Quasi-continuous Lithologic Accumulation System: A New Model for Tight Gas Occurrence in the Ordos Basin, China*

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Abstract

The Ordos Basin has China's largest deposits of tight gas resources in its 250000 square kilometers area. However, gas accumulation process and trapping mechanisms have long been in controversy and several models, such as lithologic or stratigraphic trap, deep-basin gas trap, and tight-gas model, were proposed. In this article, we demonstrate that the Upper Paleozoic gas accumulation is neither basin-centered nor lithologic, but is what we refer to as continuous lithologic accumulation system. The new model has the following significant characteristics.

1. Every giant gas field comprises numerous smaller-sized lithologic traps that are superimposed vertically and combined or even connected laterally like strings of beads over vast area. Besides, most of lithologic traps are gas-bearing and no well-defined boundaries are diagnosed.

2. Water occurrence is complex. No updip water zone is observed. Gas-water contact is absent for most reservoirs. The complex occurrence of water is mainly controlled by factors of source, structure, reservoir, and preservation, of which source condition is most critical.

3. The accumulations are predominantly underpressured and possess multiple pressure systems showing poor connectivity among the numerous smaller-sized traps. But it has been widely proved that the reservoirs were overpressured in geologic history.

4. The sandstones are mostly tight and extend vastly but exhibit a strong heterogeneity laterally, showing no trend of updip improvement for reservoir quality. Moreover, because the accumulation occurred within the lithologic traps, lateral seal condition is extraordinary, with no need of other seal factors like water locking.

5. Source rocks are nearly basin-wide in distribution and mostly interbedded with reservoirs so that gas generation is extensive and gas charge is pervasive. But gas charge is not strong enough for gas to thoroughly displace water in the reservoirs.

6. Migration is mainly short-distanced and dominated by primary migration. Its drive comes from two sources: one is overpressure caused largely by gas generation and another from diffusing of gas molecules. The migrating style is thus convinced to be non-Darcy movement.

7. The Upper Paleozoic gas accumulation system has experienced 3 stages of development: formation of tight sandstones; peak gas generation, extensive accumulation and development of overpressure; and recharging and adjusting of gas reservoirs and formation of underpressure.

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Outline

1. Introduction
2. New Model
3. Major controls on the Large Tight Gas Fields
4. Conclusion

1. Introduction

The Ordos Basin is a major tight gas producing province with most abundant resources, largest proved reserves and greatest exploration potential for tight gas in China. Within its 250,000km^2 area, at least 5 large tight gas fields, namely the Sulige, Wushenqi, Yulin, Zizhou, and Daniudi, from Carboniferous and Permian with proved reserves of more than 100 ×10^{9}m^3 (bcm) each have been discovered during the last decade, of which the Sulige is the largest in China where more than 2×10^{12}m^3 (tcm) proved reserves of tight gas have been found out. In 2010, over 10 ×10^{9}m^3 gas was produced from the Sulige.

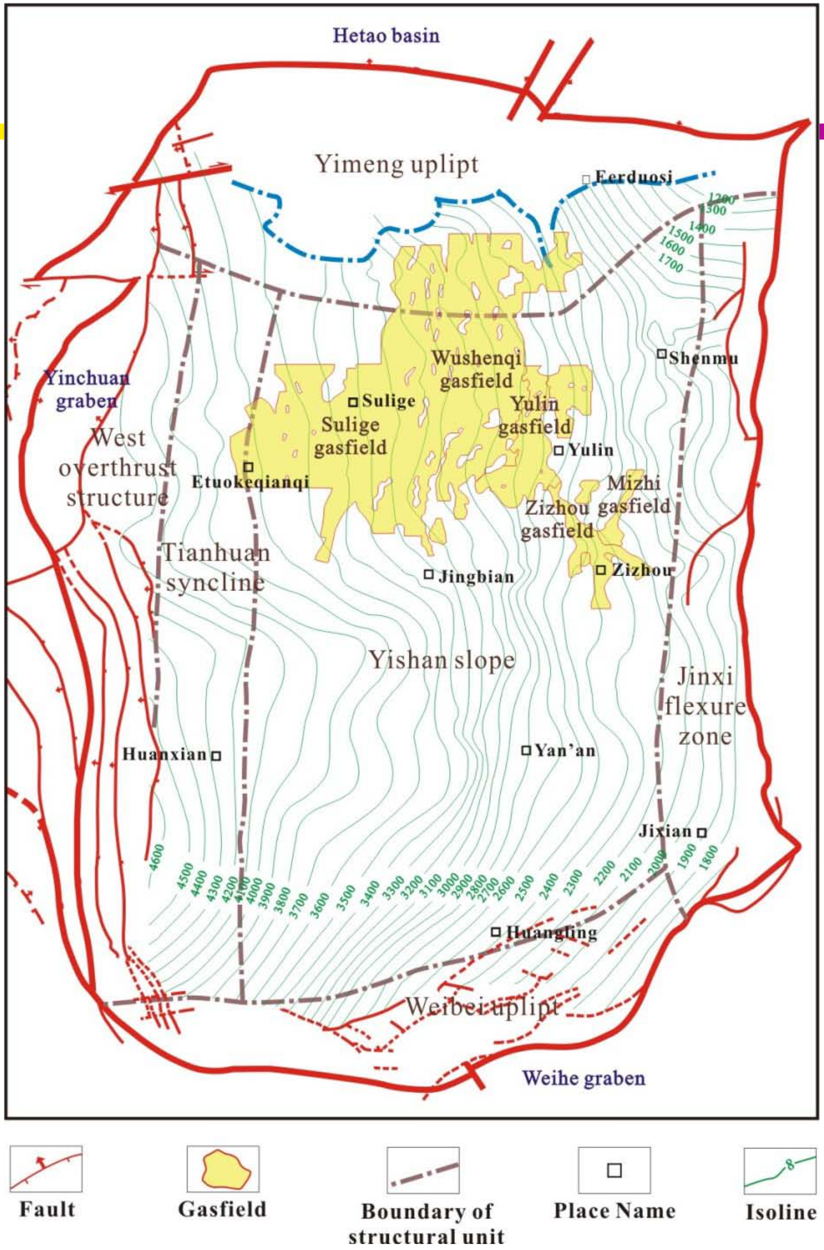


Fig.1 Distribution of Upper Paleozoic natural gas fields in the Ordos Basin

1. Introduction

Nevertheless, there exist some different opinions on the accumulation model of tight gas in the Ordos Basin.

1.1 Conventional trapping model

This is the most prevailing viewpoint, starting from initial exploration until present. Many workers regarded the Upper Paleozoic gas accumulations as lithologic or stratigraphic traps or structural-stratigraphic traps (Editorial Group of Changqing Oilfield Petroleum Geology, 1992; Yang, 2002; He et al., 2003; Li et al., 2008, 2009; Zhao et al., 2010). In other words, the Upper Paleozoic gas accumulations are widely accepted as conventional accumulations in terms of trapping mechanism.

Some workers, however, have proposed the concept of “large lithologic traps”, “large lithologic reservoirs” or “large combined lithologic reservoirs” (Fu et al., 2000, 2001, 2005, 2008; Li et al., 2000; Yang et al., 2001, 2005; You and Li, 2001; Hao et al., 2006, 2007).

1. Introduction

1.2 Deep Basin Gas Model

This model, or basin-centered gas model, was proposed near the end of 20th century and prevailed in the beginning of 21st century. Li et al.(1998), Min (1998, 2000), Li et al.(2001), Wang(2002), Ma(2005), Wang and Zhang (2006) were among those who claimed that Upper Paleozoic natural gas accumulation in the Ordos Basin was in the form of deep-basin or basin-centered type.

Recently, Hu et al.(2010) pointed that the Upper Paleozoic gas accumulation was basin-centered type in Jurassic to Early Cretaceous, but has transformed into the present special lithologic or stratigraphic reservoirs.

1. Introduction

1.3 Continuous accumulation model

The concept “continuous accumulation” was initially proposed by USGS in 1990’s (Gautier et al., 1995；Schmoker, 1995). This concept was first employed by Zou et al.(2009a, 2009b, 2009c) to explain the natural gas accumulation pattern in the Upper Paleozoic tight sands of the Ordos Basin and Upper Triassic Xujiahe Formation of the Sichuan Basin.

2. New Model for Tight Gas Accumulation in the Ordos Basin

2.1 Accumulation model

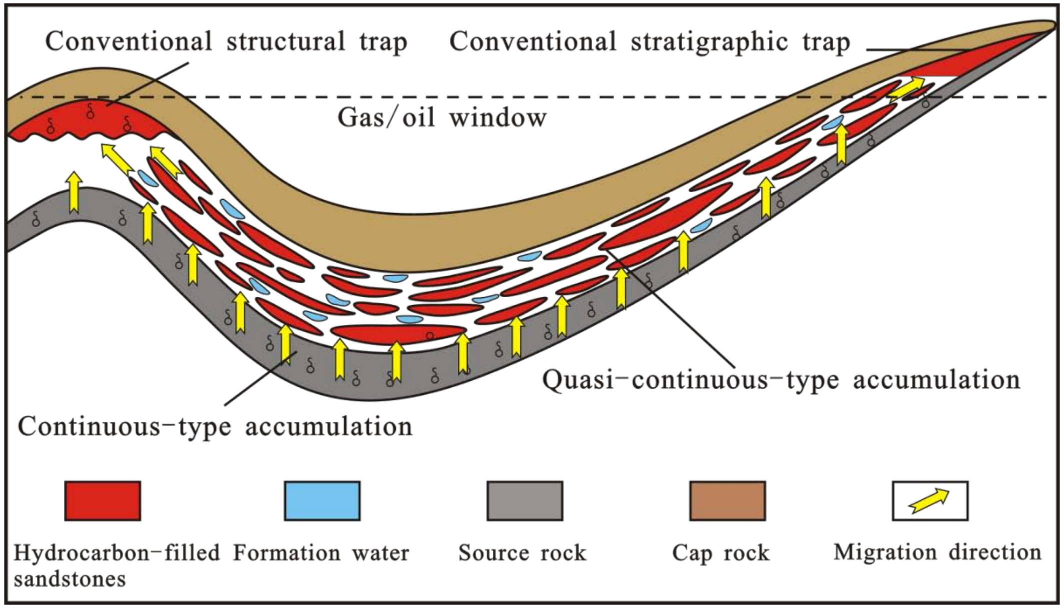
2.2 Comparison of quasi-continuous and continuous tight gas accumulation

2.3 Comparison of quasi-continuous and discontinuous tight gas accumulation

2.1 Accumulation model

Our study shows that most, if not all, tight gas accumulations in the Upper Paleozoic of the Ordos Basin are neither typical traditional lithologic (or stratigraphic) entrapment nor typical unconventional continuous accumulation. In fact, they are a transitional type between conventional and unconventional accumulations, which is termed as quasi-continuous accumulation.

The quasi-continuous accumulation is defined as such an accumulation that is composed of numerous small to medium sized gas-bearing lithologic traps or sweet spots that are connected or half-connected laterally and stacked vertically and characterized by wide quasi-continuous distribution, without defined boundaries and reversed gas-water occurrence.

