IPTC-19378-MS

Comprehensive Evaluation of NMR Characteristics of Complex Volcanic Reservoirs with Different Types of Rock lithology

Junchang Sun, Research Institute of Petroleum Exploration & Development, PetroChina; Shijie Zhang, Xinjiang Oilfield Company, PetroChina; Jieming Wang, Hekun Guo, Chun Li, Hongcheng Xu, Sinan Zhu, and Kai Zhao, Research Institute of Petroleum Exploration & Development, PetroChina

This paper was prepared for presentation at the International Petroleum Technology Conference held in Beijing, China, 26 – 28 March 2019.

Abstract

Compared with sandstones and carbonates, volcanic reservoirs are much more complex and heterogeneous due to the special eruption diagenesis mechanism, many types of rock lithology, various mineral compositions and a broad wide of pore sizes according to previous studies. Consequently, accurate characterization of volcanic reservoirs using the powerful nuclear magnetic resonance (NMR) logging requires a comprehensive laboratory NMR investigation of volcanic rock because currently used NMR interpreted methods were only developed for sedimentary reservoirs.

To gain an in-depth understanding of NMR characteristics of volcanic reservoirs with different lithology, a total of 108 low-permeability volcanic reservoir rock plugs from three large volcanic gas reservoirs named Xushen, Changling and Dixi, respectively, were prepared to perform NMR measurements and other related tests including CT scans, thin section petrography, mercury injection and mineral compositions analysis. The selected plugs comprise 9 types of lithology representing the main producing formation lithology of the three reservoirs. Specially, centrifuge tests were conducted with the maximum centrifugal forces up to 500 psi to explore the suitable capillary pressure for T_2 cutoff determination.

Results indicate that, obviously different from sandstone and carbonate plugs, NMR porosity of volcanic plugs at fully brine-saturated state is strongly dependent on rock lithology. NMR porosities of trachyte, trachytic volcanic and granite porphyry are significantly less than the conventional ones measured by the Archimedes method, which means that, accurate identification of reservoir intervals lithology is a primary prerequisite before correct interpretations of NMR logging. Paramagnetic minerals mainly iron and manganese elements contained in volcanic reservoirs are the fundamental cause resulting in this abnormal phenomenon. The critical values of iron and manganese elements contents are approximately 2% and 0.06% by weight, respectively, above which the NMR porosity will be considerably less than the conventional one suggesting by inductively coupled plasma-atomic emission spectrometry (ICP-AES) tests on 14 representative plugs. Then, a new NMR porosity corrected formula was developed to improve interpreted quality of NMR logging. It was found that the suitable capillary pressure for determination of T2 cutoff of volcanic reservoirs is 400psi, 3 times larger than the commonly recommended standard (100psi)

for sandstones. The calculated T_2 cutoff ranges from 3 to 120ms and its average values is 50ms. T_2 cutoff between different volcanic reservoirs and lithologies exhibits significant difference.

The laboratory NMR results were used to interpret NMR logging of the Xushen reservoir of Daqing oilfield in eastern China and aided in detailed reservoirs evaluation. The outcome of beneficial intervals selection and high productivity well completion based on the NMR logging interpretation is very encouraging. This study indicated that a comprehensive laboratory NMR tests is very essential to successful application of NMR logging for complex reservoirs such as volcanic reservoirs.

Introduction

A breakthrough has been achieved in petroleum logging since nuclear magnetic resonance (NMR) was introduced into the petroleum industry in 1990s, for it can distinguish movable fluid between irreducible fluid and it is currently the only logging technology that can obtain reservoir permeability. And especially when it is used to interpret and evaluate complex reservoirs, e.g. volcanic rocks and low-resistivity oil/gas layers, it provides the logging analysts with the new ideas and methods to deal with various difficulties. By analyzing the NMR T_2 spectrum of rock plugs at fully brine-saturated state, the distribution of reservoir pore size can be evaluated and the important reservoir evaluation parameters can be obtained, including effective porosity, NMR permeability and movable fluid saturation.

Compared with conventional sedimentary reservoirs (e.g. sandstones and carbonates), volcanic reservoirs are much more complex and heterogeneous due to the special eruption diagenesis mechanism, many types of rock lithologies, various mineral compositions and a broad wide of pore sizes. Consequently, the accurate characterization of volcanic reservoirs using the advanced NMR logging requires a comprehensive laboratory NMR investigation of volcanic rock because the models currently used for NMR logging interpretation are only suitable for sedimentary reservoirs.

