Available online at www.sciencedirect.com

ScienceDirect

Journal of Natural Gas Geoscience 1 (2016) 231–241

http://www.keaipublishing.com/jnggs

Original research paper

Logging identification for the Lower Cambrian Niutitang shale reservoir in the Upper Yangtze region, China: A case study of the Cengong block, Guizhou Province☆

Ruyue Wang [a,b,c], Wenlong Ding [a,b,c,*], Xinyu Wang [a,b,c], Zixian Cui [a,b,c], Xinghua Wang [a,b,c], En Chen [a,b,c], Yaxiong Sun [a,b,c], Zikang Xiao [a,b,c]

[a] *School of Energy Resources, China University of Geosciences, Beijing 100083, China*

[b] *Key Laboratory for Marine Reservoir Evolution and Hydrocarbon Abundance Mechanism, Ministry of Education, China University of Geosciences, Beijing 100083, China*

[c] *Key Laboratory for Shale Gas Exploitation and Assessment, Ministry of Land and Resources, China University of Geosciences, Beijing 100083, China*

Received 9 May 2016; revised 23 June 2016
Available online 24 August 2016

Abstract

Currently, China has achieved a breakthrough in the Lower Silurian Longmaxi shale in Sichuan Basin and its surrounding areas. Compared to the Longmaxi shale, the Lower Cambrian Niutitang shale, which has a greater deposition thickness and wider distribution area, is another significant stratum for China's shale gas. Geophysical well logging is one of the most significant methods used for identification and evaluation of shale gas reservoirs throughout the process of shale gas exploration and development. In this paper, the logging response of the Niutitang shale is summarized to "four high and four low", this was determined through a comparative analysis of three shale gas wells in the Cen'gong block. The Geochemical logging (GEM) data shows that as the depth goes deeper the content of Si (quartz) increases and the content of Al, Fe, K (Potassium), and Clay minerals decreases. In addition, the Niutitang shale mainly has the feature of a single peak or two continuous peaks in T_2 spectrum on the nuclear magnetic resonance (NMR) logging response. This has a longer T_2 time and greater amplitude than normal shales. The logging response of various lithology and preservation is summarized by overlapping and a cross-plot analysis with the spectral gamma-ray, resistivity, density, acoustic, and compensated neutron logging data, which are sensitive to organic-rich shales. Moreover, the resistivity and acoustic logging data are sensitive to gas content, fluid properties, and preservation conditions, which can be used as indicators of shale gas content and preservation.

Keywords: Lower Cambrian; Niutitang formation; Shale gas; Logging response; Logging identification; Formation element logging; Nuclear magnetic resonance logging; Preservation

1. Introduction

Shale gas is the absorbed and free natural gas accumulation that exists in organic-rich mudstone and/or shale layers with autogenic gas [1–5]. The exploration and development of shale gas in the North America has a history of nearly 200 years, and the "shale gas revolution" has expanded around the world. China's shale gas exploration and development, as well as related studies, are in the initial stage and many scholars

☆ This is English translational work of an article originally published in *Natural Gas Geoscience* (in Chinese).The original article can be found at:10.11764/j.issn.1672−1926.2015.12.2395.

* Corresponding author. School of Energy Resources, China University of Geosciences, Beijing 100083, China.

E-mail address: dingwenlong2006@126.com (W. Ding).

Peer review under responsibility of Editorial Office of *Journal of Natural Gas Geoscience*.

http://dx.doi.org/10.1016/j.jnggs.2016.08.004

have achieved considerable understanding [6–18]. Above all, the exploration and development of China's shale gas are significant in improving China's natural gas production, thus, easing the dependence on foreign oil and gas.

Geophysical well logging is one of the most important methods for the identification and evaluation of shale gas reservoirs throughout the process of shale gas exploration and development. Compared to the expensive cost of drilling and coring tests, geophysical well logging can obtain various physical properties of the formation from the borehole in a short period of time and deliver accurate results that can effectively make precise evaluations of the formation [19,20]. The shale gas logging evaluation theories, techniques, and methods in China are in the initial stage, and the identification of organic-rich shale reservoir is the basis for the research of shale gas. However, North American shales compared to Paleozoic organic-rich marine shales in southern China, have multiple strata, namely old formation ages, high thermal maturities, multi-stage tectonic movements, and complex surface, the stress state, and preservation conditions are also considered [21,22]. The complex geological conditions, several types of organic-rich shale reservoirs, and strong heterogeneity make shale reservoirs of different regions and types have great differences in logging response characteristics. Furthermore, the logging response characteristics in different structural locations or preservation conditions may also possess great differences. Based on the combinations of literature investigation, conventional and special logging series, and logging responses of different gas contents and preservation conditions this study abridges the logging response characteristics and exploration methods for the identification of the Niutitang shale reservoir through comparative analysis. Comprehensions obtained may guide the logging identification and evaluation of shale reservoirs in the complex structural areas in the southern China.

2. Geological setting

The Cengong block study area is located in the southwestern part of Tongren city in the northeast of Guizhou province (Fig. 1), it covers a total area of 914 km^2 in the Qianbei area. The tectonic location of the study area is in the trough-like fold belt of the western Hunan-Hubei province right on the southeastern margin of the Upper Yangtze plate,

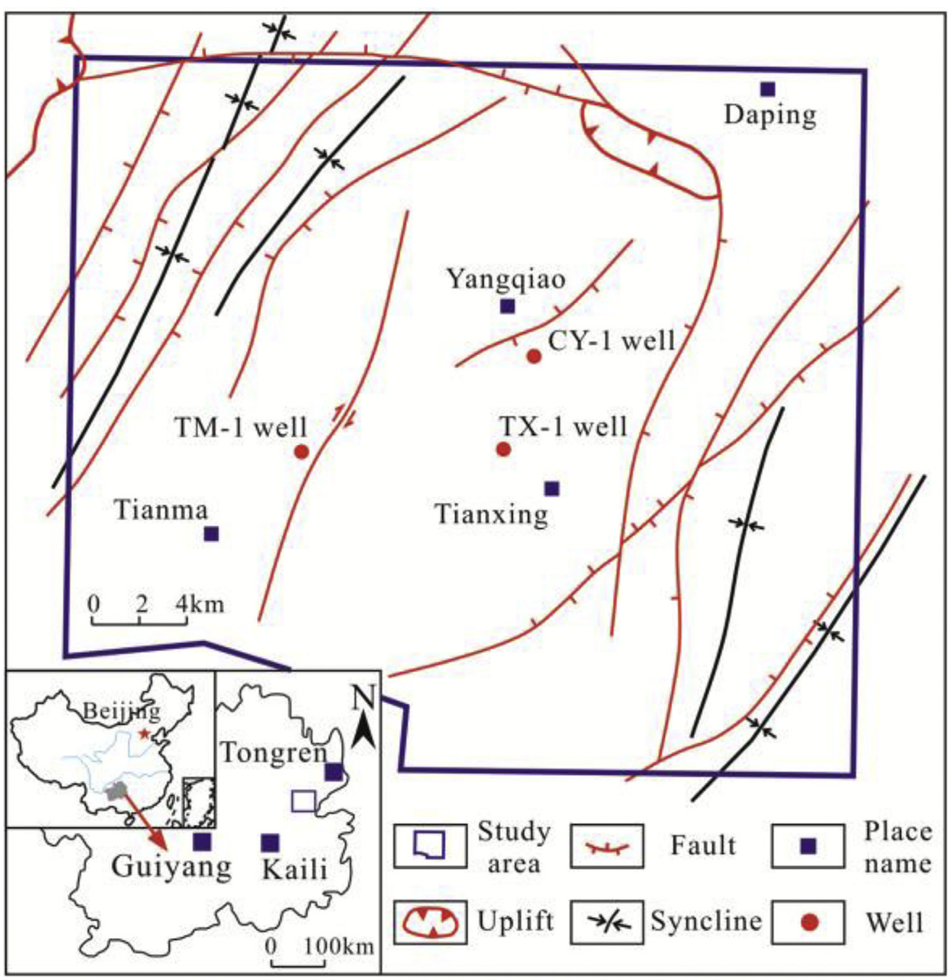

Fig. 1. Location and structure outline of the study area.