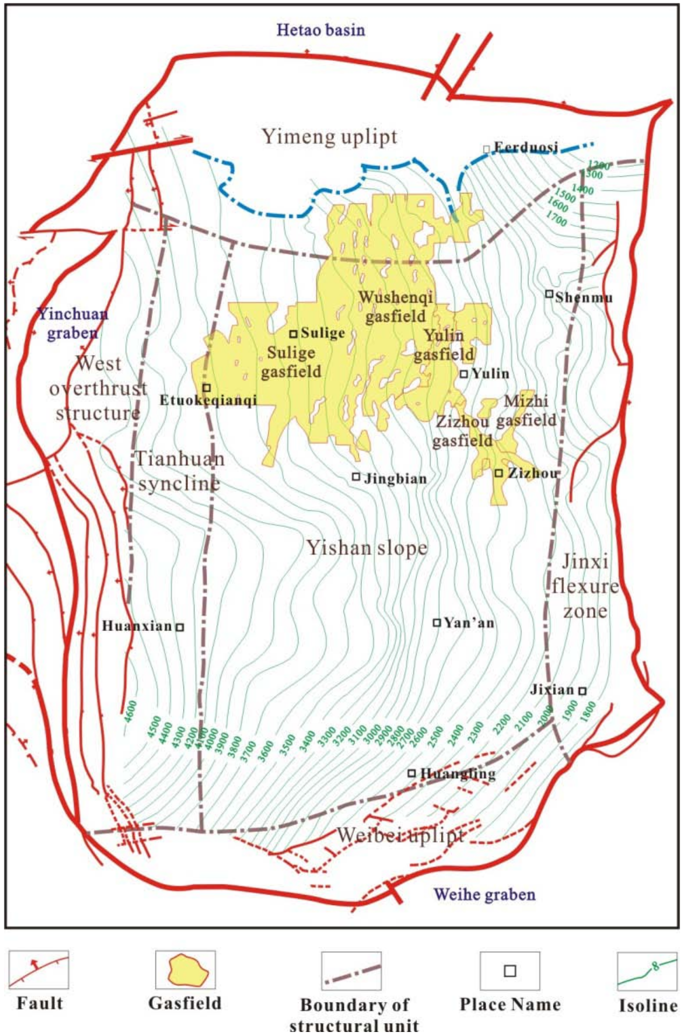


2.2 Comparison of quasi-continuous and continuous tight gas accumulation

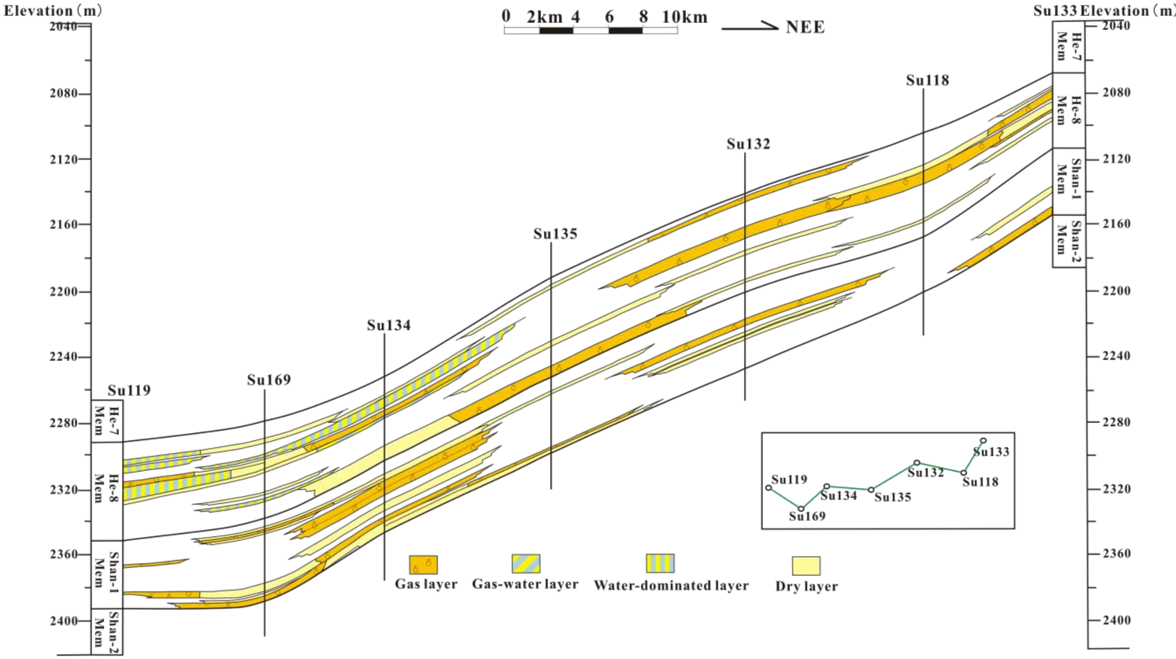
Common characteristics of quasi-continuous and continuous accumulation in tight sands

No.	Features	Characteristics in common
1	Type of trap	Unconventional traps.
2	Gas-water occurrence	Widespread continuous or quasi-continuous distribution without defined boundaries. No water leg exists.
3	Source and reservoirs	Source and reservoirs are neighboring and both are distributed in large area.
4	Reservoirs	Tight with low porosity and ultra-low permeability.
5	Driving forces	Overpressure produced by hydrocarbon generation and diffusion caused by difference of hydrocarbon concentration. Buoyancy is not important.
6	Style of migration	Non-Darcy flow, with surging flow and diffusion as major forms.
7	Pressure	Abnormal pressure, overpressure or underpressure.
8	Major controls	Source, reservoir and preservation are key controlling factors, whereas trap and migration are secondary.
9	History of accumulation	Most are primary (tight first and accumulation at the same time or later).
10	Abundance of resources	Resource potential is large but degree of abundance is unusually low.

■ Unconventional traps, extensive accumulation in large area, and no downdip water



Area of proved reserves of Upper Paleozoic gas accumulation

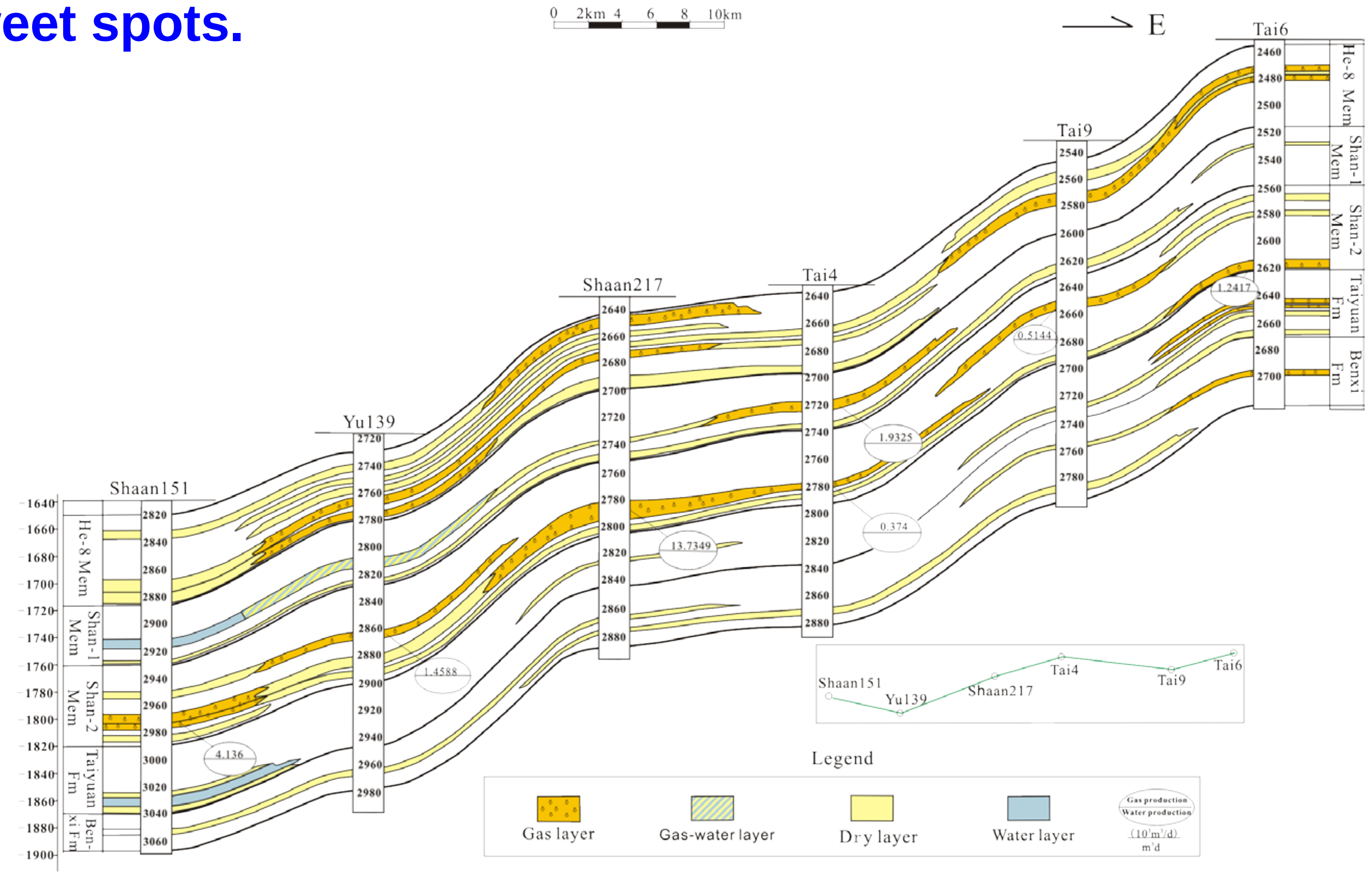


A profile of Upper Paleozoic tight gas reservoirs of Sulige Field.

Difference between quasi-continuous and continuous accumulations

No.	Features	Continuous tight gas accumulation	Quasi-continuous tight gas accumulation
1	Type of accumulation	Unconventional.	Transition between unconventional and conventional.
2	Distribution of gas	Continuous distribution over vast area without defined boundary .	Quasi-continuous distribution over vast area without defined boundary .
3	Trapping mechanism	Deep-basin type.	Combination of numerous lithologic traps or sweet spots without defined boundaries.
4	Gas/water occurrence	Updip water and downdip gas. No or little water producing within the accumulation in general.	Gas-water occurrence complicated. No obvious water leg. More or less water produced.
5	Reservoirs	Reservoirs improving toward updip direction.	Reservoirs vary laterally, showing strong heterogeneity.
6	Source condition	Hydrocarbon generation is continuous and greater than dispersion.	Source condition varies.
7	Charging	There is a generation center in source kitchen. The charging is concentrated and a predominant migration pathway is existed.	Hydrocarbon generation occurs nearly basin-wide, charging is pervasive and no predominant migration pathway existed.
8	Migration and accumulation	Both primary and secondary migration are indispensible and long distance of secondary migration is needed to form a large accumulation.	Accumulation occurs immediately after primary migration. Short distance of vertical migration is predominated. Lateral migration is just in short distance.
9	Pressure	Pressure system is simple across the whole gas-producing region. Generally only one pressure system is present.	Pressure system is complex and multiple systems can be observed.
10	Success rate and strategy of exploration	Exploration success rate is unusually high and focus is in search for gas-water boundary.	Exploration success rate is quite high, but risk of drilling water-producing and dry holes is present. Exploration can be focused on the search for sweet spots.

