Quantitative measurement on coal components through the interpretation model of geophysical log: A case study from the Qaidam Basin, NW China

Shiming Liu¹, Rui Liu¹, Shuheng Tang¹, Cunliang Zhao², Bangjun Liu², Junwei Diao³ and Zhaodong Xi¹

Abstract
The Iqe coalfield is one of the most significant coal production bases in the Qaidam Basin. Over the last few decades, core explorations have targeted the Dameigou Formation for No. 7 coal seam (M7). Although many M7 coal samples have been analyzed for coal components in the laboratory, the systematic understanding of the components and changes of coal in the whole Iqe coalfield is still inadequate. In this study, we focus on building log interpretation models to accurately calculate the content of coal components of M7, including ash yield (A_{ad}), volatile matter (V_{daf}), fixed carbon (FC_{ad}), and moisture (M_{ad}). Multiple regression analysis and statistical method, combined with the rock volume model, were used to establish log interpretation models of coal components. A total of 28 coal samples from ZK1, ZK2, ZK11-5, ZK23-4, and ZK36-9 wells in the Iqe coalfield were involved in the modeling, as well as well-logs parameters, such as radioactivity (GR), compensation density (DEN), acoustic (AC), and resistivity (RLLD). According to sensitivity analysis, the fitted A_{ad} and V_{daf} contents of M7 increase with the increasing of DEN and GR values, whereas the FC_{ad} content shows the opposite way. Furthermore, the positive relationship between A_{ad} and V_{daf} (R² = 0.59) and the negative relationship between A_{ad} and FC_{ad}...
\( R^2 = 0.92 \) as well as \( V_{daf} \) and \( FC_{ad} \) \( (R^2 = 0.69) \) indicate that \( A_{ad} \) is a key factor in coal and should be prior determined. Finally, based on the multiple regression analysis and rock volume model, we proposed log interpretation models for M7 coal components in the Iqe coalfield, these models have been examined successfully by the case studies from the same coalfield and will provide new insights into the application of geophysical log parameters for coal quality evaluation.

**Keywords**
Coal components, log interpretation model, No.7 coal seam, Iqe coalfield

**Introduction**
At present, the production and consumption of coal in China still account for a significant proportion (e.g. around 60% in total primary energy consumption; Chen et al., 2017; He et al., 2021; Yang et al., 2018), and China is the largest coal producing country around the world (Gao et al., 2019; Kalkreuth et al., 2020; Ward, 2016). In recent years, green and clean utilization of coal has been vigorously promoted by China government. Understanding the petrologic compositions and contents of coal is necessary for better utilization of coal (Feng et al., 2020). The primary coal components are ash \( A_{ad} \), volatile matter \( V_{daf} \), fixed carbon \( FC_{ad} \), and moisture \( M_{ad} \), occurring in a complex compound formation. Commonly, the coal components can be determined by geochemical analysis in laboratory and geophysical log interpretation (Fu et al., 2009a; Roslin and Esterle, 2015; Shao et al., 2013). However, different coal types have obviously variations in geophysical log data such as natural gamma ray (GR), compensation density (DEN), acoustic (AC), and deep investigate double lateral resistivity log (RLLD) (Lamberson and Bustin, 1993; Scott et al., 2007).

Generally, geochemical test in laboratory is more reliable for coal components. However, sample collection and analysis are cost- and labor-intense, as well as high uncertainty during the collection and transportation process. As an alternative, in the past decades, geophysical log data have been widely used for calculating the coal petrologic components, albeit with variable success (Mavor et al., 1994; Roslin and Esterle, 2015; Shao et al., 2013; Yegireddi and Bhaskar, 2009). In the analysis of coal by well logs, parameters mainly include spontaneous potential (SP), GR, borehole diameter (CAL), DEN, AC, RLLD, and shallow investigate double lateral resistivity log (RLLS). However, due to the relatively loose structure of coal seam, CAL is prone to expansion in coal seam (Safar et al., 2009; Vieira et al., 2007) and can be affected by the coalbed methane content with changes of inverse (Hamada and Hegaxy, 2007; Trcka et al., 2006). The coal types has a close relationship with the SP log (Hou, 2000), and the detection depth of RLLD is higher than that of RLLS. Previous researchers reviewed that the geophysical log responses of coal components include the followings: 1) low ash yield generally corresponds to low DEN and GR logging values (Chatterjee and Paul, 2013; Ghosh et al., 2014); 2) the higher \( V_{daf} \) content commonly along with the greater DEN and GR logging values; 3) the \( FC_{ad} \) content is negatively correlated with DEN and GR logging data (Fu et al., 2009b). Therefore, we selected the well logs of DEN, GR, AC, SP, RLLS, and RLLD to identify the coal seam and evaluate the coal components in present study.

Different statistical approaches and regression models have been used to calculate coal components, and the representative and widely applied methods and models are as follows:
1) Bond et al. (1971) proposed a physical bulk-volume model of rock, providing a fundamental theory for calculating the coal components. 2) Mullen (1988) proposed a statistical analysis method to determine the physical properties of coal, such as coal components, coalbed methane content, and coal seam structure, whereas no geophysical log model have been established to calculate coal components. However, the statistical analysis is benefit for establishment of multiple regression model. 3) Pan and Liu (1996) found a positive correlation between coal ash yield and DEN values, and this relationship can be used to calculate $A_{ad}$ content in coal. However, the measurement of DEN is influenced by multiple factors, such as the quality of well, mud raw materials, and water and gas content of coal seam. Thus, the results may be not reliable by only using DEN to obtain coal component content. 4) Hou and Wang (1999) used the BP neural network method to program multiple logging data as the input layer of model and finally obtained the percentages of coal component in the output layer. However, the respective specimen has a great impact on the results. 5) Gagarin (2008) attempted to use mineral content to determine ash content of Karaganda coal, but did not involve other coal components. In addition, the mineral content is difficult to determine quantitatively. 6) Man and Yang (2008) proposed fuzzy mathematics to evaluate the content of coal component and achieved a certain success (Huang et al., 2020). However, this method requires specific conditions which are difficult to popularize.

