Characteristics of Volcanic Gas Reservoir and Practices of Development Technologies in Xushen Gas Field

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Abstract Xushen Gas Field, located in Daqing, Heilongjiang, China, is mainly a volcanic gas reservoir whose reserve accounts for 88% of the total reserve. The major pay zones are Cretaceous Yingcheng I and III Formation, whose main lithologies are acidic eruption rocks. The reservoir is in low porosity and permeability which is distributed complexly. What's more, the productivity for single well is usually low which causes big challenges for economic and effective development. In this work, based on the research on the gas reservoir characteristics and dynamic performances of the gas field, it can be found that the lithologies and lithofacies are complex varying quickly in lateral and vertical direction and the reservoir space is mainly composed of pores with some fractures and the heterogeneity is strong. It also can be found that the reservoir can be classified as four types, and the reservoir is controlled by geological structure and lithologies with complex gas-water relationships. Furthermore, the productivity for single well differs very much with uneven lateral distribution, and the well-control reserve differs greatly with complex types of watering out. With the application of horizontal wells, it provides the technical support for large scale and effective development, which may be a reference for other similar gas reservoirs.

Key words volcanic gas reservoir, geological characteristics, dynamic performances, development technologies

1 Geological Characteristics

The geological characteristics of the volcanic gas reservoir can be understood from the identification of lithologies, identification and prediction of lithofacies, evaluation of the reservoir storage-seepage characteristics, reservoir fracture characterization and prediction as well as reservoir classification and prediction by applying geology, logging, seismic and well testing technologies to analyze the main blocks in Xushen Gas Field [1][2][3].

1.1 Lithologies and Lithofacies

The lithofacies of the major pay zones in the volcanic gas reservoir are mainly composed of proximal eruptive and effusive facies with little volcanic conduit facies, which are distributed discontinuously. The lithologies are mainly rhyolite and rhyolitic crystal (welded) tuff.

The lithofacies in Xushen Gas Field can be classified as 5 types roughly and further classified as 15 types of subfacies. And the lithologies contain two major types, 8 subtypes and 17 definite types. There are 9 periods of thermal fluid activities according to the statistics of the average temperature of 455 inclusions (Fig.1). It also can be found that the age of lava's eruption is between 110Ma and 115Ma based on the results of dating of 120 zircons. From the statistics of elemental analysis of 30 wells, it shows trough for high field strength elements and rare elements, which reflect a strong crystal differentiation of plagioclase before lava's eruption with intraplate forming environment, which is a result of mixing action of the earth's crust and mantle (Fig.2). Further, it also can be found that the reservoir is mainly distributed in gas-pore rhyolite with upper subfacies in proximal effusive facies, rhyolitic crystal (welded) tuff with hot pyroclastic flow subfacies in eruptive facies, and breccia with cryptoexplosive breccia subfacies in volcanic conduit facies.

The research result indicates that the scale for different facies differs greatly according to the characterization of seismic facies. For the largest scale of effusive facies, its thickness varies from 200m to 400m with lateral extension from 6000m to 7000m. For the largest scale of eruptive facies, its thickness varies from 100m to 200m with lateral extension from 4000m to 6000m. The favorable reservoir facies are upper subfacies in effusive facies and hot pyroclastic flow subfacies in eruptive facies with lateral extension from 200m to 800m and vertical extension from 2m to 60m (Fig3).

1.2 Reservoir Space

The volcanic gas reservoir has the characteristic of ternary structure which is composed of high storage-seepage stripes, rock matrix and fracture stripes (Fig.4). The heterogeneity is strong with three poor characteristics which are poor linear relation between porosity and permeability, poor matching between porosity, permeability and saturation, and poor correlation between porosity, permeability and depth, respectively. In general, it shows the characteristics of middle to low porosity, low permeability, and high saturation of irreducible water. The reason for this is that different types of rocks have different reservoir space. For volcanic lava, its primary gas pores are developed with some secondary dissolved pores and composite fractures. While for pyroclastics, its secondary pores are developed with some primary pores and different types of fractures. And the fractures are mainly composed of structural fractures and diagenetic fractures.