In this paper, NMR sample analysis technology was adopted to perform NMR measurements and other related tests including CT scan, thin section petrography, mercury injection and mineral composition analysis on a total of 108 rock plugs from three large volcanic gas fields named Xushen of Daqing, Changling of Jilin and Dixi of Xinjiang, respectively. The research results play an important role in guiding the in-depth understanding of NMR characteristics of volcanic reservoirs and the implementation of NRM reservoir evaluation in the corresponding areas.

Materials and Methods

In this research, a total of 108 rock plugs of low-permeability volcanic reservoirs with different lithologies from Daqing, Jilin and Xinjiang are selected. NMR experiments are carried out using the RecCore04 low-magnetic NMR sample analyzer. In the NMR experiments, the waiting time (TW) is set at 5000 ms, the echo spacing (TE) is 0.6 ms, the number of echo (NE) is 2048 and the scan times (SCAN) is 128. The experimental procedure is as follows.

1. According to the effective measurement size and probe size of NMR device, cut the selected rock samples of volcanic gas reservoirs into the rock plugs with diameter of 2.5 cm and length of 3 cm. After the core plugs are dried, measure their dry weight and gas logging permeability. Pressurize the rock plugs and saturate them with simulated formation water.
2. Calculate the conventional porosity. After the core plugs are dried to the constant weight, measure the dry weight. Then, evacuate the core plugs, pressurize and saturate them with simulated formation water. Finally, measure their wet weight and calculate the conventional porosity.
3. Carry out NMR measurement on rock plugs at the brine-saturated state, and conduct inversion calculation to obtain NMR T_2 spectrum.

4. Calculate NMR porosity. Carry out NMR experiment on the rock plugs at the brine-saturated state, and then conduct NMR experiment on the fluid pattern contained in RecCore04 device whose porosity and total volume are known. Fit the functional relation between the porosity of fluid pattern and the nuclear magnetic signal per unit volume, mathematically fit and determine the calibration factor and calculate NMR porosity of rock plugs.
5. Carry out centrifuge and NMR experiments by applying different centrifugal forces on the rock plugs, including 0.35 MPa, 0.69 MPa, 1.38 MPa, 2.07 MPa, 2.76 MPa and 3.45 MPa. Explore the centrifugal force suitable for the calibration of NMR T_2 cutoff ($T_{2\text{cutoff}}$) of low-permeability volcanic reservoir plugs according to the variation of water saturation of rock plugs after the application of different centrifugal forces.
6. Calculate $T_{2\text{cutoff}}$ according to NMR T_2 spectrum before and after the centrifugal forces are applied on the rock plugs.

Experimental Results and Discussion

NMR Porosity

Table 1 shows the conventional physical property parameters and NMR porosity of 102 rock plugs. And Fig.1 is the comparison diagram of conventional porosity and NMR porosity between the samples of conventional reservoirs and those of volcanic reservoirs with different lithologies.

Table 1—Conventional physical property parameters and NMR porosity of 102 volcanic rock plugs

Gasfield	Lithology	Qnty.	φ/%	Φ_{NMR}/%	Absolute error/%
Changling	Tuff	34	8.17	6.70	1.47
	Rhyolite	11	14.71	12.72	1.99
Xushen	Gray trachytic volcanic breccia	4	6.17	3.85	2.32
	Trachyte	10	5.03	1.19	3.84
	Rhyolite	8	6.31	5.74	0.57
	Dark-gray rhyolitic agglomerate lava	2	7.65	7.14	0.51
	Gray rhyolitic breccia lava	2	8.40	8.35	0.05
	Tuff	1	6.49	5.49	1.00
Dixi	Fluorescent granite porphyry	17	8.11	3.58	4.53
	Andesite	9	11.92	10.28	1.64
	Andesitic basalt	4	16.24	16.66	−0.42

Note: φ: conventional porosity, Φ_{NMR}: NMR porosity, absolute error: the error between φ and Φ_{NMR}.

Fig.1(a) shows that the accuracy of NMR porosity of sandstone and carbonate rock plugs is quite high, and the error between NMR porosity and conventional porosity of most samples is within 1%. For example, average NMR porosity and average conventional porosity of 10 carbonate rock plugs are 8.62% and 8.10%, respectively, and their error is only 0.52%. In Fig.1(b), 1(c) and 1(d), however, the relationships between NMR porosity and conventional porosity of rock plugs of volcanic gas reservoirs with different lithologies are more complex. In general, NMR porosity of most rock samples is lower than their conventional porosity and their error is strongly dependent on rock lithology.