Although many statistical approaches and regression models have been proposed, the application conditions and settings of each method or model vary considerably. In this paper, a multiple regression analysis quantitative method with independent multi-factor variables is proposed based on geophysical log data to determine the content of coal component in coal seam No. 7 (M7) from the Iqe coalfield. We selected coal samples at depths ranging from 1083 to 1374 m to investigate $A_{ad}$, $V_{daf}$, $F_{Ca}$, and $M_{ad}$ of coal by geophysical log and compared the results with laboratory analyses. The results from this study provides new insights for determining the content of coal components using geophysical log data.

**Geological setting**

The Qaidam Basin, located in the northwest (NW) China, is one of the basins with the most petroleum and coal production developed on the Qaidam block, with an area of around $1.2 \times 10^5$ km$^2$ (Figure 1a and b). Over 10-km-thick sediments were deposited throughout the Late Neoproterozoic to Cenozoic in the Qaidam Basin, and several coal seams were developed during the Carboniferous and Jurassic epochs (Liu et al., 2013). The Jurassic strata in the Qaidam Basin have been widely studied in recent years due to tremendous coal mining in this basin (Li et al., 2020; Lu et al., 2020; Shao et al., 2014).

The Iqe coalfield is one of the most significant coal production bases in Qinghai Province and located in the northern margin of the Qaidam Basin (Figure 1b). The basement of Iqe coalfield is Proterozoic and Ordovician metamorphic rock, and the overlying strata is filled with complete Middle Jurassic sediments (Chen et al., 2019; Liu et al., 2013) (Figure 2). Coal-bearing strata in the Middle Jurassic consist of the Dameigou Formation ($J_2d$) and the Shimengou Formation ($J_2s$), which contain a total of seven coal measures (M1–M7) (Figure 2). Of these, M5 and M7 are the primary mineable coal seams in the Iqe coalfield, with a potential distribution area of 620 km$^2$. The Shimengou Formation is composed of five coal seams and black shale, oil shale, mudstone, and siltstone, whereas only M5 is minable in the entire coalfield, ranging from 0.12 to 41.4 m with an average of 4.9 m (M1 and M2 are
un-mineable, M3 and M4 are partly mineable measures), these coal measure strata were formed in delta, fluvial, and lacustrine environments (Liu et al., 2013; Qin et al., 2018). The Dameigou Formation is composed of M6 and M7 coal seams, mudstone, carbonaceous mudstone, and sandstone, which were deposited in fluvial and delta settings (Hu et al., 2019; Lu et al., 2020; Zhao et al., 2017). The thickness of M7 ranges from 1.7 to 105.8 m with an average of 19.3 m, and forming two separate parts in the Iqe coalfield (Figure 1c). In this paper, we focus on the main, mineable M7 coal measure, which is successively distributed in the central part of the Iqe coalfield. Coal types of M7 in the Iqe coalfield are mainly subbituminous coal and non-caking coal. The macrolithotypes of M7 primarily consist of semibright coal, followed by bright coal and semidull coal, with a dark to black color, parallel bedding, and a lumpy structure, as well as a glass-golden luster (Chen et al., 2019).

Samples and analytical procedures

For this study, 28 samples were collected from M7 coal seam of the ZK1, ZK2, ZK11-5, ZK23-4, and ZK36-9 wells. Samples depths ranged from 1,083 to 1,374 m and sample thickness from 0.4 to 1.1 m (Figure 1d). All samples were analyzed for ash yield, volatile
Ash yield determination was performed using a heating furnace with 1-g sample. Air was advanced into the furnace, and subsequently, the temperature was set at 500°C and maintained for 30 min, followed by further heating to 815°C. The samples were automatically weighed every 5 min until constant weight for 10 min, with weight variations less than 0.0005 g. The moisture content was determined using a heating furnace. For this, 1-g sample was placed on a dry crucible and air was fed into the heating furnace. The temperature was increased to 105°C–110°C at 5°C/min. The samples were automatically weighed every 5 min until constant weight for 10 min, and subsequently, the moisture content was determined based on mass loss. Volatile matter was measured with 1-g samples using a heating furnace. The temperature was increased to 900°C, and during this period, nitrogen was fed into the heating furnace at 120 times per hour, then transported the sample into the

**Figure 2.** Integrated histogram of the coal measure strata in the Middle Jurassic of Iqe coalfield.

matter, and moisture in the Key Laboratory of China National Administration of Coal Geology.

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furnace keeping for 7 min. Ash yield, volatile matter, and moisture analysis followed the Chinese Standard Method GB/T 30732–2014 with a precision above ±0.0005 g. Fixed carbon is the organic matter remaining in the coke slag after high-temperature pyrolysis of coal samples. The fixed carbon content is the percentage of coal samples (100%) minus the moisture, ash yield, and volatile contents (China National Coal Association, 2009). The results of coal petrol analysis are shown in Table 1.

Geophysical logging data used in this study were determined using PSJ-2 type digital logging apparatus on these selected wells. The log parameters include SP, CAL, DEN, GR, AC, SP, RLLS, and RLLD, and the logging data have been demonstrated that are available and reliable by standardized correction and practical application in coal exploration.