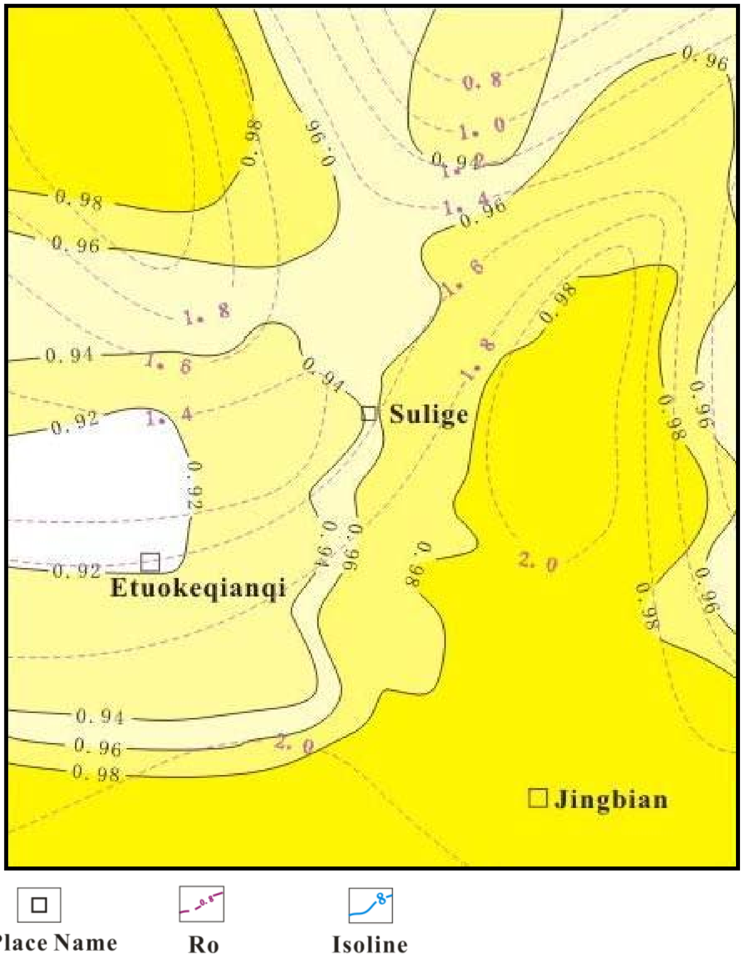
■Trap of the quasi-continuous accumulation: combination of numerous small to medium sized lithologic traps or sweet spots.



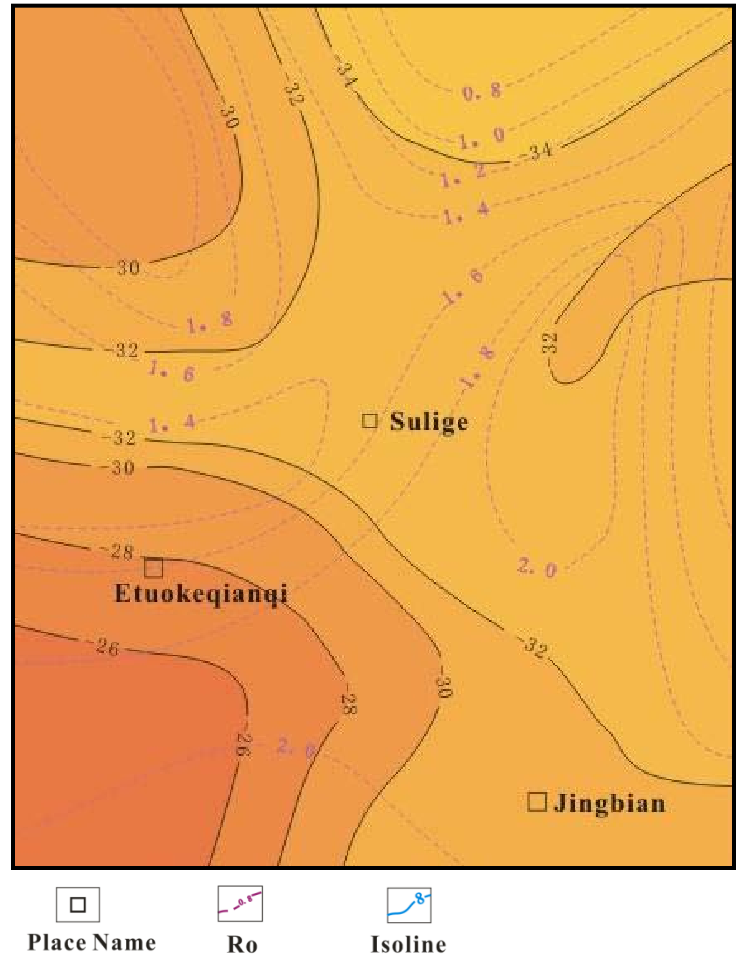
A profile of the Yulin Upper Paleozoic Gas Field

quasi-continuous accumulation: extensive generation, pervasive charging, vertical expulsion and near-source accumulation

Surging flow and diffusion are major forms of gas migration. Overpressure caused by gas generation and difference of hydrocarbon concentration between source and reservoir rocks are main driving forces. Charging process is predominated by pervasive and vertical manner rather than locally intensive manner.

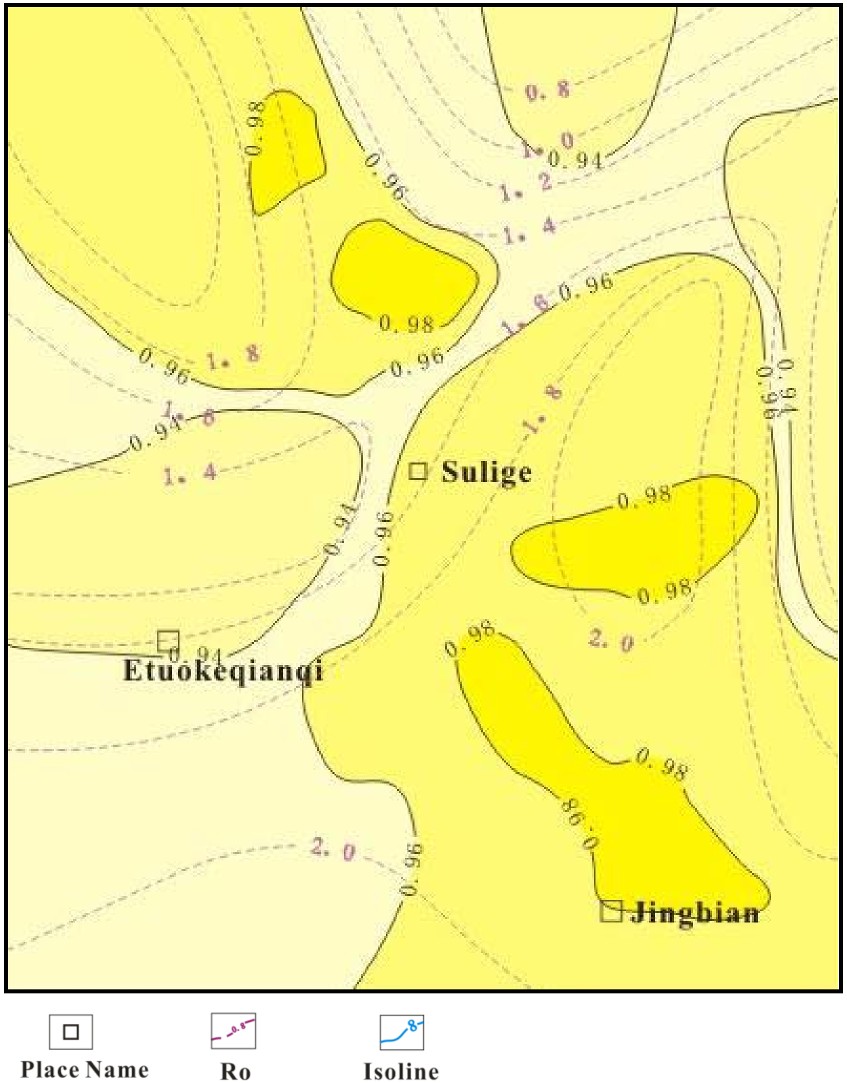


Distribution of C_1/C_{1+5} and Ro of He-8 gas member

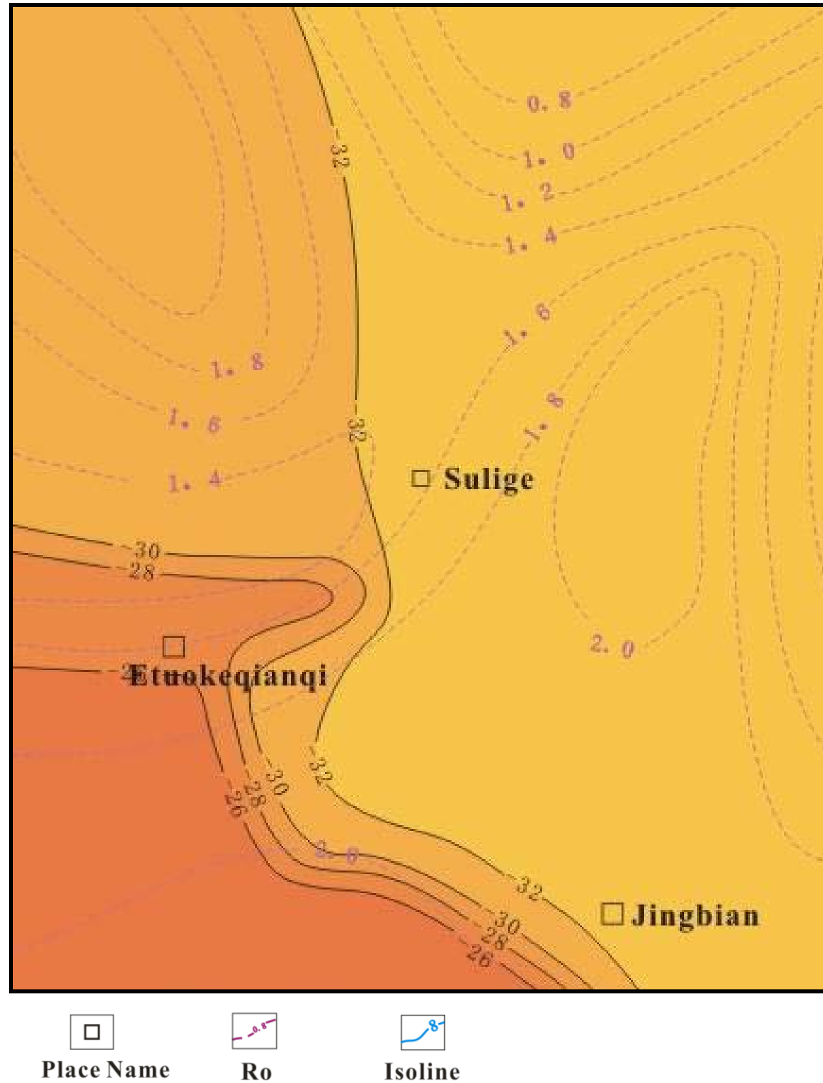


Distribution of $^{13}\delta C_1$ and Ro of He-8 gas member

■ quasi-continuous accumulation: extensive generation, pervasive charging, vertical expulsion and near-source accumulation



Distribution of C_1/C_{1+5} and Ro of Shan-1 gas member



Distribution of $^{13}\delta C_1$ and Ro of Shan-1 gas member

2.3 Comparison of quasi-continuous and discontinuous tight gas accumulation

Difference between quasi-continuous and discontinuous accumulations

Features	Quasi-continuous tight gas accumulation	Discontinuous tight gas accumulation
Type of accumulation	Transition between unconventional and conventional accumulation	Conventional
Distribution of gas	Quasi-continuous distribution over vast area without defined boundary.	Discontinuous accumulation in local area with defined boundary.
Trapping mechanism	Combination of numerous lithologic traps or sweet spots without defined boundaries.	Traditional structural, stratigraphic, or combination trapping with defined boundaries.
Gas/water occurrence	Gas-water occurrence complicated. No obvious water leg existed. More or less water produced.	Updip gas and downdip water. Edge or bottom water can be observed.
Relation between source and reservoirs	Near source accumulation, and short-distance migration.	Accumulation near source or far away from it. Migration being short or long distanced.
Driving force	Mainly overpressure caused by hydrocarbon generation and diffusion. Buoyancy is weak.	Buoyancy, hydrodynamic and/or tectonic forces.
Style and phase state of migration	Non-Darcy flow is predominated. Separate phase is the major phase state.	Darcy or non-Darcy flow. Migration can be either in dissolved phase or in separate phase.
Migration and charge	Entrapment occurs just via primary migration. Charge is pervasive. No dominant migration pathway.	Entrapment happens usually via secondary migration. Charge is generally focused and via one or few dominant migration pathway.
Pressure	Abnormal pressure (overpressure or underpressure).	Normal or abnormal pressure.
Key factors for accumulation	Source, reservoirs and preservation. Trap and migration are less important.	Source, reservoir, seal, trap, migration and preservation are all important.
History of evolution	Most accumulations are primary type (reservoirs get tight prior to entrapment).	Most accumulations are secondary type (reservoirs get tight after entrapment).
Resource abundance and potential	Large resource potential and low abundance.	Both resource potential and abundance are low to medium.
Success rate and strategy of exploration	Success rate is quite high. Exploration can be focused mainly on the search for sweet spots.	Success rate varies. Exploration focus is mainly on the search for favorable traps.