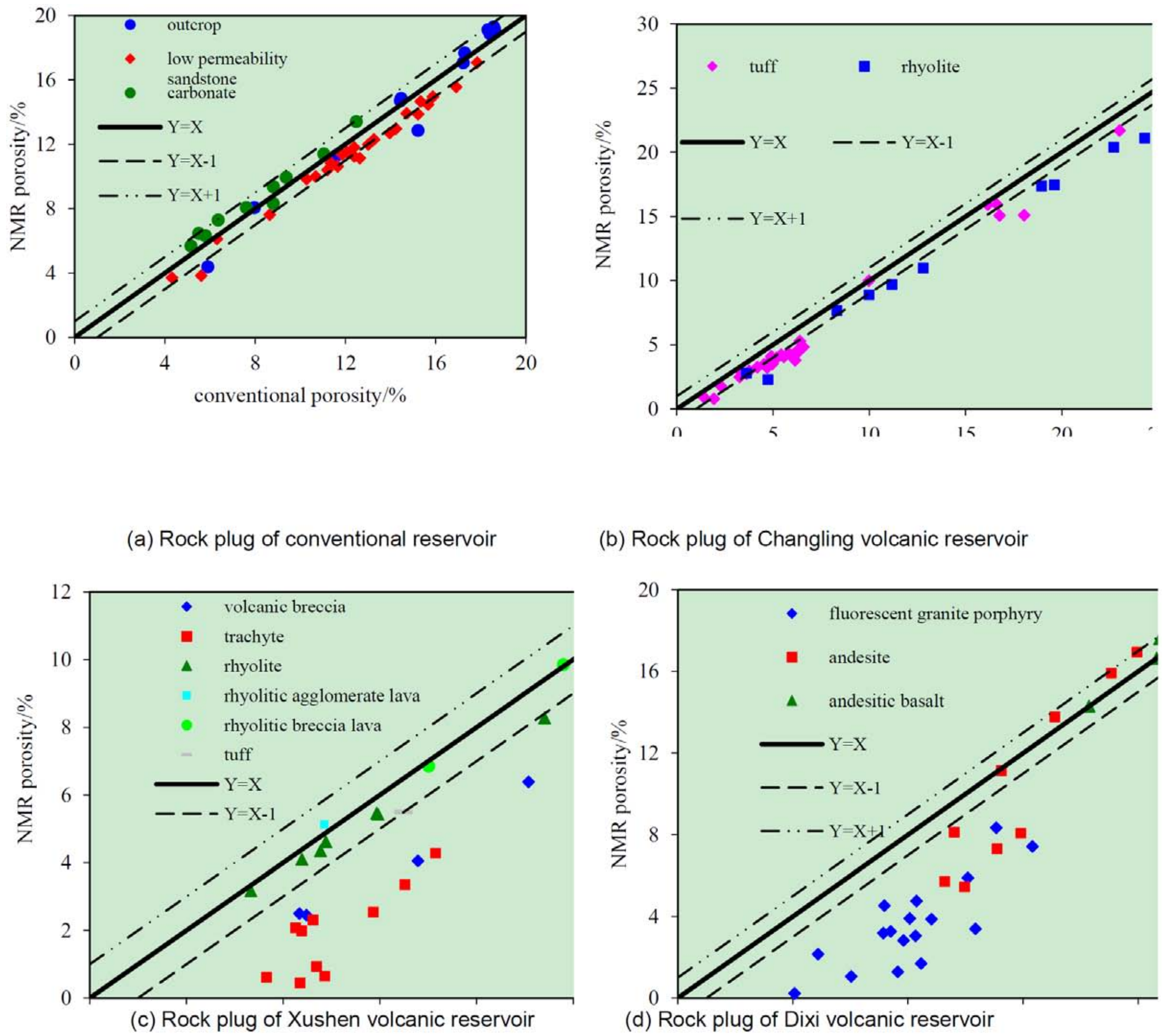

Figure 1—Relationship between NMR porosity and conventional porosity of rock plugs

Table 1 and Fig.1(b) show that the accuracy of NMR porosity of tuff and rhyolite plugs from Changling Gasfield is higher, and the error between NMR porosity and conventional porosity of 34 tuff plugs and 11 rhyolite plugs is lower than 2%, which is acceptable in the development and production of gas fields. In the meantime, however, it is shown in Fig.1(b) that the NMR porosity of 4 rock plugs whose conventional porosity is about 25% is much lower than the conventional porosity.

Fig.1(c) shows that the volcanic rocks in Xushen Gasfield are composed of 6 lithologies. The error between NMR porosity and conventional porosity of rhyolite, rhyolitic agglomerate lava, rhyolitic breccia lava and tuff is within 1%, and the NMR porosity of 4 trachytic volcanic breccia plugs and 10 trachyte plugs is much lower than their conventional porosity.