By analyzing 2518 rock samples, it can be found that there are 5 types of pore structure characteristics (Fig5). Pores are connected by throats with big pore-throat ratio, low uniformity of pore space. The throat is mainly composed of micro-throats and fine throats with big radius of effective pores and throats and wide distribution range. The big pores are controlled by small throats with strong reservoir heterogeneity. And the reservoir is water wet with high saturation of irreducible water, low range of two-phase flow and low efficiency of water displacing gas. Fractures are usually developed and are composed of structural and diagenetic fractures whose opening is good with multi-periods and belts which control the gas migration and accumulation. The diagenetic fractures are relatively scattered with strong anisotropy which act as connecting structural fractures.

The analysis of core samples shows that 66.57% of samples have the porosity ranging from 2% to 10% with average value of 6.57% and 83% of samples have the permeability ranging from 0,01mD to 0.5mD with average value of 0.43mD among which the gas-pore rhyolite has the highest porosity and permeability and the crystal tuff is the second (Fig6).

1.3 Reservoir Types

The reservoir type is mainly litho-structural reservoir which is controlled by structure and lithology. The volcanic gas reservoir is mainly in low to tight permeability with small local area of high productivity stripes developed laterally. And the reservoir's lateral distribution is discontinuous and changes quickly and well spacing of 500m can not drain the whole reserve. High productivity reservoir is only developed in parts of the well section vertically, too (Fig.7).

Generally, the gas-water relationship is very complex in Yingcheng Formation. Laterally, the distribution of the hydrodynamic system is mainly controlled by volcanic edifices and different volcanic edifice is non-communicated belonging to different hydrodynamic systems. Vertically, there are several hydrodynamic systems within the same volcanic edifice. The reservoir is rich in gas and has high productivity where the structure is relatively high, the petrophysics is good and the fractures are developed. While in lower parts of the reservoir, gas pay zones can be formed locally because of the effects of factors such as lithology, fault and petrophysics. Among these blocks, Block A and some other blocks has no uniform gas-water contact and shows the characteristics of gas in upper parts and water in lower parts which can be classified as structural-litho reservoir. While Block B has a uniform gas-water contact and shows the characteristics of gas in upper parts and water in lower parts which can be classified as litho-structural reservoir (Fig.8).

2 Reservoir Performances

The reservoir performances are characterized by applying gas reservoir engineering methods such as pressure drop, rate transient, modified isochronal well testing and back-pressure well testing according to the characteristics of the volcanic gas reservoir since 2005 when the gas field is put into large scale development [4][5].

It can be found that there is big difference between wells in gas rate and 84% of wells need to be fractured in order to improve productivity and some wells have watered out. What's more, the well-control reserve differs from well to well and the drainage area is small with slow pressure build-up and extended drainage area for wells with long term shut-in which shows the characteristics of low supplement and low permeability.

2.1 Gas Productivity and Well-Control Reserve

The statistics of production test and production of 82 wells indicate that 84% of wells need to be fractured to get commercial gas rate with 1/3 wells watering out. The productivity differs from well to well with uneven lateral distribution. The stable daily gas rate ranges from $1.0\times10^4m^3/d$ to $30\times10^4m^3/d$ with average value of $5.1\times10^4m^3/d$ among which 33% of wells' productivity is higher than the average value (Fig.9). The performances show the characteristics of exponential decline when the well is produced with high rate as a result of slow energy supplement and quick pressure loss. The reason is that the reservoir is distributed discontinuously with strong heterogeneity and the wells with high productivity are only located in areas where the petrophysics is good.

The statistics of well-control reserve for 52 wells show that the reserve ranges from $0.1\times10^8m^3$ to $20\times10^8m^3$ and the average value is $3.7\times10^8m^3$ with 38% of wells higher than the average value (Fig.10).

2.2 Flow Characteristics

The flow characteristics of the volcanic gas reservoir are complex because of its poor communication. There are several flow regimes such as radial flow, spherical&hemi-spherical flow, linear flow, hindered flow as well as improved flow. There are three types of dynamic models: enclosed or half-enclosed type (accounting for 16%), continuous type (accounting for 36%), striped type (accounting for 48%). Usually, the equivalent width for a stripe ranges from 36m to 240m which results in poor communication and low pressure build-up. In late stage of the pressure build-up, it shows a decreased speed of build-up which reflects the characteristics of slow supplement and low permeability.

