Gas accumulation rules and exploration prospects of volcanic rocks of deep formations in Songliao basin, northeast China

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Abstract: Deep formations of Songliao basin are defined as between basement and second member of Quantou formation in lower Cretaceous, including later Jurassic Huoshiling formation, early Cretaceous Shahezi formation, Yincheng formation, Denglouku formation and 1-2 members of Quantou formation. Songliao basin was made up of groups separated fault depressions in Shahezi age of early Cretaceous.

The volcanic rocks in Yincheng and Huoshiling formations are the major reservoirs for deep gas. By the means of systematically analyzing the form conditions, accumulation patterns and exploration prospects of the deep gas, it is suggested that the deep volcanic gas pools are characterized by the short distant migration for gas, locating around main trough and along the fault. The existence of deep volcanic gas pools are controlled by source rocks. High quality volcanic reservoir takes controls of the extent of the gas pools. The locations and high production of volcanic gas pools are controlled by faults. Generally, the source rocks, reservoirs and faults all make the contribution to the formation of volcanic gas pools. From the point of view of the forming conditions of deep volcanic gas pools, it is suggested that the beneficial tectonic zone with both development of the source rock and the volcanic reservoir are the favorable exploration zone.

For exploration prospects, the most practical fault depressions are Xujiaweizi, Changlin and Yingtai, the replacing ones are Gudian, Shuangliao, Wangfu, Shuangcheng and Dehui fault depressions, while the prepared ones are Daan, Renminzhen, Lishu, Yushudong, Yushu, Yingshan, Gulong and Lindian fault depressions and so on. For deep gas exploration, the volcanic rock is the major exploration object, the minor one is the glutenite. The mainly exploration layer system is Yingcheng formation. The replaced layer systems are Huoshiling formation, Shahezi formation and Denglouku formation.

Key words: Songliao basin; deep fault depression; volcanic gas pool; gas accumulation rule; gas exploration prospect

0 Introduction

Songliao basin is a continental basin developed on Paleozoic orogenetic basement, located in northeast China, with a two-layered framework of which the upper is depression (above and include Denglouku formation), and the lower is fault subsidence between Huoshiling age and Yingcheng age [1], and was made up of groups separated fault depressions in Shahezi age of early Cretaceous （**Fig.1**）. The deep zone of Songliao basin refers to formations between basement and second member of Quantou formation in lower Cretaceous, including later Jurassic Huoshiling formation, early Cretaceous Shahezi formation, Yincheng formation, Denglouku formation and 1-2 members of Quantou formation (**Fig.2**). Volcanic rocks mainly developed in Yingcheng and Huoshiling formations, which are the target layers of gas exploration in deep zone of Songliao basin. Volcanic rock reservoirs become the primary gas reservoir in deep zones. Until the end of 2009, the proved geological reserves of volcanic rocks are $2700\times10^8 m^3$, and are about 80 percent of all the proved reserves in deep zone.

