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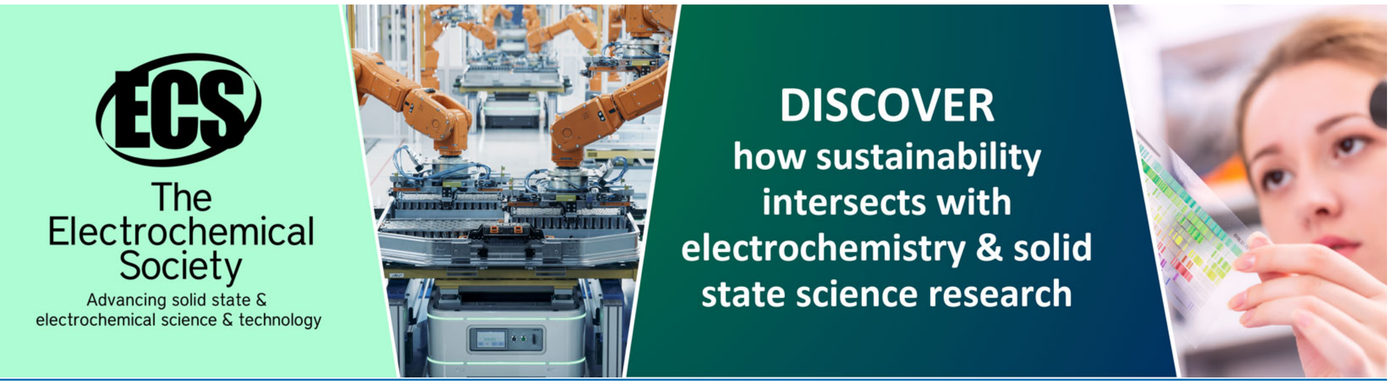

Integrated Petrophysical Evaluation of Shale Gas Reservoirs for Wufeng-Longmaxi Formation in Southeast Chongqing

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Abstract. Shale gas is an important unconventional natural gas resource. Different from conventional oil and gas exploration, gas shale is not only the source rock of natural gas, but also the cap rock and reservoir. This paper presents a logging interpretation method for comprehensive evaluation of shale gas. Taking well A in southeast Chongqing from Sichuan Basin as an example, the shale gas reservoir of Wufeng-Longmaxi formation is evaluated. This method makes full use of conventional logging data (gamma ray, array lateral resistivity, density, neutron, acoustic, spectral gamma ray), unconventional log data (NMR Nuclear Magnetic Resonance, ECS Elemental Capture Spectroscopy) and core experiment data (X-ray Diffraction, Tight Rock Analysis, Methane Adsorption Isotherm). This method of combining logging data with core measurement can provide mineralogy, porosity, permeability, saturation, kerogen volume, total organic carbon content, absorbed gas content and free gas content. The methods provide a means to understand the petrophysical properties and reservoir quality of Wufeng-Longmaxi shale. This information can help to determine the “sweet spot” along the vertical to land and design a selective completion strategy to optimize well productivity.

Keywords: Shale gas, kerogen, TOC, adsorbed gas, free gas, integrated petrophysical evaluation, core analysis.

1. Introduction

The study area is located in the southeast of Chongqing and eastern Sichuan basin, it belongs to Upper Yangtze Platform depression tectonic units. Upper Ordovician Wufeng- Lower Silurian Longmaxi formation is an important sequence in Sichuan basin for shale gas exploration. Comprehensive analyses of the geological parameters indicate that there is big shale thickness (>80m), shallow buried depth(<4500m), high total organic carbon content(TOC>1.5%) and high organic matter maturity (R_0=1.9%-2.7%) in Wufeng-Longmaxi formation (Tan Linyun et al., 2015). Moreover, the type of organic matter is mainly type I. In a word, Wufeng-Longmaxi formation has good potential for shale gas accumulation.