where the structural conditions and stress fields are intricate due to multi-stage tectonic movements and deformations. The Lower Cambrian Niutitang Formation, which developed stably in the study area, has a thickness of 50−70 m, it averages 60 m, and it represents a deep shelf depositional environment [23,24]. The lithology of the Niutitang Formation primarily consists of gray-black shale and siliceous shale, which is in blocks or flakes and is commonly observed in local pyrite enrichment. The TOC content ranges from 0.51% to 10.49%, with an average of 4.6%. The measured bitumen reflectance values vary from 2.04% to 4.19%, and it averages 2.72%, and the calculated equivalent vitrinite reflectance (R_O) is between 2.27% and 4.42%. The brittle mineral content of quartz, feldspar, pyrite, and carbonate is greater than 60%, not to mention, the clay minerals are mainly illite and illite/smectite mixed layers. The gas content of the Niutitang shale varies from 0.1 to 2.88 m^3/t, this shows a good potential for shale gas resources.

3. Logging series of shale gas

Up until January 2015, three shale gas wells had been drilled in the study area, namely, Well CY-1, Well TM-1, and Well TX-1. Both the Well CY-1 and Well TM-1 used the conventional well logging series. As for the Well TX-1, it used the combination of conventional and special logging series (Table 1) including formation elemental logging (GEM), orthogonal dipole array acoustic logging (XMAC), nuclear magnetic resonance logging (MRIL-P), and resistivity imaging logging (FMI).

4. Logging response of organic-rich shales

The gas-bearing shales have apparent characteristics on the logging response, which are commonly shown as "four high, two low, and one expansion" (Table 2). Marine shales in southern China, in comparison to North America, have the

Table 1
Logging series in different shale gas wells.

Logging items	Applications	Well CY-1	Well TM-1	Well TX-1
Spontaneous potential	Formation permeability, stratigraphic correlation, formation water property	√	√	√
Natural gamma-ray spectralog	Stratigraphic correlation, kerogen indicator, mineral composition, clay mineral types	√	√	√
Caliper, inclinometer, thermometer	Well track、geothermal gradient, gas temperature correction.	√	√	√
Litho-density	Mineral composition, porosity, clay and organic matter contents.	√	√	√
Compensated neutron (CNL)	Mineral composition, porosity	√	√	√
Acoustic time	Stratigraphic division, porosity, formation compaction trend	√	√	√
Resistivity	Stratigraphic division, fluid property, fracture identification etc.	√	√	√
Array sonic	Dynamic rock mechanical parameters, formation anisotropy, in-situ stress parameters			√
Formation micro scanner image	Rock texture, structure, fracture, sedimentary environment, stress direction etc.			√
Formation element	Mineral composition, porosity, permeability etc.			√
Nuclear magnetic resonance	Porosity, permeability, bound water volume, movable fluid volume etc.			√
Variable density log	Cementing quality	√	√	√

Table 2
Logging response of shale gas reservoir [19,20].

Logging curves	Logging response	Influence factors
Natural gamma-ray spectralog	High values of GR and Uranium	Clay and organic matter contents are positively correlated with GR and Uranium (U)
Deep and shallow Resistivity	Medium-low values (higher than normal shales) with local high values; Deep and shallow resistivity almost coincide with each other	Clay content and bound water volumes are negatively correlated with the resistivity; kerogen, organic matter, and natural gas is positively correlated with the resistivity
Acoustic time (AC)	High values or cycle skip	The content of clay mineral, organic matter, and natural gas is positively correlated with AC value. Diameter expansion and fractures can also increase the AC value
Neutron porosity	Medium values (lower than normal shales)	Organic matter, bound water volume, and fractures are positively correlated with the neutron porosity, and the gas content has a negative correlation
Litho-density	Medium-low values	Organic matter, gas content, diameter expansion and fractures are negatively correlated with density. Hydrocarbon and gas make the photoelectric absorption cross-section index (Pe) decrease, and the heavy minerals make the Pe increase
Hole diameter	Diameter expansion	Diameter expansion is common in shale formations, especially for the shales with high TOC content and well-developed fractures

characteristics of old formation ages, high thermal maturities, multi-stage tectonic movements and complex surface, stress state and preservation conditions All of the aforementioned lead to different logging response characteristics of various gas-bearing properties and preservation conditions of organic-rich shales. Therefore, this paper combines conventional and special well loggings to compare and analyze logging response characteristics of shale reservoirs with different gas-bearing properties and preservation conditions.

4.1. Response characteristics of natural gamma-ray spectral logging

Natural gamma ray spectral logging uses the method of spectrum analysis to quantitatively measure the contents of U, Thorium (Th), Potassium (K), and the total gamma-ray radiation intensity. The total natural gamma-ray radiation intensity in the rock is positively correlated with clay content. Additionally, the presence of organic matter is also beneficial to the enrichment of radioactive substances, which increases the radioactivity of the rocks as well [25]. The X-ray diffraction data from the Well TX-1 shows that the brittle minerals of quartz, feldspar, and carbonate generally surge with the depth; the clay minerals are mainly illite and illite/smectite mixed layers (Fig. 2). The natural gamma-ray spectralog data show that the logging curves and lithology of the three wells are similar in the upright position, indicating the same lithology and mineral composition of the Niutitang shale in the Well CY-1, Well TM-1, and Well TX-1 (Fig. 3). For the different clay mineral has different absorbability of radioactive elements, the response of natural gamma-ray spectral logging can be used to evaluate the mineral composition and clay mineral types [25,26].