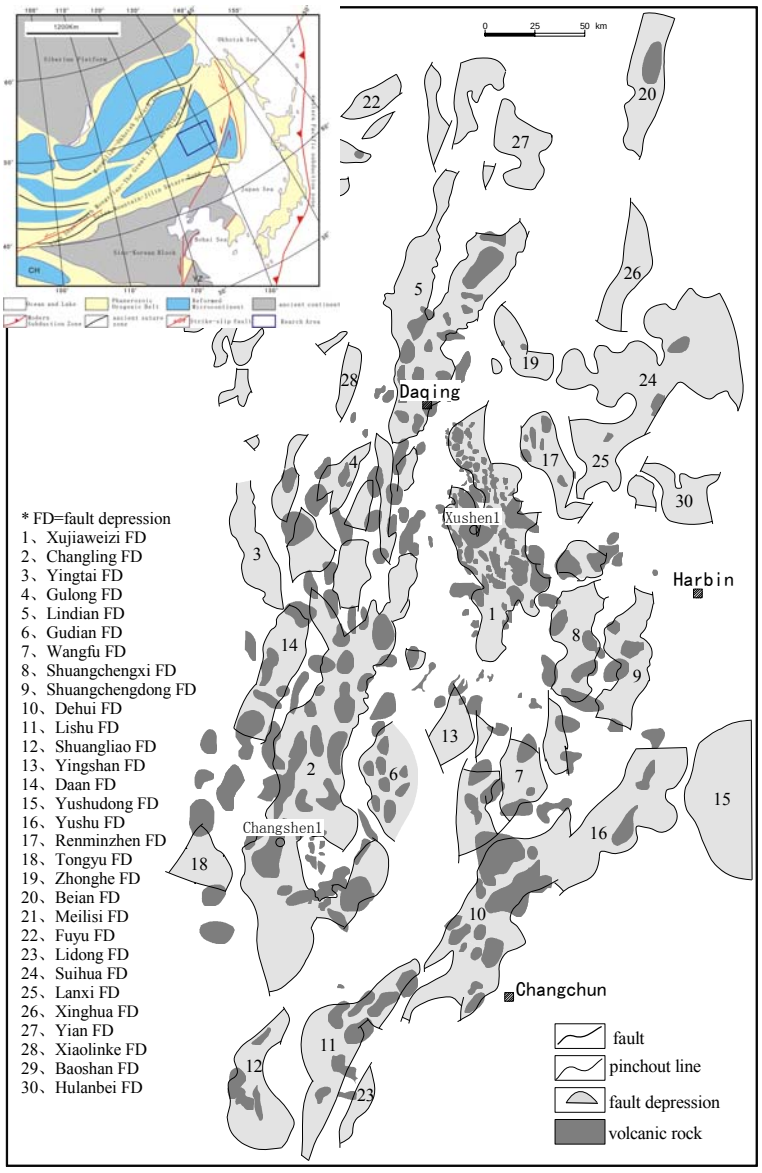
With the further development of the deep volcanic reservoir exploration, problems become more obvious, i.e. exploration in fault depressions such as Gulong, Lindian, Dehui and Shuangcheng which are initially considered with good accumulation conditions don't achieve any key breakthrough. In Changling fault depression only Changling No.1 structure drill out gaseous hydrocarbon while others are all carbon dioxide. In general, the enrichment regularity of deep volcanic gas reservoir remains unclear. Based on systematical analysis of accumulation conditions and typical gas reservoir, discussions focus on the enrichment regularity of volcanic gas pools and prediction of exploration perspectives, which have great significance on volcanic gas reservoir exploration in deep Songliao basin.

1 Analysis on accumulation conditions of gas pool

1.1 Source rock

According to well drilling, the deep formations developed multiple-episode source rocks mainly composed of mud stone and coal, which are upper Jurassic Huoshiling formation, lower Cretaceous Shahezi, Yingcheng and Denglouku formations upward. Gas sources comparison reveals that the source rock sedimented in Shahezi rifting period is the dominant source rock for

deep volcanic gas pools[2] .



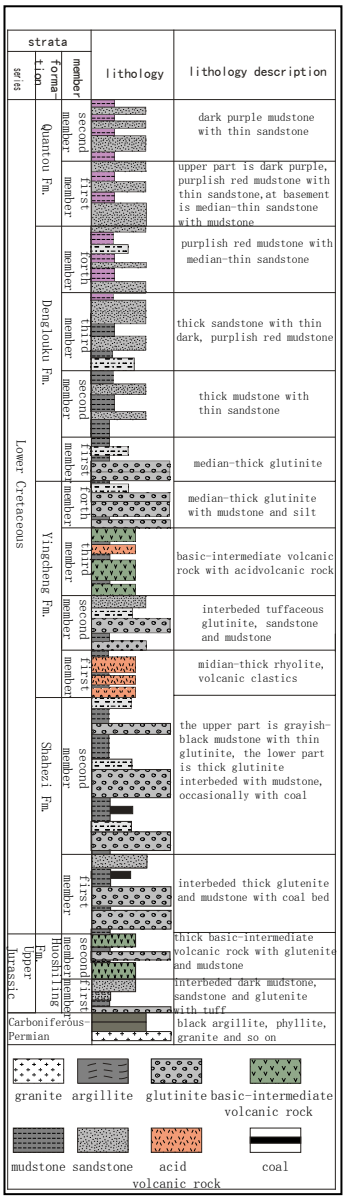


Fig.1. Distribution Map of fault depressions in deep Songliao basin（the insert map illustrates the regional tectonic setting）