2. Organic shales identification

Just as conventional oil and gas have important logging curve response characteristics, shale gas reservoir also has obvious reaction on conventional curve, making it different from conventional shale (conventional shales with little or no potential). The interval of red shading in Well A is the organic shale section (figure 1). Compared with the conventional shale, organic shale has higher levels of naturally radioactive (e.g. higher uranium >4.0ppm in Well A), the resistivity of shale gas reservoir is usually higher than that of the conventional shale section around. Shale gas reservoir has the characteristics of large curve change, low bulk density, high neutron porosity and high acoustic slowness. In the measurement of density porosity, the bulk density of kerogen (1.2g/cm3) is far lower than that of sandstone or limestone. Therefore, the existence of kerogen will lead to low density value and high density porosity. In order to calculate the density porosity of gas shale accurately, it is necessary to obtain the accurate grain density from ECS Elemental Capture Spectroscopy tool.

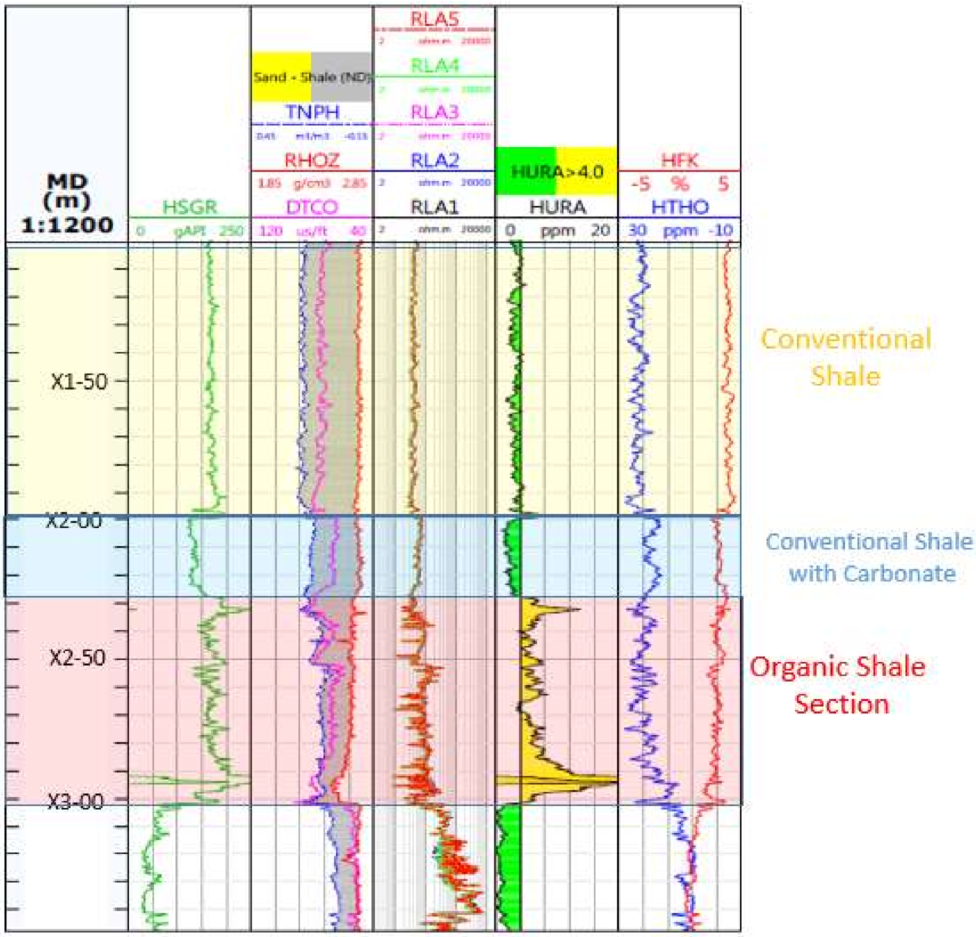

Figure 1. Identification potential organic shale using conventional logging data, Well A