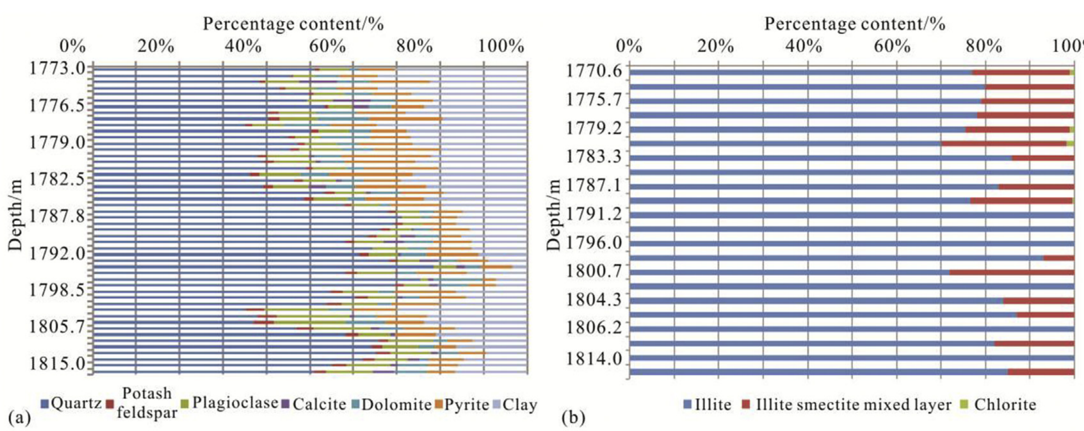

Fig. 2. Mineral composition of the Niutitang Formation in the Well TX-1.

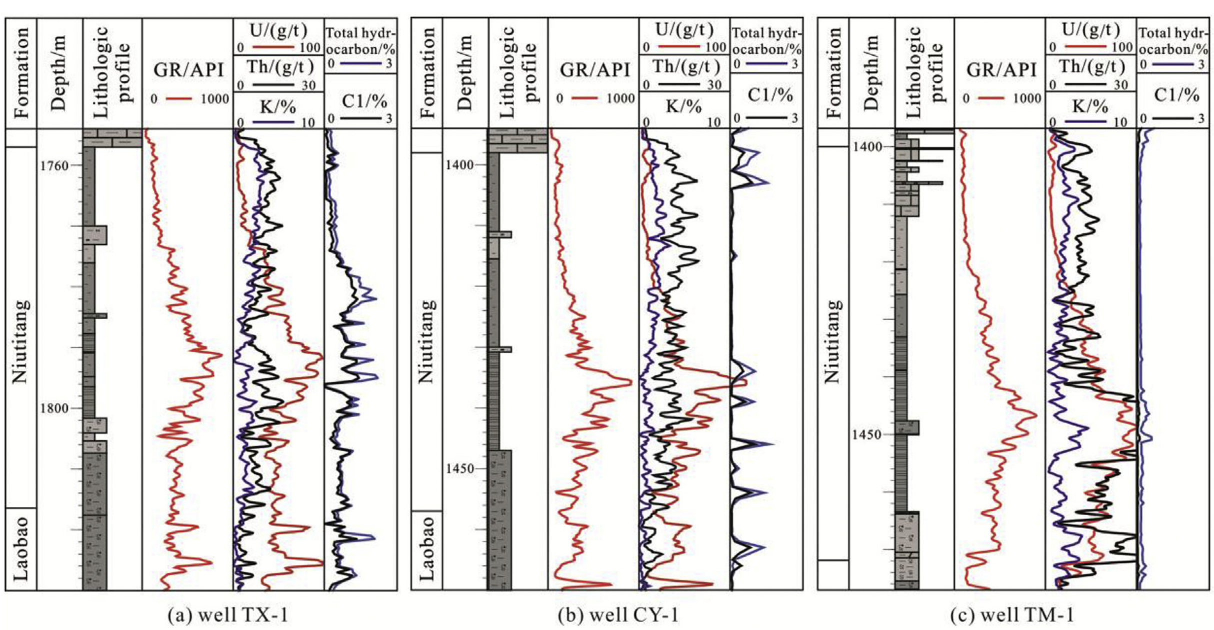

Fig. 3. Natural gamma-ray spectral logging response in the different wells.

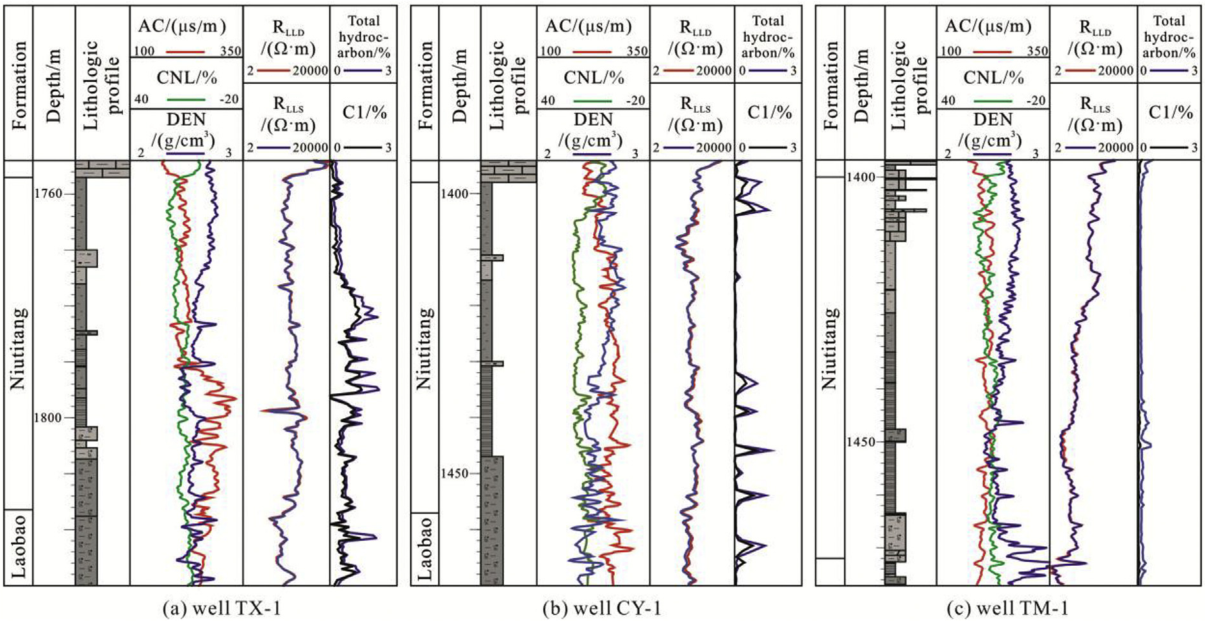

Fig. 4. Tri-porosity and lateral resistivity logging response of different wells.

The natural gamma-ray spectral logging response of the Well TX-1, Well CY-1, and Well TM-1 (Fig. 3) shows that the U, Th, and K curves of the Well TX-1 and Well CY-1 with good preservation conditions are basically consistent. Th and K content are relatively high in the upper section and it generally decreases with the depth. The logging curve (content) of U is similar to GR, both are extremely high in the middle section with high TOC content. The lower section has an average content of U, and low content of Th and K. Well TM-1 is located in the strike-slip fault zone, its high dip-angle fractures and faults are well-developed leading to gas logging abnormity in shallow layers and a low gas content of 0.1−0.4 m^3/t. In addition, amounts of dissolved pores and cavities in the siliceous shales of the Laobao Formation results in a great loss of drilling fluid and poor shale gas preservation condition (Fig. 5). Furthermore, the Th and K contents in the middle and lower sections of the Niutitang Formation, in the Well TM-1, are greater than those in the Well TX-1 and Well CY-1 (Fig. 3). The reason of this may be related to the high absorbability of organic matter and the epithermal deposits in the Yangtze plate. There are three stages of epithermal deposits in the Guizhou area, and these are the Late Proterozoic-Early Paleozoic, Late Caledonian, and Yanshanian (Jurassic-Cretaceous). The concentrated distribution areas are obviously related with the discordogenic faults' deep structures [27−29]. The strike-slip fault which cuts through the basement makes the low-temperature hydrothermal liquids with radioactive elements overflow and eventually be deposited. Although the Niutitang-Laobao Formations in the Well TM-1 have suffered from dissolution and washing of formation water, the contents of Th and K in the organic-rich sections are still anomaly high, which may be due to the strong absorbability of organic matter to the radioactive elements.