Establishment of the relationship between log parameters and coal components

Principle of log interpretation

The geophysical log interpretation is widely applied for calculating coal components, such as ash yield, volatile, fixed carbon, and water contents (Lu et al., 2021; Sayan et al., 2016; Shao et al., 2013). The primary theoretical basis for using logging data to evaluate coal components is multiple regression analysis (Sayan et al., 2016; Shao et al., 2013; Scott et al., 2007). Based on the different contributions of coal components to DEN, GR, AC, and RLLD, we propose the response equation to determine the petrological parameters of M7 in the Iqe coalfield. In addition, as a low-porosity and low-permeability character, coal not only develop matrix pores but unique cleat fractures (Bond et al., 1971; Edwards and Banks, 1978). Therefore, the establishment of coal petrological volume model is the prerequisite and basis for logging interpretation and evaluation.

Multiple statistical regression analysis was widely used to determine the quantitative relationship between two or more variables (Lamberson and Bustin, 1993). The least square method can be used to program the linear relationship, such as $y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots$, where $a_0$ is a constant, $x$ is log parameter, and $a_1$, $a_2$, and $a_3$...are regression coefficients. Coal components, as dependent variable $y$, was used for multiple regression equation calculation. Through sensitivity analyzing of logging data, the most relevant log parameters, such as GR, DEN, and AC... are selected as independent variables. Finally, according to the multiple regression analysis among coal components and log parameters, the calculation model of each coal component is optimized.

Sensitivity analysis

Although some kinds of geophysical parameters of coal components (such as the acoustic velocities of ash yield, volatile components, and fixed carbon) cannot be determined directly, we can build relationships between geophysical log parameters (GR, DEN, AC, and RLLD) and coal components ($A_{ad}$, $V_{daf}$, $FC_{ad}$, and $M_{ad}$) using the least square method (Dong, 2008). However, the correlation among different coal components and log parameters exhibit a relatively large variation (Figures 3 to 5). Generally, different well logs contribute various responses to coal seam, for example, low GR and DEN, negative abnormality of SP, and high AC, RLLS, and RLLD values have been detected in coal seam (Fu et al., 2009a; Hou, 2000; Rai et al., 2004; Roger, 2005). In this study, we selected the well logs of DEN,
GR, AC, SP, RLLS, and RLLD to identify coal seam and evaluate coal components. Partially high-resolution log data have been used to identify and evaluate coal components, and the sensitivity analysis are as follows:

\( A_{ad} \): Ash yield plays a significant role and is a key parameter among the coal components because it closely relates to other coal components (Shao et al., 2013). Therefore, an effective logging interpretation model of \( A_{ad} \) should be first established to facilitate the building of other models. The relationships between \( A_{ad} \) and DEN, GR, AC, and RLLD indicate that \( A_{ad} \) is positively correlated with DEN and GR (Figure 3a and b), but has a poor correlation with AC and RLLD (Figure 3c and d). That is because of the low ash content (between 2.4 and 24.0%, av. 11.8%) of M7 in the Iqe coalfield, which generally corresponds to a low DEN (Chatterjee and Paul, 2013; Ghosh et al., 2014). The radioactivity of M7 coal is quite low, may cause by low clay mineral content, which is also supported by the mineral analysis results of M7 from Sun et al. (2015). A strong positive relationship between \( A_{ad} \) and GR of M7 indicates that GR would be a significant parameter to calculate \( A_{ad} \) (Figure 3b). Coal

### Table 1. Proximate analysis of M7 from 5 wells in the Middle Jurassic Dameigou Formation.

| Well no. | Coal measure | Sample No. | Depth (m) | \( A_{ad} \) (%) | \( V_{daf} \) (%) | \( FC_{ad} \) (%) | \( M_{ad} \) (%) |
|----------|--------------|------------|-----------|------------------|------------------|-----------------|-----------------|
| ZK1 M7   | A1           | 1306.6     | 12.2      | 34.7             | 50.9             | 2.2              |
| ZK1 M7   | A2           | 1310.0     | 15.9      | 38.4             | 43.9             | 1.9              |
| ZK1 M7   | A3           | 1313.7     | 11.6      | 37.7             | 48.8             | 2.0              |
| ZK1 M7   | A4           | 1316.1     | 13.8      | 35.7             | 48.9             | 1.6              |
| ZK1 M7   | A5           | 1322.4     | 22.0      | 40.4             | 36.3             | 1.3              |
| ZK1 M7   | A6           | 1327.7     | 8.8       | 34.0             | 55.5             | 1.7              |
| ZK1 M7   | A7           | 1331.3     | 8.3       | 32.4             | 57.2             | 2.1              |
| ZK1 M7   | A8           | 1337.4     | 16.6      | 36.3             | 45.3             | 1.8              |
| ZK1 M7   | A9           | 1343.2     | 11.3      | 35.1             | 51.7             | 1.8              |
| ZK1 M7   | A10          | 1348.9     | 14.2      | 36.5             | 47.5             | 1.8              |
| ZK2 M7   | A11          | 1362.3     | 2.4       | 30.5             | 64.8             | 2.3              |
| ZK2 M7   | A12          | 1363.6     | 2.5       | 29.4             | 65.7             | 2.4              |
| ZK2 M7   | A13          | 1367.2     | 2.5       | 30.3             | 64.7             | 2.5              |
| ZK2 M7   | A14          | 1375.2     | 2.4       | 29.7             | 65.8             | 2.2              |
| ZK11-5 M7| A20          | 1084.2     | 7.6       | 35.7             | 53.4             | 3.3              |
| ZK11-5 M7| A21          | 1092.8     | 5.2       | 35.8             | 55.5             | 3.5              |
| ZK11-5 M7| A22          | 1097.3     | 8.4       | 32.4             | 55.9             | 3.3              |
| ZK11-5 M7| A23          | 1103.5     | 9.0       | 35.0             | 52.6             | 3.5              |
| ZK11-5 M7| A24          | 1110.8     | 8.7       | 34.2             | 54.0             | 3.1              |
| ZK11-5 M7| A25          | 1118.2     | 7.5       | 38.8             | 50.5             | 3.2              |
| ZK23-4 M7| A15          | 1215.6     | 6.7       | 34.5             | 56.8             | 2.0              |
| ZK23-4 M7| A16          | 1218.0     | 14.8      | 37.6             | 45.5             | 2.1              |
| ZK23-4 M7| A17          | 1220.8     | 23.1      | 35.5             | 39.6             | 1.7              |
| ZK23-4 M7| A18          | 1223.8     | 21.7      | 35.6             | 40.9             | 1.9              |
| ZK23-4 M7| A19          | 1228.1     | 24.0      | 35.3             | 38.7             | 2.0              |
| ZK36-9 M7| A26          | 1111.5     | 18.2      | 35.1             | 44.0             | 2.7              |
| ZK36-9 M7| A27          | 1114.3     | 17.0      | 38.0             | 42.3             | 2.8              |
| ZK36-9 M7| A28          | 1117.5     | 14.4      | 37.4             | 45.4             | 2.8              |
with low DEN values commonly have well-developed pores and fractures as well as high AC values (Fu et al., 2009a). Generally, the $A_{ad}$ content tends to decrease as resistivity increases (Fu et al., 2009b). A poor relationship between RLLD and $A_{ad}$ may cause by coal structure and $M_{ad}$ content (Figure 3d). According to the sensitivity analysis of different well logs and $A_{ad}$, DEN and GR should be selected to optimize during the establishment of $A_{ad}$ model.

