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Fault Systems and their Control of Deep Gas Accumulations in Xujiaweizi Area

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Abstract: A study of faults and their control of deep gas accumulations has been made on the basis of dividing fault systems in the Xujiaweizi area. The study indicates two sets of fault systems are developed vertically in the Xujiaweizi area, including a lower fault system and an upper fault system. Formed in the period of the Huoshiling Formation to Yingcheng Formation, the lower fault system consists of five fault systems including Xuxi strike-slip extensional fault system, NE-trending extensional fault system, near-EW-trending regulating fault system, Xuzhong strike-slip fault system and Xudong strike-slip fault system. Formed in the period of Qingshankou Formation to Yaojia Formation, the upper fault system was affected mainly by the boundary conditions of the lower fault system, and thus plenty of multi-directionally distributed dense fault zones were formed in the T_2 reflection horizon. The Xuxi fault controlled the formation and distribution of Shahezi coal-measure source rocks, and Xuzhong and Xudong faults controlled the formation and distribution of volcanic reservoirs of Y1 Member and Y3 Member, respectively. In the forming period of the upper fault system, the Xuzhong fault was of successive strong activities and directly connected gas source rock reservoirs and volcanic reservoirs, so it is a strongly-charged direct gas source fault. The volcanic reservoir development zones of good physical properties that may be found near the Xuzhong fault are the favorable target zones for the next exploration of deep gas accumulations in Xujiaweizi area.

Key words: deep gas accumulation, fault system, gas source fault, volcanic reservoir, Xujiaweizi

1 Introduction

Located in the north of Songliao Basin, the Xujiaweizi area has a double-layer structure faulted in the lower part and uplifted in the upper part vertically and is a superimposed basin with superposed rift and depression (Yun et al., 2008; Zhang et al., 2011; Wang et al., 2011). The Xujiaweizi rift is a secondary structural unit in deep strata of the Songliao Basin and has a NNW strike. The rift is partitioned by faults from an ancient central uplift zone westwards, and is of transition to the Shangjia-Chaoyanggou uplift zone in slope form eastwards. The Xujiaweizi rift has a tectonic framework including three longitudinal structural zones and two transverse ones. The three longitudinal structural zones are the Xuxi fault slope zone, Xuzhong volcanic uplift zone and Xudong slope zone, and the two transverse structural zones include the Songzhan low uplift and Fengle low uplift. The Upper Jurassic Huoshiling Formation (Fm.) (J_3h), Lower Cretaceous Shahezi Fm. (K_1sh), Yingcheng Fm. (K_1y), Denglouku Fm. (K_1d) and Quantou Fm. (K_1q), Upper Cretaceous Qingshankou Fm. (K_2qn), Yaojia Fm. (K_2y), Nenjiang Fm. (K_2n), Sifangtai Fm. (K_2s) and Mingshui Fm. (K_2m) and Cenozoic strata are developed vertically in the rift from top to bottom (Liu et al., 2006), where the Huoshiling Fm. to Denglouku Fm. are deep oil bearing systems. Up to now, eight deep gas fields such as Anda, Wangjiatun, Shengping, Changde, Xushen, Xudong, Fengle and Zhaozhou have been discovered in the rift. Exploration practice has proven that natural gas comes mainly from the coal-measure strata in the Shahezi Fm. (Xu et al., 2008) and the main target formations are volcanic rocks in the Y1 Member and Y3 Member (Cheng, 2005; Yan et al., 2008; You, 2008; Yu et al., 2010). Predecessors have already made a great number of studies of volcanic reservoirs (Lei et al., 2005; Wang et al., 2008; Hu et al., 2008; Shi et al., 2011; J. Dewit et al., 2012), and more an increasing number of scholars have already realized that

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faults are one of leading factors for controlling volcanic eruptions (Tang et al., 2001; Yang et al., 2006; Wang et al., 2007; Fu et al., 2008; Wang et al., 2008; Isolde B. et al., 2010; Charles Wicks et al., 2011). However, as a part of the Songliao Basin, the Xujiaweizi area went through three structural evolution stages such as extensional rift stages in the Late Jurassic Huoshiling period to Early Cretaceous Yingcheng period, a thermal-shrinkage depression stage in the Early Cretaceous Denglouku period to the early period of the Late Cretaceous and extrusion and an inversion stage in the late period of Late Cretaceous to Cenozoic (Liu et al., 2006). Different deformation intensities and deformation properties of faults in different evolution stages had different effects on the geologic conditions for gas migration and accumulation, so that there is a large difference in gas enrichment law in different regions in the Xujiaweizi rift. Therefore, it is necessary to make a symmetrical study of the fault systems (Tang et al., 2001) and their formation and evolution in the area, thereby ascertaining the fault's role in controlling deep gas migration and accumulation and then providing a theoretical basis for next exploration of the natural gas in the deep strata of the rift.

2 Divisions of Fault Systems

Songliao Basin went through three evolution stages including a rift stage, depression stage and inversion stage (Yin et al., 2002), and accordingly three structural levels were developed, including a rift structure level composed of the Huoshiling Fm., Shahezi Fm. and Yingcheng Fm., a depression structure level composed of the Denglouku Fm., (N1 and N2 Members) and an inversion structure level composed of N3 and N4 Members in the Cenozoic. Based on the difference in geometric and kinematic characteristics of faults in different structural levels(M.Soledad Velasco et al., 2009), the Xujiaweizi area can be vertically divided into two sets of fault systems, such as the lower fault system and the upper fault system with a T_4 reflection horizon as the boundary (Fig. 1). The two sets of fault systems were of ruptural deformation of different characters in different periods; due to vertical mutual superposition of the fault systems, they control the formation and evolution of the Xujiaweizi area and thus deep gas accumulation and enrichment law.