3. Major controls on the Large Tight Gas Fields

3.1 Large gentle slope and depression is indispensable structural background for vast tight gas accumulation;

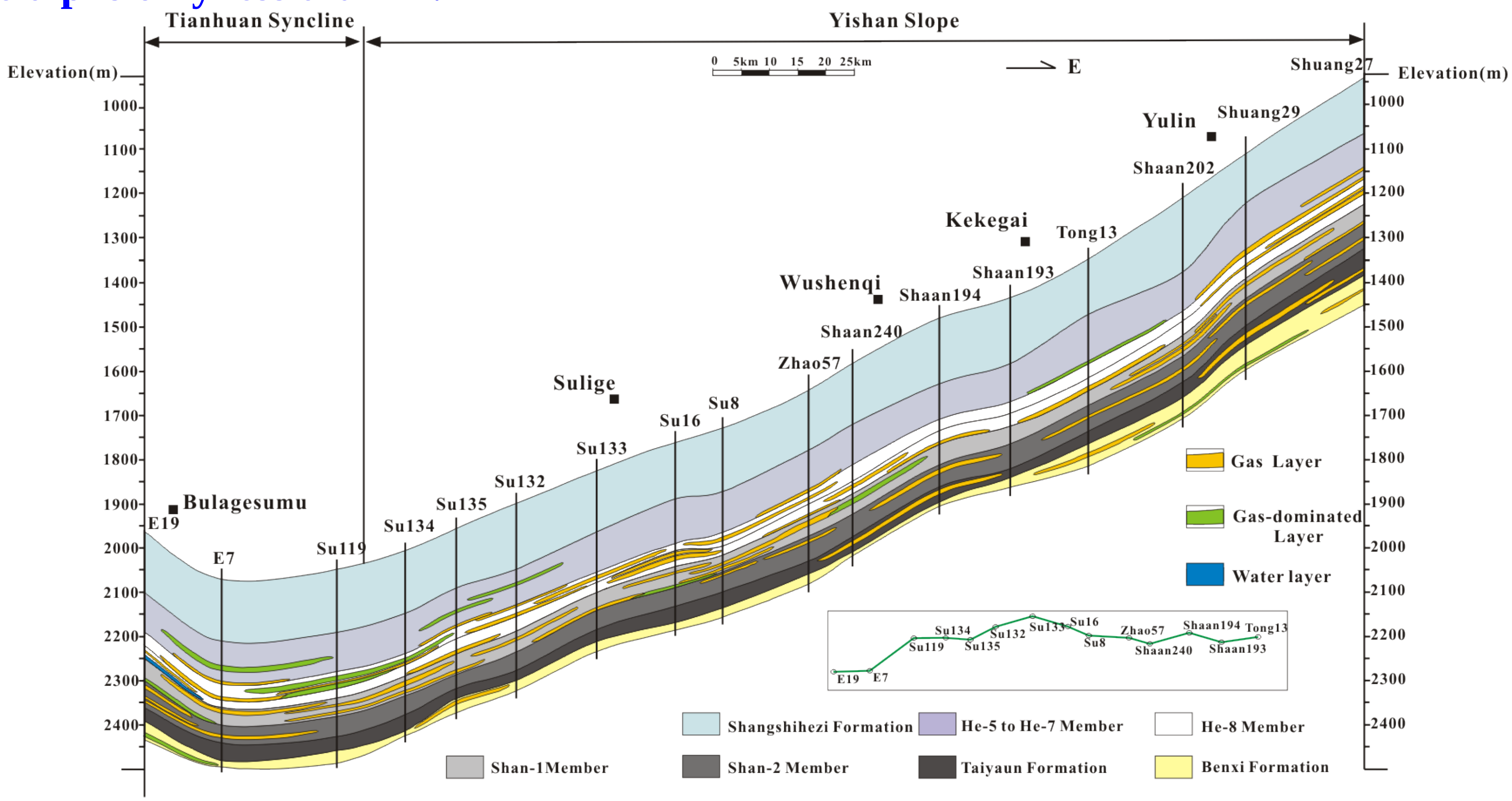
3.2 Source condition is the key element controlling the distribution of tight gas;

3.3 Reservoir heterogeneity is a decisive factor responsible for the complex distribution of gas and water;

3.4 Tectonic alteration is of significant influence on the accumulation and preservation.

3.1 Large gentle slope and depression is indispensable structural background for vast tight gas accumulation

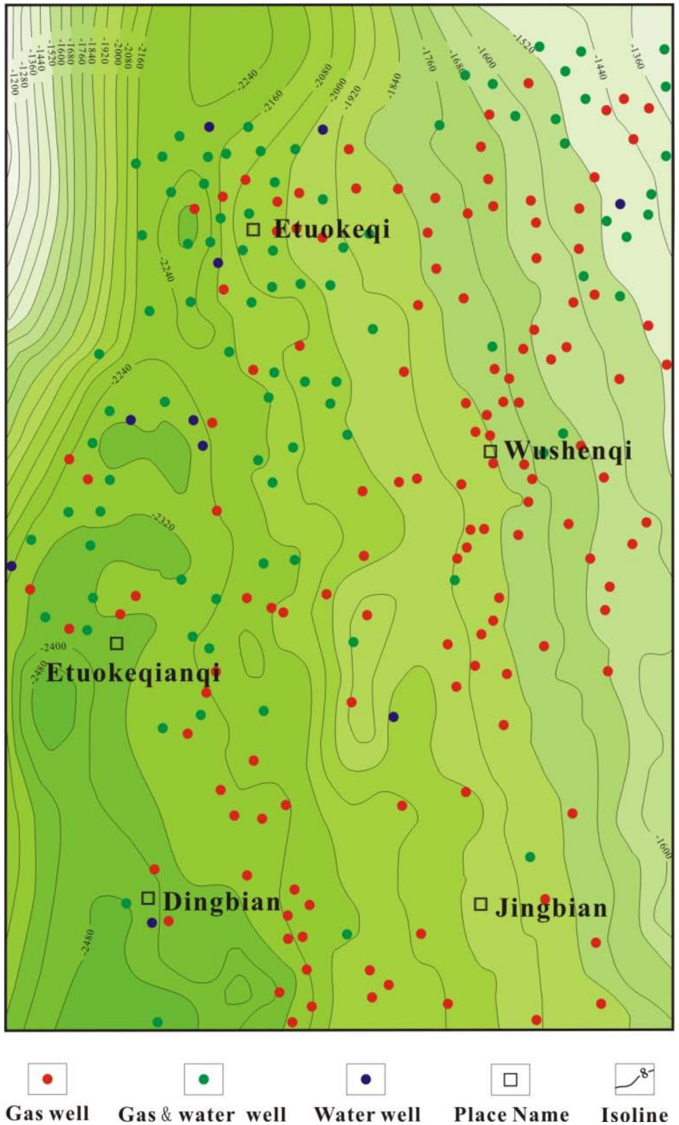
The Ordos Basin is characterized by simple structure and its principal part is a large gentle slope termed as Shaanbei Slope, where folds and faults are not developed and the dip is only less than 1°.



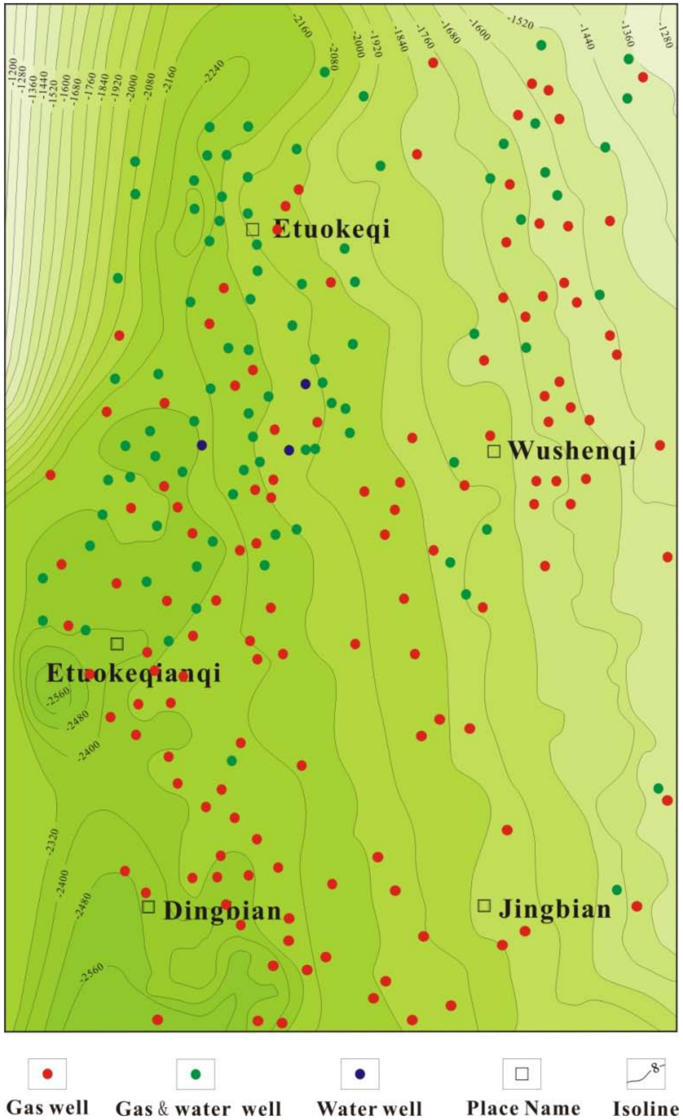
A profile showing quasi-continuous accumulation on the background of gentle slope and depression of the Ordos Basin