2.3 Types of Watering Out

Three major types of watering out can be found according to the characteristics of well performance: strong fractured water breakthrough, weak fractured water breakthrough and porous water coning. Among them, 16 wells are classified as strong fractured water breakthrough accounting for 50% of all watering-out wells and 13 wells are classified as weak fractured water breakthrough accounting for 40.63% of all watering-out wells and 3 wells are classified as porous water coning accounting for 9.37% of all watering-out wells.

3 Horizontal Well Practices

Horizontal wells are drilled because about 1/3 of vertical wells can not produce economically according to economic evaluations. The production rate of 8 horizontal wells is 4 times higher than that of vertical wells from production practices.

The advantages of applying horizontal wells lie in that they can penetrate more volcanic edifices which can drain more reservoir area, high storage-seepage stripes and natural fractures which can extend drainage area, increase gas production and postpone water coning of basal water. The practices of drilling horizontal well indicate that the prediction accuracy of structure is improved greatly and the absolute error for depth of landing point is between 2m and 6m with relative error reaching 0.11% by selecting “sweet point” and building geological models for the blocks to be drilled with the technology of “three-dimensional model building combined with well and seismic data” based on three-dimensional seismic data. Furthermore, electric modeling method is used to research the seepage characteristics of horizontal wells, the effects on productivities of horizontal wells for factors such as reservoir heterogeneity and parameters of man-made fractures. What’s more, the productivity prediction method is built for horizontal wells, which solve the problem of productivity prediction considering reservoir heterogeneity and realize the productivity prediction for conventional and fractured horizontal wells in anisotropic volcanic gas reservoir with relative error around 10% compared to well’s gas testing results.

4 Conclusions

(1) The lithofacies for the major pay zones of the volcanic gas reservoir in Xushen Gas Field are mainly composed of proximal eruptive and effusive facies in multi-periods of eruption with little volcanic conduit facies, which are distributed discontinuously. The lithologies are mainly rhyolite and rhyolitic crystal (welded) tuff. The reservoir has the characteristic of ternary structure which is composed of high storage-seepage stripes, rock matrix and fracture stripes. The heterogeneity is strong with three poor characteristics which are poor linear relation between porosity and permeability, poor matching between porosity, permeability and saturation, and poor correlation between porosity, permeability and depth, respectively, It shows the characteristics of middle to low porosity, low permeability, and high saturation of irreducible water. The gas reservoir is litho-structural reservoir with basal water.

(2) Nearly 84% of wells need to be fractured to get commercial gas rate with 1/3 wells watering out. The productivity differs from well to well with uneven lateral distribution. The flow characteristics are complex and there are three types of dynamic models: enclosed or half-enclosed type, continuous type, striped type. The performances of production wells show the characteristics of slow supplement and low permeability. There are three typical types of watering out.

(3) The average production rate of a horizontal well is 4 times higher than that of a vertical well which is an effective tool to develop the volcanic gas reservoir.