Fig.1(d) shows that the volcanic rocks in Dixi Gasfield are composed of 3 lithologies, i.e., fluorescent granite porphyry, andesite and andesitic basalt. The NMR porosity of 4 andesitic basalt plugs is close to their conventional porosity. The error between NMR porosity and conventional porosity of 9 andesite plugs is 1.64%, and the relative error of NMR porosity calculated based on the conventional porosity is 13.67%. In addition, the error between NMR porosity and conventional porosity of andesite plugs increases with the decrease of the conventional porosity.

Analysis of NMR Porosity Error

The factors influencing the NMR porosity of rock plugs in laboratory NMR experiments include the data acquisition mode, the testing parameters of NMR device, the micropore structures of rock plug and the components of sold skeleton.

The accuracy of NMR porosity calibrated by the fluid pattern is quite high, so the influence of data acquisition mode is negligible. The testing parameters of NMR device mainly include waiting time (TW), echo spacing (TE), number of echo (NE) and scan times (SCAN). The experimental study on the optimization of different parameter matching indicates that better NMR signals of volcanic reservoirs can be obtained when TW is set at 5000 ms, the number of echo (NE) is 2048 and the scan times (SCAN) is 128.

The influence of the compositions of rock skeleton on NMR porosity is more complex, and especially when there are a certain amount of paramagnetic minerals in the solid skeleton, this influence is extremely obvious and even the NMR device cannot detect the relaxation signals of fluid hydrogen nucleus. There are usually paramagnetic minerals in continental sedimentary reservoirs, including manganese, iron and nickel. The volcanic reservoirs of eruption diagenesis have a wide variety of lithologies, so their paramagnetic minerals may be more complex. The existence of paramagnetic minerals not only increases the lateral surface relaxation strength of rock (ρ), but also the susceptibility difference between solid skeleton and fluid, resulting in internal magnetic gradient. They both can decrease the lateral relaxation time (T_2) of fluid greatly. As a result, the compositions whose relaxation time (T2) is quite short cannot be detected due to the TE limitation of the devices, so the NMR porosity of rock plugs is lower than the conventional value.

To analyze the reasons why the NMR porosity of rock plugs is lower than the conventional value, inductively coupled plasma-atomic emission spectrometry (ICP-AES) tests are carried out on 14 rock plugs to detect their elemental components. It is shown that there are 15 elements in volcanic rock plugs, among which iron (Fe), manganese (Mn) and nickel (Ni) have more effects on NMR signals, seeing Table 2.

Table 2—Element detection results of 14 rock plugs

No.	Area	Lithology	φ/%	Φ_{NMR}/%	Element content/%		
					Fe	Mn	Ni
xs-1	Xushen	Gray trachyte	5.79	0	2.57	0.0862	0.00039
xs-2		Gray trachyte	4.99	0	2.68	0.0904	0.00019
xs-3		Green trachyte	5.34	0	2.79	0.1108	0.00022
xs-4		Brownish red trachyte	5.86	2.54	2.16	0.0588	0.00026
xs-5		Brownish red trachyte	4.26	2.08	2.31	0.0566	0.00032
xs-6		Gray trachytic volcanic breccia	9.07	6.39	2.62	0.0632	0.00028
xs-7		Gray trachytic volcanic breccia	6.79	4.05	2.25	0.0433	0.00011
xs-8		Breccia rhyolite	11.84	10.49	1.62	0.0224	0.00016
xs-9		Rhyolite	4.39	4.10	0.82	0.0071	0.00009
xs-10		Tuff	6.49	5.49	1.29	0.0649	0.00008
dx-1	Dixi	Greenish gray fluorescent granite porphyry	10.35	3.40	3.26	0.1150	0.00009
dx-2		Brownish gray fluorescent granite porphyry	4.87	2.16	2.47	0.1467	0.00037
dx-3		Greenish gray fluorescent andesite	11.25	11.15	2.06	0.0423	0.00028
dx-4		Greenish gray gas-bearing andesite	11.09	7.32	2.11	0.0418	0.00009
Average	/	/	7.31	5.38	2.22	0.0678	0.00021

Note: Fe: iron element, Mn: manganese element, and Ni: nickel element.

Table 2 shows that Fe content of 14 rock plugs is in the range of 0.82%-3.26%, averaging 2.22%, Mn content is in the range of 0.0071%-0.1150%, averaging 0.0678%, which is 1/33 of Fe content, and Ni content is in the range of 0.00008 %-0.00039%, averaging 0.00021μg·g^{-1}, which is negligible compared with Fe content and Mn content. Therefore, Fe and Mn are the main elements that influence the NMR response characteristics of volcanic gas reservoirs.

