

Review of Well Logs and Petrophysical Approaches for Shale Gas in Sichuan Basin, China

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Abstract: China has vast reserves of shale gas. Currently, shale gas is one of the focuses of the unconventional reservoir. Well logs play an import role in shale gas production, and it is the bridge connecting geology, geophysics and petroleum engineering. In the exploration stage, well logs are used to identify lithology, evaluate the parameters of mineral types and compositions, total organic carbon (TOC), porosity, permeability, gas content, and the potential resources quantity. In the development stage, well logs offer various parameters of geological and engineering for horizontal drilling and production, evaluate the mechanical properties and calculate the magnitude and orientation of the *in-situ* stress for hydraulic fracturing stimulation. We reviewed current well logs for shale gas in China and discussed the development trend in the paper. A case history in Sichuan Basin presented to analyze the logs response characteristics and parameters calculation for a shale gas well. The difficulty and the future attention focus are also discussed.

Keywords: China, shale gas, Sichuan Basin, unconventional reservoir, well logs.

1. INTRODUCTION

Shale is widespread, collectively termed a whole family of marine or lake sedimentary rock from claystone to slate, which is made of clay minerals, non-clay minerals of the organic-rich dark-colored mud shale and high carbon shale, fine particle silt mudstone, muddy siltstone and silt sandstone. The trapped gas in shale, clay and the fine-grained sedimentary rocks is often termed shale gas [1-2]. Shale gas is mainly stored in the shale formation with two states of the absorbed gas and the free gas. The absorbed gas is trapped in the organic matter and the interface of the minerals solid particle; and the free gas stores in the natural fracture and the relative large-size pore [3-8].

Shale, which is made up of the fine grained particles with the large specific surface area, could store a large amount of gas. The potential reserve of shale gas around the world is huge, mainly distributed in North America, Latin America, Middle East, North Africa, Central Asia, Russia and China [1]. Up to now North America has realized the commercial development. With the growing shortage of the conventional oil and gas resources, the unconventional shale gas is increasingly receiving much recognition worldwide. The shale gas reserve in China would be the second largest in the world. Hydrocarbon resources shortage forces Chinese government to accelerate its steps on the shale gas exploration and development as well.

Shale is often seen as the barrier layer (cap rock or interlayer) of the oil and gas reservoir, and it is also routinely ignored in formation evaluation. Study on shale is valued

until shale gas is regarded as a kind of the unconventional gas resources to develop. Gas-bearing shale with fracture has characteristics of low porosity and low permeability, and the logs response is also complicated. Investigation of the rock physics and the logs response would be one of the key problems to be solved for shale gas development [1, 5-8].

The technical means for shale gas has something in common with oil and gas resources exploration and development. Well logs are one of the essential methods for shale gas, and the well logs method and the tools are almost the same as the conventional oil and gas resources. Some basic problems including the types of rock and mineral, fluid identification and evaluation and rock mechanics parameters calculation for shale gas make the well logging suite the same as the conventional oil and gas reservoir. The conventional well logging suite, including nine curves, namely, Spontaneous Potential (SP) log, Gamma Ray (GR) log, Caliper log, Acoustic log (AC), Density log, Neutron log, Deep Laterolog Resistivity log and Shallow Laterolog Resistivity log (RLLD, RLLS), Micro Sphere Focused Log (MSFL), play a primary role in shale identification, the effective formation thickness and various parameters calculation. Some special well logging suites, such as elemental and mineralogy well logs (i.e., Elemental Capture Spectroscopy, ECS), Nuclear Magnetic Resonance (NMR) logging, Cross-dipole acoustic log, Imaging Logs and LWD/MWD, solve the problems of the shale minerals composition calculation and the fracture identification [9-14].

The shale gas well logs in China started late, but developed rapidly. In this paper, we review the status of shale gas well logs in China. The key well logging suites and its application was introduced. The well logs response with the conventional well logging was summarized to quickly identify the gas-bearing shale reservoir, the formation evaluation

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methods and some petrophysical parameters are also analyzed. A case history of shale gas logs in Sichuan Basin in the Southwest China, which it is a current hotspot of shale gas exploration and development, is introduced. The difficulties and the future research focus are also discussed.