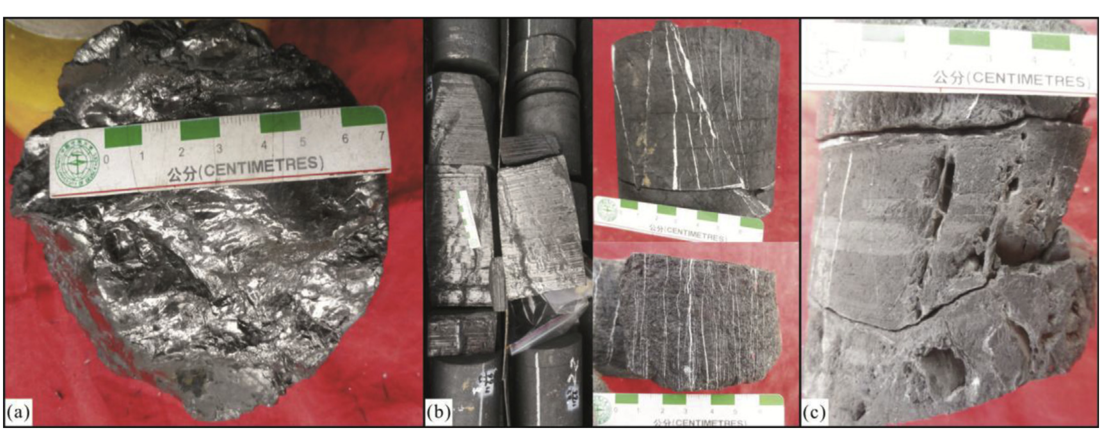

Fig. 5. Core pictures of the Niutitang and Laobao Formations in the study area (a) Well TX-1, 1798 m, graphitization of the Niutitang shale; (b) Well TM-1, 1440−1483 m, high dip-angle fractures are well-developed in the strike-slip fault zone; (c) Well TM-1, 1504 m, dissolved pores and cavities develop in the siliceous shales of the Laobao Formation, resulting in a great loss of drilling fluid.

4.2. Response characteristics of the tri-porosity logging

The tri-porosity logging curves of three wells (Fig. 4) in the study area showed that the density and neutron porosity have a decreasing trend that starts from the top to the bottom. On the contrary, except the Well TM-1, the AC logging curves of the Well TX-1 and Well CY-1 are similar, hence, a general trend of surge together with the depth. In addition, the density and neutron porosity in sections with high TOC and gas contents decrease then increase respectively in the Well TX-1 (1792−1800 m, 1804−1814 m), they also have an obvious amplitude differences with the AC. As for the Well TM-1 with poor preservation condition and low gas content, the density is high and the neutron porosity is low than those in the Well TX-1 and Well CY-1. The AC and neutron porosity in the Well TM-1 is stable upright and have barely amplitude differences with other logging parameters.

4.3. Response characteristics of resistivity logging

The resistivity logging is influenced by a series of factors such as lithology, mineral composition, fluid properties, porosity, permeability, saturation, and the occurrence of fractures, pores, and cavities. In addition, the maturity of organic matter plays an important role in the resistivity logging response [30,31]. The response characteristics to resistivity in the Lower Cambrian Niutitang Formation (Fig. 4) can be described as follows.

The values of deep and shallow resistivity are almost equivalent and are generally greater than 100 Ω m, which is greater than that of the lower siliceous shales and normal shales, but lower than that of the upper limestone. The abnormally low value of the resistivity in the Well TX-1 (1798 m) is due to the graphitization of organic matters in the Niutitang Formation (Fig. 5a). According to Wang et al. [32], the organic-rich shales with a medium to high resistivity are remarkably better than that of ultra-low resistivity (<2 Ω m) in the aspects of gas generation potential, matrix porosity, and adsorption capacity. The resistivity logging curves of the Well TX-1, Well CY-1, and Well TM-1 (Fig. 4) show that the resistivity curve shapes of the Well TX-1 and Well CY-1 are basically consistent vertically with medium values. However, for the TM-1 well with poor preservation condition, the great scale of high dip-angle fractures and faults lead to the invasion of formation water, which results in the amounts of dissolved pores and cavities in the siliceous shales of the Laobao Formation and the low values of resistivity (Figs. 4, 5b and 5c). The washing and dissolution of formation water have destroyed the gas-bearing properties of organic-rich shales, which are unfavorable for the shale gas preservation.

4.4. Response characteristics of formation element logging

The formation element logging can obtain the content of elements in order to determine the mineral types and composition of the formation by means of the spectroscopy analysis technique [33]. The logging instruments such as ECS (Elemental Capture Spectroscopy), GEM (Geochemical logging), and FLS (Formation Lithology Spectrometer) can accurately measure the content of elements such as Al, Ca, Fe, Mg, Mn, Ti, K, Si, S, and the content of minerals to obtain the lithology, fluid properties, and other formation parameters [33−38]. The GEM logging interpretation of the TX-1 well (Fig. 6) shows that the limestone in the Jiumenchong Formation (above 1760 m) has great amounts of calcium and calcite, The content of Si and quartz increases, meanwhile the contents of Al, K, Fe, and clay minerals decrease in the Niutitang Formation with the depth, which is comparable with the results from the X-Ray diffraction analysis (Figs. 2 and 6). The GEM logging also shows good identification ability to the intervals with good gas-bearing properties (such as 1792−1800 m and 1804−1814 m).

4.5. Response characteristics of nuclear magnetic resonance (NMR) logging

NMR well logging can get the T_2 spectrum in the pore fluids to calculate the effective porosity, movable fluid volume, bound water volume, pore size distribution, permeability, and other parameters on the basis of the hydrogen nucleus behavior in external magnetic fields [39]. The amplitude and length of T_2 spectrum represent the pore volume and the proportions of movable and bound fluids, respectively [40].

Sun et al. [41] divided the T_2 spectrum of the shale into 3 types: the single peak, double peaks with isolated right peak, and double continuous peaks. The left and right peaks reflect the content of irreducible water and movable fluids, respectively. The double continuous peaks reflect the relatively wider pore size distribution with higher permeability indicating the presence of dissimilar sizes of pores and fractures [39,41−43]. The unalike lithology has different responses in the T_2 spectrum in Well TX-1: the normal shales commonly have the single peak with short T_2 time, less than 20 ms, reflecting a great proportion of irreducible water (Fig. 7a); The organic-rich shales with good gas content mainly have the response of single peak or double continuous peaks with long T_2 time that can even reach up to 300 ms, this reveals a large proportion of movable fluids and better permeability (Fig. 7b); The sandstones mostly have the response of continuous asymmetry double peaks with bigger right peak, reflecting relatively greater porosity and permeability than shales (Fig. 7c); The limestones in the Jiumenchong Formation mainly have a single peak of T_2 spectrum with low amplitudes and long T_2 time that are generally greater than 20 ms, this reflects low porosity and isolated pore distribution (Fig. 7d). The NMR and GEM logging interpretation of the Well TX-1 show good correlations and has outstanding identification abilities for the gas-bearing intervals (Fig. 6).