Fig.2 is the relationship diagram of the relative error of NMR porosity vs. Fe content and Mn content. It is shown that with the increase of Fe content and Mn content, the relative error of NMR porosity increases greatly. When Fe content is lower than 1% and its corresponding Mn content is lower than 0.02%, the NMR porosity of xs9 rhyolite plug in Table 2 is quite close to the conventional porosity with their error only 0.29%. When Fe content is higher than 2% and its corresponding Mn content is higher than 0.06%, the relative error of NMR porosity increases significantly. Table 2 shows that the average Fe contents of 5 trachyte plugs, 2 trachytic volcanic breccia plugs and 2 granite porphyry plugs with higher the error of NMR porosity is are 2.50%, 2.44% and 2.87%, respectively, and their average Mn contents are 0.8056%, 0.0532.5% and 0.1038% respectively. And the average Fe content of 3 trachyte plugs whose NMR signals are not detected is 2.68%.

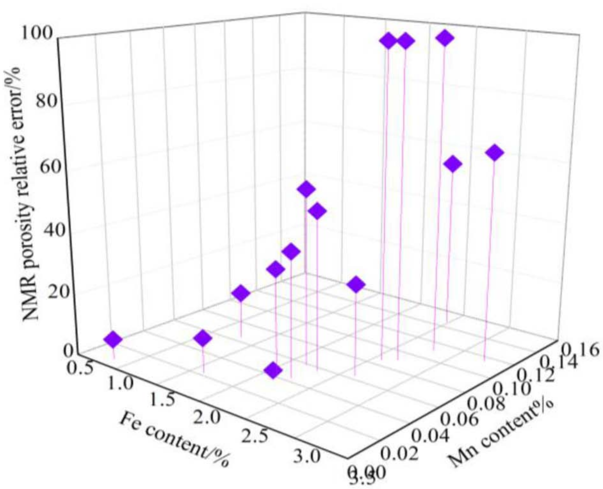

Figure 2—Relationship of the relative error of NMR porosity vs. Fe content and Mn content

The Fe content of volcanic rock plugs is much higher than the Mn content, so Fe content dominates NMR signals. Fig.3 is the relationship diagram of the relative error of NMR porosity vs. Fe content. In Fig.3, cmy, jly, lwy, nhy, hgby and asy represent trachyte, trachytic volcanic breccia, rhyolite, tuff, granite porphyry and andesite, respectively. It is shown that the corresponding relationship between the Fe content and the relative error of NMR porosity of rock plugs with different lithologies is better, and the relative error of NMR porosity increases with the increase of Fe content.

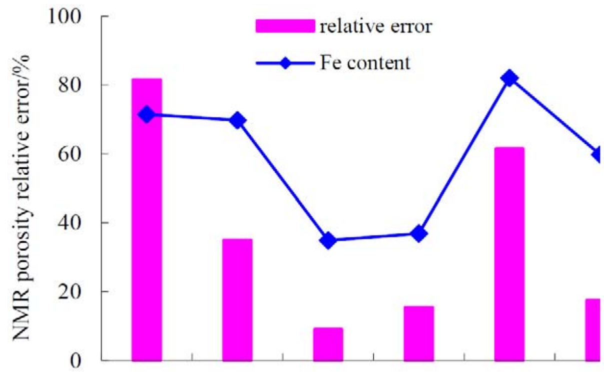

Figure 3—Relationship of the relative error of NMR porosity of rock plugs with different lithologies vs. Fe content

Centrifugal Force Suitable for Calibration of *T*2Cutoff

In order to determine the centrifugal force suitable for the calibration of T2cutoff of low-permeability volcanic gas reservoirs, 30 plugs of low-permeability volcanic rocks with different lithologies from Jilin (13), Daqing (11) and Xinjiang (6) are selected for centrifuge experiments under 6 centrifugal forces. Fig.4 shows the variation of water saturation of 6 plugs after being centrifuged under different centrifugal forces. And Fig.5 shows the NMR T2 spectrum of s1 plug.