3.1 Large gentle slope and depression is indispensable structural background for vast tight gas accumulation

Present structure of Sulige field



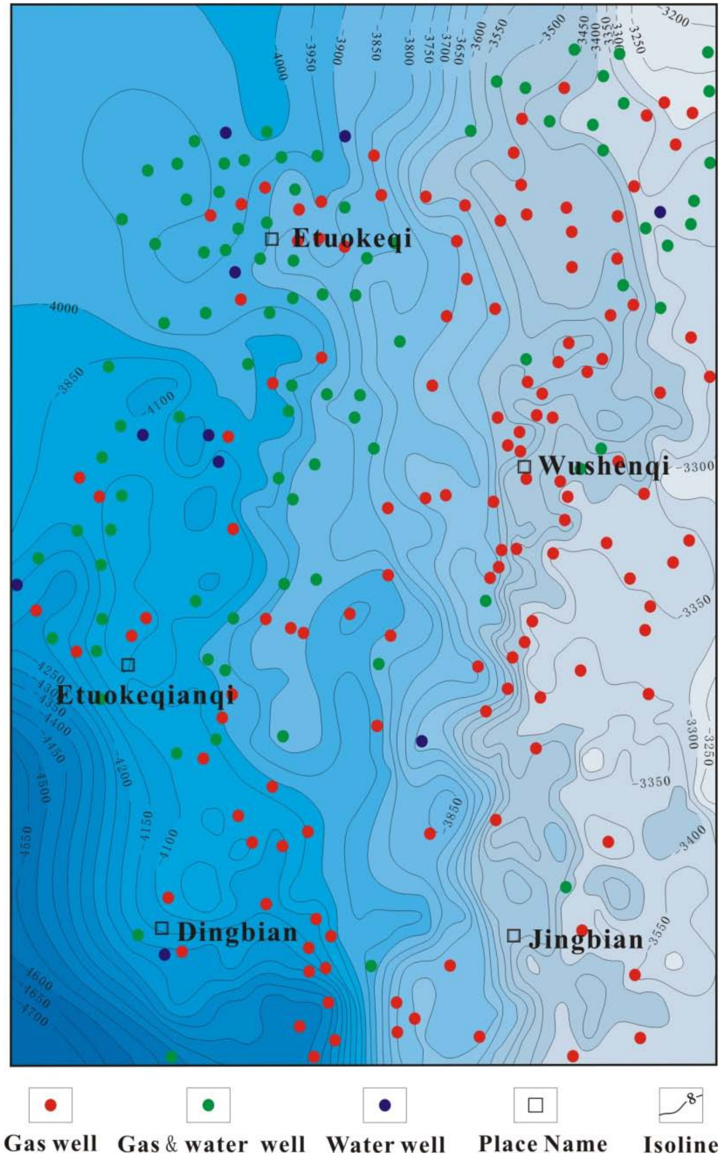
Contour map showing present structure of He-8 member of Sulige gas field



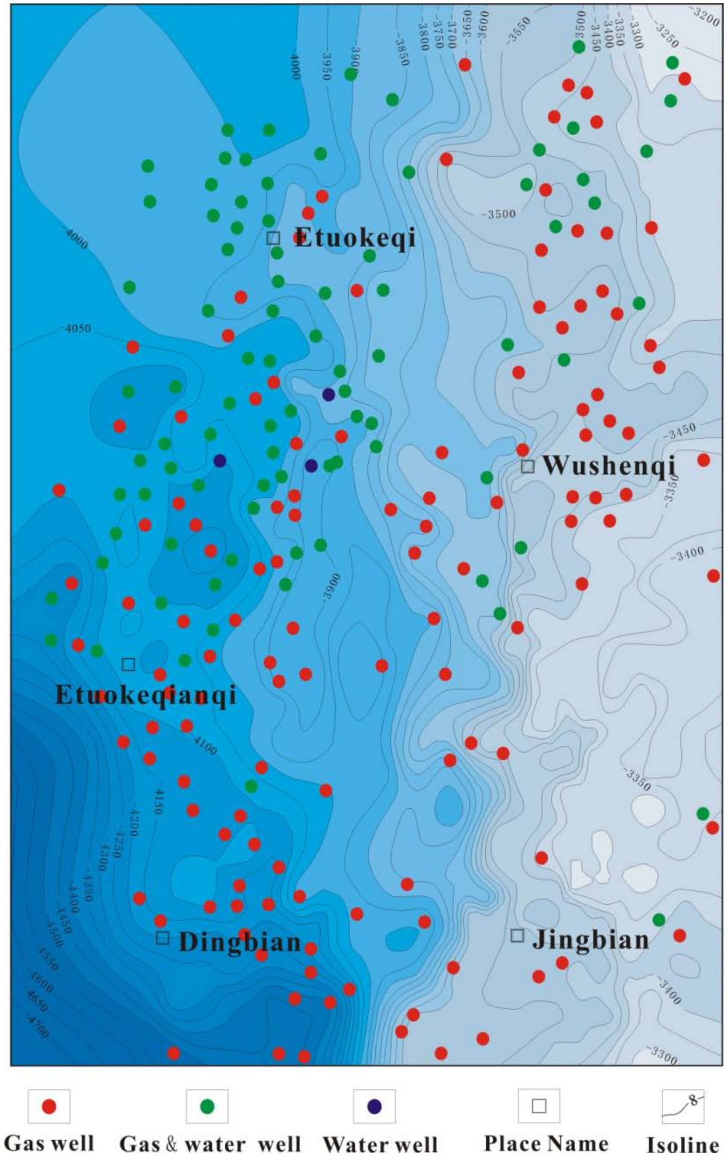
Contour map showing present structure of Shan-1 member in Sulige gas field

3.1 Large gentle slope and depression is indispensable structural background for vast tight gas accumulation

Structure of Sulige field at the end of Early Cretaceous (critical moment for accumulation)



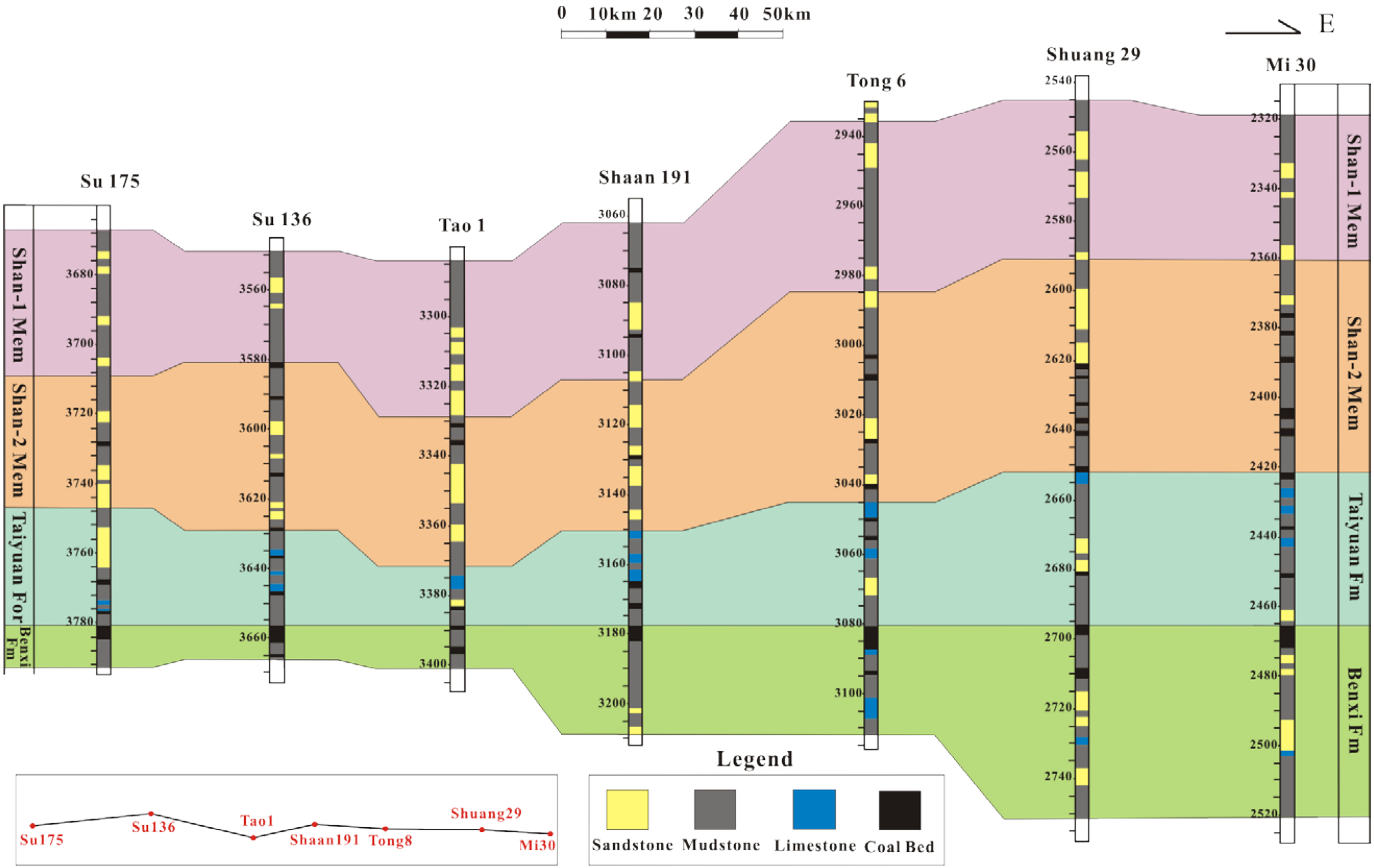
Contour map showing structure of He-8 member of Sulige gas field at the end of Early Cretaceous



Contour map showing structure of Shan-1 member in Sulige gas field at the end of Early Cretaceous

3.2 Source condition is the key element controlling distribution of tight gas

Source and reservoir rocks are contiguous and both are widely distributed.



3.2 Source condition is the key element controlling distribution of tight gas

Source condition can be characterized by gas generation intensity (GGI) that integrates TOC, Ro and other factors.
A good positive relation between pressure coefficient and gas generation intensity (GGI) is observed. The figure here shows that the pressure coefficient increases as GGI does, indicating that source condition is of great influence to the tight gas accumulation and distribution.

Pressure coefficient

Gas generation intensity (GGI)

Diagram showing relation between gas generation intensity (GGI) and pressure of Upper Paleozoic gas formation from the Ordos Basin

3.2 Source condition is the key element controlling distribution of tight gas

Based on the study on the relation between GGI and occurrence of medium to large gas fields of China, many workers (e.g. Shi et al.,1989; Qi et al., 1992) believed that the minimum GGI for the formation of medium to large gas fields of China should be greater than $20 \times 10^8 m^3/km^2$. Dai (1997) pointed that medium to large gas fields in the former Soviet Union emplaced where the GGI is greater than $30 \times 10^8 m^3/km^2$.

Yang and Wei (2007) observed that extensive gas beds are existed in the north and west parts of Sulige field where GGI is only 16 to 20 $\times 10^8 m^3/km^2$. Therefore they believed that minimum GGI can be lower for large stratigraphic gas accumulation of low permeability and low concentration. In light of that observation, they regarded $16 \times 10^8\ m^3\ /\ km^2$ as the lower limit of GGI for evaluation of Sulige field.

3.2 Source condition is the key element controlling distribution of tight gas

Our work reveals that minimum GGI for large tight gas accumulation can be as low as $10 \times 10^8 m^3/km^2$ in the Ordos Basin.