2.1 Lower fault system

Formed in the rifting stage of the basin, the lower fault system is developed mainly in the strata of Huoshiling Fm. to Yingcheng Fm. The lower fault system consists of five fault systems of different characters (Fig. 2b) including the Xuxi strike-slip extensional fault system, Xuzhong strike-slip fault system, Xudong strike-slip fault system, NE-trending extensional fault system, and the near-EW-trending regulating fault system. They are of mutual dependence and restraint (T.G. Blenkinsop, 2008; Griffith et al., 2010).

2.1.1 Xuxi strike-slip extensional fault system

Located at the west boundary of the Xujiaweizi rift, the Xuxi fault can be divided into two parts, such as the south branch and north branch, and is the main boundary fault controlling the formation and evolution of the Xujiaweizi rift. The fault converges to the tenacious horizontal detachment zone in the middle crust on profile (M.Soledad Velasco et al., 2010).. The fault is from the basement to the T_4 reflection horizon and in part sections, to only T_4^1, so that the strata of the Yingcheng Fm. overlap on uplift. The fault mainly controlled sedimentary filling of the Huoshiling Fm. and Shahezi Fm.; in the period of the Yingcheng Fm., the activities of the fault weakened and it controlled a dustpan-like half-graben rift structure "faulting and steep in the west and overlapping and gentle in the east" (Fig. 2a). Therefore, the fault is of mainly extensional

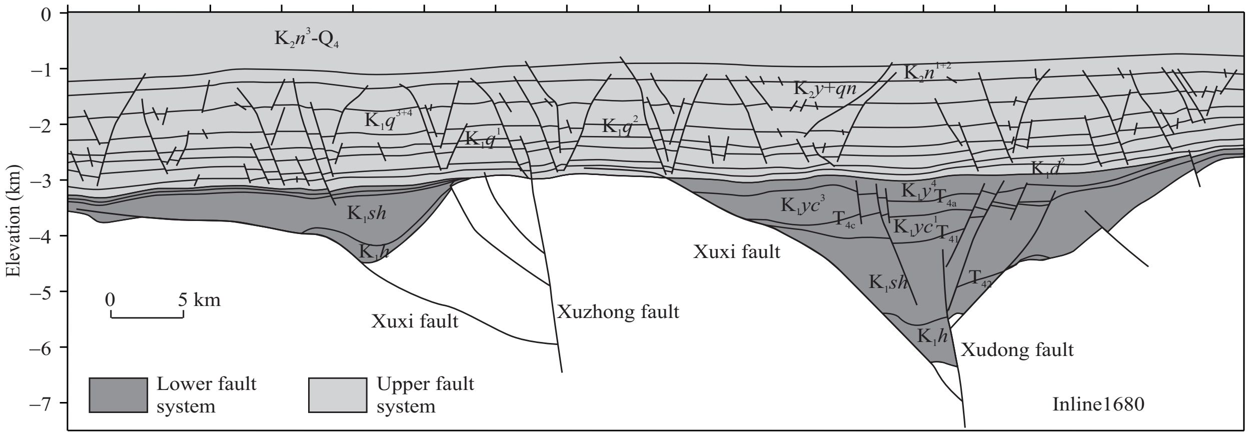


Fig. 1. Vertical fault systems in the Xujiaweizi area (for the profile location, see Fig. 2b).