3. Integrated petrophysical evaluation techniques

3.1. Mineralogy

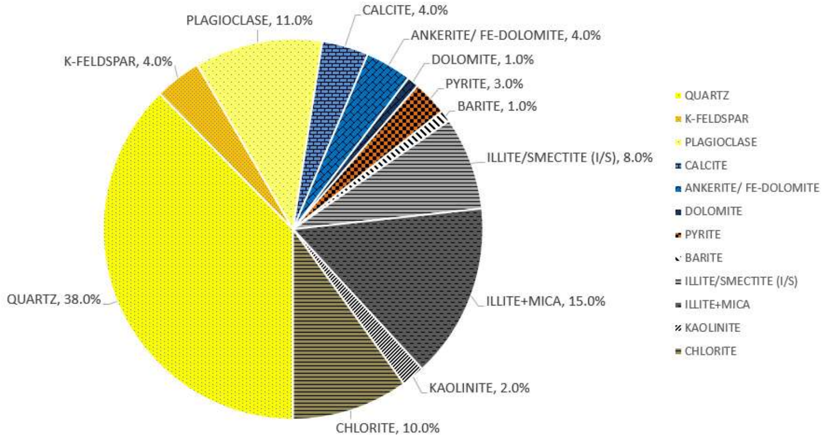

Figure 2. Full core XRD results (weight %), Well A

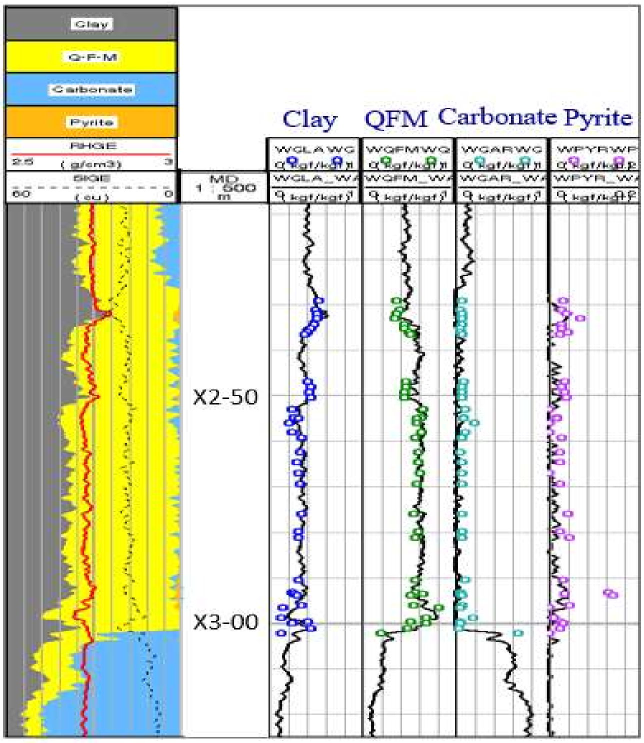

Figure 3. The dry weight fraction of clay, QFM, carbonate and pyrite from ECS is compared to the XRD analysis. Agreement is excellent, Well A.

Mineral identification is the basis of shale gas evaluation. The characterize can be done by comprehensive analysis XRD X-Ray Diffraction data and ECS Elemental Capture Spectroscopy result. A full core of Well A is acquired and an XRD analysis is performed. Figure 2 show the X-ray diffraction results for whole rock mineralogy in Wufeng-Longmaxi shale gas formation of Well A, which is also used to calibrate the ECS result. The matrix is dominated by quartz, plagioclase, chlorite, mixed layer illite/smectite and illite+Mica clay.

ECS is a geochemical log that provides continuous elements including silicon[Si], calcium[Ca], iron[Fe], sulfur[S], titanium[Ti], gadolinium[Gd], and potassium[K]. The mineral contents of clay, carbonate, QFM (quartz, feldspar and mica) and pyrite are obtained. Matrix density (RHGE in the first track of figure 3) is calculated from silicon, calcium, iron, and sulfur. Combined with the measured bulk density, the accurate density porosity can be obtained. The dry weight fraction of clay, QFM, carbonate and pyrite from ECS are presented along with XRD analysis of over 37 core samples in figure 3. Most of the XRD analysis results are in good agreement with logging curves.

