Development and Practice Development and Practice of Comprehensive Water Control Technology for Volcanic Bottom Water Gas Reservoir in Xushen Gas Field

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Abstract. Xushen gas field mainly exploits volcanic reservoirs of Yingcheng Formation. The gas reservoir type is mainly the bottom water gas reservoir. The number of water wells and water production are increasing year by year, which affects the development effect of the gas field. In view of the increasingly severe situation of water invasion and water production in gas fields, water invasion evaluation and comprehensive water control of gas reservoirs have been carried out, and a three-level evaluation process of water invasion qualitative identification, water invasion quantitative evaluation and water invasion impact quantitative evaluation has been formed. Based on the results of water invasion evaluation, combined with the characteristics of gas reservoir connectivity, structure, gas-water distribution, and water production, the three-level evaluation process has been formed. The integrated water control mode of the block (volcanic body) and single well water control mode by classification have been applied in each block, and good results have been achieved, which effectively supports the rational development and long-term stable production of bottom water gas reservoirs in Xushen gas field.

Keywords: Xushen gas field; volcanic bottom water gas reservoir; water invasion evaluation; comprehensive water control; water control technology.

1. Introduction
The development practice of the bottom water gas reservoir in China shows that the development strategy is not appropriate and the water will invade the gas reservoir unevenly, which will result in the gas production capacity decreased greatly and the final recovery rate of the gas reservoir reduced. Xu deep field volcanic rock gas reservoir types is given priority to with water drive, has the overall development of six blocks are showed different degrees of water drive characteristic, at present, a total of 52 tone well layer water origin, accounted for more than 40% of the total number of wells, the number of Wells and water rate is rising year by year, affecting the effects of gas well recovery and gas field development, therefore, how to evaluate the gas reservoir water invasion index and how to take appropriate development countermeasure for volcanic rock bottom water reservoir is xu deep gas field the efficient development of the key.
2. Reservoir geology and development characteristics of Xushen gas field

2.1. Gas field structure and reservoir characteristics

Xujiaweizi fault depression is a dustpan fault depression, mainly developed in the west of Xujiaweizi fault, the fault in the middle of Xujiaweizi and Xudonghua fault zone. The volcanic rock facies controlled by the large basement fault is distributed in a strip, and the gas reservoirs are enriched along the three major fault zones: middle of Xujiaweizi, east of Xujiaweizi, and west of Xujiaweizi. In the Xushen gas field, Denglugu sandstone, Yingcheng volcanic rock and conglomerate, and Shahezi formation tight conglomerate reservoirs are developed vertically from top to bottom. Currently, the main reservoirs of Yingcheng formation are mainly volcanic rock reservoirs of Yingcheng formation, volcanic rock reservoirs of Yingcheng formation, volcanic rock reservoirs of Yingcheng formation and conglomerate reservoirs of Yingcheng formation. Field distribution is large area of volcanic rocks, the top layer gas reservoir with a multiphase eruption source outbreak and overflow phase superimposed, clip a small volcano channels phase, a discontinuous distribution of volcanic rock gas reservoir gas-bearing area formed by multiphase volcanic eruption multiple volcanic rock composition, main monophyletic monomer, monophyletic multi-body, no obvious source of volcanic institutions and multi-source monomer four "volcanic mechanism model", give priority to with monophyletic monomer or monophyletic multi-body, basic is not connected with each other, controlled by the dual factors of structure and lithology reservoir, on the overall performance of gas water features. Change of reservoir physical property and thickness, and smaller type reservoir, with II, III reservoir is given priority, in the plane of each wellblock favorable reservoir distribution differences. The reservoir is characterized by low porosity, low permeability, density, heterogeneity and discontinuity. The depth is between 2,700 ~ 4,000m, the porosity is mainly between 2 ~ 10%, the permeability is mainly between 0.01 ~ 1×10⁻³ m², and the average pressure coefficient is 1.07 [1].