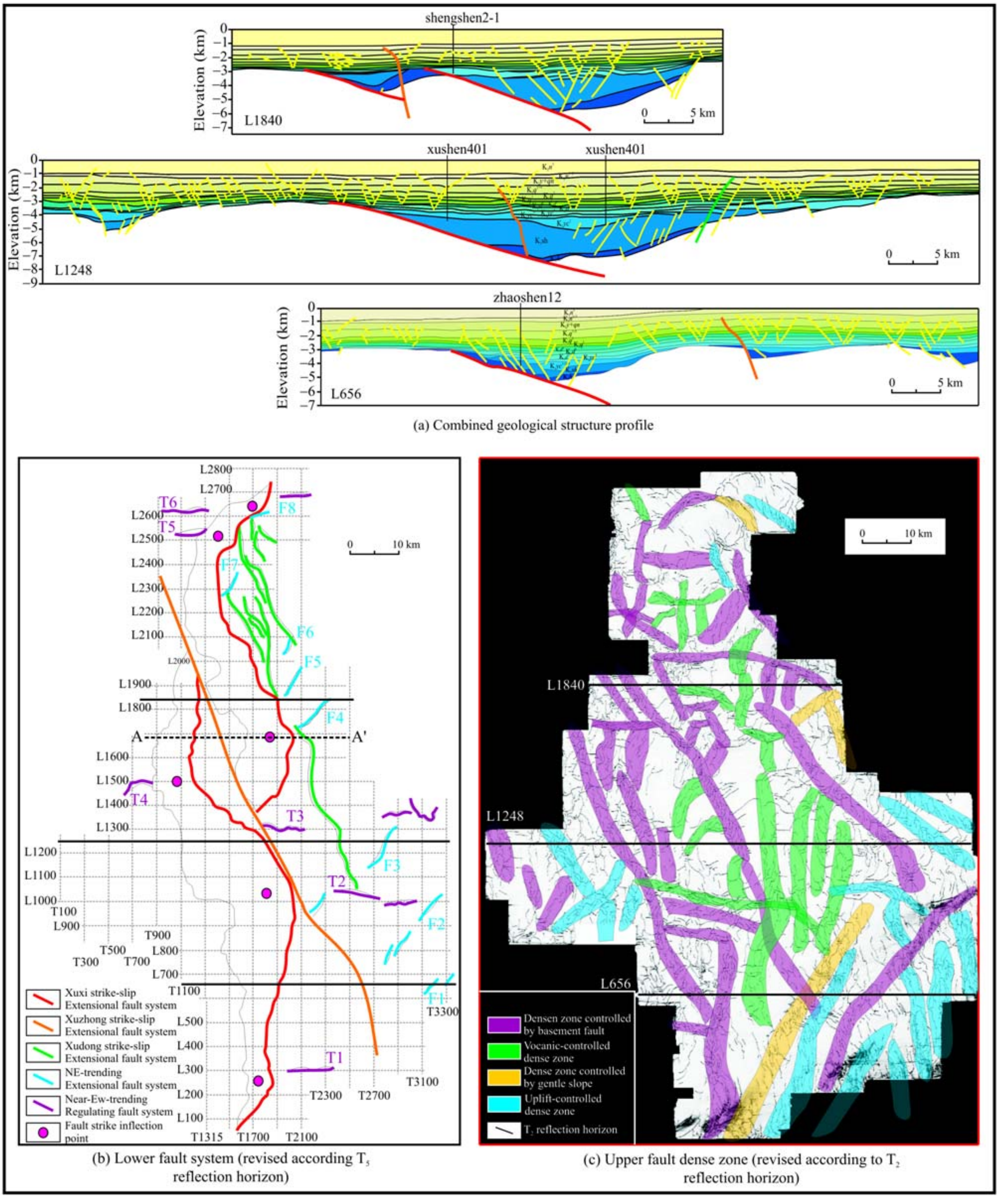


Fig. 2. Lower fault system, upper fault dense zone and combined geological profile in the Xujiaweizi area.

deformation. Having remarkable sectionalization characteristics on plane, the strike of the fault is from near-SN to NNW in the north section and from near-SN to NNW to near-SN in the south section from south to north (Fig. 2b). The fault extension length of the north branch is approximately 75.7 km, and that of the south branch approximately 106.0 km. The vertical throw of the fault is 200–800 m in general. The south and north branches of the fault are distributed in a right-stepped diagonal shape in terms of their combination form (Fig. 2b), and form a "shovel-type fan" fault combination style on profile (Fig. 1), showing dextral strike-slip deformation characteristics.

2.1.2 NE-trending extensional fault system

The overall strike of the deep rift in the Songliao Basin is NE, which was formed under SSE–NNW-trending tensile stress field conditions. The overall strike of the Xujiaweizi rift is near-SN, but it is still controlled by this regional stress field; therefore, the NE-trending fault is a typical extensional fault system in terms of stress mechanism. Eight NE-trending basement faults of large scale are developed in the east of the Xuxi fault throughout the area, including F1, F2, F3, F4, F5, F6, F7 and F8 (Fig. 2b), with an extension length of approx 10 km and a vertical fault throw of 200 m in general. These faults were of continuous activities mainly in the period of the Huoshiling Fm. and Shahezi Fm. They are depression-controlling boundary faults, but they are restricted by the Xuxi main depression-controlling fault, so they have a low development degree and also a small scale. In addition, the study shows that the NE-trending fault is cut by Xuzhong and Xudong strike-slip faults, indicating that the NE-trending extensional fault was formed early.

2.1.3 Near-EW-trending regulating fault system

Six near-EW-trending faults are developed from south to north in the Xujiaweizi rift, including T1, T2, T3, T4, T5 and T6. They have a small scale, an extension length of approximately 8 km and a vertical throw of approximately 100 m. They are distributed mainly at the inflection points of strike variation of the Xuxi fault (Fig. 2b). The seismic profile shows the thickness of the strata of the two walls is obviously inconsistent and the fault system is a typical regulating fault system formed by differential extension. Based on the kinematic characteristics of the faults on both sides of the regulating fault system, it is characterized by a dextral strike-slip. It can be seen from the fault cutting relation (Fig. 2b) that the regulating fault is restricted by the Xuxi fault and the NE-trending fault and is cut by the strike-slip fault, reflecting that the regulating fault was formed mainly with activities of the Xuxi depression-controlling fault.

2.1.4 Strike-slip fault system of Xuzhong and Xudong

The Xuzhong strike-slip fault is located in the middle part of the Xujiaweizi rift and has NNW strike. The fault passes through the superposition region of the south and north branches of the Xuxi fault, and has an extension length of approximately 85.7 km and a vertical throw of 500 m in general. The fault is nearly upright on profile and is the flower diameter of a flower-like fault complex in the rifted strata. In its shallow part, the fault is faulted to the Qingshankou Fm. and forms a large flower-like fault complex together with the upper fault system (Fig. 2a). On plane, the fault shows a dolphin effect with alternately positive and reverse change along the strike (Fig. 3). Therefore, the fault is characterized by a typical strike-slip deformation. Based on the features of the Xuxi fault divided by the Xuzhong fault into south and north branches in the right-stepped distribution form and the left-stepped distribution of the upper petal-like faults controlled by the fault, it was characterized by dextral strike-slip deformation in both the early stage and the late stage, and its activity forming period was later than the strong activity period of the Xuxi fault and was at least after the sedimentation of the Shahezi Fm.

The Xudong strike-slip fault is located in the east slope region of the Xujiaweizi rift. On plane, the fault is located in the east region of the north branch of the Xuxi fault. The Xudong strike-slip fault has a NNW strike, an extension length of approximately 50.1 km and a vertical throw of approximately 300 m in general. The fault shows a flower-like fault combination pattern on profile (Fig. 1) also, and is characterized by a strike-slip deformation. In the shallow part, the fault is faulted to the top of the Yingcheng Fm., indicating the deformation of the fault after rifting was obviously weaker than that of the Xuzhong fault.