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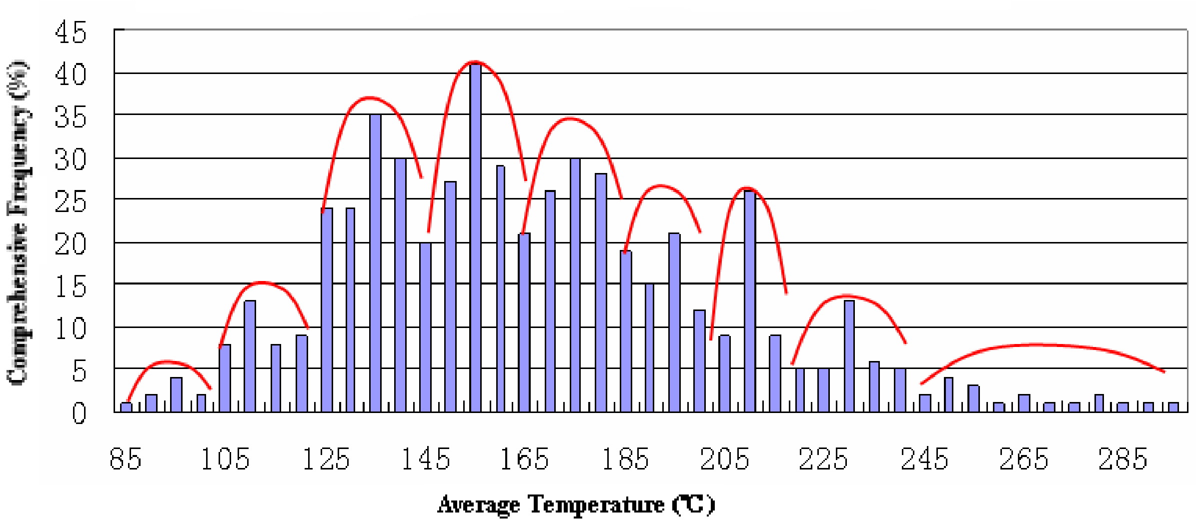

Fig.1 A Histogram of Comprehensive Frequency of Average Temperature for Fluid Inclusions Containing Hydrocarbons