3.2. Estimation of Kerogen and Total Organic Carbon from Density and Nuclear Magnetic Resonance logs

In order to quantify the total organic carbon content of rocks, a number of studies have relied on correlations such as TOC and density (Tixier and Curtis,1967; Schmoker,1979) or TOC and gamma-ray (Supernaw et al. 1978; Schmoker,1981) or TOC and spectral gamma ray (Fertl and Rieke III,1980). Passey et al. (1990) proposed a method called ΔlogR to calculate TOC by resistivity and acoustic logging. In 1996 Huang and Williamson used neural network to do the same work. In this article porosity deficit method (Michael M. Herron et al.,2011) is used, this method is estimation of kerogen from the difference between density and NMR porosities. NMR porosity corresponds to the water-filled porosity, while density porosity is the sum of kerogen-filled and water-filled porosity (figure 4).

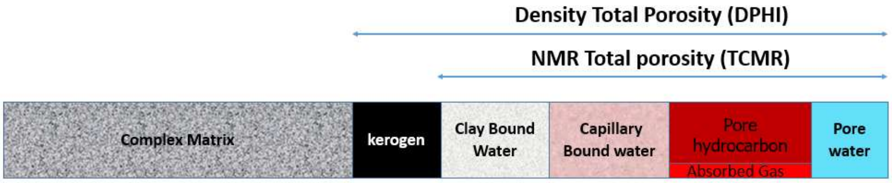

Figure 4. Petrophysical model of kerogen determination with combination of NMR and density logging

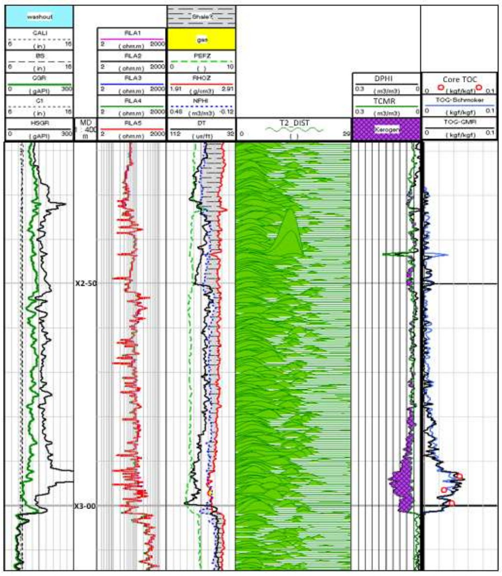

Figure 5. Kerogen and TOC determination with combination of NMR and density logging, Well A.

The kerogen-filled porosity is computed using the following equations 1,2,3, then volume kerogen must be converted to TOC. The conversion formula is 4 (Herron, and Le Tendre,1990).

$$\emptyset_D = \frac{\rho_{ma}-\rho_b}{\rho_{ma}-\rho_f} \tag{1}$$

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$$\emptyset_{NMR} = TCMR \quad (2)$$
$$\emptyset_k = \emptyset_D - \emptyset_{NMR} \quad (3)$$
$$TOC(wt\%) = \frac{\emptyset_k * \rho_{kerogen}}{\rho_b * k} \quad (4)$$

Where:
$\emptyset_k$=Kerogen-filled porosity (vol/vol)
ρ_{ma}=Matrix density from ECS (g/cm^3)
ρ_b= Bulk density (g/cm^3)
ρ_f = Fluid density (assume 1.0) (g/cm^3)
$\emptyset_{NMR}$, TCMR = NMR Total porosity (vol/vol)
$TOC(wt\%)$= Total organic carbon (wt%)
$\rho_{kerogen}$=Kerogen density (g/cm^3)
k =kerogen conversion factor

Density porosity and NMR porosity are compared over a 100m interval of Well A in figure 5. The difference of the curves corresponds the kerogen volume in track 6. The last track in figure 5 is the TOC log comparison with core data.