2.2. Gas field development characteristics

Xu deep gas reservoir types are mainly lithologic - structural reservoir with edge bottom water, have the overall development of six blocks are showed different degrees of water drive characteristic, the Wells are mostly located in the lower gas reservoir and structure of edge location, part of the well water rate is higher, including 1 M - and better H8 block reservoir connectivity, with roughly uniform gas-water contact, K1, W1, Y9, multiple volcanic F21 block development and multiple sets of air-water system, part of the fire mountain superimposed each other, no unified gas-water contact, the distribution of gas reservoir and water controlled by fire mountain, mutually connected between the volcanic rock mass (table 1). On the whole, the pressure and productivity of gas Wells decrease rapidly in the initial stage and gradually slow down in the later stage. The formation pressure of single Wells in the block drops unevenly and the pressure of some Wells drops synchronously. The productivity and reserves of single Wells vary greatly. Through development and deployment, rolling edge expansion and comprehensive adjustment, the output of the Xushen gas field has steadily increased, reaching 10×10⁸m³ in 2012 and 18.5×10⁸m³ in 2018.

| Block | Types of gas reservoirs | Characteristics of Gas-water distribution |
|-------|------------------------|------------------------------------------|
| K1    | Weak water drive       | There is no uniform gas-water interface   |
| H8    | Medium water drive     | There is a roughly uniform gas-water interface |
| Y9    | Medium water drive     | There is no uniform gas-water interface   |
| F21   | Medium water drive     | There is a roughly uniform gas-water interface |
| M-1   | Strong water drive     | There is no uniform gas-water interface   |
| W1    | Strong water drive     | There is no uniform gas-water interface   |
3. Development and application of comprehensive water control technology in the bottom water reservoir

3.1. Development and application of water intrusion evaluation technology in the bottom water reservoir

At present, a total of 123 gas Wells have been put into production in Xushen gas field, among which 52 are producing beds of water, accounting for 42% of the total Wells. The water-gas ratio has increased from 0.41m$^3$/10$^4$m$^3$ in 2010 to 0.73m$^3$/10$^4$m$^3$ in 2018. Therefore, it is necessary to carry out the evaluation of gas reservoir water invasion and implement comprehensive water control to ensure the reasonable and effective development of a gas reservoir.

Water invasion evaluation is mainly divided into three parts: water invasion identification, water invasion quantitative evaluation and water invasion impact quantitative evaluation. Water intrusion identification includes gas reservoir water intrusion identification and gas well outlet water identification. The methods of gas reservoir water intrusion identification are mainly based on the pressure drop method, apparent geological reserve method, and water intrusion volume coefficient method. Generally, when the pressure drop curve is upward, it reflects that the gas reservoir is characterized by a water drive. However, when most of the water channeling and intruding water are produced, the pressure drop curve may also be linear. Therefore, two other methods should be combined to judge. The method of gas well outlet water identification is mainly based on the water-gas ratio of production and water quality (chlorine root and salinity).

Water invasion of quantitative evaluation including water body size and water influx, the scale of water evaluation is the key to the quantitative evaluation of water invasion and difficulties, previous water scale evaluation mainly adopts the static method, and practical with the development of gas reservoir, pressure wave gradually expand outward, participate in natural waters flow scope expands unceasingly, volume of its waters increases constantly too, when pressure drop across the natural waters, participation is fixed, the flow of natural waters of water body size is the natural waters. It is difficult to accurately determine the range of water body by using the static method to evaluate the water body size, which can not reflect the actual water body size influencing the gas reservoir.

According to the relationship between the volume of underground natural gas and the volume of water, a dynamic evaluation method for the water scale of edge and bottom water reservoirs is established by solving the material balance equation.