2. KEY WELL LOGS SUITES

Now the shale gas well logs are nearly the same as the conventional oil and gas, including the conventional well logging suite and the special well logging suite. The conventional well logging suite satisfies the need of the lithology identification and formation parameters calculation [10-14]. GR often helps to distinguish the gas-bearing shale from shale. SP is used to classify the effectiveness of the shale gas reservoir. RLLD and RLLS reflect gas-bearing properties of shale. Density qualitatively analyzes lithology. The special well logging suite often plays important role in the evaluation of the element type and the content, clay minerals type and content, fracture identification, *etc.*

The shale gas productive capacity mainly depends on several factors of the intrinsic fractures, brittleness, drilling and completion [15-30]. The porosity and matrix permeability of shale are all very low. How to improve the shale permeability must be considered. The horizontal well and the volume fracturing are the two key technologies for the shale gas production. Well logs are necessary to guide drilling deployment and optimize shale reservoir reform as a technical support run through the shale gas development, especially LWD/MWD [23, 30]. Some key technologies of the formation evaluation are as follows:

- 1) Choosing the best drilling target and guiding the drilling direction with LWD/MWD.
- 2) Combination wireline logs and LWD/MWD to analyze how to obtain the most effective multi-layer fracture in reservoir reform.
- 3) Guiding drilling trajectory to avoid the large fault, troublesome region and aquifer with LWD/MWD.
- 4) Preventing the height of the fracture in the fracturing stimulation from communicating the potential karst with LWD/MWD.
- 5) Fracturing stimulation monitoring with downhole wireline microseismic.
- 6) Integrating wireline logs with core analysis to evaluate the hydrocarbon generation capacity, the storage capacity and the productive capacity.

Currently the formation evaluation of shale gas mainly focus on the following some aspects.

- 1) Shale gas reservoir identification and the potential hydrocarbon generation evaluation, including a series of qualitative or quantitative interpretation indexes, such as shale gas reservoir classification, kerogen recognition and kerogen type classification, TOC, organic matter content, thermal maturity.
- 2) Lithology and reservoir parameters evaluation, including shale lithology identification (minerals type, composition and content), porosity, gas content, permeability, *etc.*

- 3) Rock mechanics parameters calculation, anisotropy and *in-situ* stress evaluation for gas-bearing shale.
- 4) Fracture identification.
- 5) Real-time monitoring fracturing azimuth and fracturing effect.
- 6) Real-time monitoring horizontal well drilling and production process.

The target of the well logs evaluation for gas-bearing shale is to form the well logging evaluation supporting technology series with hydrocarbon generation capacity, storage capacity and production capacity. The well logging suite and the petrophysical parameters available for shale gas are shown as Table 1. The technical requirements in well logs for shale gas mainly involved some aspects as follows:

- 1) Shale petrophysical parameters calculation model.
- 2) Well logs response characteristics identification and evaluation method for the sensitive geophysical parameters.
- 3) Evaluation method and calculation model for TOC and thermal maturity.
- 4) Shale reservoir effectiveness evaluation.
- 5) Calculation model and evaluation method for the free gas content, absorbed gas content, gas saturation and the total volume of gas.
- 6) Calculation model for shale, sand content, clay minerals composition and brittle minerals content (sand, calcite and feldspar, *etc.*)
- 7) Rock mechanics parameters calculation method.
- 8) Quantitative fracture identification and *in-situ* stress evaluation.

3. WELL LOGS RESPONSE

Although the well logs response of the gas-bearing shale is complicated, shale gas reservoir has obviously characteristics in the conventional well logging curves [31-37]. Concretely, both GR and resistivity are all high. Caliper usually expands. RLLD and RLLS show medium or low value and negative separation in the shale reservoir. Three porosity curves, Density, Neutron and AC, indicate high value, and PE is low, shown as Table 2. Moreover, the gas-bearing shale also has the characteristics of low density, low hydrogen index and low sonic velocity. The organic matter content and the uranium content are all high. The density of the kerogen is low, and the density of the shale often ranges from 2.45g/cm³ to 2.75g/cm³. The gas bearing shale can be easily and quickly identified with the log curves [4, 10].

The well logs response analysis for shale gas reservoir include lithology, physical property, electrical property, gas-bearing properties, source rock, *in-situ* stress and anisotropy, also termed seven-property relationship analysis [11, 13]. Fig. (1) is the conventional well logs response of a shale gas well in Sichuan Basin. The shale gas formation locates in the bottom of the Longmaxi Formation, and the thickness is nearly 90m. The gas logging has good indication. The lithology is argillaceous shale and carbonaceous shale with

Table 1. Logging suite and parameters available for shale gas.