5. Logging identification methods of organic-rich shales

5.1. Overlapping analysis

The methodology of overlapping can be used for stratigraphic division. Through the overlapping analysis of the

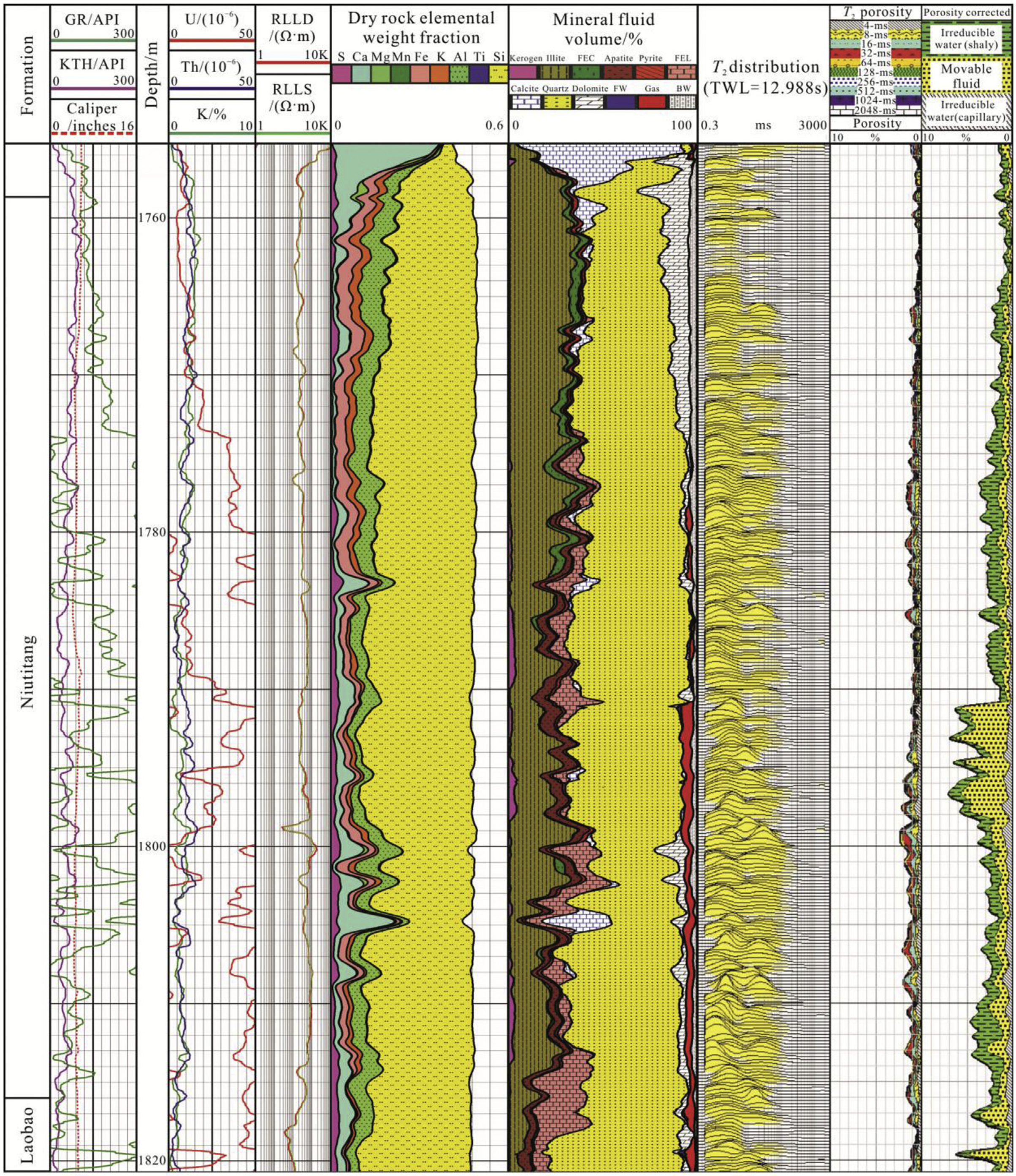

Fig. 6. GEM and MRIL-P logging interpretation of the Niutitang Formation in the Well TX-1. Note: FEC-Fe chlorite; FEL-Ca feldspar; FW-free water; BW-bound water.

logging response characteristics of the Niutitang Formation, the organic-rich shales with good gas-bearing properties can be identified and divided effectively by selecting the GR, KTH, density, AC, and compensated neutron logging curves which are sensitive to the response of the organic-rich shales to identify shale and divide organic gas shale layer.

Due to overlapping, and eventually comparing the different combinations of logging curves (Fig. 8), the organic-rich shales with good gas-bearing property have shown characteristics of high values of GR and AC, as well as low values of KTH, density, and neutron porosity. The GR and AC have obvious positive amplitude differences with their corresponding superimposed logging parameters, which are positively correlated with the TOC and gas contents.

5.2. Cross-plot method

The logging response of diverse lithology and preservation conditions from the Well TX-1, Well CY-1, and Well TM-1 is summarized by means of cross-plot analysis with the spectral

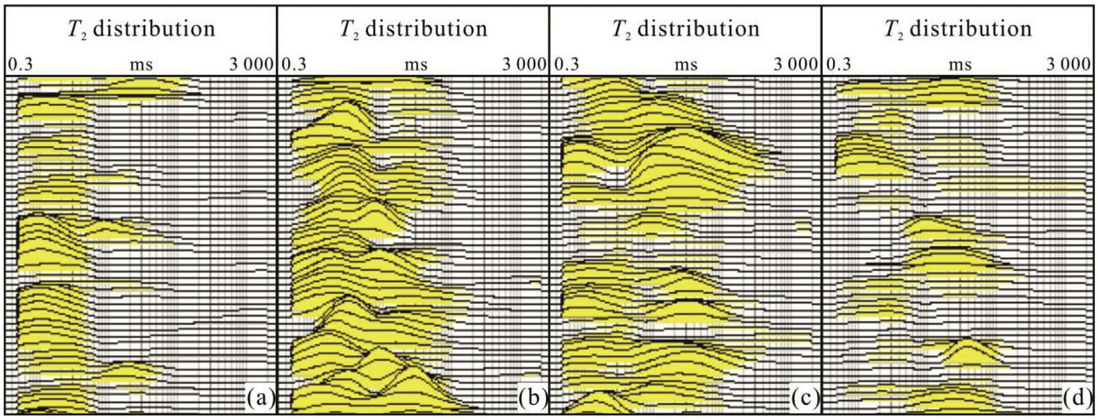

Fig. 7. NMR T_2 spectrum of different lithology in the Well TX1 (a) Normal shale (1610–1620 m); (b) Organic-rich shale with good gas content (1790–1800 m); (c) Silty-fine sandstone (1588–1598 m); (d) Limestone in the Jiumenchong Formation (1745–1755 m).