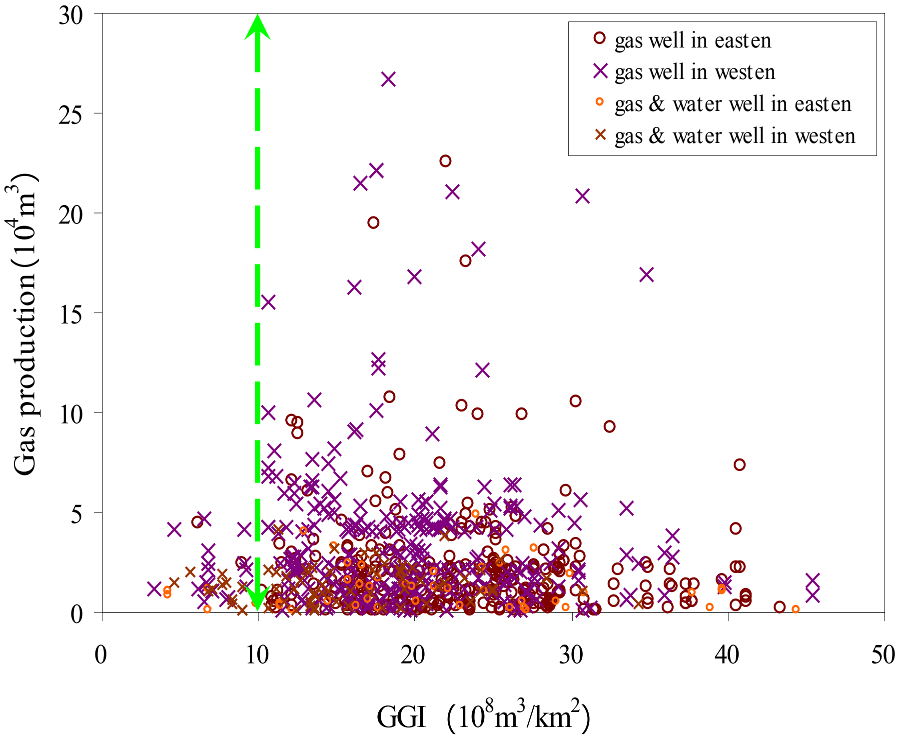


Diagram showing relation between GGI and gas production from the Ordos Basin

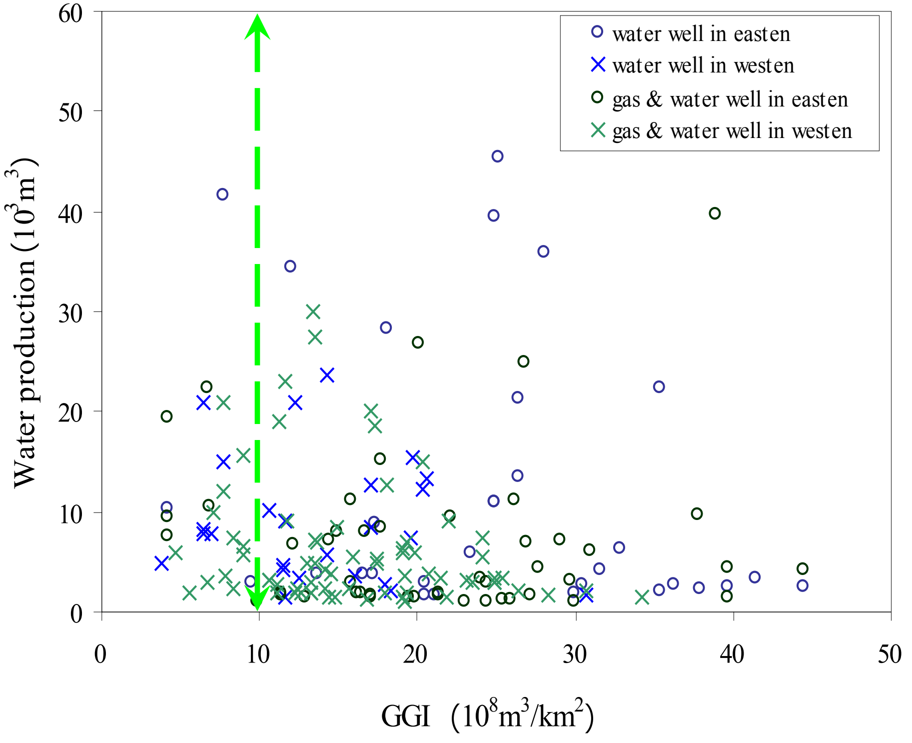
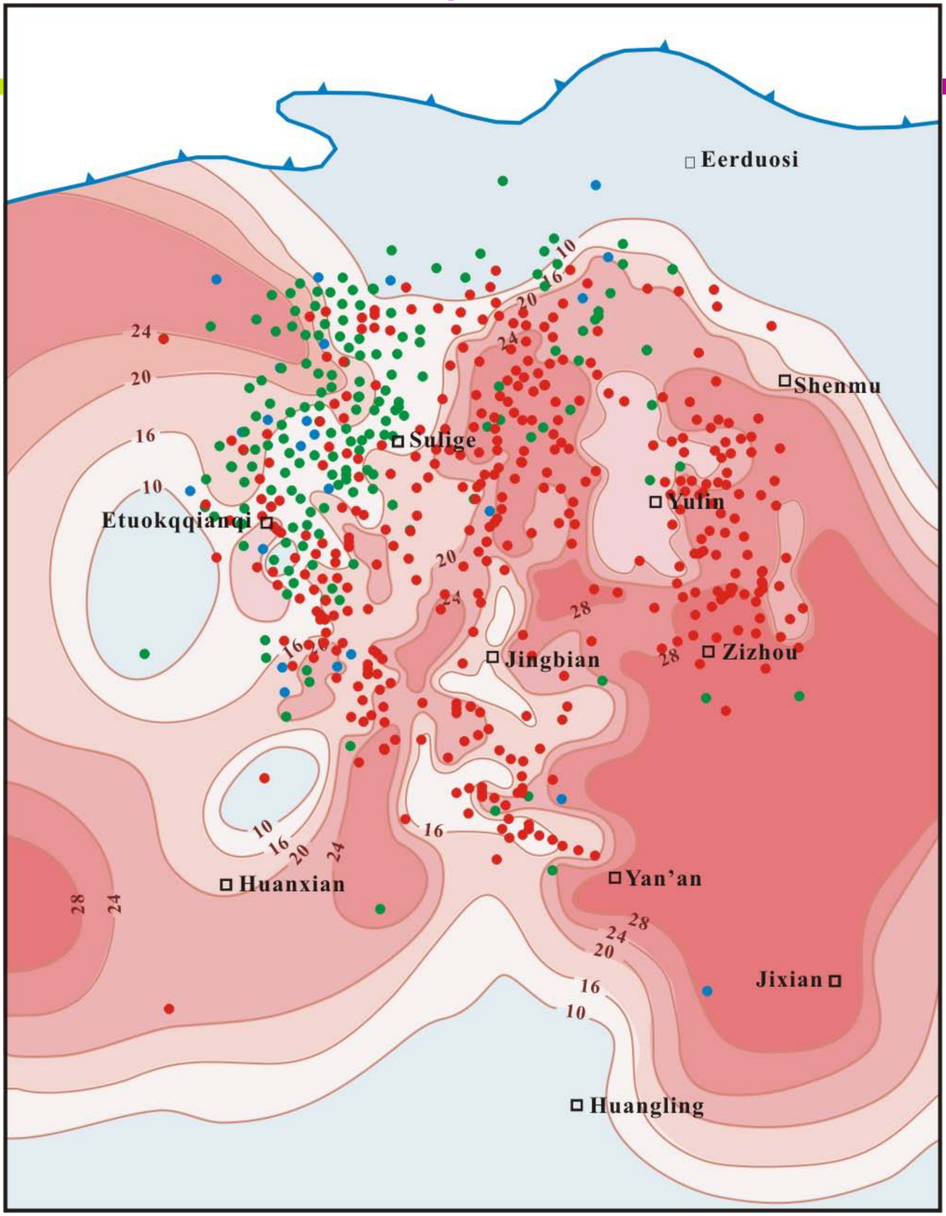


Diagram showing relation between GGI and water production from the Ordos Basin

3.2 Source condition is the key element controlling distribution of tight gas

From the data of 830 wells, we compiled a new map for the distribution of gas generation intensity (GGI) and well types of production, and found that even around the isopach of $10 \times 10^8 m^3/km^2$ there are still lots of gas wells and gas-water wells observed.

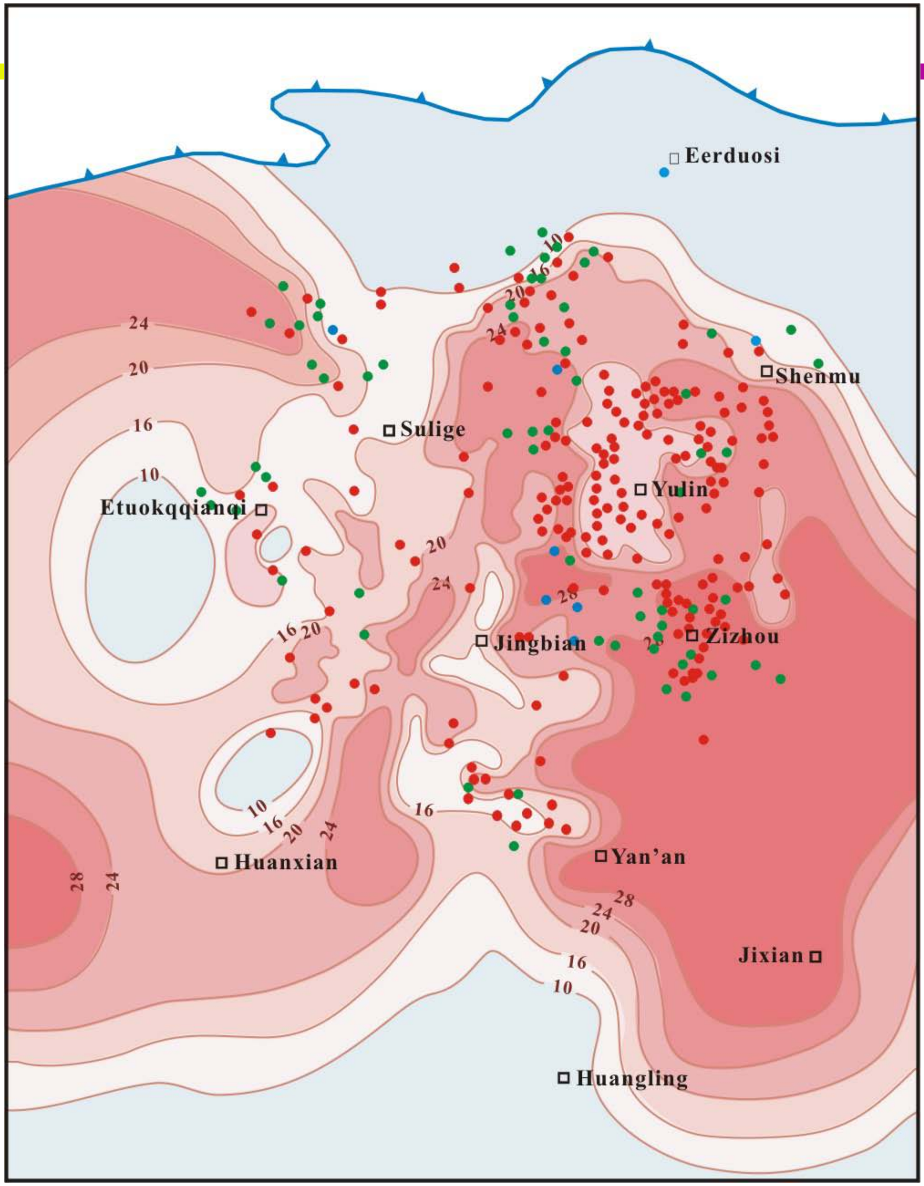


Distribution of gas generation intensity (GGI) and well types of production from He-8.

3.2 Source condition is the key element controlling distribution of tight gas

Consequently, we can conclude that the minimum GGI for large tight gas accumulation can be as low as $10\times10^8 m^3/km^2$ in the Ordos Basin. We believe this is also applicable for many other tight gas basins.