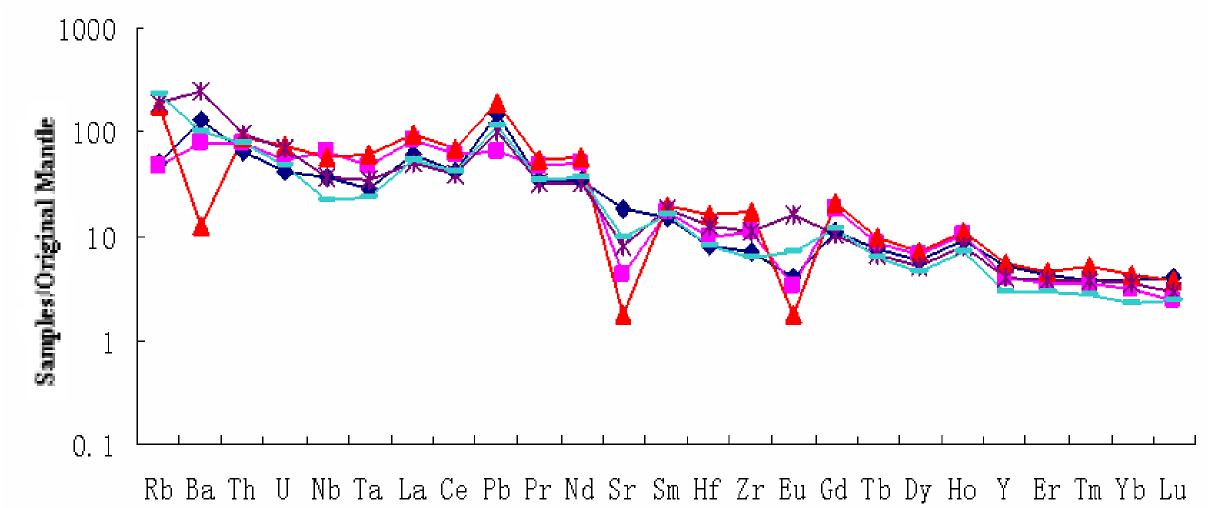

Fig.2 A Graphical Curves for Distribution of Rare Elements

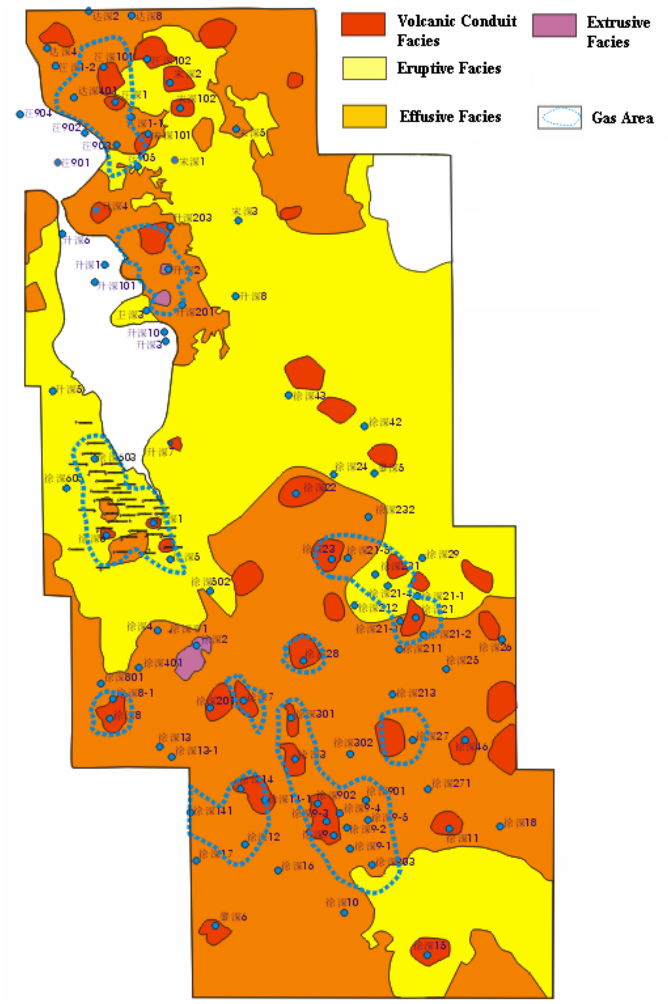

Fig.3 Lateral Distribution of Lithofacies of Volcanic Rocks

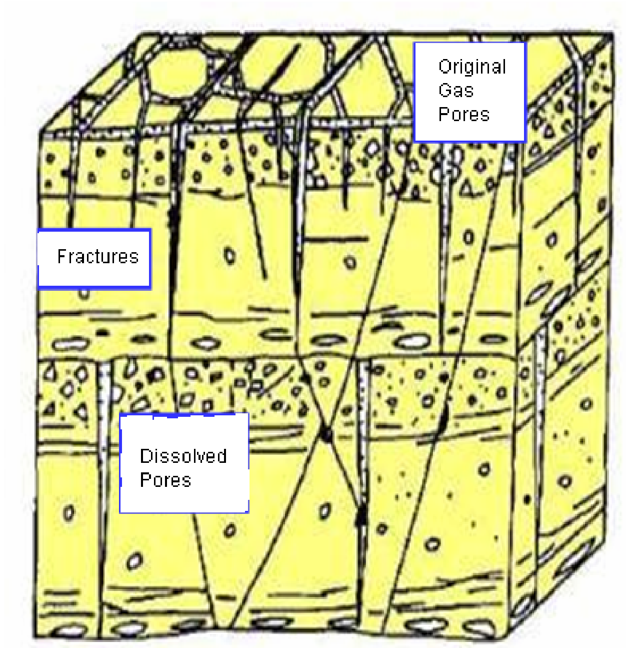

Fig.4 A Diagram of Ternary Structure of Volcanic Reservoir Space