Fig.2. Comprehensive stratigraphic column of deep Songliao basin

Shahezi formation is made up of clastic rocks deposited during intensely rifting period, in which dark mudstone is extensively developed and coal bed is drilled in many wells. In Well Songshen 3, the total thickness of dark mudstone of Shahezi formation is 384 meters while that of coal is 105 meters. The primary source rocks in Shahezi formation are mudstone in deep to half-deep lacustrine facies and coal in swamp facies. The total organic in dark mudstone is generally between 2%-4% and higher 6%-15% in mudstones near to coal. Hydrocarbon potential

is 0.52-4.08 mg/g. The organic type of the source rock in Shahezi formation is mainly Ⅱ-Ⅲ, generally speaking, with high quality and thickness. So, source rock of Shahezi formation widely distributed is the most important source rock in deep Songliao basin[3].

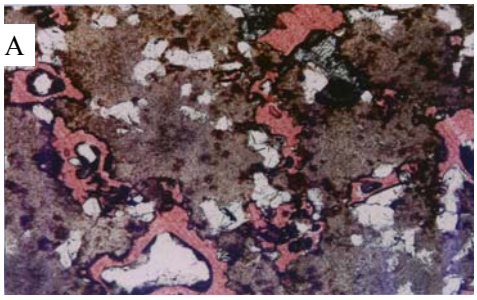
1.2 Volcanic rock reservoir

Because buried depth has little impact on volcanic reservoir physical property, compared with clastic rock reservoir, volcanic rock reservoir has more advantages in deep gas exploration. Many types of volcanic rock reservoirs in Songliao basin mainly include tuff, flood tuff, rhyolite, basalt, andesite, trachite, andestic basalt, dacite, lava breccia and so on. The volcanic lithology which controls formation and growth of the pores, is thought as a base of formation of high-quality reservoirs. The acidic volcanic rocks are suggested to be the best type of reservoir rocks on the base of comparative study different rock types of volcanic rock reservoirs with different physical properties. The volcanic lithofacies control distribution of high-quality reservoirs in independent volcanic edifice. Explosive facies around volcanic crater and the top of the flood facies are the best favorable zone for reservoirs [4].

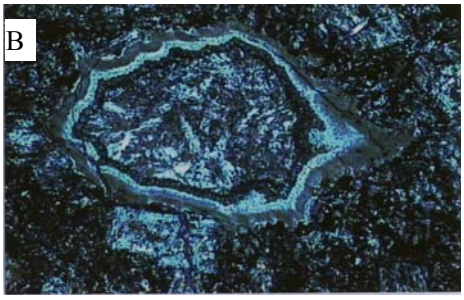
Via observation of casting and conventional thin sections, pores are divided into primary pores and secondary pores according to genetic classification. Primary pores include: primary air hole, amygdule, intergranular pore and intercrystalline pore, in which the first three are main primary pores in this area (**Fig.3. A, B, C**). Secondary pores include inner-crystalline dissolved pore, shard dissolved pore, matrix dissolved pore and modic pore, inner-crystalline dissolved pore, matrix dissolved pore and modic pore are well developed（**Fig.3.D、E、F**）.

The spaces of volcanic rock reservoir can be divided into pores and fractures. In this article, two combination types which are primary pore-fracture and secondary pore-fracture are classified according to the characteristic of volcanic reservoir space. Typical combination types of primary pore-fracture group are air hole-amygdule-fracture, stone bubble-fracture and intergranular pore-matrix shrinkage fracture-mineral cleavage crack-fractures. Typical characteristics in well Xushen 201 in Xujiaweizi depression, where late tectonic actions created fractures that make separate pores and amygdales interconnected with each other to form effective volcanic reservoir spaces which provide good reservoir conditions for forming commercial gas pools. Typical combination of secondary pore-fracture group is matrix dissolved pore-phenocryst dissolved pore-fracture. Primary vesicular and phenocryst dissolved pores resulting from hydrothermal

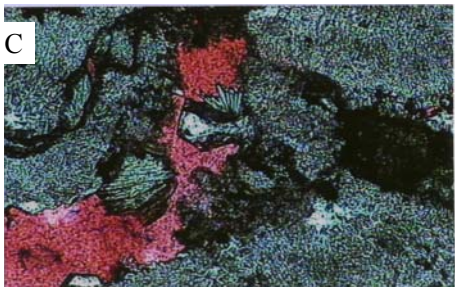
activities are connected with each other through structure fractures formed late or in the corresponding period (**Fig.3.D**). i.e. Well Wang903 in Xujiaweizi with typical secondary pore-fracture combination developed in depth between 2962-3037 meters and get a commercial natural flow of more than 5×10^4 m^3/d after fracturing.