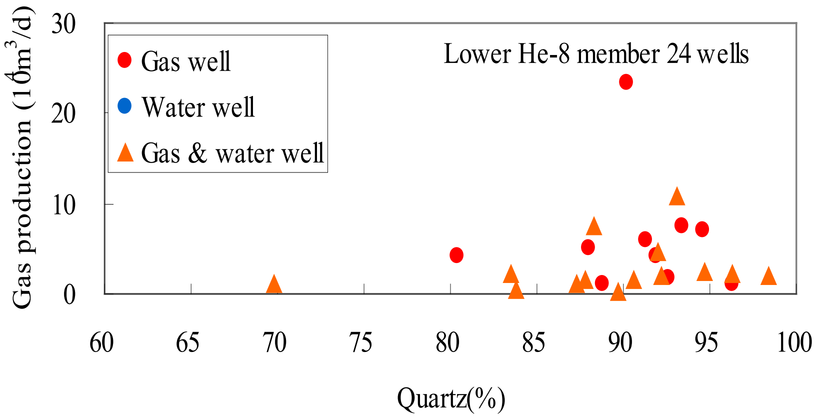
The reason is that the accumulation of tight gas occurs mostly in the vicinity of source rocks and the migration is short distanced. Accordingly, the amount of gas escapement from the migration process is extremely smaller than produced in long distanced migration as in conventional accumulations.

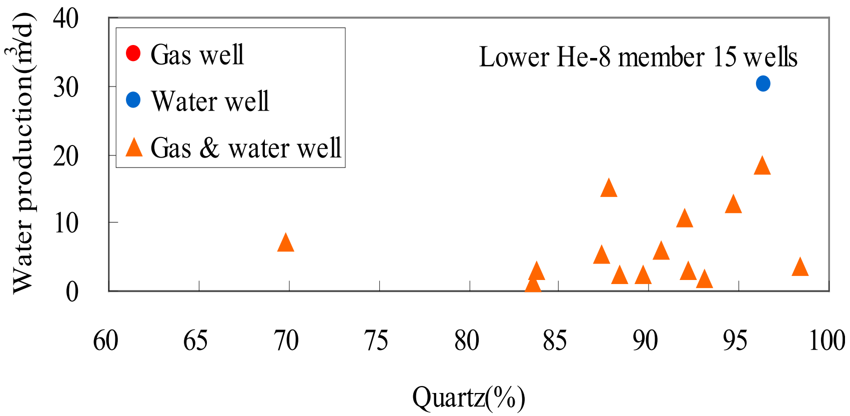


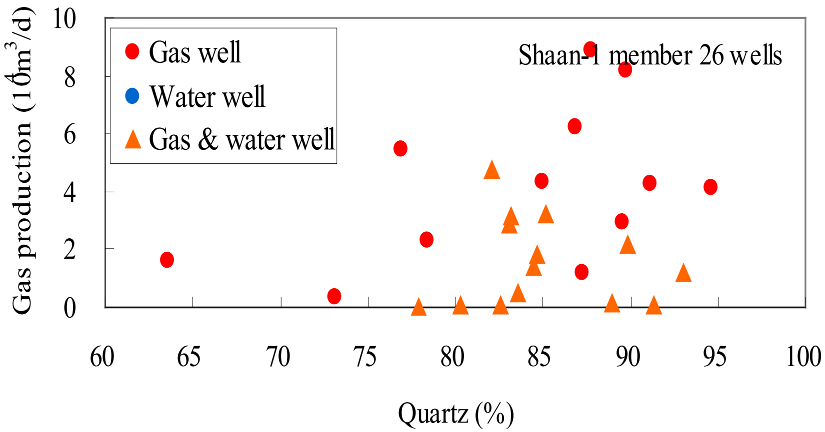
Distribution of gas generation intensity (GGI) and well types of production from Shan-2.

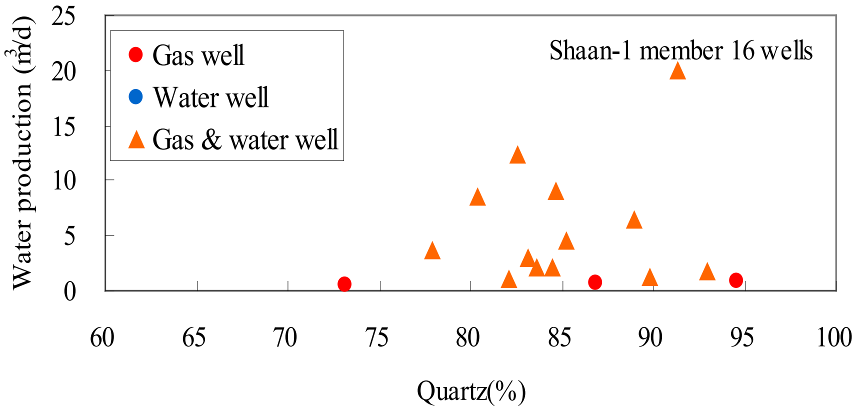
3.3 Reservoir heterogeneity is a decisive factor responsible for the complex distribution of gas and water

Quartz





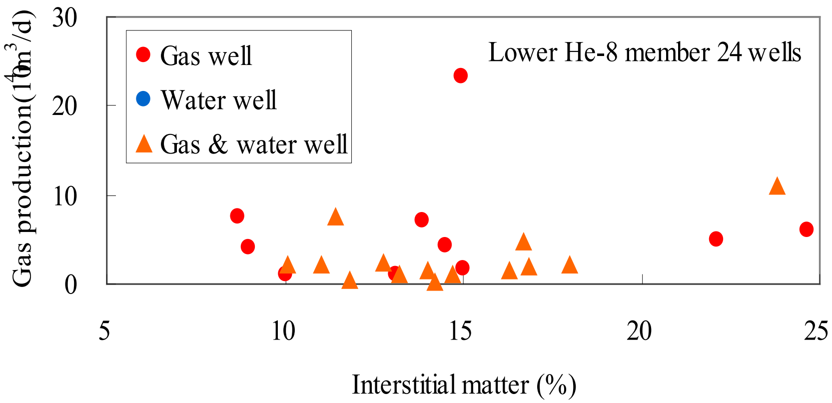


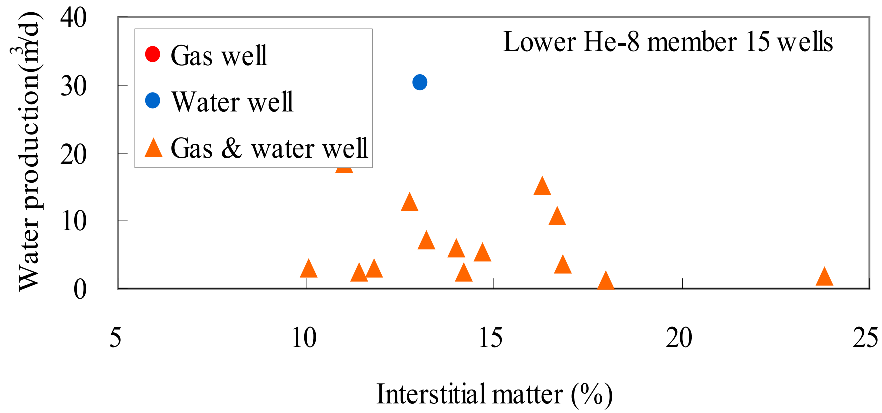


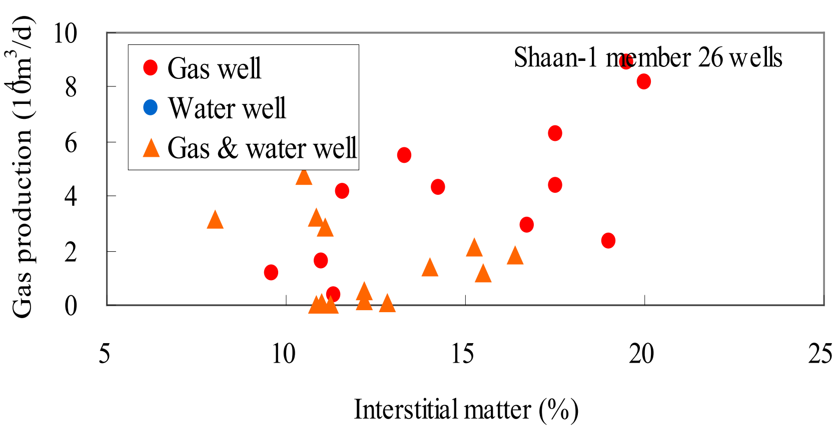
The figures reveal that the relation between the production of gas and water and content of quartz is positive for the Sulige field, showing strong influence of quartz on the production.

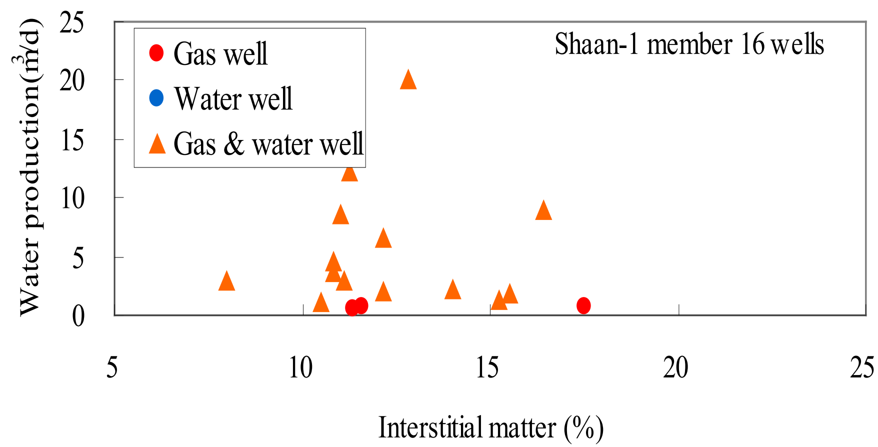
3.3 Reservoir heterogeneity is a decisive factor responsible for the complex distribution of gas and water