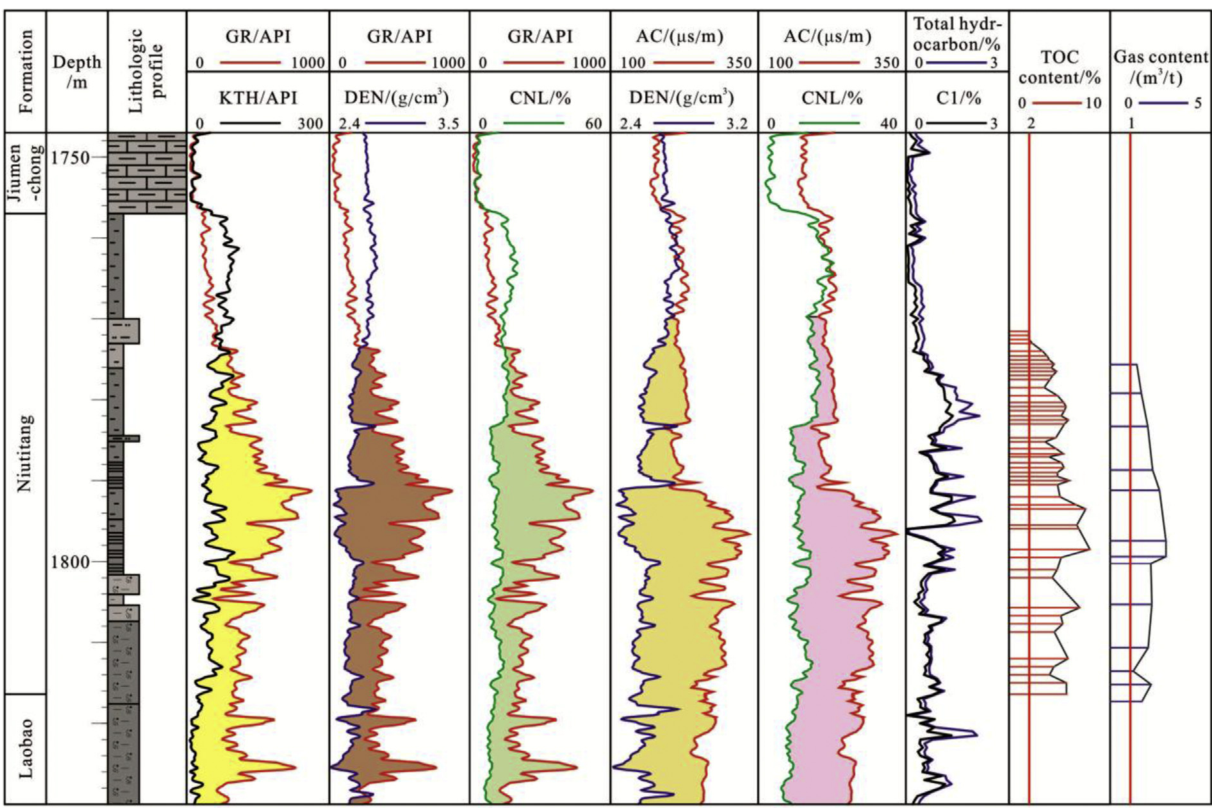

Fig. 8. Logging identification of the Niutitang Formation by overlapping analysis in Well TX-1.

gamma-ray, resistivity, density, acoustic, and compensated neutron logging data that are sensitive to organic-rich shales. The organic-rich shales with high gas content and good preservation commonly have high values of resistivity and AC, and low values of density (Table 3). The logging identification cross-plots (Fig. 9) show that the GR has good identification ability in terms of organic-rich shales with understandable logging response, and the identification abilities of density and CNL loggings decrease in turn. Nevertheless, the resistivity and AC logging data are sensitive to gas content, fluid properties, and preservation conditions in organic-rich shales, which can be used as indicators of shale gas content and preservation.

6. Conclusions

(1) The Lower Cambrian Niutitang shale in the area studied developed stably and has understandable logging responses. High-quality shales have the characteristics of “four high and four low” in conventional logging curves (high values of GR, U, resistivity [compared to normal shales]), and AC, as well as low values of density, neutron porosity, Th, and

Table 3
Logging response of different lithology and preservation conditions.

Lithology		GR/API	$U/10^{-6}$	Resistivity/(Ω/m)	Density/(g/cm^3)	Neutron porosity/%	AC/(μs/m)
Organic-rich shale	Good preservation	300-1000	30−150	200-1200	2.42−2.65	9−16	200−350
	General preservation	300-1000	30−150	100−500	2.42−2.65	6−15	200−250
	Poor preservation	300-1000	30−150	7−400	2.42−2.76	4−13	170−220
Organic-rich siliceous shale	Good preservation	180−800	30−100	70−800	2.45−2.75	5−13	200−280
	General preservation	180−800	30−100	50−150	2.45−2.75	4−13	200−250
	Poor preservation	180−800	30−100	0.9−20	2.45−2.95	3−13	180−240
Normal shale		150−220	3−15	40−400	2.50−2.72	18−25	220−260
Sandstone		60−150	2−8	400−16 000	2.60−2.70	5−15	180−270
Limestone		30−150	2−6	200−18 000	2.66−2.78	2−20	170−240

