Fluid Property Discrimination in Dolostone Reservoirs Using Well Logs

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Abstract: The Ordovician Majiagou Formation is one of the main gas-producing strata in the Ordos Basin, China. The identification of hydrocarbon-bearing intervals via conventional well logs is a challenging task. This study describes the litholog of Ma 5 (Member 5 of Majiagou Formation) dolostones, and then analyzes the responses of various conventional well logs to the presences of natural gas. The lithology of the gas bearing layers is dominantly of the dolomicrite to fine medium crystalline dolomite. Natural gas can be produced from the low resistivity layers, and the dry layers are characterized by high resistivities. Neutron-density crossovers are not sensitive to the presences of natural gas. In addition, there are no significant increases in sonic transit times in natural gas bearing layers. NMR (nuclear magnetic resonance) logs, DSI (Dipole Sonic Imager) logs and borehole image logs (XRMI) are introduced to discriminate the fluid property in Majiagou dolostone reservoirs. The gas bearing intervals have broad NMR \(T_2\) (transverse relaxation time) spectrum with tail distributions as well as large \(T_{2gm}\) (\(T_2\) logarithmic mean values) values, and the \(T_1\) spectrum commonly display polymodal behaviors. In contrast, the dry layers and water layers have low \(T_{2gm}\) values and very narrow \(T_2\) spectrum without tails. The gas bearing layers are characterized by low \(V_p/V_s\) ratios, low Poisson’s ratios and low P-wave impedances, therefore the fluid property can be discriminated using DSI logs, and the interpretation results show good matches with the gas test data. The apparent formation water resistivity (AFWR) spectrum can be derived from XRMI image logs by using the Archie’s formula in the flushed zone. The gas bearing layers have broad apparent formation water resistivity spectrum and tail distributions compared with the dry and water layers, and also the interpretation results from the image logs exhibit good agreement with the gas test data. The fluid property in Majiagou dolostone reservoirs can be discriminated through NMR logs, DSI logs and borehole image logs. This study helps establish a predictable model for fluid property in dolostones, and have implications in dolostone reservoirs with similar geological backgrounds worldwide.

Key words: fluid property, NMR, DSI, image logs, Majiagou Formation, Ordos Basin

1 Introduction

Dolostones are important hydrocarbon producing rocks globally (Warren, 2000; Ehrenberg et al., 2006; Jiang et al., 2016; Pires et al., 2019; Lai et al., 2020a). Numerous studies have conducted on the geologically genetic models and reservoir characterization of dolostones (Wang and Al-Aasm, 2002; Jones and Xiao, 2005; Wilson et al., 2007; Jiang et al., 2018; Tian et al., 2019), however, little study is focused on the fluid property prediction using well logs (Maliva et al., 2009). The Ordovician Majiagou Formation is also an important hydrocarbon producing strata in China (Lai et al., 2019a). Though with huge natural gas reserves, the Majiagou Formation dolostone reservoirs are characterized by low porosity, low permeability and high heterogeneity (Wang and Al-Aasm, 2002; Li et al., 2008; Bai et al., 2016), and the fluid property has little responses to the well logs, making the identification of hydrocarbon-bearing intervals via well logs difficult.

The objectives of this study are to: (1) describe the lithology and analyze the response of various conventional well logs to the presence of natural gas; (2) utilize nuclear magnetic resonance (NMR) logs for fluid typing and investigate the transversal relaxation time \((T_2)\) spectrum of gas bearing layers, water layers and dry layers; (3) evaluate the responses of Dipole Sonic Imager (DSI) logs to the natural gas bearing layers, and the rock elastic mechanics parameters such as \(V_p/V_s\) ratios, Poisson’s ratios and P-wave impedances are used for the fluid property discrimination; (4) derive the apparent formation water resistivity spectrum from XRMI image logs, and investigate the application of the spectrum in identifying water layers and gas bearing layers; (5) verify the interpretation results from NMR, DSI and image logs.
according to well test and production data. The NMR logs, DSI logs and borehole image logs have the advantages in discriminating the fluid property in tight Majiagou carbonate reservoirs. The results are critical for the appraisal and production of the Majiagou carbonates in Ordos Basin, and will have practical applications in similar tight carbonate reservoirs worldwide.