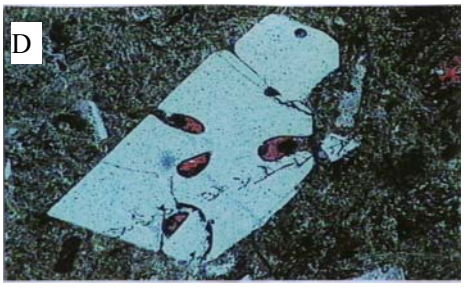
Air hole distributed in belts, surface porosity is 14%, pyromeride, Well Shengshen2-6, 2938.11m, k_1yc, 125 times (-)



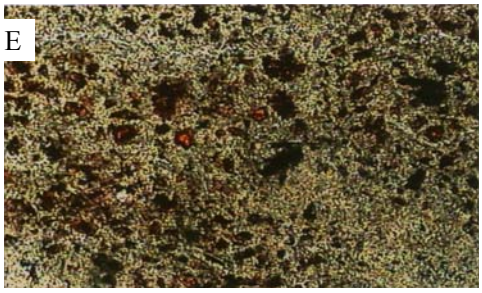
Intraamygdule pore, Well Songshen2, 2969.42m, k_1yc, 50 times (-)



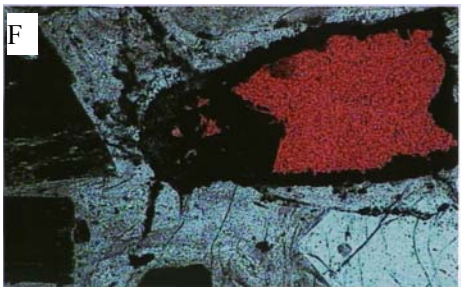
Intergranular pore, volcanic breccia, Well Xushen1, 3634.25m, k_1yc, 100 times (-)



Intracrystalline dissolved pore, Well Fangshen701, 3585.93m, k_1yc, 50 times (-)



Primary vesicular, Well Shengshengeng2, k_1yc, 100 times (-)



Crystal moldic pore, clinkery crystal tuff, Well Xushen1, 3532.55m, k_1yc, 100 times (-)

Fig.3. Different types of air hole in volcanic rocks Songliao basin

According to features of porosity and permeability, statistical analysis based on data from 70 wells shows that flood tuff has best volcanic reservoir property in Songliao basin, with porosity of 0.6%-24.6%, and with permeability ranges from 0.001 $\times10^{-3}\mu m^2$ to $11.1\times10^{-3}\mu m^2$. The second high quality rock is rhyolite with porosity of 0.4%-23% and permeability ranges from 0.001 $\times10^{-3}\mu m^2$ to $0.88\times10^{-3}\mu m^2$, generally qualified as good - medium rank reservoir .

1.3 Leading passage

Fracture is not only an important constituent of reservoir space but also a significant percolation and migration passage in deep zone Songliao basin, and it's one of the key factors that affect high hydrocarbon production. According to core observation and microscopic identification, many types of fractures exist in this area including structural fracture such as high angle structural fracture and non-structure fractures. Non-structure fractures include exploding fracture, horizontal fracture, intergranular fracture and so on (**Fig.4**.). In general, structural fracture is the majority of the fractures.