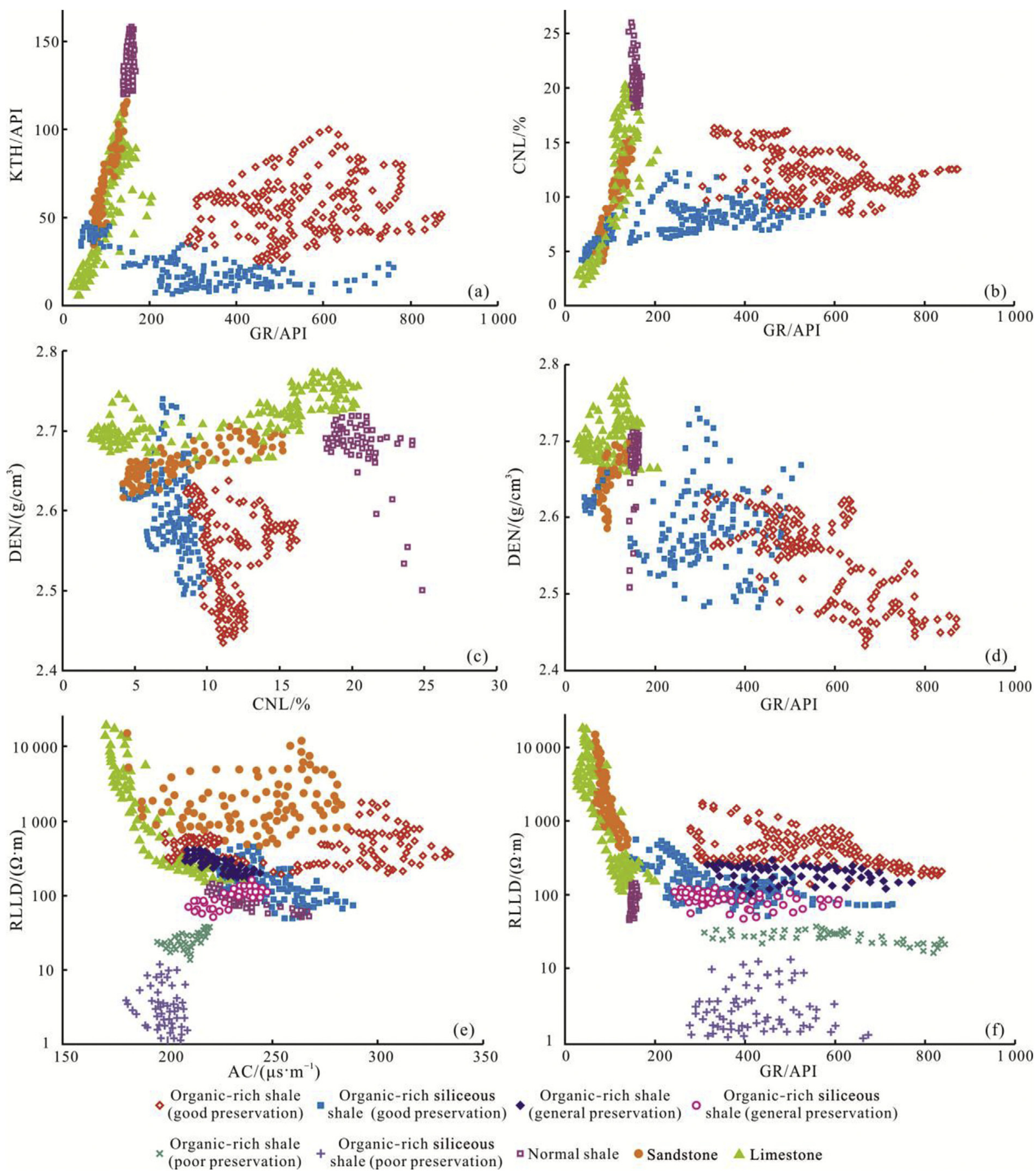

Fig. 9. Logging identification cross-plots of the Niutitang Formation.

K. The GEM data shows that the Niutitang shale has a high Si content and low contents of Al, Fe, K, and Clay minerals, which is consistent with the results of the X-ray diffraction and mineral analysis. In addition, the high-quality shales have the feature of a single peak or two continuous peaks in the T_2 spectrum on NMR logging response, which has a longer T_2 time and greater amplitude than normal shales, reflecting the high content of movable fluids and a relatively wider pore size distribution.

(2) The spectral gamma-ray, resistivity, density, acoustic, and compensated neutron logging data are sensitive to organic-rich shales, which can be used to identify lithology and preservation conditions by means of overlapping and intersection analysis.

(3) The organic-rich shale and its roof, floor, and regional cap rocks; the resistivity, AC, and density logging data are sensitive to the gas content, fluid properties, fracture, and preservation conditions, (the high values of resistivity and AC) and low values of density in shales generally represent high gas content and good preservation. The high values of resistivity and low values of AC in cap rocks represent good preservation. Therefore, these logging parameters can be used as indicators of shale gas content and preservation conditions.

Foundation item

Supported by National Natural Science Foundation of China (41372139, 41072098); China National Science & Technology Special Project (2011ZX05018-001-002, 2016ZX05046-003-001).

Conflict of interest

The authors declare no conflict of interest.

References

[1] R.C. Milici, Autogenic gas (self sourced) from shales: an example from the Appalachian Basin, in: D.G. Howell (Ed.), The Future of Energy Gases, US Geological Survey Professional Paper, US Geological Survey, Washington, 1570, 1993, pp. 253−278.
[2] J.B. Curtis, Fractured shale-gas systems, AAPG Bull. 86 (11) (2002) 1921−1938.
[3] Jinchuan Zhang, Zhijun Jin, Mingsheng Yuan, Reservoiring mechanism of shale gas and its distribution, Nat. Gas. Ind. 24 (7) (2004) 15−18.
[4] Xinjing Li, Suyun Hu, Keming Cheng, Suggestions from the development of fractured shale gas in North America, Petroleum Explor. Dev. 34 (4) (2007) 392−400.
[5] Caineng Zou, Dazhong Dong, Jiaoshe Wang, Jianzhong Li, Xinjing Li, Yuman Wang, Denghua Li, Keming Cheng, Geological characteristics, formation mechanism and resource potential of shale gas in China, Petroleum Explor. Dev. 37 (6) (2010) 641−653.
[6] C.N. Zou, S.Z. Tao, L.H. Hou, R.K. Zhu, X.J. Yuan, Y. Song, J.Y. Niu, D.Z. Dong, X.B. Liu, L.Z. Jiang, S.J. Wang, G.S. Zhang, Unconventional Oil and Gas Geology, Geological Publishing House, Beijing, 2011, pp. 128−159.
[7] Haikuan Nie, Xuan Tang, Ruikang Bian, Controlling factors for shale gas accumulation and prediction of potential development area in shale gas reservoir of South China, Acta Pet. Sin. 30 (4) (2009) 484−491.
[8] W.L. Ding, H. Wan, A.G. Su, Z.H. He, Characteristics of Triassic marine source rocks and prediction of favorable hydrocarbon generation area in Qiangtang Basin, Tibet, Energy Explor. Exploitation 29 (2) (2011) 143−160.
[9] Kai Jiu, Wenlong Ding, Yuxi Li, Jinchuan Zhang, Weite Zeng, Structural features in northern Guizhou area and reservoir fracture of lower Cambrian shale gas, Nat. Gas. Geosci. 23 (4) (2012) 797−803.
[10] Jinliang Huang, Caineng Zou, Jiangzhong Li, Dazhong Dong, Shejiao Wang, Shiqian Wang, Keming Cheng, Shale gas generation and potential of the Lower Cambrian Qiongzhusi Formation in Southern Sichuan Basin, China, Petroleum Explor. Dev. 39 (1) (2012) 69−75.
[11] Wenlong Ding, Huan Wan, Yeqian Zhang, Guangzhi Han, Characteristics of the Middle Jurassic marine source rocks and prediction of favorable source rock kitchens in the Qiangtang Basin of Tibet, J. Asian Earth Sci. 66 (2013) 63−72.
[12] Wenlong Ding, Dingwei Zhu, Junjie Cai, Meilin Gong, Fuyan Chen, Analysis of the developmental characteristics and major regulating factors of fractures in marine-continental transitional shale-gas reservoirs: a case study of the Carboniferous-Permian strata in the southeastern Ordos Basin, Central China, Mar. Petroleum Geol. 45 (2013) 121−133.
[13] Shuangbiao Han, Jinchuan Zhang, Yuxi Li, Wenli Jiang, Pengyu Long, Zhulin Ren, The optimum selecting of shale gas well location for geological investigation in Niutitang Formation in lower Cambrian, northern Guizhou area, Nat. Gas. Geosci. 24 (1) (2013) 182−187.
[14] Yongsheng Nie, Jigao Leng, Jianhui Han, Li Sun, Chungui Shen, Exploration potential of shale gas in Cen' gong block, southeastern Guizhou province, Oil Gas Geol. 34 (2) (2013) 274−280.
[15] Weite Zeng, Jinchuan Zhang, Wenlong Ding, Xiangzeng Wang, Dingwei Zhu, Zhujiang liu, The gas content of continental Yanchang shale and its main controlling factors: a case study of Liuping-171 well in Ordos Basin, Nat. Gas. Geosci. 25 (2) (2014) 291−301.
[16] Jigao Leng, Jianhui Han, Fei Li, Peng Li, Lan Meng, Exploration potential of shale gas in Huayuan Block, Northwest Hunan Prov. Nat. Gas. Geosci. 25 (4) (2014) 624−631.
[17] Ruyue Wang, Wenlong Ding, Yeqian Zhang, Zhe Wang, Xinghua Wang, Jianhua He, Weite Zeng, Peng Dai, Analysis of developmental characteristics and dominant factors of fractures in Lower Cambrian marine shale reservoirs: a case study of Niutitang formation in Cen'gong block, southern China, J. Petroleum Sci. Eng. 138 (2016) 31−49.
[18] Ruyue Wang, Dajian Gong, Wenlong Ding, Jigao Leng, Shuai Yin, Xinghua Wang, Yaxiong Sun, Brittleness evaluation of the Lower Cambrian Niutitang shale in the Upper Yangtze region: a case study in the Cen'gong block, Guizhou province, Earth Sci. Front. 23 (1) (2016) 87−95.
[19] Bin Wei, Lvshui Wang, Yongqiang Fu, Summary of Shale Gas Evaluation by Well Logging, Petroleum Industry Press, Beijing, 2014, pp. 22−82.
[20] Ruyue Wang, Wenglong Ding, Zhe Wang, Ang Li, Jianhua He, Shuai Yin, Progress of geophysical well logging in shale gas reservoir evaluation, Prog. Geophys. 30 (1) (2015) 228−241.
[21] Yuzhu Kang, Characteristics and exploration prospect of unconventional shale gas reservoirs in China, Nat. Gas. Ind. 32 (4) (2012) 1−5.
[22] Ruyue Wang, Wenlong Ding, Dajian Gong, Jigao Leng, Xinghua Wang, Shuai Yin, Yaxiong Sun, Gas preservation conditions of marine shale in northern Guizhou area: a case study of the Lower Cambrian Niutitang Formation in the Cen'gong block, Guizhou Province, Oil Gas Geol. 37 (1) (2016) 45−55.
[23] Zengzhao Feng, Yongmin Peng, Zhenkui Jin, Panliang Jiang, Zhidong Bao, Zhang Luo, Tianyin Ju, Haiqin Tian, Hong Wang, Lithofacies palaeogeography of the Cambrian in South China, J. Palaeogeogr. 3 (1) (2001) 1−14.
[24] Libo Wang, Kai Jiu, Weite Zeng, Jinglong Fu, Song Zhao, Characteristics of Lower Cambrian marine black shales and evaluation of shale gas