2 Geological Settings

The Ordovician Majiagou Formation is one of the main gas-bearing stratigraphic unit in the Ordos Basin (Wang and Al-Aasm, 2002; Hao et al., 2014; Wu et al., 2017), and abundant natural gas had been produced from this karst-modified dolostones (Wang and Al-Aasm, 2002; Yang et al., 2005). The Ordovician Majiagou Formation, which can be divided into five members (O<sub>1</sub>S<sub>1</sub> to O<sub>1</sub>S<sub>5</sub>, or Ma 1 to Ma 5), was deposited in a carbonate platform environment within several marine transgression and regression cycles (Wang and Al-Aasm, 2002; Liu et al., 2004; Li et al., 2008; Liu et al., 2009). The lithologies of Majiagou Formation are dominated by dolomite interbedded with limestone and evaporate such as gypsum and salt (Wang and Al-Aasm, 2002). The pore systems are dominantly of vugs, intercrystalline pores, intercrystalline dissolution pores and molyd pores (Li et al., 2008; Lai et al., 2019a; Lai et al., 2020b).

3 Data and Methods

Core samples were collected from 32 wells. In the 32 wells used in this study, the conventional geophysical logs include: natural gamma ray (GR), photoelectric absorption cross section index (Pe), spontaneous potential (SP), sonic transit time (AC), bulk density log (DEN), compensated neutron log (CNC), and dual lateral logs (RLLS and RLLD). The NMR downhole logging, DSI and the borehole image logs are classified as new well logging techniques, and they are only collected in 12 wells.

The Halliburton’s Extended Range Micro Imager (XRMI) image logs were run in the studied wells. The XRMI logging tool, which consists of six pads, provides a coverage of 60% in a 8.5-in borehole (Lai et al., 2017a). Each pad of the XRMI logs contains 25 sensor buttons, and a total of 150 resistivity curves can be obtained while logging (Nie et al., 2013). The sensor buttons are spaced 0.2 in. apart on each pad, resulting in a vertical resolution of 5.0 mm and a vertical sample frequency of 2.5 mm (Brekke et al., 2017). Through pre-process such as speed correction, eccentering correction, and normalization, the “pseudo-picture” of borehole wall can be obtained (Lai et al., 2017b). Static and dynamic normalization images can be displayed using two types of color designation. Image logs are commonly used for calibrating core to depth and identifying bed contacts, bed dips and sedimentary structures (Brekke et al., 2017; Lai et al., 2017c).

The DSI logging tools measure compressional (P), shear (S), and Stoneley (St) wave velocities and amplitudes (Assousa and Elkington, 2014; Lai et al., 2017b). The Schlumberger’s Dipole Sonic Imager (DSI) was used to extract the compressional wave velocity or slownesses, shear-wave slownesses (or velocity), Stoneley wave and pseudo-Rayleigh wave slowness. In addition, the main advantage of dipol sonic tool is the possibility of recording DTSX and DTSY and getting S<sub>slow</sub> and S<sub>fast</sub> wave velocities. P, S and Stoneley waves slownesses/velocities can be measured by standard monopole tools (Collett et al., 2011; Zaree et al., 2016; Lai et al., 2017b).