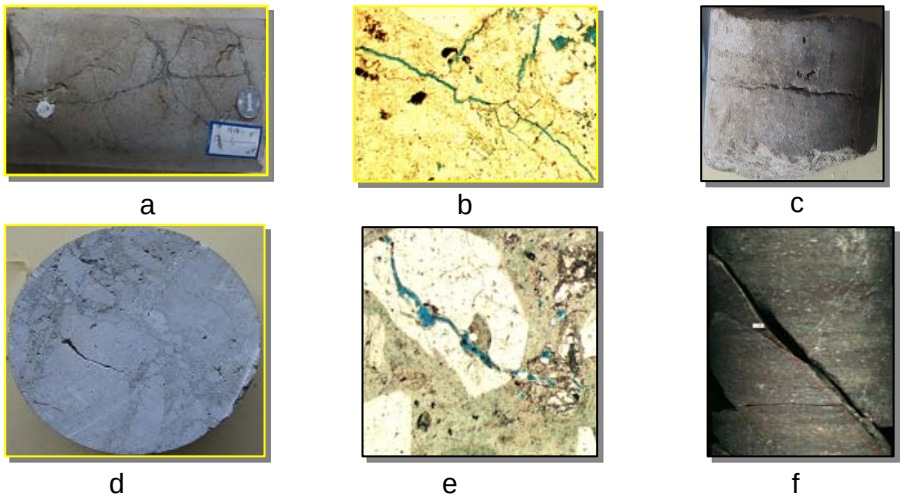


Fig.4. Different types of fractures in volcanic rocks

（a exploding fracture, b microfracture, c horizontal fracture, d intergranular fracture, e corroded fissure, f high angle fracture）

On the other hand, fractures not only connect separate primary air pores in volcanic reservoir but also increase the reservoir spaces.

For example, the reservoir rocks in well SS1 at the depth of 3500-3600 meters are contemporaneous volcanic breccia bearing rhyolite which belong to lower flood facies, and looked upon as good reservoir with few primary pores but well developed fractures. Furthermore, fractures are important percolation passage underground, by which organic acid seeping promotes the forming of dissolved pores and fractures, thus improve the reservoir porosity. Fractures are also important migration passage profitable for reservoirs to achieve high hydrocarbon yield, i.e. a large number of vertical fractures exist in Well Shengshengeng2 and Xushen1-2 may be the key factor for high yield.

2 Enriching rules and distribution

2.1 Source controls the gas pool areal distribution

Statistical study on deep gas pools in Songliao basin shows that deep gas pools are distributed near source rocks of Shahezi formation[2]. Among the 69 wells involved in this study, there are 52 wells with a distance less than 10 kilometers from source rocks and only four of them are dry layer mainly because the reservoir is too tight. Fourteen wells have a distance of 10-20 kilometers from source rocks with six gas show wells, four water layer wells, and four dry wells. Wells that are more than 20 kilometers away from source rocks have no gas show, and most are dry.

Main reason for the failure of well Changshen3 southern Songliao basin is that more than 20 kilometers long distance from source rocks, and gas can rarely migrate through such a long distance to accumulate. Shallow gas pools derived from deep source in the upper formations of Shuangcheng depression are still distributed around deep source rocks although experienced post-reformation, which further proves that gas accumulation is largely controlled by source rocks.

2.2 High quality volcanic rock reservoir controls the gas pool local distribution

The main reservoirs of deep Songliao basin are volcanic which is the major reservoir and clastic reservoir. As reservoir, volcanic rock has its own particularity with main difference from sedimentary rock is that compaction has little effect on its property. In other words, porosity of volcanic rocks decreases slowly with the increase in depth (**Fig.5.**). Volcanic rocks can still have good property at the depth of 4000-5000 meters, where porosity is still up to 18% at depth of 4200 meters. The porosity is 4.8%-6.2% in well Gushen1 at the depth of 4700 meters. But the porosity of sandstone decreases rapidly under the depth of 3000 meters. The porosity of conglomerate is 6%-10% at the depth of 4000 meters, which is up to the reservoir standard, but it's only 2% at 4500 meters. Thus volcanic reservoir is a significant type of reservoir in deep Songliao basin, which extends the depth limit for deep gas exploration.

Study on volcanic reservoirs show that explosive facies around volcanic crater and the top of the flood facies are the best favorable zone. Exploration in Xujiaweizi fault depression indicates that most industrial gas flow wells concentrate at or near volcanic crater such as well Xushen1, Xushen3, Shengshen 2-1 and so on, while well Xushen16 located far away from volcanic crater don't get achievement.