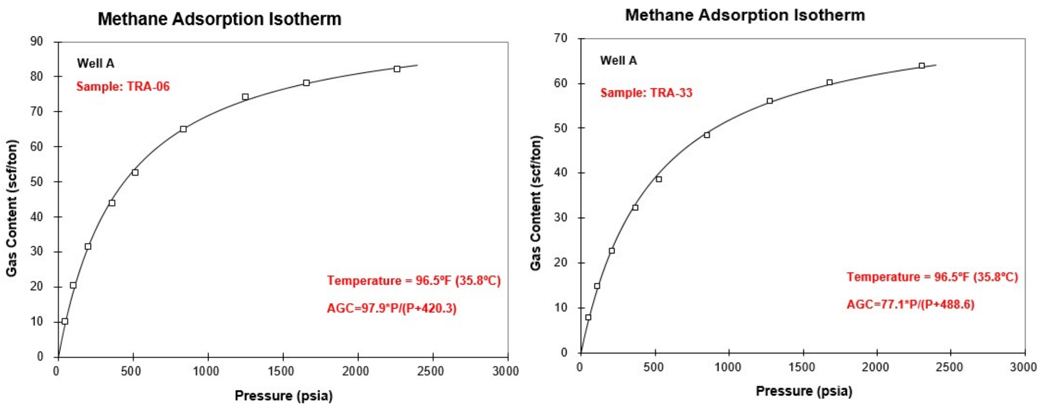
3.3. *Adsorbed Gas Content Quantification*

Once total organic carbon content is computed, the next step is to calculate the adsorbed gas content. Adsorbed gas is a kind of gas existing on the surface of kerogen in adsorption state.
The adsorbed gas content is calculated by the Langmuir isotherm(Langmuir,1918) data of shale gas reservoir (Equation 5).

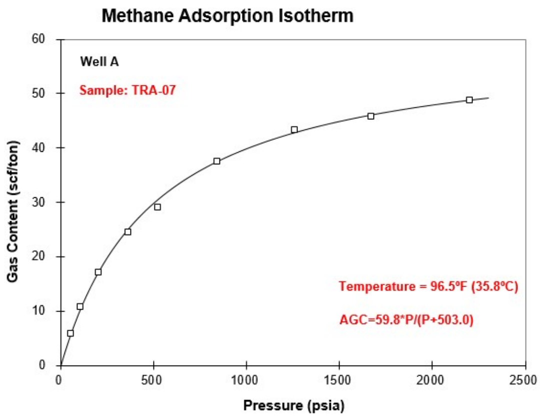
$$AGC = \frac{V_l * P}{P + P_l} \quad (5)$$

Where AGC= Absorbed gas content (scf/ton)
P =Reservoir pressure (psia)
V_l =Langmuir Volume (scf/ton)
P_l=Langmuir pressure (psia)

Langmuir isotherm can be formed by core analysis, and Langmuir volume (the volume of adsorbed gas under infinite pressure) and Langmuir pressure (the pressure corresponding to half of Langmuir volume of adsorbed gas) can be determined by the curve. Figure 6 (a)(b)(c) show the Langmuir isotherm for sample TRA-06, TRA-07 and TRA-33 of Well A at a specific TOC and temperature. The average Langmuir pressure is 470.6 psia. Table 1 and figure 7 gives the correlation between the Langmuir Volume V_l and the weight percent of TOC for Well A.



(a) Sample TRA-06 (b) Sample TRA-33



(c) Sample TRA-07

Figure 6. Methane Adsorption Isotherm for Sample TRA-06, TRA-07 and TRA-33 of Well A

Table 1. Langmuir Volume vs TOC for Well A

Sample	Depth (m)	TOC (wt%)	Vl (scf/ton)	**Pl (psia)**
Default #	n/a	0	0	0
TRA-06	Hidden	4.86	97.9	**420.3**
TRA-33	Hidden	3.74	77.1	**488.6**
TRA-07	Hidden	2.71	59.8	**503.0**
			AveragePl	**470.6**

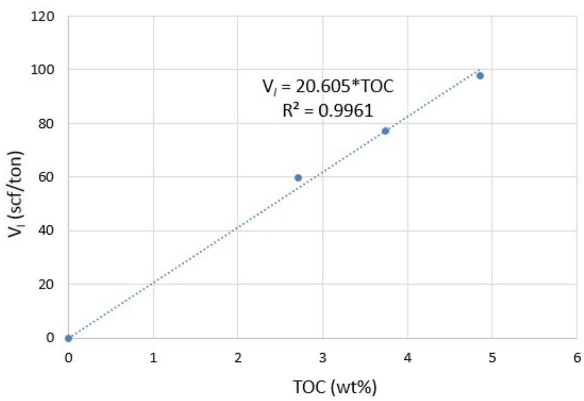


Figure 7. Correlation between Vl and weight percent of TOC for core data from Well A