$V_{daf}$ The coalification degree, the depositional environment and coal petrologic types are the main factors controlling the $V_{daf}$ content (Scott et al., 2007). Commonly, the $V_{daf}$ content decreases with increasing coalification degree duo to coal molecules structure changes (Nie and Wang, 2012), as a result, lignite has higher $V_{daf}$ values, while $V_{daf}$ values of anthracite is the lowest. The $V_{daf}$ values of studied coal samples ranged from 29.4% to 40.4%, with an average of 35.1% (Table 1), coinciding with those of subbituminous coal and non-caking coal in the Iqe coalfield (Chen et al., 2019). The relationships between $V_{daf}$ and DEN, GR, AC, and RLLD indicate that $V_{daf}$ is weak to moderate positively correlated with DEN and GR, and has a poor correlation with AC and RLLD (Figure 4). Furthermore, a moderate relationship between $V_{daf}$ and $A_{ad}$ ($R^2=0.59$) suggest that $A_{ad}$ content should be used as an independent variable in regression analysis for $V_{daf}$ content (Figure 4e). Interestingly, a good relationship between DEN and GR ($R^2=0.68$) indicates that both of them are key parameters for determining the coal components. According to

**Figure 3.** Cross-plots of $A_{ad}$ and related well logs. (a) Relationship between $A_{ad}$ and DEN. (b) Relationship between $A_{ad}$ and GR. (c) Relationship between $A_{ad}$ and AC. (d) Relationship between $A_{ad}$ and RLLD of coal.
the sensitivity analysis of different well logs and $V_{daf}$ values of M7, GR and DEN should be selected to optimize in the establishment of $V_{daf}$ model, and $A_{ad}$ can be used as the auxiliary sensitivity parameter.

$FC_{ad}$ The $FC_{ad}$ content is one of the most important geological parameters for evaluating coal property (Hong, 2008; Sayan et al., 2016). Generally, the value of $FC_{ad}$ is calculated in laboratory analysis, the results of the studied samples ranges from 36.3% to 65.8% with a mean value of 50.8% (Table 1). The relationships between $FC_{ad}$ and DEN, GR, AC, and

Figure 4. Relationships between $V_{daf}$ and discussed well log values and $A_{ad}$. (a) The intersection diagram of $V_{daf}$ and DEN. (b) The intersection diagram of $V_{daf}$ and GR. (c) The intersection diagram of $V_{daf}$ and AC. (d) The intersection diagram of $V_{daf}$ and RLLD. (e) The intersection diagram of $V_{daf}$ and $A_{ad}$. (f) The intersection diagram of DEN and GR.
RLLD indicate that FC<sub>ad</sub> has good negative correlations with DEN and GR, whereas poor correlations with AC and RLLD (Figure 5a to d). Furthermore, FC<sub>ad</sub> has strong negative correlation with V<sub>daf</sub> and A<sub>ad</sub> (Figure 5e and f), suggesting that V<sub>daf</sub> and A<sub>ad</sub> content in the studied samples have significant influence on FC<sub>ad</sub> content. According to the sensitivity analysis of FC<sub>ad</sub> and different well logs, as well as V<sub>daf</sub> and A<sub>ad</sub> content, the sensitivity parameters, such as DEN, GR, V<sub>daf</sub>, and A<sub>ad</sub>, should be chosen to optimize the FC<sub>ad</sub> calculating model.

Figure 5. Relationships between FC<sub>ad</sub> and related well log values and A<sub>ad</sub>. (a) Relationship between FC<sub>ad</sub> and DEN. (b) Relationship between FC<sub>ad</sub> and GR. (c) Relationship between FC<sub>ad</sub> and AC. (d) Relationship between FC<sub>ad</sub> and RLLD. (e) Relationship between FC<sub>ad</sub> and V<sub>daf</sub>. (f) Relationship between FC<sub>ad</sub> and A<sub>ad</sub>. 

