, $\rho_a = \rho_{mud}$; if the borehole maintains a normal diameter and the backup arm of the density logging instrument keeps in constant contact with the wall of the well, then $G_{mud} = 0$, $G_{coal} = 1$, $\rho_a = \rho_{coal}$.

Combining Equation (6) and Equation (5) derives:

$$\rho_{coal} = \frac{\rho_a - G_{mud} \cdot \rho_{mud}}{1 - G_{mud}} \tag{7}$$

Equation (7) indicates that correcting hole enlargement impact in coal rock can be performed as long as the apparent geometric factor of mud G_{mud} is known. As a result, the problem of correcting hole enlargement impact on density logs has necessitated the calculation of the apparent geometric factor of mud, G_{mud}.

In practice, correcting the impact of hole enlargement on density logs for coal rock amounts to calculation of the correction value related to the hole enlargement rate and mud density, $\Delta\rho$. True apparent volume density of coal rock ρ_{coal} may be expressed by equation as below:

$$\rho_{coal} = \rho_a + \Delta\rho \tag{8}$$

Combing Equation (7) and Equation (8) derives:

$$G_{mud} = \frac{\Delta\rho}{\rho_a + \Delta\rho - \rho_{mud}} \tag{9}$$

Use of the density log principle and Equation (4) analysis, the apparent density of coal rock ρ_a, enlargement effect correction value $\Delta\rho$ and caliper creates an exponential function relationship. Therefore, assuming $\rho_a = a \cdot e^{b \cdot CAL}$, $\Delta\rho = c \cdot e^{d \cdot CAL}$ for Equation (9), it can be converted to Equation (10)

$$G_{mud} = \frac{c \cdot e^{d \cdot CAL}}{a \cdot e^{b \cdot CAL} + c \cdot e^{d \cdot CAL} - \rho_{mud}} \tag{10}$$

where ρ_a is the density log value in the case of hole enlargement; a, b, c and d are the regression coefficients associated with the degree of hole enlargement.

When hole enlargement rate k is introduced to Equation (10), it yields Equation (11):

$$G_{mud} = \frac{c \cdot e^{d \cdot (\alpha \cdot BITS + BITS)}}{a \cdot e^{b \cdot (\alpha \cdot BITS + BITS)} + c \cdot e^{d \cdot (\alpha \cdot BITS + BITS)} - \rho_{mud}} \quad (11)$$

During the completion of a well, bit diameter and mud density are known values that are used to calculate the mud apparent geometric factor through use of the Equation (11) numerical simulation and by incorporating the least square method to evaluate the regression fitting the correction value of coal rock density, logging enlargement effect and caliper value in the study area. The apparent relative density of coal is commonly used in coal resource exploration and CBM content calculations [13]. In this work, the correction value of density $\Delta\rho$ was obtained using apparent relative density measured by lab analysis and log density in the hole enlargement section of coal rock. Fig. (**3**) shows the relationship between the density correction value and caliper. This figure indicates that hole diameter enlargement results in a large correction value.

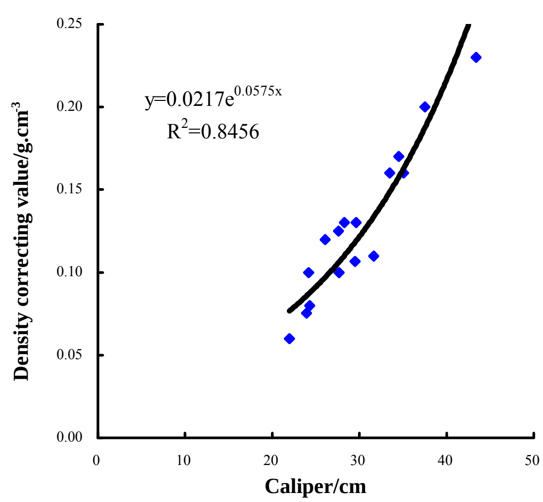

Fig. (3). Relationship of density correction value and caliper.

Using Fig. (**2**) and Fig. (**3**), $a = 3.7975$, $b = -0.0316$, $c = 0.0217$, and $d = 0.0575$ in the study area. Assuming that the a diameter of $BITS = 22.5$ cm, mud density of $\rho_{mud} = 1.05$, 1.10, and 1.15 g/cm^3, use of the Equation (11) numerical simulation can produce a mud apparent geometric factor chart (Fig. **4**).