NMR logs exploit the large magnetic moment of hydrogen abundant in rocks in the form of hydrocarbon and water (Golsanami et al., 2014; Jamshidian et al., 2015). The NMR log allows the determination of porosity, pore size distribution, permeability, wettability, viscosity, and fluid properties (Sun and Dunn, 2005; Golsanami et al., 2014). NMR well-logging is widely used for identification of the fluid types present in the reservoir pores and estimation of fluid volumes (Anand, 2017). The Schlumberger’s Combinable Magnetic Resonance Tool (CMR) was used to acquire the NMR data for fluid property discrimination. The CMR logging can also provide information on porosity, pore size distribution and permeability (Dunn et al., 2002; Hu et al., 2012; Hübler, 2014; Tan et al., 2014; Bauer et al., 2015; Olatinsu et al., 2017). The CMR Scanner provides two-dimensional NMR data consisting of the transversal relaxation time ($T_2$) spectrum and diffusion coefficient ($D$) (known as $T_2$-$D$ 2D NMR) (Kleinberg et al., 2005; Liu et al., 2005; Tan et al., 2014; Bauer et al., 2015). The CMR logging technique utilizes the enhanced $T_2$ relaxation rate in a magnetic field gradient to produce a 2D NMR plot where the hydrocarbon and water signals can be clearly separated due to the large contrast between diffusion coefficients of hydrocarbon and water (Sun and Dunn, 2005). The principles and measurements of CMR are described in more detail in Kleinberg et al. (2005).

4 Results

4.1 Lithology and well log expression

Core observations show that the lithology of the Ma 5 member is dominantly of dolomietic to fine to medium crystalline dolomite (Fig. 1a), and gypsiferous dolomite (Fig. 1b). Vugs, which are defined as visible pores that are significantly larger than the adjacent grains, are commonly observed in the silt-sized crystalline dolomite (Yousef et al., 2014; Fig. 1c). However, there are also some vugs filled with mudstones or gypsums (Fig. 1d). Vuggy porosity is one of the most important type of porosity in carbonate rocks, and it significantly affects permeability, pressure drop and hydrocarbon recovery (Yousef et al., 2014; Lai et al., 2019b; Lai et al., 2020b).

As the dominant reservoir type, the mud-sized to silt-sized crystalline dolomite are characterized by low GR readings (< 30 API), low Pe values (< 4.0 b/e), low to medium sonic transit time, medium to high bulk density, medium neutron porosity, and medium to high resistivity values (Fig. 2a). The corresponding image logs of dolomites are characterized by massive, and dark laminations can be observed (Fig. 2a). Conversely, the gypsum-bearing layers are characterized by low GR values, high bulk density (> 2.7 g/cm<sup>3</sup>), and very high resistivity values (> 200 $\Omega$·m) (Fig. 2b). The gypsum-
Fig. 1. Core photos showing the lithologies and pore systems in Ma 5 in the Ordos Basin. (a) Mud-sized to silt-sized crystalline dolomite, Well Tao 27; (b) gypsiferous dolomite, Well Tong 86; (c) vuggy dolomite, Well Jin 8; (d) vugs filled with mudstones or gypsum, Well Tong 86.

Fig. 2. Well-log expression and lithology of the Majiagou Formation at the well X86.
bearing layers are identified as bright bands on image logs due to the high resistivity of gypsums (Fig. 2b). The high GR, high neutron porosity (CNC) but low resistivity layers correspond to the mudstones (Fig. 2).

4.2 Fluid property

As discussed above, in the Ma 5 member of Majiagou Formation, the potential gas bearing reservoirs are very difficult to be identified from the water layers and dry layers. Figure 3 shows the conventional logs of well X345 in Majiagou Formation. The informal stratigraphic unit (Unit G 3989.9–3992 m) is interpreted to be the water layers. In the three intervals of 3971–3973 m, 3975–3977 m, and 3977–3986 m, a very high natural gas production of 225.44×10⁴ m³/d was obtained by well testing (Fig. 3). All of these three layers (Units B, C, E) are interpreted to contain significant amounts of natural gas. In contrast, the Units A, D and F are considered to be dry layers since no natural gas was produced from these layers (Fig. 3).

As can be observed in Fig. 3, the lithology of the gas bearing layer is the mud-sized crystalline dolomite from the core photos (Fig. 3). The water layer has low resistivity values, conversely, the dry layers are characterized by the highest resistivities (Fig. 3). Abundant natural gas can also be produced from the low resistivity layers (3984–3986 m interval), and the presence of natural gas don’t contributes to very high resistivity values (Fig. 3). Therefore it’s difficult to discriminate the gas bearing layers by resistivity logs, and the resistivity is not sensitive to the presence of gas.