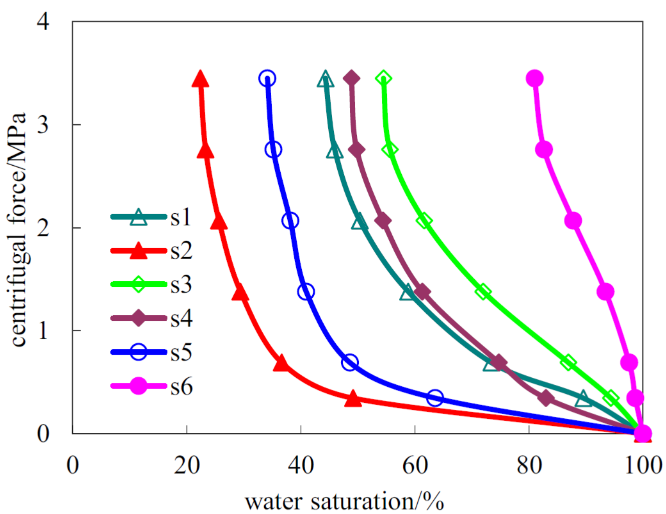

Figure 4—Water saturation of 6 rock plugs after being centrifuged under different centrifugal forces

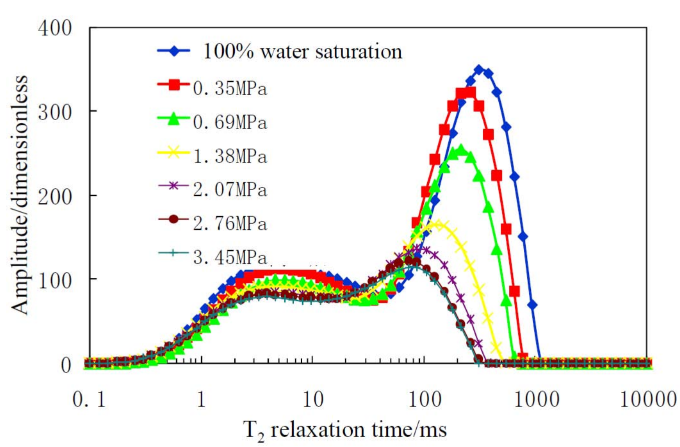

Figure 5—NMR T2 spectrum of s1 rock plug after being centrifuged under different centrifugal forces at brine-saturated state

The following understandings are obtained from Fig.4.

1. When 6 rock plugs are applied with the centrifugal force of 0.69 MPa and 1.38MPa, respectively, more movable water isn't centrifuged out of these 6 rock plugs. When the centrifugal force is increased to 2.76 MPa from 0.69 MPa and 1.38 MPa, respectively, the water saturation of 6 rock plugs drops greatly. It is indicated that neither 0.69 MPa nor 1.38 MPa is the centrifugal force suitable for the calibration of $T_{2cutoff}$ of low-permeability volcanic reservoirs.
2. As for the reservoirs of low-permeability volcanic gas reservoirs in Jilin, Daqing and Xinjiang, the centrifugal force suitable for the calibration of reservoir $T_{2cutoff}$ is 2.76 MPa. Fig.4 shows that the water saturation of 6 rock plugs decreases to a certain extent when the centrifugal force is increased from 2.07 MPa to 2.76 MPa. Calculation results reveal that the water saturation of volcanic rocks in Jilin, Daqing and Xinjiang is decreased by 3.08%, 3.98% and 4.91%, respectively, when the centrifugal force is increased from 2.07 MPa to 2.76 MPa. It is indicated that 2.07 MPa is not the centrifugal force suitable for the calibration of reservoir T2cutoff of low-permeability volcanic gas reservoirs either. When the centrifugal force is increased from 2.76 MPa to 3.45 MPa, however, the decline amplitude of water saturation of 6 rock plugs is quite small and their water saturation is basically constant. Therefore, 2.76 MPa is the centrifugal force suitable for the calibration of reservoir T2cutoff of low-permeability volcanic gas reservoirs in the experimental study.
3. Centrifugal force corresponds to throat radius of rock plug, and the throat radium corresponding to the centrifugal force of 2.76 MPa is about 0.05 μm. Therefore, the lower limit of throat radius for the effective flowing in the reservoirs of low-permeability volcanic gas reservoirs is 0.05 μm.

Variation Characteristics of $T_{2cutoff}$ of volcanic reservoir

The calibration of movable fluid T2cutoff is carried out on 102 rock plugs of low-permeability gas reservoirs based on the suitable centrifugal force of 2.76 MPa which is determined by means of centrifuge experiments, combined with NMR experiments. And the results are shown in Table 3, Fig.6 and Fig.7.