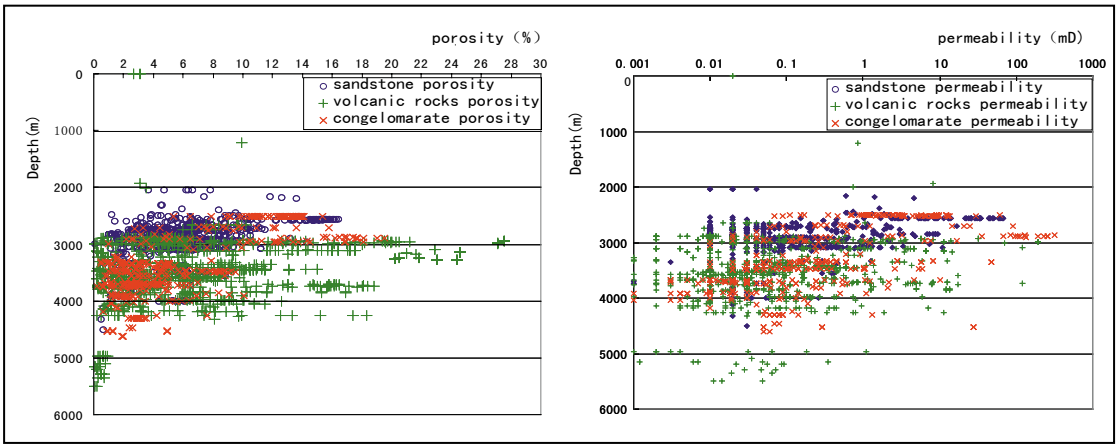


Fig.5 Porosity and permeability changes with depth applied to different rock types from deep zone of Songliao basin

2.3 Fault controls the location and high yield of volcanic gas pool in fault depression

Faults control the gas pool forming process in fault depression basin on four aspects. Firstly, faults affect the forming of fault depression and the deposition of source rock and also control the scale and subsidence of fault depression. For example, the NNW controlling faults or NNW part of controlling faults control the formation of fault trough rich in hydrocarbon with characteristics of large scale of subsidence, good quality source rock and big generation intensity result. Xujiaweizi and Changling fault depressions are typical examples with great generation intensity of $132.5\times10^8 m^3/km^2$ and $101\times10^8 m^3/km^2$, respectively. Until now, the six gas pools discovered in Changling fault depression all distribute around NNW Changling fault trough. Secondly, faults control the distribution of the volcanic rocks. Discordogenic faults formed under the rift-extensional tectonic setting may induce upwelling of magama origined from partial melting of subcontinent or mantle and be taken as passageways for upwelling of magama. On the other hand, the inner earth power release with volcanic eruption at the joint of many discordogenic faults. For example, volcanic rocks in Xujiaweizi fault depression distribute along three NNW fault belts, Xuxi, Xuzhong and Xudon respectively, where many great gas fields have been found [5, 6, 7]. Close to fault belt, there are many fractures which link pores in volcanic reservoir to increase effective reservoir space and are also percolation paths for underground fluids that improve reservoir property by promoting the forming of secondary pores. Thirdly, faults control the formation of traps. Because of the variations of displacement and inclination of faults, nosing

structures (such as Xingcheng gas field) are usually developed along the downthrown block of faults and stratigraphic overlap (such as the stratigraphic overlap traps occurred in the basal glutenite of Denglouku formation in well Fangshen5, Changde gas field, Xujiaweizi fault depression) are formed because of the upthrown blocks. On the contrary, reversal activities of controlling faults result in the formation of reversal nosing structure on the downthrown block. Fourthly, faults are the main migration passages in volcanic gas pool and play an important role in combining source rocks and traps. By now, all the discovered volcanic gas pools distribute along faults except volcanic lithological gas pools (**Fig.6**). In short, faults in the fault depression play a controlling role of migration and accumulation of volcanic gas pools.