Water intrusion is the volume change of the water body after pressure change.

$$ W_e = V_{pw} (C_u + C_p) \Delta P $$

The size of the water body is reflected by water body multiple n, which is the ratio of water body volume to the pore volume of the gas area (including free gas and bound water)

$$ n = \frac{V_{pw}}{G_{gi} / (1-S_{wi})} $$

Substitute (1) and (2) into the material balance equation of the water drive gas reservoir

$$ G_p B_g + W_p B_w = G (B_g - B_{gi}) + W_e + G B_{gi} \left( \frac{C_u S_{wi} + C_p}{1-S_{wi}} \right) \Delta P $$

Compact transformation

$$ \frac{W_p B_w}{GB_{gi}} \left( 1 - \frac{G_p}{G} \right) \frac{P}{Z} = \left( n \frac{C_u + C_p}{1-S_{wi}} + \frac{C_u S_{wi} + C_p}{1-S_{wi}} \right) \Delta P $$

Take the left side of formula (4) as the Y-axis, delta P as the X-axis as the curve, the curve tends to a straight line with slope k, and then use formula (5) to calculate the n value, so as to deduce the water multiple and water scale of the gas reservoir.
Taking block m-1 as an example, the calculated water volume is \(7.98 \times 10^8 \text{m}^3\), 14.5 times the underground volume of natural gas, which is equivalent to the simulated water volume of \(8.09 \times 10^8 \text{m}^3\). The difference between the two methods is only 1.36%. However, the water volume of the M-1 block calculated by the static method is \(6.86 \times 10^8 \text{m}^3\), which is quite different from that calculated by the dynamic method. Since the water scale evaluated by the static method is difficult to accurately determine the water range, the water volume calculated by the dynamic method is more objective and accurate and can reflect the dynamic changes of the gas reservoir affected by the edge and bottom water in real-time (Table 2).

**Fig. 1** Water body analysis curve of block M-1

**Table 2.** Comparison of evaluation methods for water body scale in M-1 block

| Methods                        | Static method | Numerical simulation | Water curve analysis |
|--------------------------------|---------------|----------------------|----------------------|
| Size of water body (108m³)     | 6.86          | 8.09                 | 7.98                 |
| The advantages and disadvantages | Strong subjectivity, great uncertainty | The calculation is accurate and the application is limited | Strong applicability and constraint, accurate calculation |

\[ n = \left[ k (1 - S_w) - \left( C_w S_w + C_p \right) / \left( C_w + C_p \right) \right] \]  

\( G \)—Original geological reserves of gas reservoirs, \(10^8 \text{m}^3\);  
\( G_p \)—Cumulative gas production, \(10^8 \text{m}^3\);  
\( V_{pw} \)—Gas reservoir water volume, \(10^8 \text{m}^3\);  
\( W_p \)—Cumulative water production, \(10^8 \text{m}^3\);  
\( W_e \)—Water influx, \(10^8 \text{m}^3\);  
\( C_w \)—Formation of water compression factor, MPa\(^{-1}\);  
\( C_p \)—Rock compressibility, MPa\(^{-1}\);  
\( P_i \)—Initial formation pressure, MPa;  
\( P \)—Current formation pressure, MPa;  
\( \Delta P \)—Difference between original formation pressure and current formation pressure, MPa;  
\( Z \)—Z-factor of primordial gas;  
\( Z \)—Z-factor of Current gas;  
\( B_{gi} \)—Gas original volume factor;  
\( B_g \)—Gas current volume factor;  
\( B_w \)—Formation water volume coefficient;  
\( S_{wi} \)—Bound water saturation, %;  
\( G_p \)—cumulative production, \(10^8 \text{m}^3\);  
\( n \)—Water body multiple.
According to the calculated results of the water scale above, the water intrusion can be obtained by using the relationship between water volume and water intrusion, namely formula (1). PVT equation of state method, water invasion volume coefficient method and apparent geological reserve method can also be used to evaluate water invasion.

Water invasion impact quantitative evaluation is mainly affected by water invasion degree and the results of the gas reservoir, mainly include the replacement water invasion coefficient, water drive index, lifting height and volume of water invasion coefficient gas-water contact, substitution of water invasion coefficient and water drive index values reflect the greater the intensity of water activity and water flooding, the greater the gas reservoirs are influenced by water, the greater the gas reservoir recovery efficiency is, the smaller (table 3).