Table 3—$T_{2cutoff}$ value of 102 rock plugs of low-permeability volcanic gas reservoirs

Area	Plug qnty.	φ/%	$K_g/10^{-3}\mu m^2$	$T_{2cutoff}$ distribution range/ms	Average $T_{2cutoff}$ /ms	
					Lithology	Area
Jilin	16 Tuff plugs	4.85	0.03	16.68~86.40	34.44	41.57
	4 rhyolite plugs	6.96	0.06	34.65~124.52	70.06	
Daqing	27 rhyolite plugs	5.98	0.04	8.03~179.46	91.35	65.50
	6 crystal tuff plugs	7.08	0.05	34.65~103.72	61.76	
	2 breccia tuff plugs	3.83	0.02	86.40~71.97	79.18	
	5 melted tuff plugs	5.89	0.01	13.89~86.40	51.25	
	10 tuff breccia plugs	8.05	0.13	3.22~86.40	30.77	
	4 volcanic breccia plugs	8.43	0.24	13.89~86.40	48.72	
Xinjiang	17 granite porphyry plugs	8.56	0.07	4.64~71.97	21.01	18.40
	7 andesite plugs	12.19	0.03	3.87~28.86	12.71	
	4 basalt plugs	16.24	0.03	8.03~34.65	17.25	

Note: φ and K_g are average porosity and average gas logging permeability of rock plugs with the same lithology, respectively.

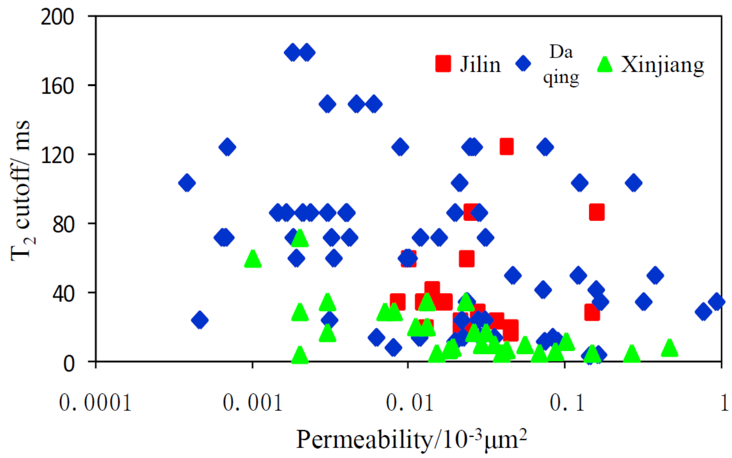

Figure 6—Relationship between $T_{2cutoff}$ value and permeability of low-permeability volcanic rock plugs

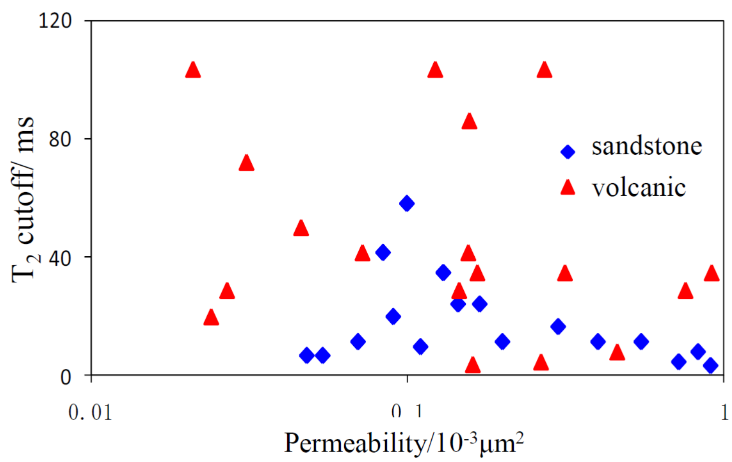

Figure 7—Relationship between $T_{2cutoff}$ value of volcanic rock plug and that of sandstone plug

Table 3 and Fig.6 show that the distribution range of reservoir $T_{2cutoff}$ of low-permeability volcanic gas reservoirs is larger, and $T_{2cutoff}$ of 102 rock plugs is distributed between 3.22 ms and 179.46 ms, averaging 49.31 ms, which is higher than that of sandstone reservoirs but lower than that of carbonate reservoirs. Reservoir $T_{2cutoff}$ of low-permeability volcanic gas reservoirs varies greatly in different areas and for different lithologies. For example, the $T_{2cutoff}$ of 4 Jilin rhyolite plugs is distributed in the range of 34.65 ms-124.52 ms, averaging 70.06 ms, while that of 27 Daqing rhyolite plugs is distributed between 8.03 ms and 179.46ms, averaging 91.35 ms. For the particular lithology in the same area, the $T_{2cutoff}$ distribution range of volcanic rocks diminishes slightly. For example, after the lithology of 27 Daqing rhyolite plugs in Table 3 is subdivided further, the $T_{2cutoff}$ of gray rhyolite, gray pyromeride and grayish green rhyolite is distributed in the range of 41.60 ms-71.97 ms, 59.95 ms-179.46 ms and 49.94 ms, respectively except two tight rock plugs whose $T_{2cutoff}$ value is lower (8.03 ms and 13.89 ms, respectively). After the lithological subdivision of the breccia tuff and the tuff from Jilin in Table 3, the same change laws are also presented.