The three porosity logs give no significant responses to the occurrences of natural gas. As we know, the three porosity logs (AC, DEN, CNC) are typically expressed in freshwater-saturated units, and the presence of freshwater

<table>
<thead>
<tr>
<th>SP (mv)</th>
<th>DEN (g/cm³)</th>
<th>CNC (%)</th>
<th>AC (μS/m)</th>
<th>RLLS (Ω·m)</th>
<th>RLLD (Ω·m)</th>
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<tr>
<td>-50</td>
<td>2.0</td>
<td>45</td>
<td>300</td>
<td>10</td>
<td>100</td>
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<tr>
<td>50</td>
<td>3.0</td>
<td>-15</td>
<td>100</td>
<td>100</td>
<td>100000</td>
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</tbody>
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Interpretation Results

- A
- B
- C
- D
- E
- F
- G

Silt–sized crystalline dolomite, 3981.51 m

Fig. 3. Conventional logging response of gas bearing layers, water and dry layers in Well X345.
can be evidenced by the equal neutron and density porosities (Ajayi and Torres-Verdin, 2016). The neutron-density crossover, which means the neutron porosity is significantly less than the bulk density porosity, can be used for the discrimination of gas layers (Ajayi and Torres-Verdin, 2016; Pirie et al., 2016). Neutron-density crossovers occur due to effects of the lower hydrogen index of natural gas, which results in a decrease in apparent neutron porosity (Xiao et al., 2012; Ajayi and Torres-Verdin, 2016). However, there are no evident neutron-density crossovers in the gas-bearing intervals as would be expected (Fig. 3). For instance, compared with the water layers, there is no evident decrease of neutron porosity in the gas bearing layers (Fig. 3). In the Layer B (3971.8–3973.1 m), the decrease of bulk density results in an increase of density porosity, and this may result in the neutron-density crossovers, however, the increase of neutron porosity doesn’t contribute to the separation between neutron and density porosity logs (Fig. 3). Additionally, the presence of natural gas doesn’t result in a significant increase in sonic transit times (AC) compared with the water layers. However, the AC values of the gas-bearing layers are commonly larger than those of the dry layers (Fig. 3).

Another example showing the conventional well log responses of the gas bearing layers is presented in Fig. 4. The lithologies of intervals A and B are dominantly of dolomites, which can be recognized by the low GR reading and low-medium resistivity values. The intervals characterized by low GR but high resistivities ad bulk densities mainly correspond to the gypsum bearing layers, and are commonly considered to be dry layers. The high GR but low resistivity layers, which correspond to the mudstones, are interpreted to be the non-reservoir units (Fig. 4). By well testing, the intervals A and B in Fig. 4 have a daily natural gas production of 1640 m³, and a daily water production of 45.0 m³. Natural gas can be produced from the relatively low resistivity layers, and the deep lateral log readings (RLLD) are higher than the shallow lateral logs (RLLS). There are no evident neutron-density crossovers in both of the layers. In addition, the presence of natural gas doesn’t result in a significant increase in sonic transit times compared with the adjacent layers. Therefore, though by using a combination of conventional well logs, to discriminate the natural gas bearing layers is still a challenging task. New logging techniques are encouraged to be used for the fluid property discrimination.

5 Discussion

In this section, the combination of NMR logs, DSI logs as well as borehole image logs (XRMI) is introduced to discriminate the fluid property in Ma 5 member of Majiagou Formation.

5.1 NMR well logs

CMR logging tools used in this study can provide two-dimensional measurements of diffusion (D) and T₂ relaxation time of pore fluids, and the contrasts in D and T₂ spectrum were used for the fluid type differentiation (Anand, 2017).