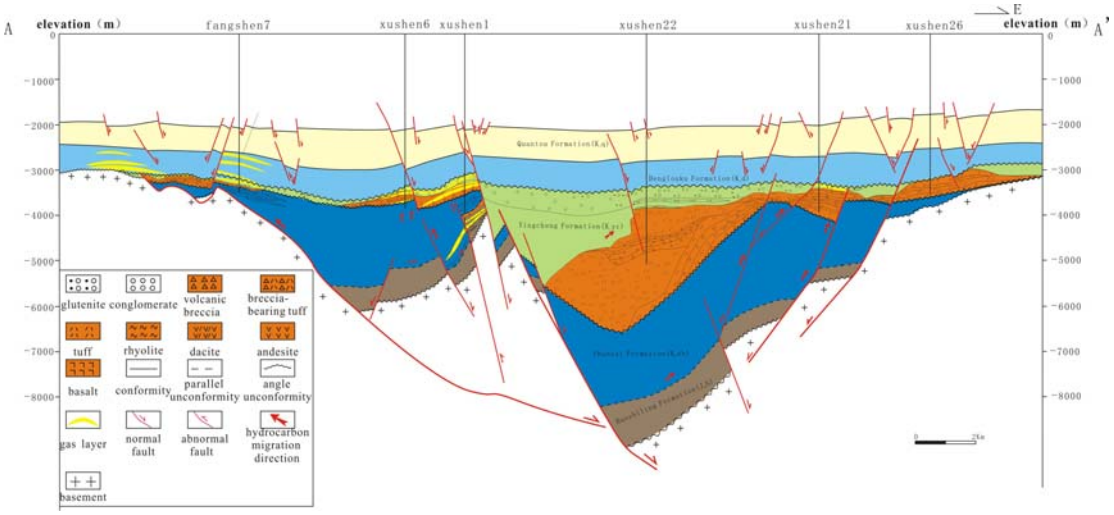


Fig.6. Gas pool profile wiht Fangshen2-Xushen1-Xushen26 wells in Xujiaweizi fault depression

3 Exploration perspectives

The deep zone of Songliao basin is made up of a group of separated small fault depressions, and each depression consists of one or several sublevel fault troughs[8]. Gas exploration potential of deep fault depressions is related to scale of fault depression, distributed area and thickness of source rock in Shahezi formation, distributed area of volcanic rocks and post-reformation activities. Fault depressions with great resources are priority to prospective exploration in the deep zone. Besides, the main prospective target for deep zone exploration is volcanic reservoir with lithologic and litho-tectonic types[9]. Areas where source rocks and volcanic rocks are interbeded well with each other are favorable zones for the formation of volcanic gas pool.

Comprehensive study on the structure and scale, source rocks, volcanic reservoir and tectonic

evolution of deep fault depressions shows that the most practical fault depressions for exploration in deep zone are Xujiaweizi, Changling and Yingtai where big gas field and industry gas wells have been found and the gas resource is up to $21414\times10^8m^3$ which occupies 60% of the total gas resource in deep zone. Important replacing fault depressions for exploration include Gudian, Shuangliao, Wangfu, Shuangcheng and Dehui, with the total potential resources of $13273\times10^8m^3$. Prepared fault depressions are Daan, Renminzhen, Lishu, Yushudong, Yushu, Yingshan, Gulong and Lindian fault depressions and so on with the total potential resources of $3127\times10^8m^3$.

The breakthrough of well Lingshen1 in Gudian fault depression got industry gas flow in glutenite of Huoshiling formation illustrates new formation in deep zone for gas exploration and brings about great confidence and potential in glutenite exploration on overlapped alternative formations such as Shahezi, Yingcheng and Denglouku. Besides, volcanic rock exploration in Huoshiling formation in Wangfu and Shuangliao fault depressions also achieve great breakthroughs, providing new areas for deep volcanic rock exploration. In brief, volcanic rock is the high quality target for gas exploration in deep zone of Songliao basin and glutenite as next. Yingcheng formation is the most important exploration layer and Huoshiling, Shahezi and Denglouku formations are favourable alternative layers.

4 Conclusions

Based on above systematical analysis on forming conditions, regular pattern of accumulation and exploration prospect of deep volcanic gas pools, conclusions can be drawn as follows.

（1） The deep volcanic gas pools are characterized by the short distant migration for gas, locating around main trough and along the fault. Source rock controls the gas pool areal distribution, and high quality volcanic rock reservoir controls the gas pool local distribution, and fault controls the location and high yield of volcanic gas pool in fault depression. Generally, the source rocks, reservoirs and faults all make the contribution to the formation of volcanic gas pools. So it is suggested that the beneficial tectonic zone with both development of the source rock and the volcanic reservoir are the favorable exploration zone.

（2） For exploration prospects, the most practical fault depressions are Xujiaweizi, Changlin and Yingtai, the replacing ones are Gudian, Shuangliao, Wangfu, Shuangcheng and Dehui fault depressions, while the prepared ones are Daan,

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（3） For deep gas exploration, the volcanic rock is the major exploration object, the minor one is the glutenite. The mainly exploration layer system is Yingcheng formation. The replaced layer systems are Huoshiling formation, Shahezi formation and Denglouku formation.

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