The Langmuir Volume V_l is computed using the equation 6

$$V_l = 20.605 * TOC \tag{6}$$

The equation 7 is used to compute adsorbed gas for Well A:

$$AGC = \frac{20.605 * TOC * P}{470.6 + P} \tag{7}$$

Where

P=reservoir pressure (reservoir pressure gradient of Wufeng-Longmaxi formation for Well A is 0.53psia/ft)

3.4. Free Gas Content Quantification

The content of free gas is related to effective porosity, water saturation and bulk density. The calculation method is shown in (8).

$$\mathrm{Gcfm} = \frac{1}{\mathrm{B_g}} * \left(\boldsymbol{\phi}_{\mathrm{eff}}(\mathbf{1} - \boldsymbol{S}_{\mathrm{w}})\right) * \frac{\psi}{\rho_{\mathrm{b}}} \tag{8}$$

Where
Gcfm =free gas content (scf/ton)
B_g =gas formation volume factor (reservoir cf/scf)
$\boldsymbol{\phi}_{\mathrm{eff}}$ =effective porosity(vol/vol)
S_w =water saturation(vol/vol)
ρ_b =bulk density(g/cm^3)
$\boldsymbol{\psi}$ =conversion constant (32.1052)
Simandoux equation shown below is used for water saturation S_w calculation in shale gas reservoir:

$$\frac{1}{R_t} = \frac{V_{sh}S_w}{R_{sh}} + \frac{\emptyset_e^m S_w^n}{aR_w(1-V_{sh})} \tag{9}$$

Where $\emptyset_e$ = effective porosity (vol/vol)
V_{sh} = volume of shale (vol/vol)
R_{sh} = resistivity of shale (ohm.m)
R_w =resistivity of water (ohm.m)
m =cementation fractor
n = saturation exponent
R_t = resistivity of formation (ohm.m)
a =constant, 1.0

3.5. Permeability

Permeability of gas shales is a key parameter for stimulation design and production prediction. The permeability of shale rock is typically 10^{-4} to 10^{-8}mD. It can be accurately measured with core analysis. The correlation between pressure decay permeability and gas-filled porosity of Wufeng-Longmaxi shale gas reservoir for Well A is shown in figure 8. A well log property for permeability can be estimated from the gas filled porosity-permeability transform equation 10.

$$K{=}4\times10{-}5\times e0.5206*GFP\ K{=}4\times10{-}5\times e0.5206*GFP \tag{10}$$

Where K = Pressure-Decay Permeability(mD)
GFP = Gas Filled Porosity (%)

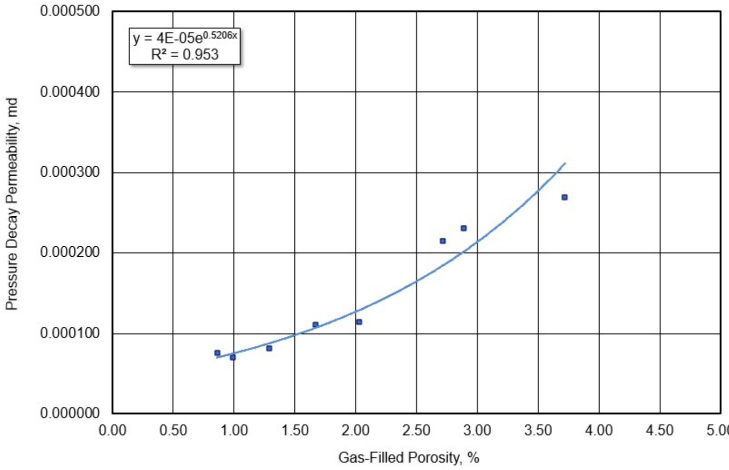


Figure 8. Correlation between pressure decay permeability and gas-filled porosity of Wufeng-Longmaxi shale gas reservoir, Well A.