NMR relaxation data are commonly displayed as a plot of T₂ times (in milliseconds) versus amplitude (Fig. 5) (Maliva et al., 2009). The T₂ spectrum of nuclear magnetic resonance log is shown in the sixth track of Figure 5. The T₂ spectrum are recorded as normalized amplitudes versus logarithmic relaxation time (from 0.3 to 3000 ms), and the higher waveform peaks (green shading) correspond to higher amplitude (D Lubac et al., 2013). The T₂ logarithmic mean values (T₂gm) and the T₂ distribution diagrams are provided in the same track. The T₂ time cut-offs between microporosity (short) and macroporosity (long) are also marked (Fig. 5). The T₂cut-off divides the T₂ spectrum into one component consisting of small pore sizes containing bound water and the other consisting of large pore sizes containing free fluids (Hübner, 2014). By well testing, the intervals B and C in Fig. 5 have a daily natural gas production of 266 m³, and water of 36 m³. The gas-bearing intervals (A, B and C) are characterized by broad T₂ spectrum and large T₂ values (Fig. 5). They commonly have large amounts of T₂ components and large T₂gm values, and there are tail distributions of T₂ larger than 300 ms (Fig. 5), and the T₂ spectrum commonly display poly-modal behaviors. Conversely, the clay-bound and capillary-bound waters, i.e., dry layers (intervals D) have very short T₂ values and narrow T₂ spectrum due to the significant surface interaction with the clay particles (Fig. 5; Anand, 2017), and their corresponding T₂ spectrum commonly display uni-modal or bi-modal behaviors (Fig. 5). Additionally, these layers (3941–3946m interval) have no tails in the T₂ spectrum, and have low T₂gm values. Therefore, the T₂ spectrum of natural gas bearing intervals can be differentiated with the T₂ spectrum of the water layers or dry layers (Fig. 5).

Likewise, the interval D in Fig. 6 has a daily natural gas production of 220 m³, and water of 153 m³ by drill stem testing. It can be observed that natural gas can be produced from the low resistivity layers, and these gas bearing water intervals A, B and D also have a tail distribution of T₂ and relatively large T₂gm values, and the T₂ spectrum display poly-modal behaviors (Fig. 6). Conversely, the dry layers (Layers C and E) have very short T₂ values and very narrow T₂ spectrum with uni-modal or bi-modal behaviors, and they have small T₂gm values (Fig. 6). Therefore, the T₂ spectrum of nuclear magnetic resonance log can be used for discrimination of fluid properties such as gas bearing layers, water layers and dry layers (Figs. 5 and 6).

5.2 DSI well logs

As we know, the presence of natural gas reduces the P-wave velocity but not the S-wave velocity, therefore the Vp/Vs ratio is sensitive to the presence of natural gas, and often used as a qualitative gas indicator (Qi et al., 2017). The zones with low Vp/Vs ratio are commonly interpreted as being gas-saturated (Jia, 2008; Zhang et al., 2015; Qi et al., 2017). P-wave impedances are also assumed to be available for discrimination of the pore fluid property (Russell et al., 2003), and the presences of natural gas reduce the P-wave impedances significantly. The Poisson’s ratio can also be used for a sensitive indicator
Fig. 4. Conventional logging response of gas bearing layers in Well X33.
for natural gas, and the Poisson’s ratio will be reduced significantly due to the presence of natural gas.

The P-wave impedances ($Z_p$) can be computed from the DSI logs using the following Eq.(1). The Poisson’s ratio ($\nu$) can be calculated from the DSI derived compressional- and shear-wave velocities ($V_p$ and $V_s$) through the following relation (Eq.(2), developed by Gassmann (1951) (Collett et al., 2011):

\[ Z_p = \rho V_p \]  \hspace{1cm} (1)

\[ \nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \]  \hspace{1cm} (2)