No.	Logging Suite	Parameters Available
1	Resistivity, Density and Neutron combination logs	1) porosity, permeability, saturation
2	Natural Gamma-ray Spectral Log	2) minerals composition, siliceous index, brittleness
3	Elemental Capture Spectroscopy (ECS)	3) shale lithofacies
4	NMR	4) TOC
5	Micro Resistivity Imaging, Circumferential Acoustic Scanning Imaging log	5) thermal maturity
6	Cross-dipole acoustic log	6) gas content
7	Sidewall Coring and Core analysis	7) fracture and its occurrence
8	LWD/MWD	8) dynamic and static rock mechanics parameters
9	Microseismic monitoring for hydraulic fracturing stimulation	9) pressure gradient 10) <i>in-situ</i> stress state

Table 2. The response characteristics of well logs curves.

Well Logs Curves	Parameters	Curves Characteristics	Influence Factor
GR	Natural radioactivity	High (>100API), local low value	GR is high with shale increasing. The organic matter has high radioactive material, GR is more than 100 API, some exceeds 400 API
Caliper	Borehole diameter	Borehole diameter expanding	The diameter of shale is expanding, and it is more serious with organic matter existing
AC	slowness	High and cycle skip	Slowness is large with high organic matter abundance or high gas content. The cycle skip is induced by crack or fracture
Neutron	porosity	high	The clay bound water leads to high neutron porosity. But neutron porosity decreases with gas content increasing
Density	density	low	The high gas content, organic matter abundance, high fracture density and diameter expansion
Lithology density	PE	low	Hydrocarbon, gas content, fracture
Resistivity	RLLD, RLLS	high, local low value, and RLLD is nearly overlaps RLLS	Permeability, shale content and bound water induces low resistivity. The resistivity of the kerogen is higher, the response is also high

inclusions of the grey and siltstone. The Caliper is normal without washout. GR in the shale gas layer is high, and the average is larger 160API. High TOC in the bottom is corresponding for high gas content, where the average of GR is larger than 180API. AC slowness in shale gas reservoir usually increases. The slowness of Longmaxi Formation moderately increases, where the average of sandstone is 72us/ft. and the shale is 78us/ft.

The density of the organic matter is often low, and density of the matrix is relative high. The density is gradually reduces from 2.75g/cm³ to 2.45g/cm³ with TOC and gas content increasing. The highest TOC and gas content corresponds to the lowest density. The neutron porosity reduces to 12% with obvious excavation effect, but the porosity of the surrounding rock is about 21%. The resistivity slowly changes, and the average is about 42Ω.m. The content of the

uranium element is high and the thorium is low. The difference of GR and natural GR spectrum (NGS) without uranium become large with TOC and gas content increasing.

4. SHALE GAS RESERVOIR IDENTIFICATION METHODS IN FORMATION EVALUATION

The lithology identification is primary in the shale gas formation evaluation, then the petrophysical parameters calculation and the productivity evaluation. Several methods have been developed to identify gas-bearing shale, namely the conventional well logs combination, the well logging cross-plot, the gas logging, ΔlogR method, the dielectric constant method and the combination parameters method [4, 30]. The log methods applied in shale reservoir identification have been gotten good results.