4. Results

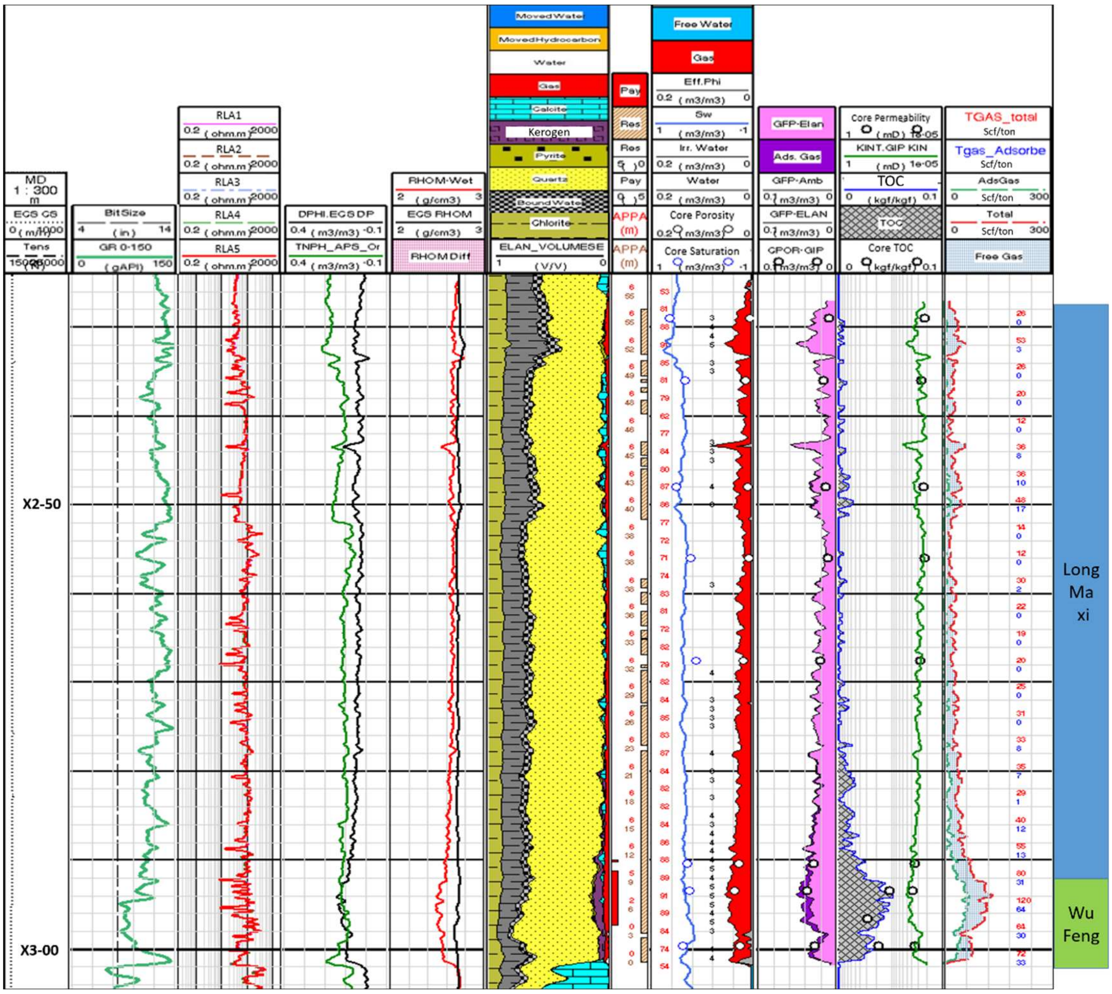


Figure 9. Integrated petrophysical evaluation result of wufeng-longmaxi shale gas reservoir, Well A