The formula for calculating the water invasion replacement coefficient
\[ I = \frac{\omega}{R} = \frac{W_e - W_p B_w}{G_p B_g} \] (6)

The formula for calculating water drive index:
\[ WEDI = \frac{W_e}{G_p B_g + W_p B_w} \] (7)

I—Water intrusion replacement factor, Dimensionless;
ω—Water Invasion Volume Coefficient;
R—Extraction degree, %;
WEDI—water drive index, Dimensionless.

| Classification indexes | Water invasion substitution coefficient I | Water drive index (WEDI) |
|------------------------|------------------------------------------|--------------------------|
|                        | The activity of formation of water        | Water invasion substitution coefficient | Recovery range values | Classification by energy | Water drive index |
| I Water drive           | Ia (Active)                              | \(\geq 0.4\)              | 0.4~0.6               | Weak water drive         | <0.1               |
|                        | Ib (Sub-active)                          | 0.15\(\leq I<0.4\)       | 0.6~0.8               | Medium water drive       | 0.1< WEDI<0.3      |
|                        | Ic (inactive)                            | 0<\(I<0.15\)             | 0.7~0.9               | Strong water drive       | \(\geq 0.3\)       |
| II Gas drive            | 0                                        | 0                         | 0.7~0.9               |                          | 0                  |

The formula for calculation of gas-water interface uplift
\[ H = \frac{W_e - W_p B_w}{A\Phi(1 - S_w - S_{gr})} \] (8)

H—Air-water interface elevation, m;
A—Gas reservoir area, m2;
Φ—Porosity, %;
Sgr—Residual gas saturation.

The formula for calculating water invasion volume coefficient
\[ \omega = \frac{W_e - W_p B_w}{G_b g} \] (9)
Taking block M-1 as an example, various water invasion indicators (table 4) are calculated to provide a basis for block water control.

**Table 4. Evaluation results of water invasion in M-1 block**

| Types of the gas reservoir                                      | Strong water drive and active bottom water reservoir |
|----------------------------------------------------------------|--------------------------------------------------------|
| Multiple of the water body                                     | 14.5                                                   |
| Water influx (104m³)                                            | 604                                                    |
| Water invasion substitution coefficient                         | 0.38                                                   |
| Water drive index                                              | 0.4                                                    |
| Water intrusion volume coefficient (%)                         | 10.7                                                   |
| Elevation of Gas-water interface (m)                           | 8.8                                                    |

The volcanic rock accumulation in the Xushen gas field is controlled by the structure and volcanic rock mass, and the connectivity between different blocks, volcanic rock mass and gas wells and the distribution of gas and water are quite different. For example, Shengshen 2-1 and Xushen 8 blocks have good connectivity, a relatively unified gas-water interface, the pressure keeps dropping synchronously, and the block is taken as the unit for an overall evaluation. The gas-water relationship in blocks K1, W1, Y9 and F21 is complex, and multiple gas-water systems are developed. There is no uniform gas-water interface, and the gas-water distribution is controlled by volcanic mountains. Different volcanic rocks are disconnected from each other, and the connectivity between wells is poor. To review and summarize finally passed, formed the water invasion qualitative identification and quantitative evaluation and water invasion influence evaluation of three-level evaluation process (figure 2), according to the gas reservoir connectivity and water distribution characteristics, the implementation of overall classification evaluation and single well block, could invoke a systematic and comprehensive evaluation process, provide effective theoretical guidance and basis for comprehensive harnessing of gas reservoir.

**Figure 2. Flow chart of water invasion evaluation technology for bottom water gas reservoir in Xushen gas field**

The evaluation results of water invasion in each block of Xushen gas field show that m-1 and W1 (W101 volcanic rock mass) are strongly water-driven gas reservoirs with relatively active water bodies, while other blocks are dominated by the medium-water drive and sub-active gas reservoirs (Table 5).
Table 5. Evaluation of Water Infiltration Indicators in Blocks of Xushen Gas Field