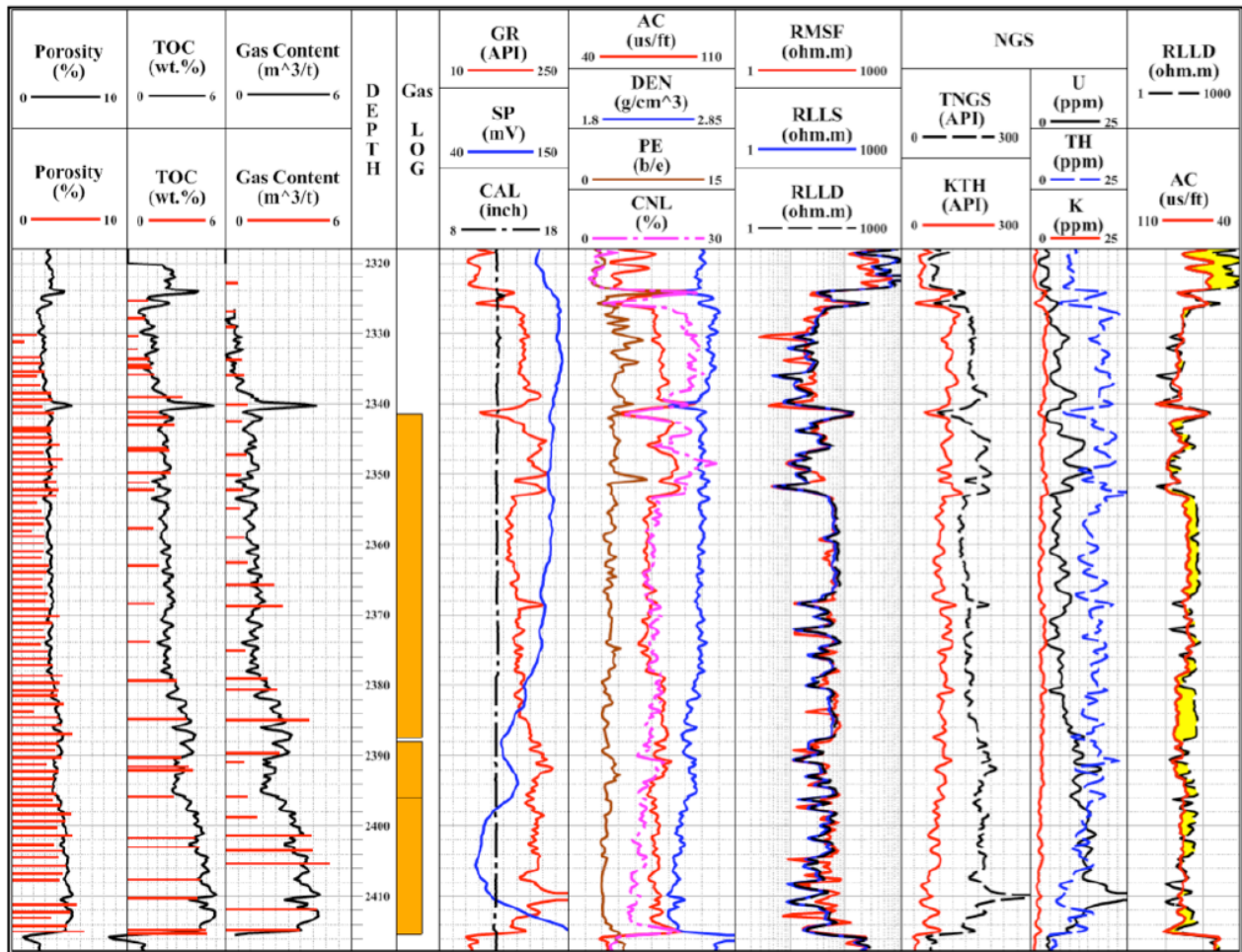


Fig. (1). A logs interpretation plot of shale gas well in Sichuan Basin. The three tracks on the left are porosity, TOC and gas content respectively, where the black solid line is the calculation with logs data and the red bar is the core analysis data. The fourth track is depth, and the fifth track is gas logging. The sixth track, the seventh track and the eighth track are the conventional logs, including CAL, SP, GR, AC, DEN, PE, CNL, RLLD, RLLS and MSFL. The ninth track is natural GR spectrum (NGS). U, TH and K are the content of uranium, thorium and potassium respectively. TNGS is total NGS and KTH is NGS without U. The tenth track is the overlaps graph of AC and RLLD. The unit of each curve is in the bracket.

4.1. The Conventional Well Logs Combination

The conventional well logs combination, such as GR, Density, AC, Neutron and Resistivity, effectively identify the shale gas reservoir and lithology according to the typical well logs response [4-5].

4.2. The Well Logs Cross-plot

The well logs cross-plot with AC slowness and Resistivity is used to determine the shale boundary to identify lithology, furthermore distinguish the gas-bearing shale zone with organic-rich matter.

4.3. Gas Logging

The gas logging indications have close corresponding relation with lithology in the process of drilling. The cap rock of the shale layers, with low permeability and high hydrocarbon content, such as calcilutite, dolomite, salt rock, easily occur kick and leakage. It also shows the growing fractures and high gas content. The shale gas reservoir is well identified accordingly. The gas logging method has been used to identify shale gas reservoir in the Longmaxi Formation in

Sichuan Basin, and find out the direct evidence of the growing shale, shown as Fig. (1). The gas logging indication is abnormal and active, kick and leakage occasionally occur, shows the presence of shale gas and widespread.

4.4. Radioactivity Logs Combination with the Conventional Well Logs

The fine grained clastic rock with high abundance of organic matter is usually accompanied with the trend of high concentration of the radioactive elements, low bulk density, low sonic velocity and high resistivity [4,38-39]. The combination of the radioactivity logs and the conventional logs easily identify the shale gas reservoir.

4.5. ΔlogR Method

ΔlogR method is often used to evaluate the hydrocarbon content of the source rock with the well logs [38-39]. The scaled porosity logs curve (slowness) superimposes on the resistivity curve (RLLD). As the two curves all corresponds to the difference of the porosity, the basic coincidence together reflects the formation saturated with water but lack of

organic matter. The amplitude separation of $\Delta\log R$ indicates the source rock with abundant organic matter, the reservoir containing hydrocarbon and lithology difference.