Where $\nu$ (dimensionless) is the dynamic Poisson’s ratio and $Z_p$ is the P-wave impedances (m·g/cm$^3$·s) (Russell et al., 2003), $\rho$ is the bulk density logs (g/cm$^3$), while $V_p$ is the compressional (P waves) wave velocities (m/s), and $V_s$ is shear wave (S waves) velocities (m/s) (Fjaer et al.,...
Fig. 6. Nuclear magnetic resonance (CMR) $T_2$ distribution curves and conventional logs for gas bearing water layers in Well X367.
If the $V_p/V_s$ ratio and the P-wave impedances in the well profile are scaled conversely, for instance, the $V_p/V_s$ ratio is plotted from small to large, whereas the P-wave impedances were scaled from large to small ranges (Fig. 7), then the $V_p/V_s$ ratios will overlap with the P-wave impedances in the gas bearing layers (Fig. 7), resulting in a crossover similar to the density/neutron crossover. However, the combination of rock elastic mechanics parameters can be more reliable than neutron/density crossover to identify natural gas bearing zones.

In the interval A of 3595 m to 3597 m and interval C of 3516 m to 3618 m in Figure 7, evident crossovers of $V_p/V_s$ ratios and P-wave impedances are observed (Fig. 7), and an initial natural gas production of 205 m$^3$/day was obtained by well testing. In these two gas bearing layers, the Poisson’s ratios are also significantly reduced (Fig. 7). Therefore the gas bearing zones can be discriminated through the reduction of $V_p/V_s$ ratios, Poisson’s ratios and P-wave impedances. The interpreted pore fluid types (i.e., gas-bearing versus water-bearing reservoirs) show a good match with the gas test data. Conversely, in the dry layers...

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![Graph showing crossovers in gas bearing layers](image-url)
such as Interval B (3612.2 m to 3613.5 m), Interval D (3633.7 m to 3636.5 m) and Interval E (3638.6 m to 3640 m), there are no evident crossovers of $V_p/V_s$ ratios and P-wave impedances observed, and additionally the Poisson’s ratios are higher than that of gas bearing layers.

However, it should be noted that the $V_p/V_s$ ratio of the low-permeability reservoir rocks can also be dependent on lithology (Domnesteanu et al., 2002; Jia, 2008; Zhang et al., 2015; Qi et al., 2017). The $V_p/V_s$ ratio can be used to differentiate gas bearing layers. However, the mudstone layers (non-reservoir units) (3609 m to 3611 m interval), which are characterized by high GR readings but low resistivity values, also have low $V_p/V_s$ ratio, low Poisson’s ratio and low P-wave impedances like the gas bearing layers. The mudstone layers have overall lower $V_p/V_s$ ratio than the clean dolomites, as expected, since the mudstone have a lower shear modulus (Qi et al., 2017). Therefore the $V_p/V_s$ ratio is sensitive not only to the fluid property but also to the lithology (Qi et al., 2017). However, we can distinguish the mudstones (nonreservoir units) from the gas bearing layers (reservoir units) based on their conventional log responses (very high GR readings but low resistivity and bulk density values) (Fig. 7).

Figure 8 shows the conventional logs and the rock elastic mechanics parameters ($V_p/V_s$ ratio, Poisson’s ratio and P-wave impedances) calculated from DSI logs in Well X23.
X23. Evident crossovers of $V_p/V_s$ ratios and P-wave impedances are observed in interval A (4103.5 m to 4104.8 m), interval B (4129.6 m to 4132.2 m) and interval C (4133.2 m to 4137.6 m), and they have low Poisson’s ratios. Additionally, it can be concluded from the conventional logs that they are reservoir units (dolomites) since they have low GR readings, low Pe values, low to medium AC, medium to high DEN, and medium to high resistivity values. Therefore, these three intervals are interpreted as gas bearing layers according to the DSI logs (Fig. 7). By gas testing data, the interval A (4103.5 m to 4104.8 m) in Fig. 8 has a daily natural gas production of 1486 m³, and water of 5.6 m³, and this proves that the interpretation results from DSI logs are correct. Some intervals (4107 m to 4110 m) may have crossovers of $V_p/V_s$ ratios and P-wave impedances, however, they are not interpreted as gas bearing layers since they have high GR but low resistivity and density values, and they are considered to be non-reservoir mudstone layers (Fig. 8).