| Types                      | Blocks | Multiple of the water body | Waterflood index | Water intrusion replacement factor | Type of Water drive gas reservoir |
|---------------------------|--------|----------------------------|------------------|------------------------------------|----------------------------------|
| Block overall evaluation  |        |                            |                  |                                    |                                  |
| M-1                       | 14.5   | 0.35                       | 0.38             | Strong water flooding and sub-active |
| H8                        | 4.3    | 0.24                       | 0.24             | Reclaimed water and secondary active |
| Single well classification evaluation |        |                            |                  |                                    |                                  |
| K1                        | 0-5.1  | 0-0.16                     | 0-0.16           | Air drive or weak water drive, not active |
| W1(W101 Volcanic body)    | 0-41.4 | 0-0.63                     | 0-0.61           | Strong water drive and sub-active mainly |
| Y9                        | 0-8.84 | 0.05-0.35                  | 0.04-0.36        | To water flooding and secondary active mainly |
| F21                       | 1.6-16.9 | 0.08-0.38                | 0.03-0.37        | To water flooding and secondary active mainly |

3.2. Development and application of water control technology in subaqueous volcanic gas reservoirs

On the basis of the evaluation results of the whole block and the single well-classified water intrusion, combined with the gas reservoir connectivity, structure, gas-water distribution, and water production characteristics, the integrated (or volcanic rock) and the single well-classified water control countermeasures were established to implement the classified water control of one kind and one method. Connectivity for good conduct points well group gas reservoir, water conservancy, edge is strong, the overall harnessing of water control in central or in volcanic rock, edge is strong, central control pressure overall harnessing countermeasures, through a strong line of effective control of edge and bottom water invasion to central China, the central water control effectively delay the bottom water coning, so as to realize the overall rank balance. For the gas reservoirs with poor connectivity, water control by single good classification and combined with drainage control can prolong the period of anhydrous gas recovery as far as possible and effectively improve the recovery rate of gas reservoirs. It has formed the idea of classification and treatment, low discharge and high control, a combination of control and discharge, and gas and water extraction.

Figure 3. Water control countermeasures for gas reservoirs in Xushen gas field

The overall water conservancy, M - 1, for example, according to the block for strong water drive, the large and active edge water energy of bottom water reservoir, good connectivity between the Wells, reserves producing degree is high, a large amount of water invasion, producing Wells in gas reservoir
characteristics of tectonic edge, could be divided into three blocks well group, according to the characters of each well group gas well production characteristics and water formulated the "control, belt, line" with the combination of the overall water conservancy development countermeasure [6-12].

Table 6. M-1 Gas Well Production and Water Control Measures

| Well group | Type of water breakthrough | Well number | Reasonable production (10^4 m^3/d) | Water production (m^3/d) | Development countermeasures |
|------------|----------------------------|-------------|------------------------------------|--------------------------|-----------------------------|
| In the north | Porous weak water cone | M-5 | 2.0 | 2.2 | Gas production with water |
| | Crack-type weak water channeling | M-6 | 2.0 | 22.0 | Gas production with water |
| | Crack-type strong water channeling | M-7 | 0.8 | 8.2 | Connected gas lift drainage |
| | Porous weak water cone | M-P1 | 12.0 | 2.1 | Water Controlled Gas Production |
| | | M-G2-1 | 15.0 | 2.1 | |
| In the middle | Porous effluent | M-12 | 7.0 | 2.4 | Gas production with water |
| | | M-17 | 10.0 | 1.3 | Water Controlled Gas Production |
| | | M-19 | 9.0 | 1.4 | |
| | | M-21 | 11.0 | 1.3 | |
| | | MG2 | 7.0 | 1.3 | |
| In the south | Porous strong water cone | M-25 | 6.0 | 1.3 | Water Controlled Gas Production |
| | | M202 | 5.0 | 3.6 | Gas production with water |
| | | M201 | | | Monitoring well |

W1 blocks development of multiple fire mountain, plane is relatively dispersed, reservoir continuity is poorer, and the gas Wells in the same volcanic rock gas water interface is relatively uniform, according to the characteristics of volcanic rock body W101 as unit to carry out the whole water conservancy, volcanic rock edge active drainage and water, maintain high gas pressure, reducing the speed of edge and bottom water coning (Table 7).