The shale formation without hydrocarbon can easily be identified and eliminated with GR, compensated neutron porosity and SP. The separation of the two curves in the shale reservoir with abundant organic matter often induces two factors. The separation of the porosity curves is the response of the kerogen with low density and low sonic velocity (high slowness). There is no hydrocarbon generation in the immature and abundant organic matter formation, and the observed difference of the two curves is only the response of the porosity difference. In the mature hydrocarbon source rock, the difference becomes bigger with resistivity increasing.

4.6. The Dielectric Constant

Both the experiments and the well logs data have proved that the shale containing hydrocarbon has high dielectric constant value, but the shale without hydrocarbon has low value. The response of the dielectric log would be taken as a sign for shale gas reservoir [41-44].

5. THE KEY PETROPHYSICAL PARAMETERS

The exploration and development of shale gas need with help of well logs and core analysis to know about the petrophysics and evaluate the amount of the organic matter and types, trace elements, maturity, types of kerogen, hydrogen content, petrophysical parameters, rock mechanics parameters, *in-situ* stress and anisotropy, etc.

The key petrophysical parameters in formation evaluation include shale minerals composition, thickness, types and content of kerogen, TOC, maturity, dry absorbed gas (gas saturation), free gas content in pore and fracture, porosity, permeability, etc.

5.1. The Shale Minerals Composition

The gas bearing shale is composed of shale, clay and silt sandstone, which the grain range of the particle size changes from clay (<5 μ m) and silt (5-63 μ m) to sand (>63 μ m) [4, 6, 39].

Generally the shale has high content of quartz to increase the brittleness. Moreover the shale also contains some metal minerals. The minerals content, clay and the quartz, influence the engineering and well logs.

The minerals composition of shale would be measured by X-ray diffraction and X-ray energy spectrum in the laboratory. ECS and radioactivity logs directly provide the minerals and oxide content. The cross-plot with the various conventional well logs also can be used to identify the minerals composition of the shale.

5.2. Thickness

The shale gas productive capacity depends on two key technologies, horizontal well and hydraulic fracturing stimulation. The thickness of gas-bearing shale would be significant, if the thickness is small, the operation of the horizontal well and fracturing stimulation would be lost the commercial feasibility. The vertical thickness of the organic matter abundant is most important for fracturing stimulation. In

general speaking, the profitable target would be the vertical thickness of 45m with high TOC. The average thickness of the source in the Lower Cambrian in South China is about 139m, and the Lower Silurian is about 100-700m. The shale thickness of Jiyang Depression in North China to Northeast China is more than 100m, and Yanchang Formation in Upper Triassic in Ordos Basin is about 300-600m [13]. They are the potential shale gas development areas. The thickness of the shale gas reservoir can be determined with the conventional well logs and sometimes combined with mud logging, gas logging and core analysis data.

5.3. TOC

TOC is an important parameter for shale gas. TOC is close related with kerogen content and types. The organic matter content is the main influence factors of the hydrocarbon-generating intensity and the quantity of hydrocarbon generation. TOC also can be used to evaluate the hydrocarbon generation capacity. The experiment results have shown that the absorption capability of the shale is linearly correlated with TOC and gas content.

Several methods are used to estimate TOC with well logs [4, 33, 36, 38-40]. $\Delta\log R$ method not only identifies shale gas reservoir but also calculates TOC [38-39]. The relationship between $\Delta\log R$ and TOC is given by

$$\Delta\log R = \lg\left(\frac{R}{R_{\text{baseline}}}\right) + K \times (\Delta t - \Delta t_{\text{baseline}}) \quad (1)$$

$$\text{TOC} = (\Delta\log R) \times 10^{2.297 - 0.1688 \cdot \text{LOM}} \quad (2)$$

Where $\Delta\log R$ is the separation between the scaled porosity curve and resistivity curve. R is the logging reading of resistivity, and R_{baseline} is resistivity baseline of the non-hydrocarbon source. Δt is the logging slowness reading of AC, and $\Delta t_{\text{baseline}}$ is the slowness baseline of the non-hydrocarbon source. K is scale factor, and for units of $\mu\text{sec}/\text{ft}$ and $\mu\text{sec}/\text{m}$, it is 0.02 and 0.065, respectively. LOM is thermal maturity, which has relation with vitrinite reflectance (R_0), commonly provided by the laboratory.