Fig. (**4**) shows that for mud density under certain conditions, along with an increasing enlargement rate, mud apparent geometric factor increases. Fig. (**4**) also shows that borehole enlargement causes density log value distortion. There is little change in the mud apparent geometric factor (mud apparent geometric factor less than 0.15) when the enlargement rate is less than 20% (caliper less than 27 cm). This can be approximated when the density log value is not affected by the influence of hole enlargement. In practical work, there is no need for correction of hole enlargement impact on density logs. The density logging value can be approximated as the density value of coal rock; however, with enlargement rates of greater than 20% the mud apparent geometric factor increases sharply. Therefore, in cases that the caliper is greater than 27 cm, there is significant influence from the enlargement impact, resulting in a need to perform an enlargement impact correction for the density log.

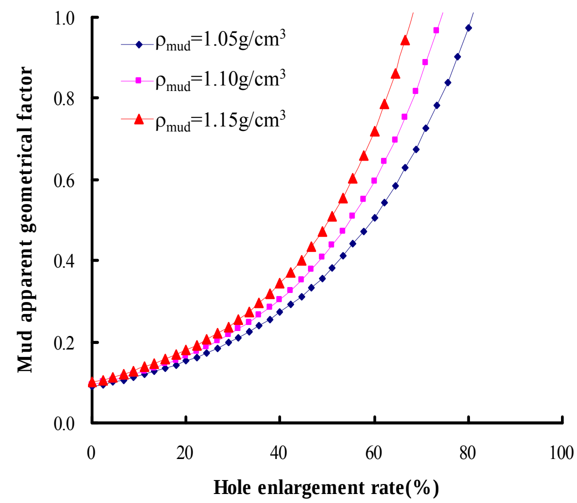

Fig. (4). Relationship diagram for expansion rate and mud apparent geometric factor.

If the caliper is respectively 22, 24 and 26 cm, and mud density is different, we evaluate the relationship between mud density and mud apparent geometric factor. Use of the numerical calculation in Equation (10) produces a relationship chart of mud density and mud apparent geometric factors, as shown in Fig. (**5**). The chart shows that when mud density is small ($\rho_{mud} < 1.2$ g/cm^3) for the study area, there is a corresponding small change in the mud apparent geometric factor. The actual mud density used is 1.06 g/cm^3, with a minimum density of 1.02 g/cm^3, so the effect of mud density can be negligible; however, along with the hole diameter enlargement there is an increase in the mud apparent geometric factor. Fig. (**5**) also shows that changes in hole diameter significantly influences the mud geometric factor.

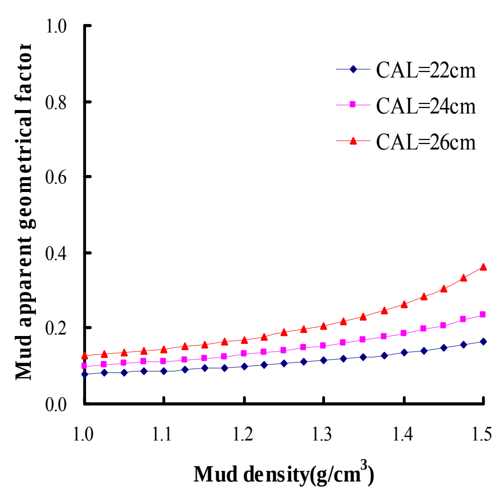

Fig. (5). Relationship diagram of for mud density and mud apparent geometric factor.

In general, mud density is less than coalbed density and borehole enlargement results in measured density log values less than true density of the coal bed, i.e., with the increase of mud density, the closer the mud density gets to true density of the coal bed, the smaller the correction value is. Alternatively, the correction value increases as the enlargement rate increases. Therefore, the correction value for density log enlargement impact has a positive correlation with hole enlargement rate and has a negative correlation with mud density. In practice, mud density and bit diameter for drilling are given and hole enlargement rate can be derived from the caliper logging value and bit diameter. Therefore, the problem of correcting hole enlargement impact on the density log will be readily solved.