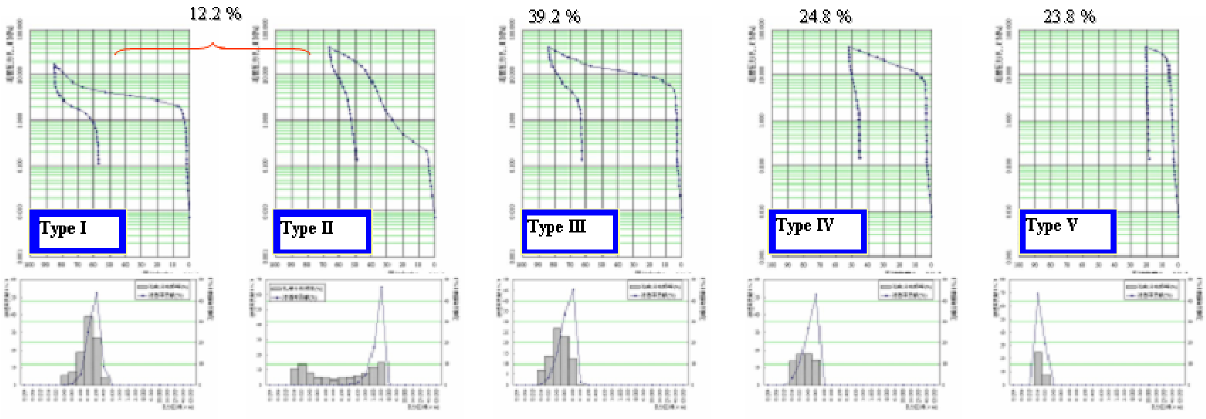

Fig.5 Characteristics of Pore Structure of the Volcanic Reservoir

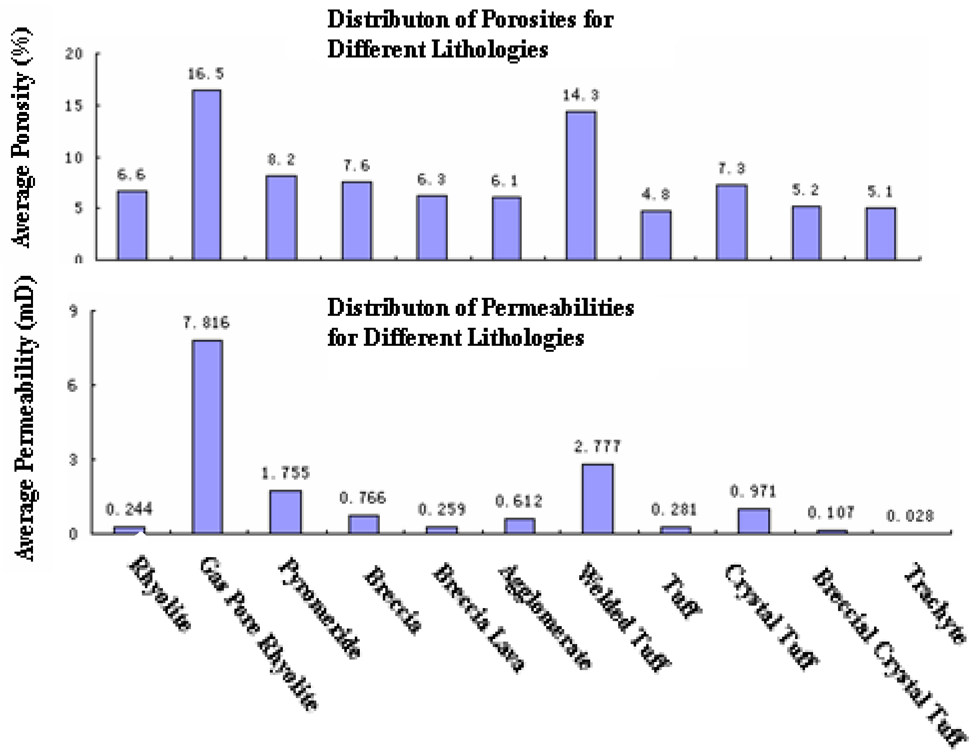

Fig.6 Distribution of Porosities and Permeabilities for Different Lithologies

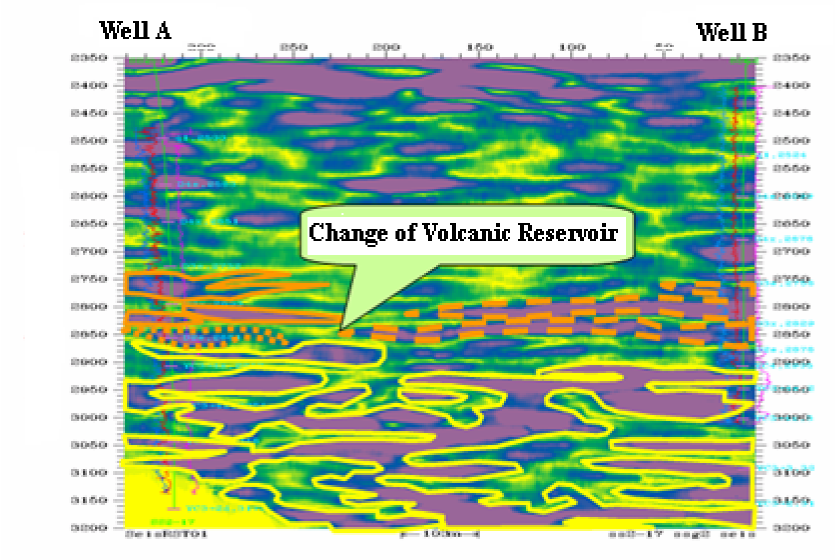