5.3 Image logs

Archie (1942) proposed the well-known Archie’s formula (Eq.(3)–Eq.(4)) for water saturation calculation in clean sandstones.

$$ F = \frac{R_0}{R_w} = a \phi^m $$

(3)

$$ I = \frac{R_i}{R_0} = b S_w^n $$

(4)

$$ S_w^n = \frac{abR_{wa}}{\phi^mR_{t}} $$

(5)

Where $F$ is the formation factor (dimensionless), and $I$ is resistivity index (dimensionless). $S_w$ is the water saturation (fraction), $R_0$ and $R_0$ are the water resistivity and the true formation resistivity ($\Omega\cdot m$), respectively, $\phi$ is the total porosity (fraction), “a” is the tortuosity factor (dimensionless), “b” is the lithology factor, “m” is the cementation exponent; and “n” is the saturation exponent, and its value is affected by pore structure and/or wettability (Archie, 1942; Xiao et al., 2013; Tudge et al., 2014; Adebayo et al., 2015). Archie’s value of “a” and “b” were commonly taken equal to 1 and “n” and “m” were taken equal to 2 (Archie, 1942; Adebayo et al., 2015; Nabawy, 2015; Norbirsath et al., 2015; Xu et al., 2017).

The traditional Archie’s formula can also be used in the flushed zone, and the following Eq.(6) and Eq.(7) can be obtained (Wu et al., 2008; Li et al., 2012).

$$ S_{xo} = \frac{abR_{mf}}{\phi^mR_{xo}} $$

(6)

$$ \phi^mR_{xo} = \frac{abR_{mf}}{S_{xo}^n} $$

(7)

where $S_{xo}$ is the water saturation of the flushed zone (fraction), $R_{xo}$ and $R_{mf}$ are the flushed zone resistivity and the mud filtrate resistivity ($\Omega\cdot m$), respectively (Archie, 1942).

As can be derived from the Archie’s formula, the apparent formation water resistivity can be calculated by the following Eq.(8) (Archie, 1942):

$$ R_{was} = \frac{R_0}{F} = \frac{R_w\phi^m}{a} $$

(8)

where $R_{was}$ is apparent formation water resistivity ($\Omega\cdot m$). This pore water resistivity is actually an “apparent” water resistivity ($R_{wa}$) since it is calculated accurately in water saturated (no hydrocarbons) and clean (shale-free) reservoir-type rocks only (Collett et al., 2011; Fan et al., 2019).

In the XRMI image logs, a total of 150 micro-resistivity curves can be obtained, and the effective detecting depths of image logs are only 5cm, therefore the 150 micro-resistivity curves measured by the imaging tool are correctable to the resistivity of the flushed zones ($R_{xo}$ or RLLS) (Li et al., 2012).

If the 150 resistivity channels from the image logs are used for the apparent formation water resistivity, then a set of 150 apparent formation water resistivity curves can be obtained. The calculated apparent formation water resistivity based on the image logs can be written as (Eq. (9)):

$$ R_{was} = \frac{R}{F} = \frac{R_w\phi^m}{a} $$

(9)

where $R_i$ is ith (i=1, 2, 3, … , 150) resistivity curves of image logs, $R_{wa}$ is ith apparent formation water resistivity ($\Omega\cdot m$) calculated from the image logs.