RLLD indicate that FC<sub>ad</sub> has good negative correlations with DEN and GR, whereas poor correlations with AC and RLLD (Figure 5a to d). Furthermore, FC<sub>ad</sub> has strong negative correlation with V<sub>daf</sub> and A<sub>ad</sub> (Figure 5e and f), suggesting that V<sub>daf</sub> and A<sub>ad</sub> content in the studied samples have significant influence on FC<sub>ad</sub> content. According to the sensitivity analysis of FC<sub>ad</sub> and different well logs, as well as V<sub>daf</sub> and A<sub>ad</sub> content, the sensitivity parameters, such as DEN, GR, V<sub>daf</sub>, and A<sub>ad</sub>, should be chosen to optimize the FC<sub>ad</sub> calculating model.
The content of $M_{ad}$ in coal samples can be calculated according to the “rock volume model”, which divide the unit volume of coal into four parts ($A_{ad}$, $V_{daf}$, $F_{C ad}$, and $M_{ad}$). Here note that not considering the gas content in coal because only a small amount of gas was contained within the coal reservoirs (Sayan et al., 2016; Shao et al., 2013; Yang et al., 2007):

$$A_{ad} + V_{daf} + F_{C ad} + M_{ad} = 1 \quad (1)$$

$$M_{ad} = 1 - F_{C ad} - A_{ad} - V_{daf} \quad (2)$$

Where $A_{ad}$ is the ash yield, %; $V_{daf}$ is the volatile matter content, %; $F_{C ad}$ is the fixed carbon, %; $M_{ad}$ is the moisture, %.

As discussed above, we found that the $A_{ad}$, $V_{daf}$, and $F_{C ad}$ of studied samples from five wells in the Iqe coalfield are closely related to DEN and GR logs. In contrast, AC and RLLD logs have a poor correlation with these coal components. Therefore, DEN and GR are the primary proxies for building the log interpretation models, as well as considering the relationships among coal components.

**Log interpretation model of coal components**

Based on the sensitivity analysis results of coal components and DEN, GR, AC, and RLLD logs, the regression calculations for three kinds of coal components were performed using different log interpretation models to obtain the available correlation coefficients.

**$A_{ad}$ model.** To establish the $A_{ad}$ model, the following equations have been acquired based on DEN and GR logs (Table 2). The regression coefficient in model 3 is relatively high and can be regarded as an available calculating model for M7 coal in the Iqe coalfield.

| Model | Regression equation | Coefficient | Effect |
|-------|---------------------|-------------|--------|
| 1     | $A_{ad} = 39.92 \text{ DEN} - 45.29$ | 0.78 | Bad |
| 2     | $A_{ad} = 0.58 \text{ GR} - 0.39$ | 0.84 | Good |
| 3     | $A_{ad} = 18.17 \text{ DEN} + 0.37 \text{ GR} - 21.96$ | 0.88 | Best |

**$V_{daf}$ model.** As mentioned above, a good positive relationship between $V_{daf}$ and GR, DEN logs, as well as $A_{ad}$ content suggest that these factors are important to $V_{daf}$. Thus, the log interpretation model of $V_{daf}$ was established using these sensitivity parameters based on multivariate regression analysis, and the acquired models are exhibited in Table 3. By comparing the regression coefficient, we propose that model 5 is the best calculating model for $V_{daf}$ in this study.

**$F_{C ad}$ model.** According to the sensitivity analysis, the well logs of DEN and GR, and $A_{ad}$ are significant sensitivity parameters to evaluate $F_{C ad}$. Multiple regression analysis has been performed to obtain the regression equation and regression coefficient using these significant sensitivity parameters and laboratory analysis results of coal samples, and the results
Table 3. Regression equations and coefficients of the $V_{daf}$ content.

| Model | Regression equation                      | Coefficient | Effect |
|-------|------------------------------------------|-------------|--------|
| 1     | $V_{daf} = 13.71 \ln (DEN) + 30.22$    | 0.23        | Bad    |
| 2     | $V_{daf} = 3.54 \ln (GR) + 24.73$       | 0.47        | Bad    |
| 3     | $V_{daf} = 3.06 \ln (A_{ad}) + 28.09$  | 0.59        | Bad    |
| 4     | $V_{daf} = 0.35 \ln (GR) + 2.83 \ln (A_{ad}) + 27.60$ | 0.75 | Bad    |
| 5     | $V_{daf} = 0.89 \ln (GR) + 3.80 \ln (A_{ad}) - 12.05 \ln (DEN) + 28.07$ | 0.81 | Best   |

Table 4. Regression equations and coefficients of FCad content.

| Model | Regression equation                      | Coefficient | Effect |
|-------|------------------------------------------|-------------|--------|
| 1     | $FC_{ad} = -47.44 DEN + 118.64$         | 0.66        | Bad    |
| 2     | $FC_{ad} = -0.72 GR + 65.87$            | 0.77        | Bad    |
| 3     | $FC_{ad} = -1.24 A_{ad} + 65.42$       | 0.92        | Good   |
| 4     | $FC_{ad} = -16.53 DEN - 0.53 GR + 85.49$ | 0.78 | Bad    |
| 5     | $FC_{ad} = 9.08 DEN - 1.42 A_{ad} + 54.52$ | 0.92 | Good   |
| 6     | $FC_{ad} = 0.009 GR - 1.25 A_{ad} + 65.38$ | 0.92 | Good   |
| 7     | $FC_{ad} = 9.11 DEN - 0.004 GR - 1.41 A_{ad} + 54.51$ | 0.93 | Best   |