The integrated petrophysical evaluation for shale gas reservoir can be done using the petrophysical interpretation program like ELANPlus (Mayer and Sibbit, 1980; Quirein et al., 1986; Cannon,1998) and ShaleGAS (Frantz et al.,1992,1999) modules. The primary answer sought from the ELANPlus application is the volumes of certain formation components at each data level. The main formation components of Wufeng-Longmaxi gas shale exist in two groups: minerals (quartz, calcite, chlorite, illite, pyrite, kerogen) and fluids (gas, water). Figure 9 presents the integrated petrophysical evaluation results of Wufeng-Longmaxi shale gas reservoir in Well A. Track 6 shows the ELANPlus volumes. Track 8 shows water saturation (blue), effective porosity (red shading). Track 9 shows gas-filled porosity (pink shading). Track 10 shows TOC and permeability. Track 11 shows adsorbed and total gas in scf/ton, the difference, shaded in gray, is the free gas. Core results (water saturation, effective porosity, gas filled porosity and permeability) in table 2 are also plotted in the figure 9.

Table 2. Tight rock analysis for Wufeng-Longmaxi shale gas reservoir, Well A

Sample ID	Depth (m)	As Received Bulk Density (g/cc)	As Received Grain Density (g/cc)	Effective Dry Grain Density (g/cc)	Effective Porosity (% of BV)	Water Saturation (% of PV)	Gas Saturation (% of PV)	Mobile Oil Saturation (% of PV)	Gas Filled Porosity (% of BV)	Bound Hydrocarbon Saturation (% of BV)	Bound Clay Water (% of BV)	Pressure-Decay Permeability (mD)
1	Hidden	2.674	2.697	2.727	2.53	62.65	33.91	3.44	0.86	0.01	8.30	0.000076
2	Hidden	2.710	2.756	2.774	2.67	34.10	62.53	3.37	1.67	0.01	6.30	0.000111
3	Hidden	2.649	2.683	2.709	2.79	50.58	46.28	3.14	1.29	0.01	6.90	0.000082
4	Hidden	2.689	2.716	2.723	1.41	23.40	70.40	6.19	0.99	0.01	2.62	0.000070
5	Hidden	2.644	2.699	2.706	2.38	11.23	85.17	3.61	2.03	0.01	4.68	0.000115
8	Hidden	2.589	2.666	2.690	4.23	29.65	68.32	2.04	2.89	0.01	5.74	0.000231
6	Hidden	2.518	2.615	2.638	5.09	25.34	73.05	1.61	3.72	0.01	4.45	0.000269
7	Hidden	2.579	2.650	2.681	4.46	37.26	60.82	1.92	2.71	0.01	6.27	0.000215

The gross thickness of Wufeng-Longmaxi shale gas reservoir in Well A is 74.8m, the net pay is 9.8m. Wufeng formation is the sweet spot, the average effective porosity of Wufeng is 4.6%, the average gas-filled porosity is 3.5%, the average permeability is 115nD, the average TOC is 3.8 %, the average total gas is 105 scf/Ton. Wufeng formation is the optimal lateral landing point with good reservoir quality.

5. Conclusions

The calculation of mineralogy, total organic carbon, porosity, saturation, permeability, adsorbed gas and free gas of shale gas reservoir is a complex process, which requires a lot of wireline logging measurement and core experimental analysis data. In this paper an integrated workflow is designed in detail that results in accurate petrophysical parameters predictions for Wufeng-Longmaxi shale gas reservoir in an example Well A in southeast Chongqing area. Conventional logs are used to identify the organic shale zone. ECS is very useful because it converts elemental concentrations to major minerals groups. Accurate estimates of kerogen are determined with bulk density, NMR and ECS logs. ELANPlus and ShaleGas modulus are used to combine all the data to calculate accurate and continuous lithology, effective porosity, saturation, TOC, free, adsorbed and total gas throughout entire gas shale. Core data are used to calibrate and verify log interpretation results. The result indicates that Wufeng shale gas formation is the “sweet spot” of the Sichuan basin with good reservoir quality and the optimal lateral landing point of horizontal wells. The integrated petrophysical evaluation techniques provide technical support for shale gas exploration in southeast Chongqing area.

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