To sum up, all lower fault systems in the Xujiaweizi area

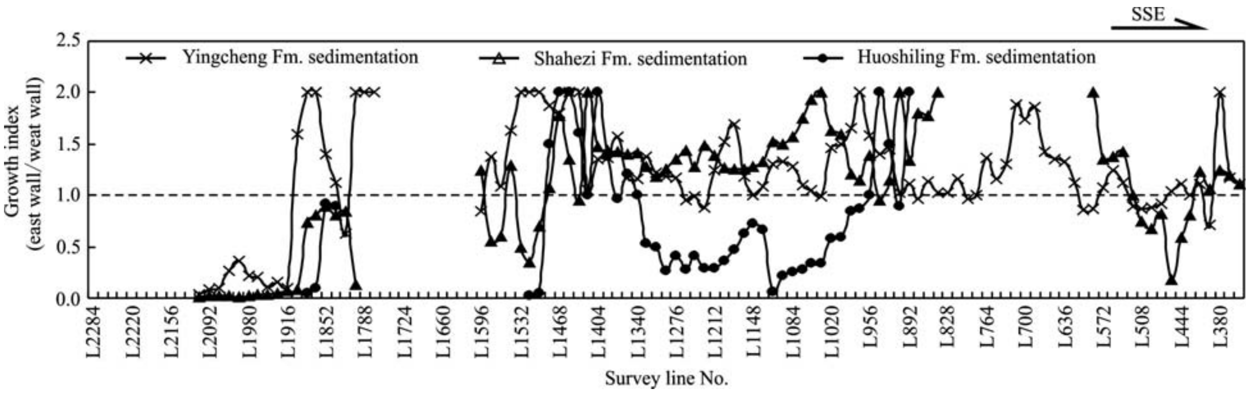


Fig. 3. Strike growth index profile of the Xuzhong fault.

were formed successively under the action of the uniform NNW-SSE-trending tensile stress field; affected by the deformation-restricted boundary conditions of ancient basement faults such as the Xuxi fault and Xuzhong fault in different azimuths, multi-directional fault systems of different characters were formed under the uniform stress field. The Xuxi fault and the NE-trending fault were the main depression-controlling faults of contemporaneous activities in the period of the Huoshiling Fm. and Shahezi Fm.; in addition, affected by the differential extensional deformation of the Xuxi main depression-controlling fault of a strike-slip displacement, a near-EW-trending regulating fault was formed; the strike-slip deformation activity period of Xuzhong fault and Xudong fault is later relatively. The close relation between the distribution of volcanic rocks in the Y1 Member and the Xuzhong fault and between the distribution of volcanic rocks in the Y3 Member and Xudong fault indicates that the Xuzhong fault was formed mainly in the period of the Y1 Member, and the Xudong fault mainly in the period of Y3 Member.

2.2 Upper fault system

Formed in the post-rifting stage of the basin, the upper fault system is concentrated in the depression structure level of Denglou Fm. to N1 and N2 Members. The surface density of faults on each reflection horizon gradually increases from bottom to top longitudinally. Affected by the plastic mudstone caprock of the Q1 and Q2 Members, the fault density is the highest on T_2 reflection horizon, the fault extension length is generally short and no larger than 6 km, and the fault throw is generally 20–80 m. On profile, the faults show a V-shaped pattern of alternate “grabens-horsts”. Affected by the plastic mudstone strata of the D2 Member, the upper fault system is in non-direct connection with the lower fault system in most cases, thus forming a large “flower-like” fault combination pattern of upper and lower fault systems.

All “grabens” on profile are dense fault zones. Through profile tracking and planar correlation, multiple dense fault zones in different azimuths have been identified in T_2 reflection horizon in the Xujiaweizi area (Fig. 2c). The strike and azimuth of these dense fault zones are of certain correlation to those of deep geologic bodies. The study shows the main factors that control the distribution of dense zones include lower fault strike, crater distribution direction, the long axis direction of gentle slope zones and the distribution direction of uplift zones. The dense zones controlled by lower faults are developed most extensively, and the main controlling faults are the Xuxi fault, Xuzhong fault, Xudong fault, NE-trending fault and near-EW-trending fault in the lower fault system. The dense zones controlled by craters are developed relatively extensively and distributed mainly near the eruptive craters along the Xuzhong and Xudong faults. The dense zones controlled by basement uplifts are developed mainly on the Chaoyanggou terrace and Changchunling anticline belt. The distribution of the dense zones controlled by gentle slope zones is limited.

A comprehensive analysis indicates the strike of all secondary faults in a dense fault zone formed by four factors is near-SN, reflecting that the upper fault system was formed under the action of the uniform near-EW-trending tensile stress field in the area, and due to it being affected by the distribution azimuth of lower or deep geologic bodies, multi-directional dense fault zones of different characters were formed under the uniform stress field.

3 Active Periods, Formation and Evolution of Faults

3.1 Determination of active periods of faults

The extensional deformation intensity of faults reflects the magnitude of vertical throw and horizontal throw. The ratio of vertical throw to absolute age – the vertical activity rate of faults and the ratio of horizontal throw to initial profile length – the profile’s horizontal extension rate can comprehensively reflect the activity intensity difference of faults. The histogram of the average vertical activity rate (Table 1) of 28 large-scale faults throughout the area and the horizontal extension rate of a typical profile (Table 2) indicates that the activity intensity of faults was remarkably high in the Huoshiling Fm. period, Shahezi Fm. period and the Yingcheng Fm. period, and they were the main periods of forming the lower fault system. The Qingshankou Fm. to Yaojia Fm. period was the main period of forming the upper fault system; the activity intensity of faults was not high after the period of the N1 and N2 Members, also reflecting that the structural inversion and deformation in the late stage of Songliao Basin had a small impact on the Xujiaweizi area.

3.2 Formation and evolution history of faults

The above active periods of faults indicate the strong activity periods of the faults in the Xujiaweizi area include the Huoshiling Fm. period, the Shahezi Fm. period, the Y1 Member period, the Y3 Member period and the Qingshankou Fm. to Yaojia Fm. period. The activity intensity and deformation characters of faults were different somewhat in different periods, so that various complex fault systems were formed (Fig. 4).