Figure 6. The results of experimental and calculated values of M7 coal components from ZK1 well in the Iqe coalfield.
| Well no. | Coal seam | Depth  | Ash content/% | Fixed carbon content/% | Volatile component content/% |
|---------|-----------|--------|---------------|------------------------|-----------------------------|
|         |           |        | Experimental | Calculated          | Relative error   | Experimental | Calculated | Relative error | Experimental | Calculated | Relative error |
| ZK1     | M7        | 1306.64| 12.16        | 10.88                | 11.72           | 50.93        | 53.44      | 4.70           | 34.72        | 35.86      | 3.19           |
|         |           | 1310.00| 15.85        | 16.87                | 6.05            | 43.91        | 42.09      | 4.32           | 38.36        | 38.05      | 0.81           |
|         |           | 1313.72| 11.60        | 9.98                 | 16.23           | 48.75        | 54.64      | 10.78          | 37.70        | 35.29      | 6.84           |
|         |           | 1316.10| 13.77        | 11.76                | 17.05           | 48.94        | 51.79      | 5.51           | 35.65        | 35.95      | 0.85           |
|         |           | 1322.22| 21.83        | 19.75                | 10.54           | 36.32        | 40.21      | 9.68           | 40.41        | 37.91      | 6.59           |
|         |           | 1327.84| 8.79         | 8.25                 | 6.56            | 55.54        | 55.60      | 0.11           | 33.97        | 34.76      | 2.27           |
|         |           | 1331.04| 8.31         | 7.88                 | 5.44            | 57.20        | 56.77      | 0.76           | 32.42        | 34.30      | 5.48           |
|         |           | 1337.36| 16.57        | 14.94                | 10.93           | 45.31        | 50.27      | 9.87           | 36.33        | 36.91      | 1.57           |
|         |           | 1343.16| 11.34        | 10.42                | 8.83            | 51.72        | 55.13      | 6.18           | 35.13        | 35.01      | 0.33           |
|         |           | 1348.90| 14.21        | 14.87                | 4.43            | 47.45        | 47.12      | 0.71           | 36.51        | 36.32      | 0.53           |
| ZK11-5  |           | 1084.18| 7.60         | 8.20                 | 7.35            | 53.39        | 55.11      | 3.11           | 35.69        | 34.94      | 2.13           |
|         |           | 1092.80| 5.17         | 5.57                 | 7.18            | 55.53        | 56.07      | 0.97           | 35.84        | 34.65      | 3.42           |
|         |           | 1097.30| 8.43         | 8.47                 | 0.52            | 55.86        | 55.11      | 1.36           | 32.41        | 34.64      | 6.43           |
|         |           | 1103.49| 8.95         | 8.05                 | 11.18           | 52.61        | 56.61      | 7.06           | 34.98        | 33.04      | 5.87           |
|         |           | 1110.83| 8.72         | 8.25                 | 5.70            | 53.96        | 57.35      | 5.91           | 34.20        | 33.80      | 1.19           |
|         |           | 1118.23| 7.52         | 7.67                 | 1.97            | 50.47        | 55.91      | 9.73           | 38.80        | 36.58      | 6.07           |
| ZK19-4  |           | 995.39 | 9.82         | 10.64                | 7.67            | 49.90        | 50.02      | 0.24           | 36.51        | 35.74      | 2.15           |
|         |           | 997.00 | 15.20        | 16.18                | 6.06            | 48.09        | 45.31      | 6.14           | 34.56        | 36.68      | 5.78           |
|         |           | 999.00 | 13.21        | 14.48                | 8.77            | 48.95        | 47.62      | 2.79           | 35.96        | 36.24      | 0.77           |
|         |           | 1001.03| 29.65        | 31.05                | 4.52            | 26.26        | 25.07      | 4.76           | 38.24        | 39.14      | 2.29           |
|         |           | 1004.00| 13.44        | 12.48                | 7.69            | 49.40        | 50.74      | 2.64           | 31.56        | 33.38      | 5.45           |
Figure 7. The results of experimental and calculated values of M7 coal components from ZK11-5 well in the Iqe coalfield.

Figure 8. The results of experimental and calculated values of M7 coal components from ZK19-4 well in the Iqe coalfield.
are shown in Table 4. Obviously, model 7 is more proper to calculate the FC$_{ad}$ values of M7 in Iqe coalfield.

**Case studies**

In order to identify the reliability and practicability of log interpretation models, we randomly select two wells (ZK1 and ZK11-5) which involved in model calculation and a new well (ZK19-4) in the Iqe coalfield to test these models. We use these selected optimal multiple regression models to calculate the coal component contents of M7 coal, such as $A_{ad}=18.17\ \text{DEN} + 0.37\ \text{GR} - 21$, $V_{daf}=0.89\ \text{Ln}(\text{GR}) + 3.80\ \text{Ln}(A_{ad}) - 12.05\ \text{Ln}(\text{DEN}) + 28.07$, and $FC_{ad}=9.11\ \text{DEN} - 0.004\ \text{GR} - 1.41A_{ad} + 54.51$. In the ZK1 well, the average relative error between log interpretation and experimental results of $A_{ad}$, $V_{daf}$, and $FC_{ad}$ are 9.78, 2.85, and 5.26%, respectively (Figure 6, Table 5). Meanwhile, the average error of ZK11-5 is relatively low in $A_{ad}$ and $FC_{ad}$, which is 5.65 and 4.69%, respectively (Figure 7, Table 5). As a completely new well (ZK19-4), the average error values of log interpretation to experimental results about $A_{ad}$, $V_{daf}$, and $FC_{ad}$, which is 6.94, 3.29, and 3.31%, respectively (Figure 8, Table 5). Most of the experimental results show a good relationship with the calculated values indicating that these models are credible and utility in Iqe coalfield, and the calculated values can meet the needs of coal quality evaluation. Although some individual points have great errors, they may be caused by enlarged borehole and interbedded siltstones within M7 coal seam, and do not affect the application of log interpretation model for calculating the M7 coal components.