In the Eq.(9), the parameters of “m” and “a” can be fixed values, and the porosity (\( \phi \)) can be derived from the three porosity logs (AC, CNC and DEN) (Ping et al., 2014; Bai et al., 2016). For carbonates with good to average porosity (dolostone and limestone), “m” and “a” are generally taken to be 2.0 and 1.0 (Kamel and Mabrouk, 2002). Therefore, for a sliding window in the image logs, a total of 150 apparent formation water resistivity values can be calculated. Suppose the horizontal axis is the $R_{wa}$ value (\( \Omega \cdot m \)), whereas the y-coordinate is the frequency of $R_{wa}$, then a histogram of apparent formation water resistivity distribution, i.e., the apparent formation water resistivity spectrum can be obtained (Fig. 9; Wu et al., 2008; Li et al., 2012; Ping, 2014; Bai et al., 2016). The water layers commonly have relatively low $R_{wa}$ values and very narrow apparent formation water resistivity distribution (Fig. 9a), in contrast, the gas bearing layers are characterized very broad apparent formation water resistivity spectrum (Fig. 9b) (Xiao et al., 2015).

The actual apparent formation water resistivity spectrum derived from the image logs is presented in Fig. 10 and Fig. 11 (the sixth track). Interval A (3397 m to 3399.2 m) in Fig. 10 is a typical gas bearing unit, and the corresponding apparent formation water resistivity spectrum is characterized by a broad distribution, and
evident tail distributions can be observed. The related image logs (static and dynamic) are presented in the seventh track, and vugs, which are recognized as dark spot in the image log, can be observed in this gas bearing layers (Fig. 10). In contrast, Interval B (3412 m to 3414.4 m) in Fig. 10 is a typical dry layer, and the corresponding apparent formation water resistivity spectrum is narrow without tail distribution (Fig. 10). Bright bands interbedded with dark bands are observed on the corresponding image logs, but no evident vugs can be observed (Fig. 10).

The apparent formation water resistivity spectrum of
intervals A and B in Fig. 11 are broad with tail distribution compared with the adjacent layers, and they are interpreted to be gas bearing layers according to the apparent formation water resistivity spectrum (Fig. 11). The image logs of these two layers have abundant dark spots, which are related with the vugs. As discussed above, the vuggy porosity is important reservoir space in Majiagou carbonate rocks, and the development of vugs makes the two layers to be good potential gas reservoirs. By gas testing, the two intervals in A and B Fig. 11 have a daily natural gas production of 430 m$^3$, which is in accordance with the interpretation results from image logs. In contrast, the adjacent layers, which have narrow apparent formation water resistivity spectrum, are all dry or water layers according to gas test data (Fig. 11). The interpretation results of image logs exhibit good agreement with gas test data. Therefore the gas bearing layers can be discriminated through the apparent formation water resistivity spectrum derived from image logs.

6 Conclusions

The lithology of the Majiagou Formation Ma 5 member is dominantly of dolomicrite to fine to medium crystalline dolomite, and vugs are important reservoir spaces. The crystalline dolomite, which is the main gas bearing units, are characterized by low GR, low $Pe$, low to medium AC values, medium to high bulk density, and medium to high resistivity values. Natural gas can be produced from low resistivity layers, and the dry layers are characterized by the highest resistivities. Discriminating the gas bearing layers from water layer or dry layers via conventional well logs is difficult due to the poor reservoir quality. NMR logs, DSI logs as well as borehole image logs (XRMI) are used to discriminate the fluid property.

The gas-bearing intervals are characterized by broad NMR $T_2$ spectrum with tail distributions and have large $T_{2gm}$ values, and the $T_2$ spectrum commonly display poly-modal behaviors. Conversely, the dry layers have low $T_{2gm}$ values and very narrow $T_2$ spectrum. By using DSI logs,
the gas bearing layers can be discriminated through the reduction of $\frac{V_p}{V_s}$ ratios, Poisson’s ratios and P-wave impedances, and the interpretation results show good matches with the gas test data. By applying the Archie’s formula, the apparent formation water resistivity spectrum can be derived from the 150 resistivity curves from image logs. The apparent formation water resistivity spectrum of gas bearing layers are broad with tail distribution compared with the dry and water layers, and the interpretation results of image logs exhibit good agreement with the gas test data. The fluid property in Majiagou carbonate reservoirs can be discriminated through NMR logs, DSI logs and borehole image logs.

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