Huoshiling Fm. period and Shahezi Fm. period are the strong rifting periods of the basin, during which the regional stress field was aa NNW–SSE-trending tensile

Table 1 Statistical table on average vertical activity rate of faults in the Xujiaweizi area

Sedimentary Period	N1 and N2 Members	Yaojia Fm. to Qingshankou Fm.	Q3 and Q4 Members	Q2 Member	Q1 Member	D3 and D4 Members	D2 Member	Yingcheng Fm.	Shahezi Fm.	Huoshiling Fm.
Activity Rate （m/Ma）	1.0	9.9	3.8	6.6	1.3	5.6	8.8	31.7	47.9	40.9

Table 2 Statistical table on horizontal extension rate of the typical profile in the Xujiaweizi area

Sedimentary Period		N1 and N2 Members	Yaojia Fm. To Qingshankou Fm.	Q3 and Q4 Members	Q2 Member	Q1 Member	D3 and D4 Members	D2 Member	Yingcheng Fm.	Shahezi Fm.	Huoshiling Fm.
Extension Rate (%)	L360	0.06	0.80	0.20	0.26	0.09	0.17	0.26	0.54	1.22	1.01
	L656	0.15	1.00	0.15	0.14	0.10	0.11	0.30	0.83	1.48	1.18
	L1248	0.37	0.86	0.42	0.18	0.19	0.21	0.31	1.08	1.37	1.20

stress field. The activities of the near-SN-trending basement fault were mainly successive activities of the Xuxi fault, and it was of extensional deformation with a strike-slip displacement and controlled the sedimentary filling pattern of the basin; meanwhile, a near-EW-trending regulating fault was formed at the inflection point of different sections of the Xuxi fault. In the meantime, an NE-trending extensional fault was newly formed in the east slope zone far away from the Xuxi fault, and its growth boundary was restricted by the Xuxi fault, so it played a role in secondary depression control only. The basin entered a fault-depression conversion period in the Yingcheng Fm. period, and the depression controlling features of the Xuxi and NE-trending faults were not remarkable, but mantle magma materials invaded the crust's shallow part along a deep and large basement fault and even erupted to ground surface so as to form volcanic rocks. In the Y1 Member period, the Xuzhong fault was of strong dextral strike-slip deformation, so that the Xuxi fault was divided into the two branches such as south and north ones, and the Xuzhong fault became the main channel for volcanic eruption. In the late stage of the Y1 Member period, volcanic activities stopped and the basin was uplifted regionally, so that the strata of the Y2 Member were lost in the research area. In the Y3 Member period, the activities of the Xuzhong fault weakened, but it was of strong strike-slip deformation, thereby providing channel conditions for volcanic eruption again. In the Y4 Member period, the activities of all faults were weak, and the fault-depression conversion process of the basin was near the end.

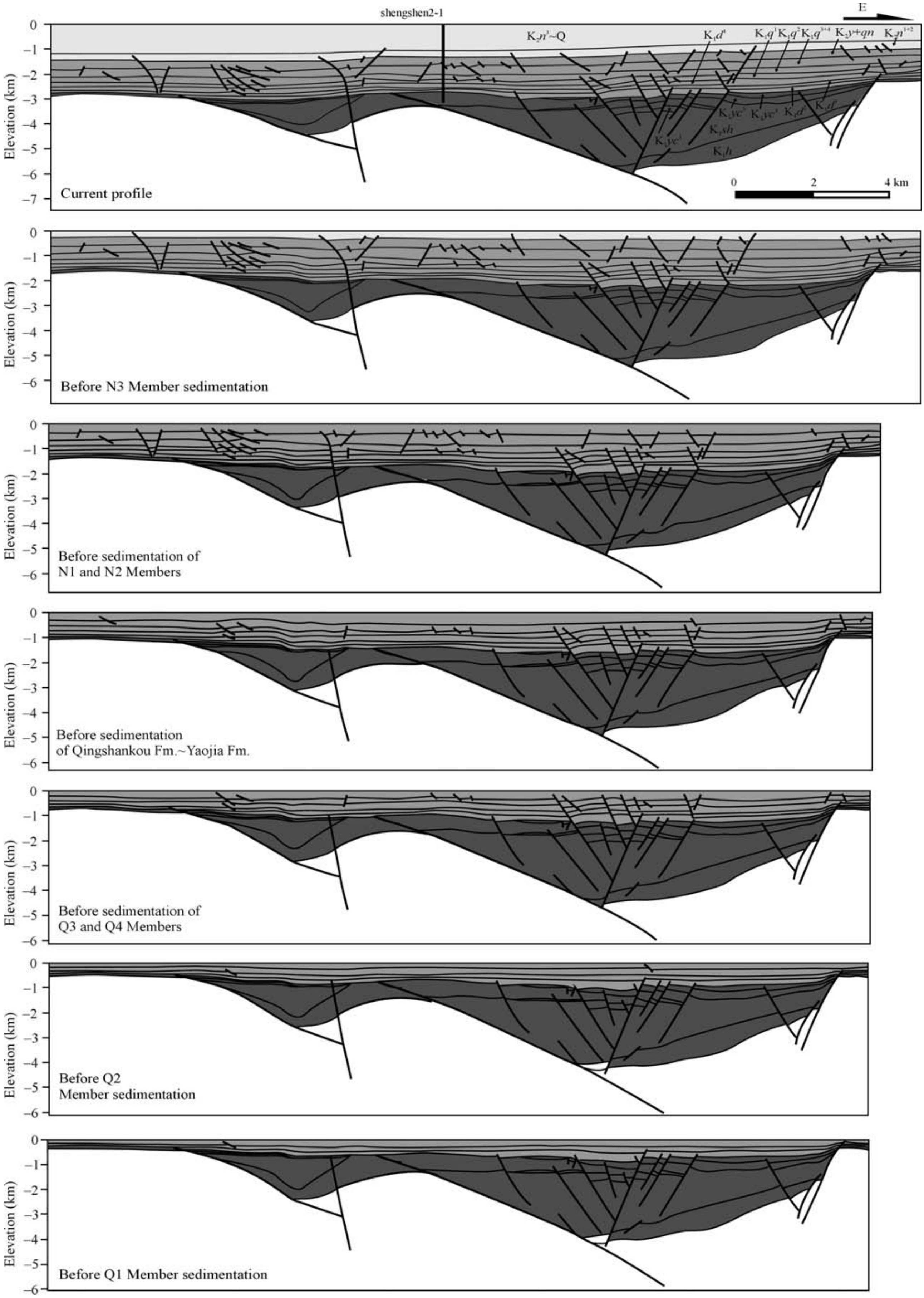
The basin had entered a depression evolution stage since the Denglou Fm. sedimentation, and the regional stress field was a near-EW-trending tensile stress field. Strong tension occurred in the Qingshankou Fm. to Yaojia Fm. period, and plenty of SN-trending secondary faults were formed. In addition, affected by the distribution azimuth of the lower fault system, volcanic rocks, uplift zones and gentle slope zones etc., dense fault zones were distributed in multiple strikes and azimuths. Most dense fault zones were formed due to being controlled by the lower fault system. The upper and lower fault systems were connected directly in the development part of the Xuzhong fault so as to form a "flower-like" fault complex. Xuxi and Xudong faults and the upper fault system showed a non-directly connected "flower-like" fault complex, indicating that the successive activity intensity of Xuzhong fault was high during formation of the upper fault system (Jiang et al., 2010).