Fig.7 Profile of Reflection Strength of the Volcanic Reservoir

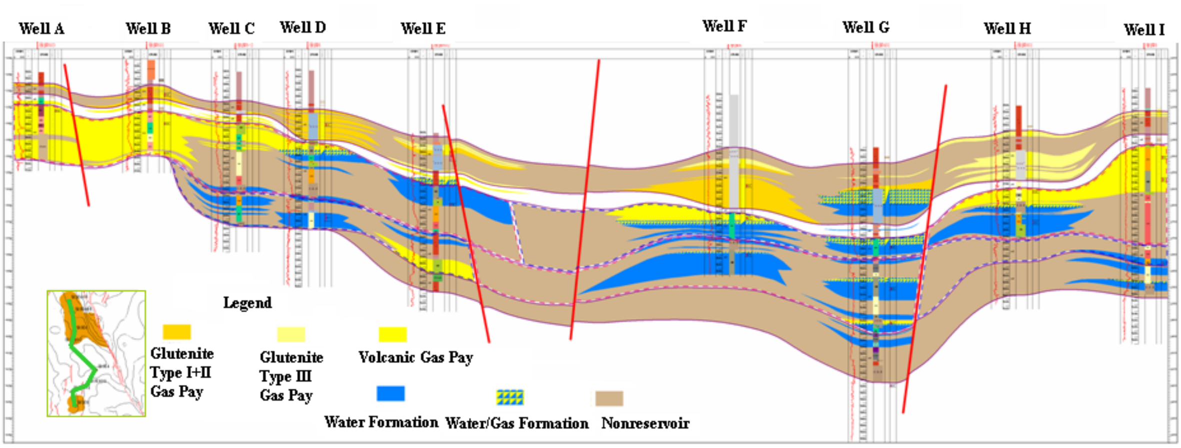

Fig.8 Cross Section of the Volcanic Gas Reservoir

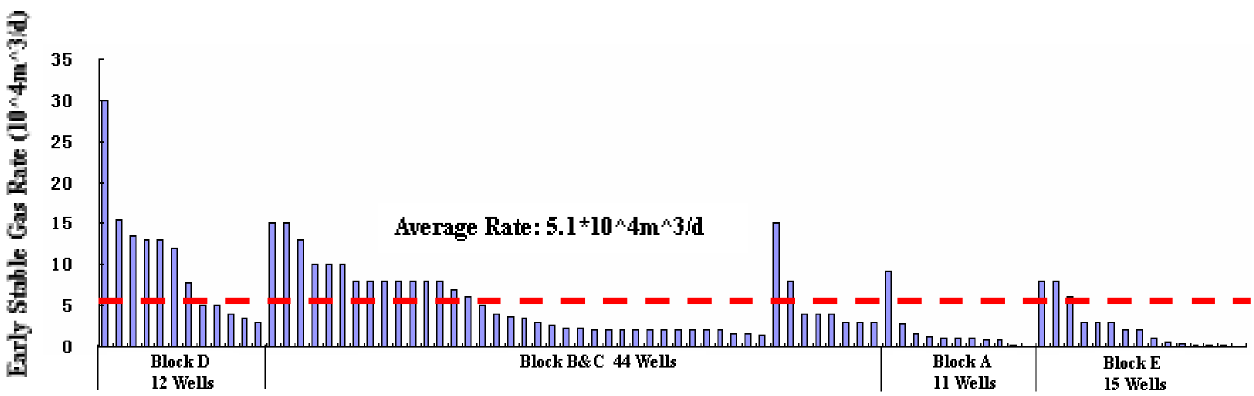

Fig.9 Statistics of Early Stable Gas Rate of Single Well in Each Block of Xushen Gas Field