Actually $\Delta\log R$ appears in source rock, oil-prone formation and evaporate [38]. In the logs data continuous processing of TOC profile, other lithology interference should be discharged with GR and Caliper to find out the mature source. Higher GR based on the generation of kerogen is in the reducing environment with relatively high uranium (U) content. The main elements content obtained by ECS could approximately get TOC.

TOC also has empirical linear relation with density log using regression method with core analysis data, which is given by

$$\text{TOC} = -15.47\rho + 42.98 \quad (3)$$

Where ρ is density logging reading. The density is negative correlation with TOC. The density and TOC from core analysis data show the good relevance, shown as Fig. (2).

There is a good linear relationship between TOC and shale gas production rate. The exploration target in North America mostly chooses TOC larger than 2 wt%, even over 4 wt%. In Lower Cambrian of Sichuan Basin, TOC of Qiongzhusi Formation is 1wt%-11wt% and generally larger than 1wt%, Longmaxi Formation is in the range of 0.5wt%-

5wt%, even up to 9wt% with high gas content. TOC in gas shale is 1wt%-20wt% [13]. Higher TOC frequently means higher gas production capacity.

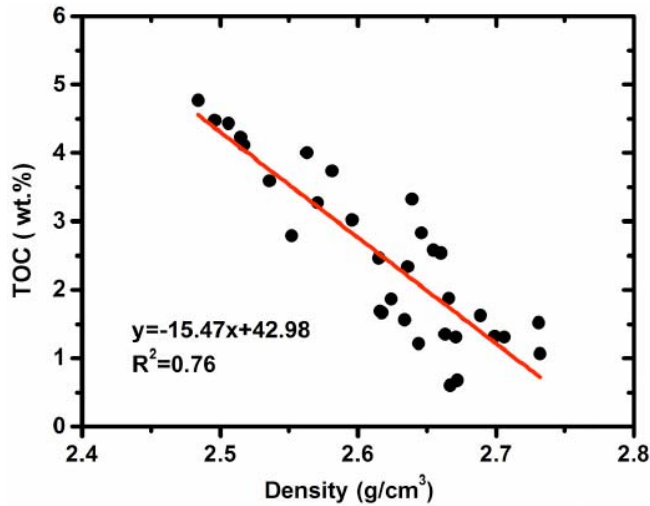


Fig. (2). The cross-plot of density and TOC. The x-axis is density, and the y-axis is TOC. The circle black dot is the core analysis data, and the red line is the fitting. The formula is linear fit.

The separation between porosity and resistivity has weak correlation with TOC, and the separation doesn't rise with TOC increasing, shown as Fig. (1). TOC is calculated with Density, where the density of organic matter is low and close to 1.0g/cm³ and the density of the matrix clay is 2.7g/cm³.

5.4. Maturity

The maturity is an essential index to evaluate the source. There are several indexes referred to maturity, vitrine reflectance R₀, thermal alteration index (TAI), RockEval pyrolysis temperature (Tmax) and conodont alteration index (CAI), and these parameters usually are related with R₀. At present the logs data is available for the maturity index (MI) evaluation with resistivity and the combination methods of neutron log and density log [25, 40]. The formula of MI is given by [25].

$$MI = \sum_{i=1}^N \frac{N}{\phi_{n9i}(1-S_{w75i})^{1/2}} \quad (4)$$

Where N is the sample numbers which density porosity is greater than or equal to 9% and water saturation less than or equal to 75% at sampling depth. ϕ_{n9i} is neutron porosity where density porosity is greater than or equal to 9% at each sampling depth. S_{w75i} is water saturation where density porosity is greater than or equal to 9% and saturation less than 75% at each depth.

$$S_{wi} = \left(\frac{R_w}{\phi_{d9i}^m R_t} \right)^{1/2} \quad (5)$$

$$\phi_{d9i} = \phi_d - 0.09 \quad (6)$$

Where S_{wi} is water saturation. R_w is water resistivity. m is cementation index. ϕ_d is matrix porosity estimated by density logging data. R_t is resistivity. MI is average value integrated the core analysis data and the logs reading in effective gas shale layers which density porosity is greater than

9% and hydrocarbon saturation greater than the minimum 25%. MI is an inverse correlation with neutron porosity.

5.5. Porosity

Porosity estimation is mainly calculated based on the three porosity logs data, and core analysis data is often used to correct the results. Density porosity has relative high precision. The volume physical model is modified with TOC considering. It is given by [10]

$$\rho_b = \rho_{ma} * (1 - \phi - V_{TOC}) + \rho_f * \phi + \rho_{TOC} * V_{TOC} \quad (7)$$

$$\phi = \frac{\rho_{ma} - \rho_b + V_{TOC} * (\rho_{TOC} - \rho_{ma})}{\rho_{ma} - \rho_f} \quad (8)$$

Where ρ_b is density log reading. ρ_{ma} is density of the matrix. ρ_f is the density of the pore fluid. ρ_{TOC} is the density of the organic matter. Φ is porosity. V_{TOC} is the content of the organic matter. It is difficult to get high-precision porosity of shale because of the complicate lithology and logging response.