**Conclusions**

Understanding the content of coal components is significant for the clean and green utilization of coal. In this study, we chose the well log parameters of DEN, GR, AC, SP, RLLS, and RLLD to identify M7 coal seam variation and evaluate coal components of M7 in the Iqe coalfield. Multiple regression analysis with well log parameters (DEN, GR, AC, and RLLD) as independent variable provides a new approach to build log interpretation models. Based on the significance of $A_{ad}$ in coal and its key control factor for other coal components, we firstly established the $A_{ad}$ model using closely related well logs (DEN and GR) through sensitivity analysis. We seriously considered the relationships between $V_{daf}$, $FC_{ad}$ and $A_{ad}$ when building the multiple regression model for calculating $V_{daf}$ and $FC_{ad}$. Finally, according to the rock volume model derivated as $M_{ad}=1-FC_{ad}-A_{ad}-V_{daf}$, we acquired the calculation method of $M_{ad}$. The results of case studies (ZK1, ZK11-5, and ZK19-4) suggest that the proposed log interpretation models of coal components can meet the needs of coal quality evaluation for M7 in Iqe coalfield. These log interpretation models not only can satisfy to conveniently and economically evaluate M7 coal components in the Iqe coalfield, but also provide new insights into the connections between coal components and well log parameters.

**Declaration of conflicting interests**

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ORCID iD
Shiming Liu https://orcid.org/0000-0002-8599-9452

References
Bond LO, Alger RP and Schmidt AW (1971) Well log application in coal mining and rock mechanics. *Soil Mechanical Engineering Transactions* 250: 355–362.

Chatterjee R and Paul S (2013) Classification of coal seams for coal bed methane exploitation in central part of Jharia coalfield, India-A statistical approach. *Fuel* 111: 20–29.

Chen L, Tian JC, Wen HJ, et al. (2019) Jurassic coal bed methane characteristics and gas-bearing property evaluation in Iqe Coalfield, Northern Qaidam Basin. *Petroleum Geology Experiment* 41(2): 215–221.

Chen Y, Ma SQ and Yu Y (2017) Stability control of underground roadways subjected to stresses caused by extraction of a 10-m-thick coal seam: a case study. *Rock Mechanics and Rock Engineering* 50(9): 2511–2520.

China National Coal Association (2009) *GB/T 212-2008 Proximate Analysis of Coal*. Beijing: China Standard Press.

Dong S (2008) Test on elastic anisotropic coefficients of gas coal. *Chinese Journal of Geophysics* 51(3): 947–952.

Edwards KW and Banks KM (1978) Theoretical approach to the evaluation of in-situ coal. *CIM Bulletin*, 71: 124–131.

Feng Y, Lu JJ, Wang JC, et al. (2020) Desulfurization sorbents for green and clean coal utilization and downstream toxics reduction: A review and perspectives. *Journal of Cleaner Production* 273: 123080.

Fu XH, Qin Y, Wang GX, et al. (2009a) Evaluation of coal structure and permeability with the aid of geophysical logging technology. *Fuel* 88(11): 2278–2285.

Fu XH, Qin Y, Wang GX, et al. (2009b) Evaluation of gas content of coalbed methane reservoirs with the aid of geophysical logging technology. *Fuel* 88(11): 2269–2277.

Gagarin SG (2008) Relation between the petrographic content of mineral components in coal and its ash content. *Coke and Chemistry* 51(7): 241–246.

Gao MZ, Zhang S, Li J, et al. (2019) The dynamic failure mechanism of coal and gas outbursts and response mechanism of support structure. *Thermal Science* 23(Suppl 3): 867–875.

Ghosh S, Chatterjee R, Paul S, et al. (2014) Designing of plug-in for estimation of coal proximate parameters using statistical analysis and coal seam correlation. *Fuel* 134: 63–73.

Hamada GM and Hegaxy AA (2007) Hydrocarbon potential monitoring in gas sandstone reservoirs using TDT and CHFR techniques. SPE 105003.

He Z, Xie H, Gao M, et al. (2021) The fracturing models of hard roofs and spatiotemporal law of mining-induced stress in a top coal caving face with an extra-thick coal seam. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources* 7(1). DOI: 10.1007/s40948-020-00202-9

Hong Y (2008) *Logging Principle and Comprehensive Interpretation*. Shandong: Petroleum University Press. pp.222–223.

Hou JS (2000) *Logging Evaluation Method and Application of Coalbed Methane Reservoir*. Beijing: Metallurgical Industry Press. pp.1–30.

Hou JS and Wang Y (1999) Interpretation of well logging data for coalbed methane using BP neural network. *Geology and Prospecting* 35(3): 41–45.
Hu J, Ma Y, Wu Y, et al. (2019) Jurassic palaeoclimate evolution of the Qaidam Basin: Evidence from chemical weathering analyses. *Geological Journal of China Universities* 25(4): 548–557.

Huang B, Qin Y, Zhang WH, et al. (2020) Prediction of high-quality coalbed methane reservoirs based on the fuzzy gray model: an investigation into coal seam no. 8 in Gujiacao, Xishan, North China. *Energy Exploration & Exploitation* (5): 014459872090144.

Kalkreuth W, Levandowski J, Weniger P, et al. (2020) Coal characterization and coalbed methane potential of the Chico-Lom Coalfield, Paraná Basin, Brazil – Results from exploration borehole CBM001-CL-RS. *Energy Exploration & Exploitation* 38(5): 1589–1630.