In the late stage of N1 and N2 Members, the Songliao Basin began to uplift. Structural inversion occurred successively in the late stage of the Nenjiang Fm. sedimentation, Mingshui Fm. sedimentation and Paleogene (Zhang et al., 2006; Zhang et al., 2008), but inversion and deformation of faults in Xujiaweizi area were not remarkable, it was characterized by integral uplifting, no inverted fault of large scale was formed, and fault activities were weak.

4 Controls of Gas Accumulation Conditions by Formation and Evolution of Faults

4.1 Control effect of the Xuxi fault

The gas genetic type of Xujiaweizi rift in the Songliao Basin is typical coal-formed gas (Xu et al., 2008), so the coal seams in the Shahezi Fm. control the distribution of volcanic gas accumulations. Shahezi Fm. sedimentation period was a strong rifting period of basin evolution after initial rifting of the Huoshiling Fm. In the Shahezi Fm. sedimentation period, the Xuxi fault was a main depression-controlling fault, extensional deformation with strike-slip displacement occurring mainly, and the fault controlled wedge-shaped sedimentary filling of the Shahezi Fm. In addition, the subsidence and sedimentation center was located in the top wall of the Xuxi fault, and as lacustrine deposits were expanded, coal-measure strata of large thickness were mainly deposited and became the main volcanic gas source rocks in the Xujiaweizi rift (Ehrenberg S N et al., 2008; Ma Y et al, 2009). Their large thickness zone is located mainly in the NWW-trending section of the south and north branches of the Xuxi fault, and the maximum thickness was approximately 1000 m (Fig. 5).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Current profile
Before N3 Member sedimentation
Before sedimentation of
N1 and N2 Members
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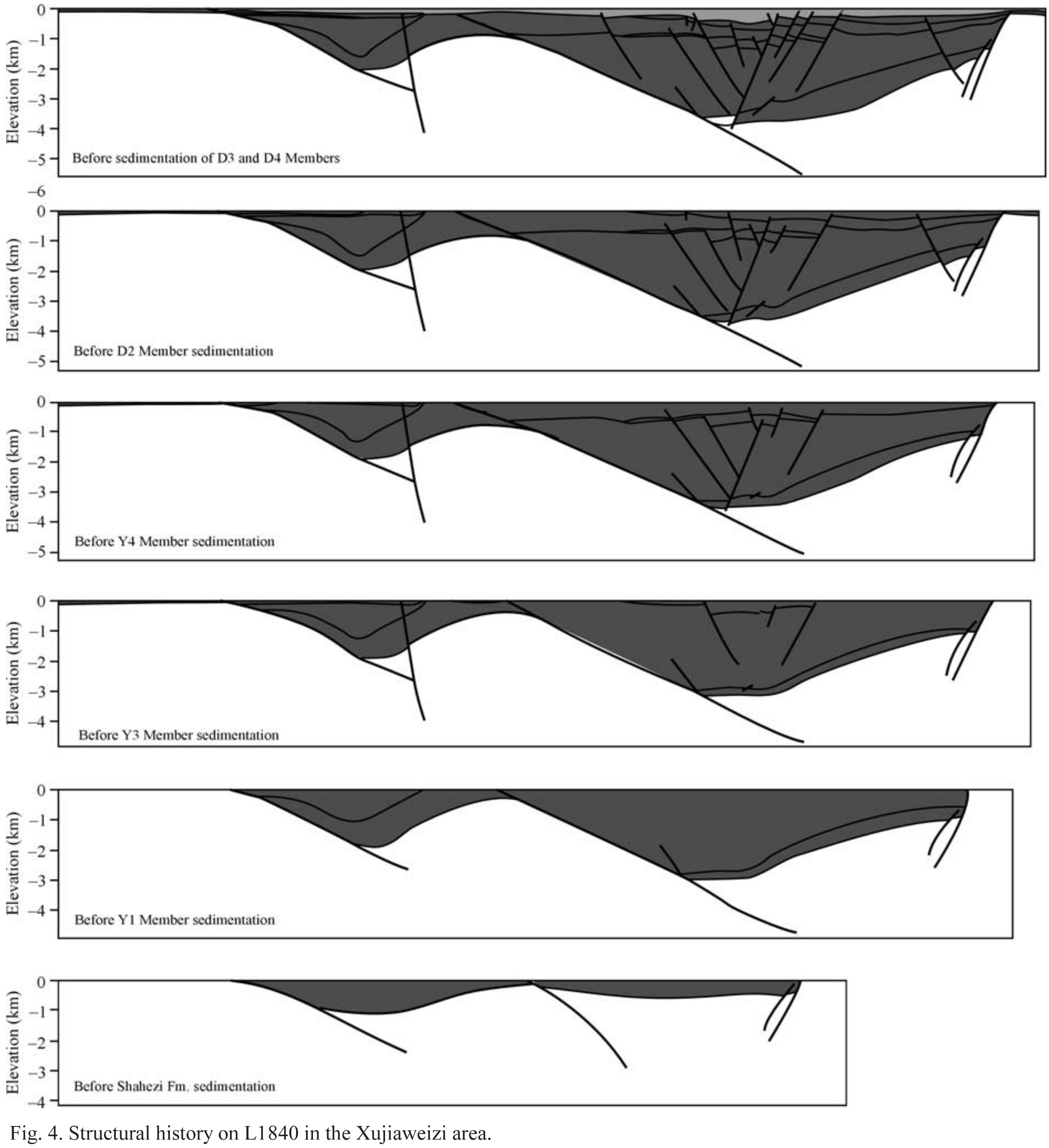