Interstitial matter





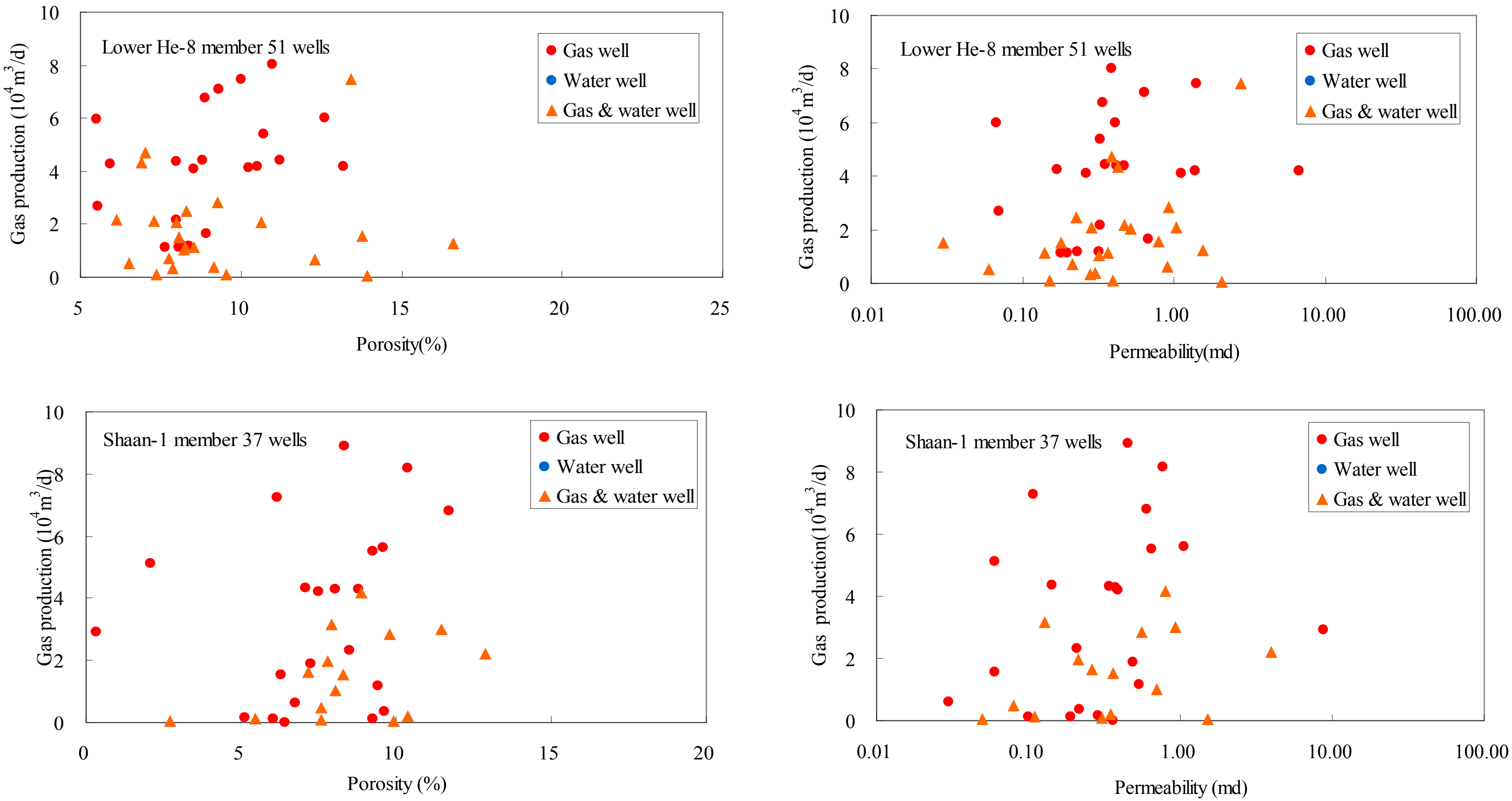




From the figures we can see no clear relation between the content of interstitial matter and production in the Sulige field, showing the impact of the amount of interstitial matter on the production is complex.

3.3 Reservoir heterogeneity is a decisive factor responsible for the complex distribution of gas and water

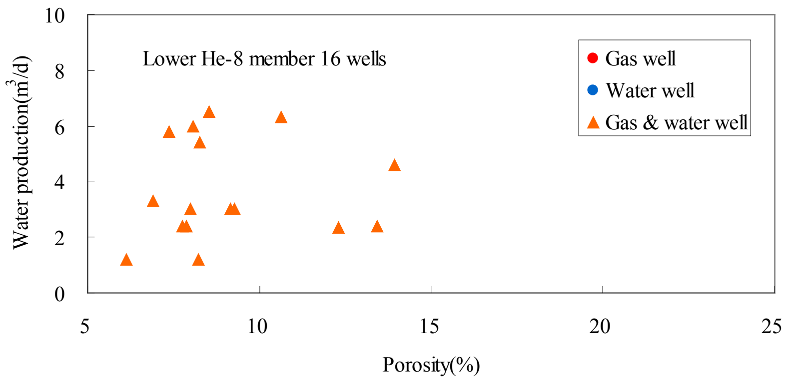
Porosity and permeability

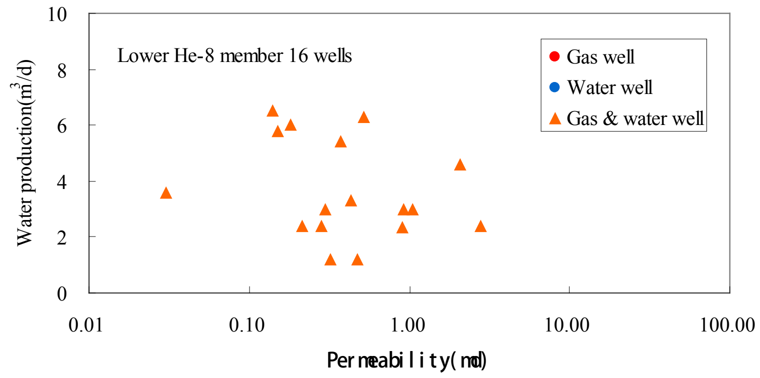


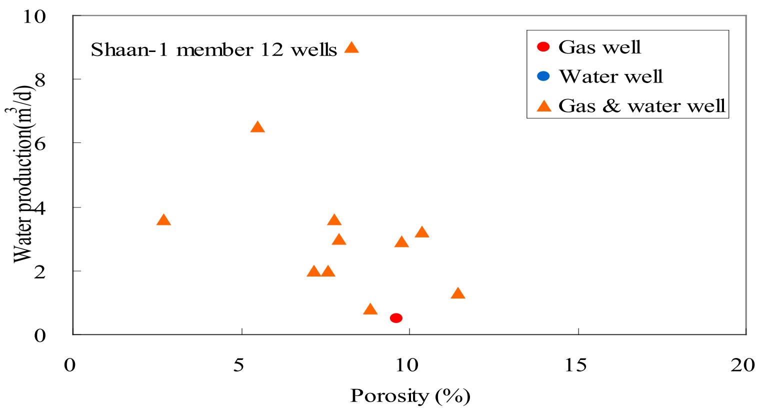
Relation between the porosity and permeability and production of gas in the Sulige field also exhibits a complex pattern, showing porosity and permeability play no important role in controlling the production. In other words, quality reservoirs are not necessarily the abundant storage site for tight gas.

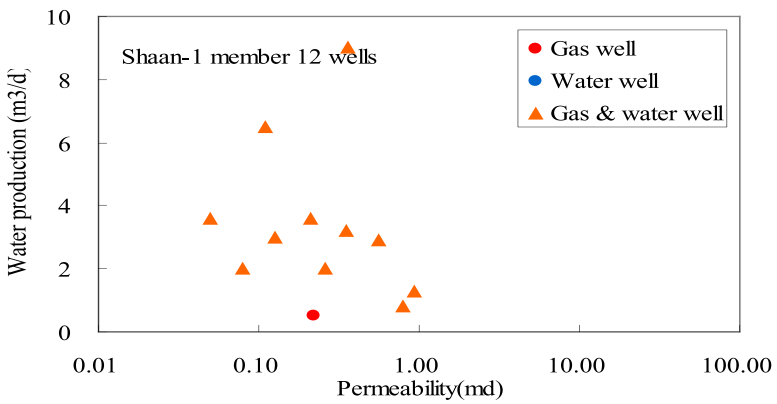
3.3 Reservoir heterogeneity is a decisive factor responsible for the complex distribution of gas and water

Porosity and permeability





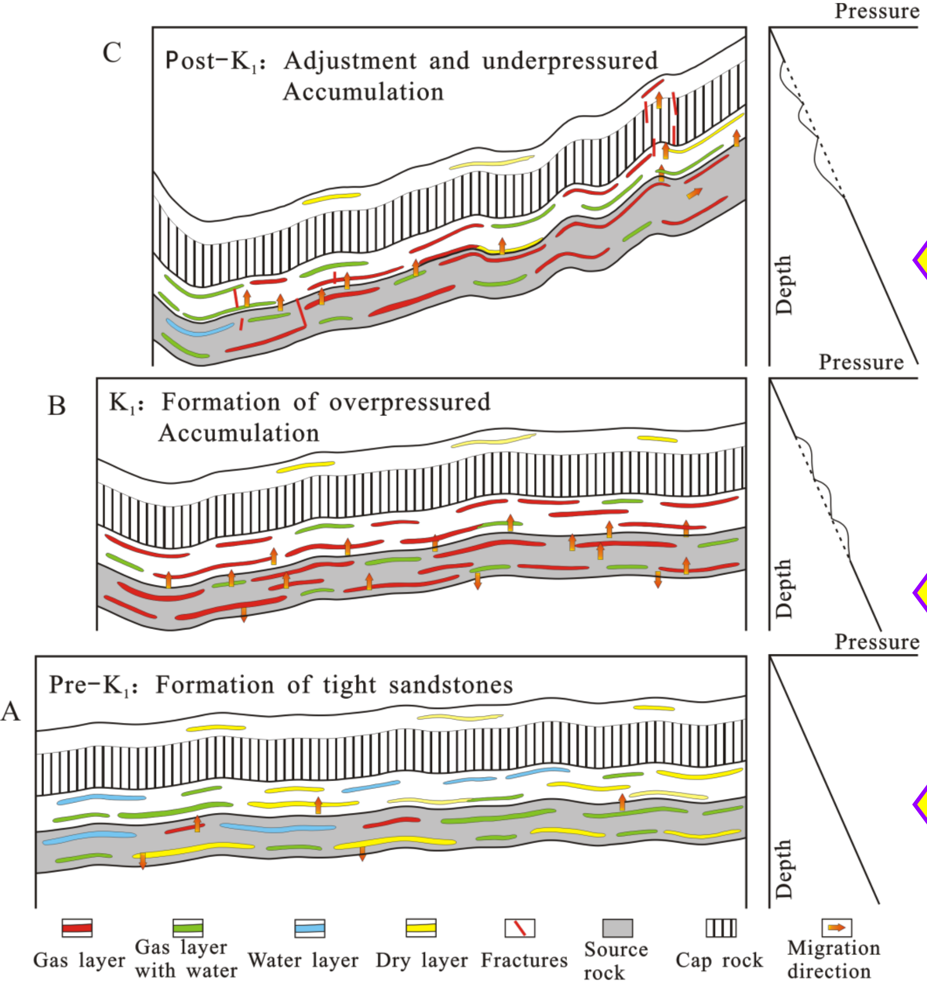




As far as the relation between the porosity and permeability and production of water in the Sulige field is concerned, a slightly negative relation seems existed, indicating quality reservoirs are probably not occupied by water.

3.4 Tectonic alteration is of significant influence on the accumulation and preservation

Tight gas accumulation primarily occurred during the period of late Early Cretaceous. But at the end of Early Cretaceous a strong uplift movement took place to the Ordos Basin, which produced remarkable impact to the tight gas accumulation.



Evolution of quasi-continuous accumulation of Upper Paleozoic tight gas in the Ordos Basin

Post-Early Cretaceous:

Adjusting of accumulations and formation of underpressured tight gas accumulation.

- Reduction of temperature and pressure caused by the uplift, leading to underpressured accumulation.
- adjusting of primary accumulation, leading to secondary accumulations.
- Desorption of absorbed gas, leading to re-charge.

Early Cretaceous:

High intensity charge and formation of overpressured tight gas accumulation.

Pre-Cretaceous:

Initial stage for reservoirs to get tight and gas to charge.

4.Conclusion

■ Tight gas accumulations in Upper Paleozoic of the Ordos Basin are neither typical traditional lithologic (or stratigraphic) entrapment nor typical unconventional continuous accumulation. In fact, they are a transitional type between conventional and unconventional accumulations, which is termed as quasi-continuous type.

■ Quasi-continuous accumulation is defined as such an accumulation that consists of numerous small- to medium-sized lithologic traps or sweet spots that are connected or half-connected laterally and stacked vertically and characterized by wide quasi-continuous distribution, without defined boundaries and reversed gas-water occurrence.

■ The Upper Paleozoic tight gas accumulation and distribution is largely controlled by regional structural background, source condition, reservoir heterogeneity, and post-accumulation tectonic alteration. As such, the accumulation have undergone 3 stages of evolution:

Pre-Cretaceous: Initial stage for reservoirs to get tight and gas to charge.

Early Cretaceous: High intensity charge and formation of overpressured tight gas accumulation.

Post-Early Cretaceous: Adjusting of accumulations and formation of underpressured tight gas accumulation.

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