From the viewpoint of general statistical laws, reservoir $T_{2cutoff}$ of low-permeability volcanic gas reservoirs presents a certain area empirical characteristic, which means T2cutoff is different in different areas. $T_{2cutoff}$ of volcanic reservoirs is ranked as Daqing, Jilin and Xinjiang from the top to the bottom, seeing Table 3. However, its area empirical characteristic is inferior to the statistical $T_{2cutoff}$ of conventional sandstone reservoirs, and the difference of $T_{2cutoff}$ of volcanic reservoirs in different areas is much larger that of low-permeability sandstone reservoirs. For this, the NMR logging interpretation of volcanic reservoirs in different areas shall meet higher requirements. In order to provide the $T_{2cutoff}$ of volcanic reservoirs that is in line with the actual value, therefore, it is necessary to carry out fine experimental study based on the specific reservoir characteristics before the logging, so as to interpret and evaluate the reservoirs of oil and gas reservoirs more accurately.

Application

According to the design, the gas in the hole section of 3901-3926 m in one well of Daqing volcanic gasfield is produced in the mode of flowing, and its initial daily gas production is in the range of (15.16-21.00)×104m3. In order to analyze the reasons for the stable gas production comprehensively, 4 full-diameter cores in the corresponding depth are selected for NMR analysis. The irreducible water saturation and movable fluid saturation of full-diameter cores are calculated still by using the T2cutoff which is centrifugally calibrated by slim cores. Conventional physical property analysis indicates that the conventional porosity of 4 full-diameter cores is in the range of 5.20%-7.26%, averaging 6.17%. The eventual analysis based on laboratory NMR experiments and centrifuge experiments reveals that the irreducible water saturation of 4 full-diameter cores ranges from 19.40% to 45.36%. Mathematical statistics shows that the average value of irreducible water saturation is 32.22% and its corresponding movable fluid saturation averages 67.78%, which is much higher than that of 102 volcanic rock plugs. Therefore, the gas saturation of the corresponding gas reservoir is higher and the gas production of gas well is higher, which is in accordance with the actual production result of this hole section.

Conclusions

1. The studies on 3 typical volcanic gasfields (Xushen, Changling and Dixi) indicate that the paramagnetic mineral content of rhyolite, tuff, rhyolitic agglomerate lava, rhyolitic breccia lava and basalt is lower and their NMR porosity is more accurate, while Fe content and Mn content of trachyte, trachytic volcanic breccia, granite porphyry and andesite are higher, and their NMR porosity is much lower than the conventional porosity.
2. When Fe content and Mn content are lower than 1% and 0.02%, respectively, NMR porosity is in better accordance with the conventional porosity. When Fe content and Mn content are higher than 2.5% and 0.06%, respectively, NMR porosity is much lower than the conventional porosity.
3. It is determined that the centrifugal force suitable for the calibration of reservoir T2cutoff of low-permeability volcanic gas reservoirs is 2.76 MPa, which is also the lower limit of centrifugal force corresponding to movable reservoir fluid, and the lower limit of throat radium for fluid flowing is about 0.05 μm.
4. Average $T_{2cutoff}$ of 102 plugs of low-permeability volcanic rocks from Jilin, Daqing and Xinjiang is 49.31 ms, which is higher than that of sandstone reservoirs but lower than that of carbonate reservoirs. Value and distribution range of $T_{2cutoff}$ of volcanic rocks vary greatly in different areas and for different lithologies, but after lithological subdivision, the distribution range of $T_{2cutoff}$ is decreased slightly. $T_{2cutoff}$ of volcanic rocks is ranked as Daqing, Jilin and Xinjiang from the top to the bottom. Average $T_{2cutoff}$ of Daqing rhyolite is the highest and its distribution range is the largest. And $T_{2cutoff}$ of Xinjiang granite porphyry, basalt and andesite is the lowest.

Acknowledgment

The authors thank PetroChina for permission to publish this paper. The authors also thank PetroChina colleagues LI Haibo for conducting the NMR testing work.

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