Fig. 4. Structural history on L1840 in the Xujiaweizi area.

This indicates that the extensional deformation of the Xuxi fault controlled the formation and distribution of gas source rocks in the Shahezi Fm.

4.2 Control effect of the Xuzhong fault and Xudong fault

Deep gas in the Xujiaweizi area accumulates mainly in volcanic reservoirs in the Y1 Member and Y3 Member (Zhao, 2002; Cheng, 2005; Yan et al., 2008; You, 2008). The study of fault systems indicates that large scale volcanic activities occurred in the research area in two periods including the Y1 Member sedimentation period and the Y3 Member sedimentation period. The thickness distribution of volcanic rocks in the Y1 Member indicates that the large thickness zone is distributed in a NNW direction along the Xuzhong strike-slip fault zone (Fig. 5) and developed mainly in the middle and south of the Xuzhong strike-slip fault, and the maximum thickness value was approximately 1000 m. The thickness distribution of the volcanic rocks in the Y3 Member indicates the large thickness zone was distributed discontinuously in a NNW direction along the Xudong fault zone (Fig. 5) and located mainly in the north of the Xudong strike-slip fault, and the maximum thickness value was approximately 1000 m. Therefore, the Xuzhong strike-slip fault controlled the formation and distribution of volcanic reservoirs in the Y1 Member, and the Xudong strike-slip fault controlled the formation and distribution of volcanic reservoirs in the Y3 Member.

4.3 The upper fault system play a key role

An analysis of typical gas accumulations indicates the coal-measure source rocks in the Shahezi Fm. in the Xujiaweizi rift generated and expulsed plenty of hydrocarbons in the late Quantou Fm. Period to the Qingshankou Fm. Period (Li et al., 2006); although the second hydrocarbon generation and expulsion peak occurred in the late Nenjiang Fm. period, the gas generation rate was relatively low. From the Qingshankou Fm. period to the Yaojia Fm. sedimentation period, the upper fault system was formed, and faults were of strong tension-shear deformation, so that natural gas was accumulated with large scale in volcanic rocks in the Y1 and Y3 Members while highly dense fault zones were formed in the T_2 reflection horizon. During late basin inversion, the faulting activities of the upper fault system in the Xujiaweizi area were weak, and the conditions for large scale vertical migration of natural gas were not provided(Kang et al., 2010). These relatively stable inversion structure conditions caused weak destruction to the regional caprock in the D2 Member and the Q1 and Q2 Members, ensuring the natural gas was not destroyed after the hydrocarbon accumulation period. Therefore, the deep gas in the Xujiaweizi area accumulates mainly in the volcanic rocks of the Yingcheng Fm. below the regional caprock of the D2 Member, and only part of the gas in the Changde gas field and Shengshen gas field accumulates in the strata of the D3 and D4 Members below the regional caprock of the Quantou Fm. after breaking through the regional caprock of D2 Member.

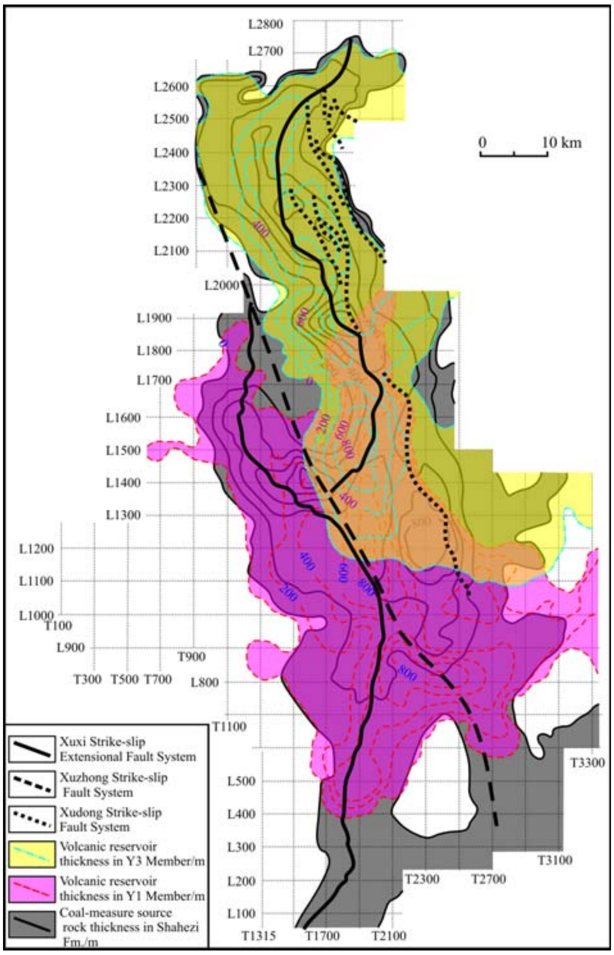

Fig. 5. Congruent map of coal-measure gas source rocks and volcanic reservoirs and fault systems in the Xujiaweizi area (adapted from Exploration and Development Research Institution of Daqing Oil Field in 2008).