Porosity in the core interval is calculated with model built by core calibration logs. Density is used to obtain porosity without core analysis porosity, and the density of matrix and TOC are from ECS. Otherwise porosity is estimated by density log with the fitting relationship, shown as Fig. (3). And core analysis porosity has a good correlation with density in the shale gas reservoir.

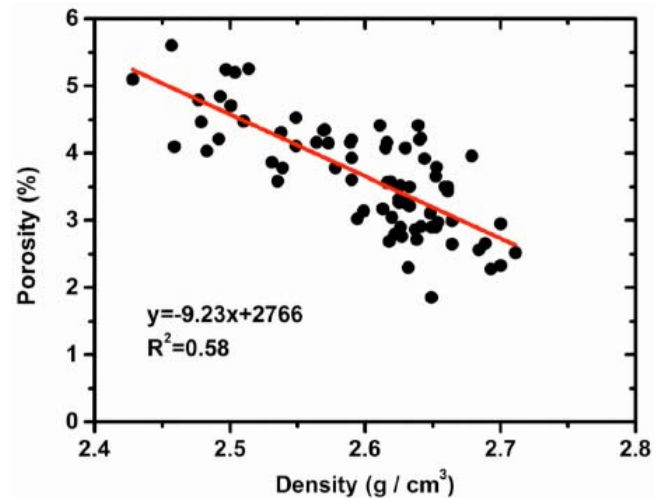


Fig. (3). The cross-plot of density and porosity. The x-axis is density, and the y-axis is porosity. The circle black dot is the core analysis data, and the red line is the fitting. The formula is linear fit.

5.6. Gas Saturation

High gas shale content corresponds to large resistivity reading, which it is in accord with the conventional reservoir. Archie formula is often used to estimate the gas saturation. The gas content and TOC obtained by core analysis data also show good dependent, shown as Fig. (4), then the gas content would be calculate with TOC. In Fig. (1) porosity, TOC and gas content calculate with the logs data based on the fitting relationship is good consistent with core analysis data.

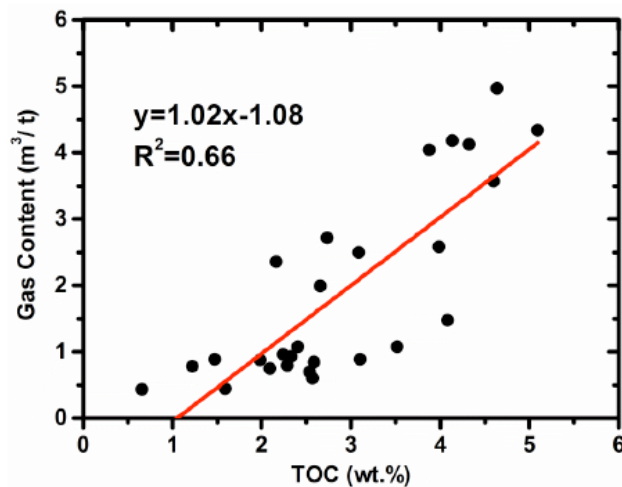


Fig. (4). The cross-plot of TOC and gas content. The x-axis is TOC, and the y-axis is gas content. The circle black dot is the core analysis data, and the red line is the fitting. The formula is linear fit.

5.7. Permeability

The permeability of shale is very low, mostly in the range of $0.001-0.11 \times 10^{-3} \mu\text{m}^2$. But shale also has high porosity and permeability with fractures. The measurement in the laboratory with GRI method show that the matrix permeability generally less than $0.1 \times 10^{-3} \mu\text{m}^2$, and the average throat radius is also less than $0.005 \mu\text{m}$ [13, 45-47]. The average matrix porosity of Qiongzhusi Formation and Longmaxi Formation is about 1.6%, the range of the matrix permeability is $(0.001-0.11) \times 10^{-3} \mu\text{m}^2$ and the average is $0.019 \times 10^{-3} \mu\text{m}^2$ [13]. But fractures and cracks often increase porosity and permeability of shale.

Currently permeability evaluation with well logs is still the same as sandstone with core calibration logs. The relationship between the permeability and the porosity is built with core analysis data, and permeability is calculated with porosity.