APPLICATION EXAMPLES

Based on the model discussed above, FORTRAN language was used to program the process of correcting hole diameter enlargement impacts and link it to a FORWARD logging interpretation platform to achieve apparent automatic computer correction of hole enlargement impacts on density logs for CBM reservoirs. Fig. (**6**) shows the effect of correcting density log hole enlargement impacts on the density log for well H3, where the yellow area represents hole enlargement. The lithologic profile shows that coal beds are found in sections 1206.3~1208.1 m, 1211~1217 m and 1226.5~1228 m. The corresponding caliper curve reveals that borehole diameter enlargement in varying degrees exists in the coal bed sections, particularly in upper sections of 1206.3~1208.1 m and 1211~1217 m. The density log response value in these sections is only 1.28~1.40 g•cm^{-3}. Through laboratory analysis and testing of the coal core's relative apparent density, the calculated apparent relative density in these sections is 1.60~1.65 g•cm^{-3}, which indicates that distortion of measured density logging values is caused by hole enlargement impact.

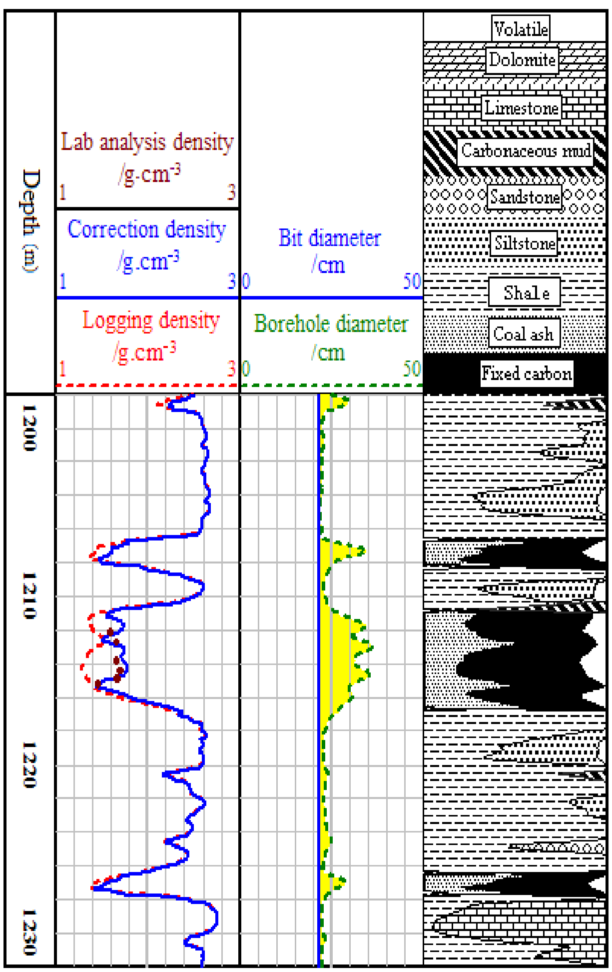

Fig. (6). Effect of correcting the hole enlargement impact on density log for well H3.

Based on a comparison of density logging values before and after correction using lab assay values of relative density for a coal core, there is little variance in density before and after correction within the normal borehole section. The density logging value after correction is greater than the density value before correction in the hole enlargement section and is much closer to apparent relative density determined through lab analysis. Correction results are within the range of normal logging response values for the coal beds. To some extent, this method has eliminated hole enlargement impact and the results of correction can satisfy requirements for evaluating coalbed reservoir logging.

CONCLUSION

Compared with other types of rock, coal rock has a lower volume density and distinguishable features. In the study area, the coal beds are characterized by weak cementation, slackness, brittleness and softness. Well-developed face and end cleats in the coal beds will collapse easily and give rise to borehole enlargement, which is the main cause for significant distortion of density log response values in the study area.

Using the "apparent geometric factor" method, we numerically calculated the caliper range correction for enlargement impact on density logging. Based on the relative density evaluated through laboratory analysis, logging density value and caliper value, we determined the relevant parameters required for the mud apparent geometric factor in the equation used in our calculations. An expansion rate, a mud apparent geometric factor chart and a correction model for density logging were applied to the work area. Practical applications have shown that this method is capable of correcting density log hole enlargement impact for coal beds within the study area and can also be used for effective correction of density log hole enlargement impact for CBM reservoirs both at home and abroad.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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