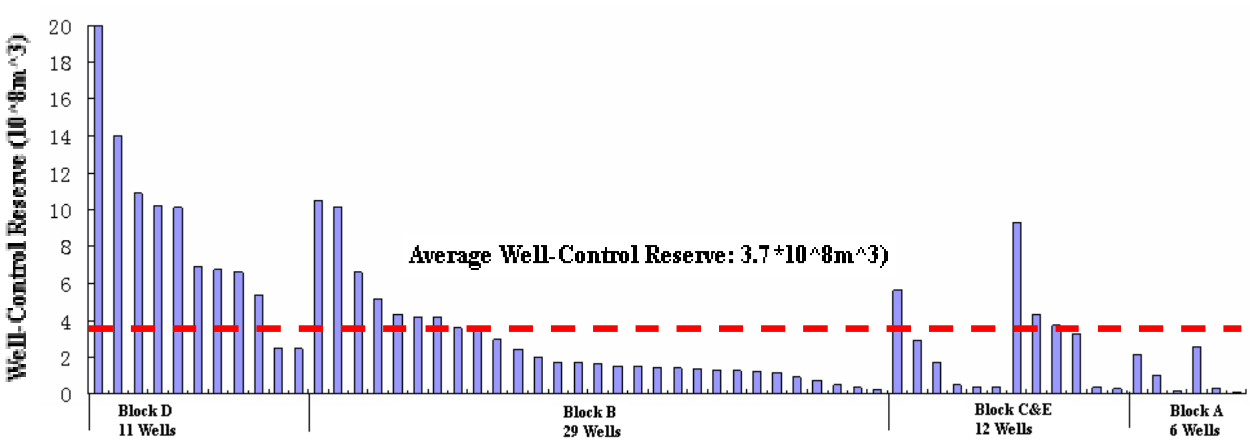

Fig.10 Statistics of Well-Control Reserve of Each Block of Xushen Gas Field

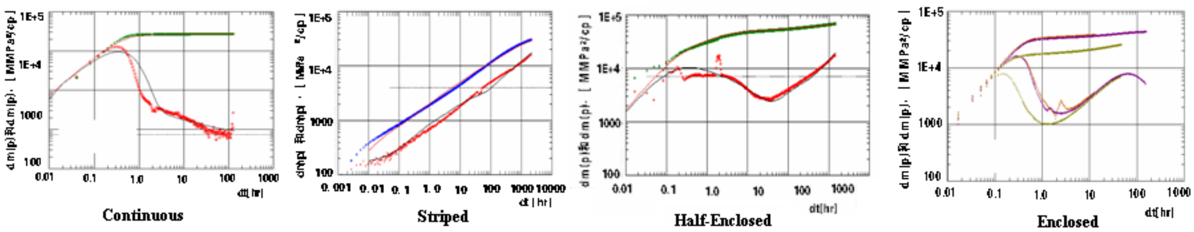

Fig.11 Typical Dynamic Flow Models In Xushen Gas Field

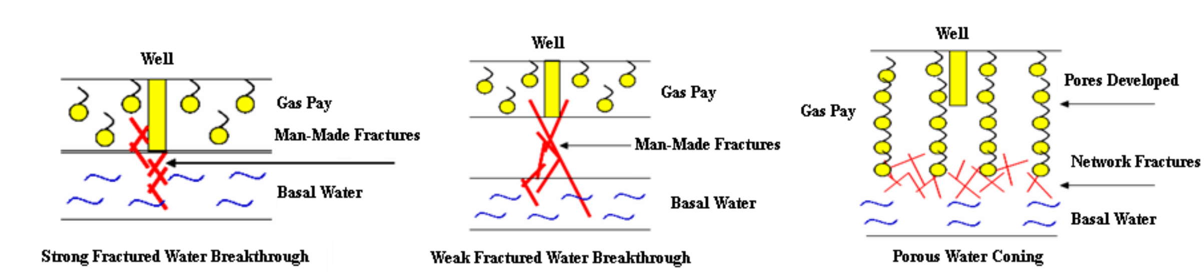

Fig.12 Typical Types of Watering Out in Xushen Gas Field