prospective area in Qianbei area, Upper Yangtze region, Acta Petrol. Sin. 29 (9) (2013) 3263−3278.

[25] Qian Huang, Jinghua Liu, Zhuwen Wang, The Application of natural Gamma-Ray logging data in determining the content of clay minerals, J. Jilin Univ. Earth Sci. Ed. 37 (supplement1) (2007) 143−150.

[26] Qiang Shi, Preliminary investigation on quantitative analysis of the composition of clay minerals using NGS log, Well Logging Technol. 22 (5) (1998) 349−352.

[27] Chaoyang Li, Some geological characteristics of concentrated distribution area of epithermal deposits in China, Earth Sci. Front. 6 (1) (1999) 163−170.

[28] Ruizhong Hu, Jiantang Peng, Dongsheng Ma, Wenchao Su, Chunhua Shi, Xianwu Bi, Guangchi Tu, Epoch of large-scale low-temperature mineralizations in southwestern Yangtze massif, Mineral. Deposits 26 (6) (2007) 583−596.

[29] Denghong Wang, Yan Qin, Chenghui Wang, Yuchuan Chen, Lan Gao, Mineralization pedigree for epithermal Hg, Sb, Au deposits in Guizhou Province—Taking the Dachang Sb deposit, the Zimudang Au deposit and the Luanyantang Hg deposit for examples, Geotect. Metallogenia 36 (3) (2012) 330−336.

[30] H. Zhao, N.B. Givens, B. Curtis, Thermal maturity of the Barnett shale determined from well-log analysis, AAPG Bull. 91 (4) (2007) 535−549.

[31] T.J. Kinley, L.W. Cook, J.A. Breyer, D.M. Jarvie, A.B. Busbey, Hydrocarbon potential of the Barnett shale(Mississippian), Delaware Basin, west Texas and southeastern New Mexico, AAPG Bull. 92 (8) (2008) 967−991.

[32] Yuman Wang, Dazhong Dong, Xiangzhi Cheng, Jinliang Huang, Shufang Wang, Shiqian Wang, Electric property evidences of the carbonification of organic matters in marine shales and its geologic significance: a case of the Lower Cambrian Qiongzhusi Shale in southern Sichuan Basin, Nat. Gas. Ind. 34 (8) (2014) 1−7.

[33] Feng Zhang, Juntao Liu, Xiuwen Ji, Chao Yuan, Development of formation element logging technique and its application, J. Isotopes 24 (1) (2011) 21−28.

[34] Zugui Yuan, Xiaoning Cheng, Juang Sun, ECS—new well-logging technique for completely evaluating the reservoir, Atomic Energy Sci. Technol. 38 (supplement1) (2004) 208−213.

[35] R.R. Pemper, A. Sommer, P.J. Guo, E. Rodriguez, F. Mendez, X. Han, A new pulsed neutron sonde for derivation of formation lithology and mineralogy, in: San Antonio Annual Technical Conference and Exhibition, SPE 102770, 2006.

[36] E.S. James, O. Omole, J. Diedjomahor, J. Crowe, Calibration of the elemental capture spectroscopy tool using the Niger delta formation, in: Nigeria Annual International Conference and Exhibition, SPE 111910, 2007.

[37] J.A. Galford, J.A. Quirein, S. Shannon, J.A. Truax, J. Witkowsky, Field test results of a new neutron induced gamma ray spectroscopy geochemical logging tool, in: New Orleans Annual Technical Conference and Exhibition, SPE 123992, 2009.

[38] Chao Yuan, Cancan Zhou, Development process and technology prospect of elemental logging based on Gamma ray spectroscopy, Prog. Geophys. 29 (4) (2014) 1867−1872.

[39] Lizhi Xiao, Frontiers Investigation in Well Logging Science, Petroleum Industry Press, Beijing, 2007, pp. 2−23.

[40] Qiusheng Xiao, Juyi Zhu, Analysis method of rock NMR and its application in oilfield exploration, Petroleum Geol. Exp. 31 (1) (2009) 97−100.

[41] Junchang Sun, Jingping Chen, Zhengming Yang, Xuewei Liu, Yuanjun Liu, Experimental Study of the NMR characteristics of shale reservoir rock, Sci. Technol. Rev. 30 (14) (2012) 25−30.

[42] Weimin Wang, Chaohui Ye, Hekun Guo, Experimental studies of NMR properties of continental sedimentary rocks, Chin. J. Magnetic Reson. 18 (2) (2001) 113−121.

[43] Zuxin Xu, Shaobin Guo, Application of NMR and X-CT technology in the pore structure study of shale gas reservoirs, Adv. Earth Sci. 29 (5) (2014) 624−631.