Lamberson MN and Bustin RM (1993) Coalbed methane characteristics of gates formation coal, northeastern British Columbia: Effect of maceral composition. *AAPG Bull* 77: 2062–2076.

Li ZX, Wang DH, Wang XC, et al. (2020) Structural modeling and evolution of the piedmont zone in North margin of Qaidam Basin, northeastern Tibetan Plateau. *Energy Exploration & Exploitation* 38(3): 014459872091901.

Liu TJ, Shao LY, Cao DY, et al. (2013) *Formation Conditions and Evaluation of Coal Resources of the Middle Jurassic in the Northern Qaidam Basin*. Beijing: Geological Press, pp.1–276.

Lu H, Li Q, Yue D, et al. (2021) Study on optimal selection of porosity logging interpretation methods for Chang 73 segment of the Yanchang Formation in the southwestern Ordos Basin, China. *Journal of Petroleum Science and Engineering* 198: 108153.

Lu J, Zhou K, Yang M, et al. (2020) Jurassic continental coal accumulation linked to changes in palaeoclimate and tectonics in a fault-depression superimposed basin, Qaidam Basin, NW China. *Geological Journal* 55(12): 7998–7919.

Man JK and Yang G (2008) Industrial analysis of coal based on fuzzy mathematics. *China Mining Magazine* 17(12): 74–77.

Mavor MJ, Close JC and McBane RA (1994) Formation evaluation of exploration coalbed-methane wells. *SPE Formation Evaluation* 9(4): 285–294.

Mullen MJ (1988) Log evaluation in wells drilled for coalbed methane, geology and coalbed methane resources of the northern San Juan Basin, Colorado and New Mexico. Rocky Mountain Association of Geologists, Denver. *Rocky Mountain Association of Geologists*, 113–124.

Nie XF and Wang F (2012) Industrial analysis process and significance of coal. *Energy Technology and Management* 12(1): 125–127.

Pan HP and Liu GQ (1996) Evaluation gas content of coalbeds from density log data. *Progress in Geophysics* 11(4): 41–45.

Qin J, Wang S, Sanei H, et al. (2018) Revelation of organic matter sources and sedimentary environment characteristics for shale gas formation by petrographic analysis of Middle Jurassic Dameigou formation, Northern Qaidam Basin, China. *International Journal of Coal Geology* 195: 373–385.

Rai DK, Roy S and Roy AL (2004) Evaluation of coal bed methane through wire line logs Jharia field: A case study. In: *5th Conference & exposition on petroleum geophysics*, Hyderabad, India, 01 January 2004, pp.910–914.

Roger HM (2005) Hydrologic properties of coalbeds in the Powder River Basin, Montana. Geophysical log analysis. *Journal of Hydrology* 308: 227–241.

Roslin A and Esterle JS (2015) Electrofacies analysis using high-resolution wireline geophysical data as a proxy for inertinite-rich coal distribution in Late Permian Coal Seams, Bowen Basin. *International Journal of Coal Geology* 152: 10–18.

Safar H, Azhary S, Hijazi A, et al. (2009) The first dual lateral well successfully drilled underbalanced in Libya. *SPE* 125870.

Sayan G, Rima C and Prabhat S (2016) Estimation of ash, moisture content and detection of coal lithofacies from well logs using regression and artificial neural network modelling. *Fuel* 177: 279–287.

Scott S, Anderson B, Crosdale P, et al. (2007) Coal petrology and coal seam gas contents of the Walloon Subgroup-Surat Basin, Queensland. Australia. *International Journal of Coal Geology* 70(1–3): 209–222.
Shao L, Li M, Li Y, et al. (2014) Geological characteristics and controlling factors of shale gas in the Jurassic of the Northern Qaidam Basin. *Earth Science Frontiers* 21: 311–322.

Shao X, Sun Y, Sun J, et al. (2013) Log interpretation for coal petrologic parameters: A case study of Hancheng mining area, Central China. *Petroleum Exploration and Development* 40(5): 599–605.

Sun YZ, Zhao CL, Li YH, et al. (2015) Anomalous concentrations of rare metal elements, rare-scattered (dispersed) elements and rare earth elements in the coal from Iqe coalfield, Qinghai province, China. *Acta Geological Sinica (English Edition)* 89(1): 229–241.

Trcka DE, Gilchrist A, Riley S, et al. (2006) Field trials of a new method for the measurement of formation gas using pulsed-neutron instrumentation. SPE 102350.

Vieira P, Larroque F, Al-Saleh AM, et al. (2007) The successful application of under-balanced drilling technology for reservoir evaluation and drilling performance improvement in Kuwait. SPE 106680.

Ward CR (2016) Analysis, origin and significance of mineral matter in coal: An updated review. *International Journal of Coal Geology* 165: 1–27.

Yang X, Zhao W, Zou C, et al. (2007) Genetic mechanism of low-permeability reservoir and the formation and distribution of high-quality reservoir. *Acta Petrolei Sinica* 28(4): 57–61.

Yang N, Tang S, Zhang S, et al. (2018) In seam variation of element-oxides and trace elements in coal from the Eastern Ordos Basin, China. *International Journal of Coal Geology* 197: 31–41.

Yegireddi S and Bhaskar GU (2009) Identification of coal seam strata from geophysical logs of borehole using adaptive Neuro-Fuzzy inference system. *Journal of Applied Geophysics* 67(1): 9–13.

Zhao CL, Liu BJ, Xiao L, et al. (2017) Significant enrichment of Ga, Rb, Cs, REEs and Y in the Jurassic No. 6 coal in the Iqe Coalfield, Northern Qaidam Basin, China—A hidden gem. *Ore Geology Reviews* 83: 1–13.