Table 7. Gas Well Exploitation Strategy of Volcanic Body W101 in Block W1

| NO | Type | Tectonic location | Well number | Rational allocation (10^4 m^3/d) | Nissan water (m^3) | Development countermeasures |
|----|------|-------------------|-------------|---------------------------------|-------------------|-----------------------------|
| 1  | Unspent well | Middle | W-P1 | 5 | 0.5 | Water Controlled Gas Production |
| 2  | | | W-P5 | 9 | 2.5 |
| 3  | Discharging well | Middle | W1 | 0.06 | | |
| 4  | | Edge | W1-3 | 0.5 | 18 | Gas production with water |
| 5  | | Middle | W401 | 4 | 41 |
| 6  | | Edge | W1-P3 | 7 | 82 |
| 7  | | Edge | W101 | 3 | 86 | Connected gas lift drainage |

M - 1 M - 7 W1 and the block of W101 Wells in gas reservoirs (volcanic rock) structure side, the water rate is higher, to block the overall water conservancy, slow speed in the direction of central edge-bottom water, respectively in 2015 and 2017, to carry out the interconnection gas-lift drainage test, as of the end of July 2019, two Wells increased 1171 x 104 m^3, gas accumulated more drainage 4.65 x 104
m₃, the gas and relieve edge-bottom water effect in the direction of gas reservoir in central. Since the implementation of the overall water control in the M-1 block, the water yield, water gas ratio, and water invasion situation have remained stable, no new Wells has been added for 8 consecutive years, and the daily and annual production have remained stable for 11 years above 100×10⁴m₃ and 2×10⁸m₃, respectively.

According to the energy and activity of the water body of the gas reservoir, combined with the characteristics of gas well type and water production, a targeted single-well classification water control strategy was established (Table 8). For low-yielding Wells, the methods of reasonable production distribution, regulating production and carrying fluid, and injecting foam and drainage agent are mainly adopted to prevent and eliminate wellbore effusion, while for medium-high yield Wells, the methods of water-based gas extraction or drainage gas extraction are mainly adopted.

| Classification       | Outlet type               | Water outlet mechanism and characteristics                              | Water control measures                                         | Representative Well |
|----------------------|---------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------|--------------------|
| High production well | Early and middle effluent | Water flow in cracks or strong water cones in pores, large water production | Implement drainage gas extraction or gas extraction with water   | Y9-5               |
|                      | Significant effluent hazard | Fracture development, water production in the middle and late stages of mining | Decide on waste or drainage according to the degree of extraction and process costs |                    |
| Vertical Wells        | Early and mid-term water output | Mostly located on the side, the effect is obvious after water out | Prevent wellbore fluid accumulation, stabilize gas and water control, and moderately control gas well production | K6-204             |
| Low production well   | A small amount of effluent in early and middle hazards | The water body is small, cracks are not developed, and influence is small | Prevent and eliminate wellbore fluids                           | K1-205             |
|                      | Late effluent small non-hazardous | The cracks are not developed and the impact is small                    |                                                                  | K6-108             |
| Horizontal well       | Early and middle effluent | Gas well pressure and production decline after water production        | Maintain continuous gas production with water or drainage        | F21-P1             |
| Low production well   | Controllable water output in the middle and late period |                                                                  | Water control and gas production, stable production, and prevent large quantities of water | Y9-P2              |

4. Cognition and conclusion

(1) By summarizing the water invasion evaluation method, a three-level evaluation process of water intrusion identification, water invasion quantification evaluation, and water invasion impact quantification evaluation was formed. (Wangshen 101 volcanic rock body) is a strong water flooding gas reservoir, and the water body is more active. The remaining blocks are mainly medium water flooding and sub-active gas reservoirs.

(2) Based on the evaluation results of water invasion, combined with the gas reservoir connectivity, volcanic body, and gas-water distribution characteristics, the overall gas reservoir (or volcanic rock body) water treatment or single well classification water treatment was carried out. In M-1, W1, H8 and other areas. The overall effect of water treatment has been improved.
(3) The implementation of comprehensive water treatment technology for the bottom water and gas reservoirs in the Xushen gas field effectively guarantees the rational and efficient development of bottom water and gas reservoirs in the Xushen gas field.

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