Otherwise some imaging analysis methods are often used to obtain porosity and permeability of shale in the laboratory. But it is dependent of image resolution and imaging processing method, and has large uncertainty [47-50].

5.8. Rock Mechanics Parameters

Rock mechanics parameters, such as elastic modulus, poisson ratio, shear modulus and bulk modulus, are very important for engineering operation in shale gas production. The shale gas reservoir has obvious anisotropy. Understanding of the orientation and the magnitude of the *in-situ* stress would help engineering design and operation [51-60]. Cross-dipole acoustic log provides the slowness of compressional wave and shear wave to calculate the rock mechanics parameters based on the assumption of ideal elasticity, homogeneous and isotropy. The *in-situ* stress evaluation with well logs is combined with pore pressure analysis, image logs and core analysis. The *in-situ* stress test in fracturing is used to correct the calculation results.

6. THE DIFFICULTY OF THE FORMATION EVALUATION

Some differences between the shale gas and the conventional gas define the differences of the well logs, which is the difficulty of the well logs evaluation lies.

- 1) The shale reservoir has the characteristics of low porosity, low permeability, self-source. The logs response of low porosity and low permeability is complicated and not obvious, which is also one of the difficulties of current formation evaluation.
- 2) The gas is mainly absorbed in the shale. The logs response of the absorbed gas is complicated and less understanding. The responses of the shale reservoir need to be furthermore investigated.
- 3) The lithology of shale reservoir is complicated and different from the conventional oil and gas reservoir. The silicon content of the known commercial developing shale gas reservoirs is larger than 28%, and the micro-fracture is developed. The well logs interpretation model is quite different from the conventional.
- 4) The well logs theory and models based on assumption of the linearity, homogeneity, isotropy, ideal elasticity is not completely suitable for shale gas reservoir.
- 5) As shale is both self-source and reservoir, the trapped gas includes absorbed gas and free gas, and how to identify the state and content of the absorbed gas is another problem. The study of well logs interpretation for shale gas is insufficient.

In the recent years resource survey of shale gas in China has been carried out. The works indicate that the shale gas resources are very rich, largely distributed in the South China, North China, North-East China, South-West China and North-West China. The shale gas development is in its beginning stage compared with the abroad. The well logs evaluation faces some difficulties as following:

- 1) The depositional environment of shale reservoir is complex. The shale in China mainly formed in the marine facies and the littoral facies with high clay content, and the thickness, maturity and TOC, are all poor than those who have successfully development in North America. We should set up the well log methods and the formation evaluation methods to adapt to the shale gas reservoir without blindly copying the abroad experience.
- 2) The burial depth of shale gas is deep. The depth of the shale gas in Sichuan Basin is in the range of 2000-3500m, and the difficulty in developing is large. The lack of the supporting technology put forward a new challenge to the well logs.
- 3) Currently China lacks the core technologies of the well logs for the shale gas. As the shale reservoir have the characteristics of low productivity, less natural productivity and long-cycle production, the gas production depends on the horizontal well and the fracturing stimulation. The productivity evaluation is also difficult. Both experiences and the core technologies are all short, such as LWD/MWD and fracturing stimulation monitoring.

- 4) Recently the well logs in oil and gas reservoir has been applied in shale gas reservoir and obtained some application effects. But the shale gas logs cannot satisfy with its the needs, such as lithology identification and geology evaluation, quantitative method for shale content, fracture and *in-situ* stress evaluation, LWD/MWD monitoring for horizontal well, microseismic monitoring for fracturing stimulation, etc.

7. THE FUTURE RESEARCH FOCUS

- 1) Quantitative identification method and model. As the lithology and hydrocarbon accumulation is uniqueness, the currently well log interpretation methods can't satisfy the production requirement. The novel logs interpretation methods and models in connection with shale reservoir should be built.
- 2) The quantitative evaluation models for the special logging suite. ECS and Imaging logs is also important for shale gas. The fracture identification, pore configuration, rock mechanics parameters and minerals composition obtained with the special logs should be investigated.
- 3) Real-time monitoring technology and well logs interpretation for the horizontal well. The horizontal well is also important for shale gas development. The monitoring and logging interpretation of the horizontal well is a direction attention, especially LWD/MWD application study.
- 4) Fracturing stimulation monitoring with well logs. The fracturing stimulation must be conducted for shale gas production as shale reservoir is tight and low productivity. The real-time monitoring of the fracturing operation is used to evaluate the fracture length and orientation. Currently microseismic monitoring in borehole is a developing direction.

CONFLICT OF INTEREST

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

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