4.4 The important function of gas source faults

The above analysis indicates the tension-shear deformation of the upper fault system in the Qingshankou period controlled large scale migration and accumulation of deep gas. Therefore, among the active faults in the Qingshankou Fm. to the Yaojia Fm. period, the faults connecting the coal-measure gas source rocks of the Shahezi Fm. with the volcanic traps of the Yingcheng Fm. are the main source faults of deep gas. The study shows that there are mainly two types of gas source faults (Figs 6, 7). The first type of gas source fault is a fault faulted from a rift layer directly to a depression layer, and on profile, the fault shows a long-term active fault and the upper fault system forms a "flower-like" structure. This type of long-term active fault, directly connecting deep gas source rock formations with volcanic reservoirs, is of strong activity and enables natural gas to migrate on a large scale along the fault and charge traps, so it is a strongly charged gas source fault. A typical fault of this type is the Xuzhong fault. Many large-scale gas accumulations have now been discovered in the two walls of the Xuzhong fault, including the Xushen gas field and the Fengle gas field, etc. In addition, the Zhaozhou gas field is also a deep gas accumulation controlled by a strongly charged gas source fault. The second type does not directly connect a rift layer fault with the upper fault system, and on profile, they form a "flower-like" structure with separated "leaf" from "stalk". The activity intensity of the rift layer fault was low in the strong activity period of the upper fault system. Therefore, gas migrates along the fault with a small scale, and it is a weakly charged gas source fault, e.g. Anda gas field, Wangjiatun gas field, Shengping gas field, Changde gas field and Xudong gas field, etc.

Based on the above comprehensive analysis, on one hand, the Xuzhong strike-slip fault system controlled the formation and distribution of volcanic reservoirs; on the other hand, the fault was of strong activity in the period of expulsing plenty of gas from gas source rocks and directly connected the main gas source rocks of the Shahezi Fm. with the volcanic reservoirs of the Yingcheng Fm. so as to become a strongly charged gas source fault (Stacy A C et al., 2010). Therefore, the volcanic reservoir development zones of good physical properties that may be found near the Xuzhong fault are the favorable target zones for next exploration of deep gas accumulations in the Xujiaweizi area on the premise of being affected by late tectonic inversion and deformation in the Xujiaweizi area and thus ensuring deep gas accumulations are not destroyed.

5 Conclusions

(1) Xujiaweizi area includes two sets of fault systems vertically with T_4 reflection horizon as the boundary, including a lower fault system and an upper fault system. The lower fault system formed five sets of fault systems under the action of the uniform NNW–SSE-trending regional tensile stress field. Among them, the Xuxi strike-slip extensional fault system is a main depression-controlling fault, and the NE-trending extensional fault system is a secondary depression-controlling fault. The two faults were of consecutive activity in the Huoshiling Fm. to the Yingcheng Fm. period and formed a near-EW-trending regulating fault system. The Xuzhong strike-slip fault system and the Xudong strike-slip fault system were formed by activities in the Y1 Member period and the Y3 Member period, respectively, and were of mainly dextral strike-slip deformation. The upper fault system was formed under the action of a near-EW-trending tensile stress field

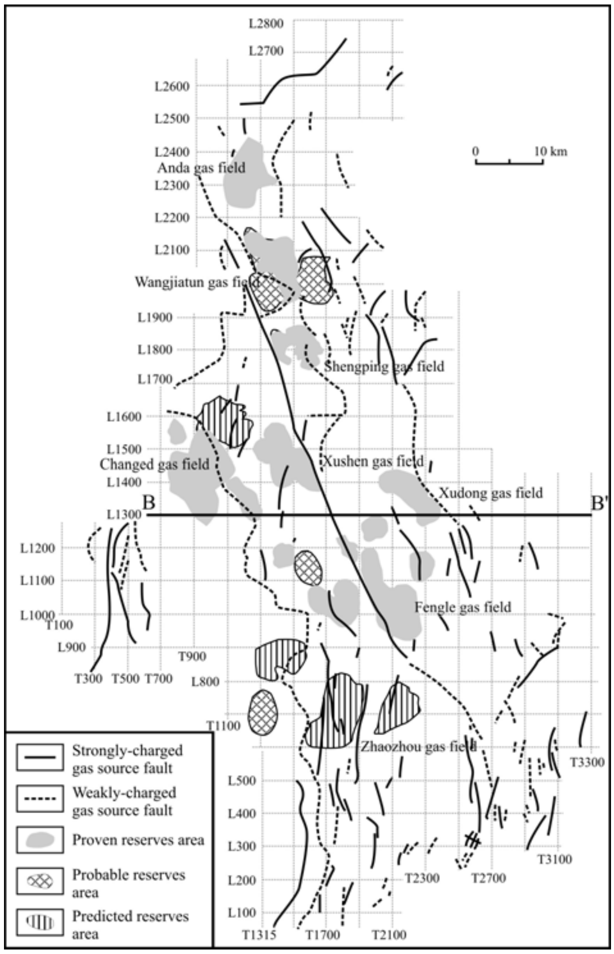

Fig. 6. Congruent map of planar distribution of deep gas accumulation and gas source faults in the Xujiaweizi area (adapted from T_4^1 reflection horizon).

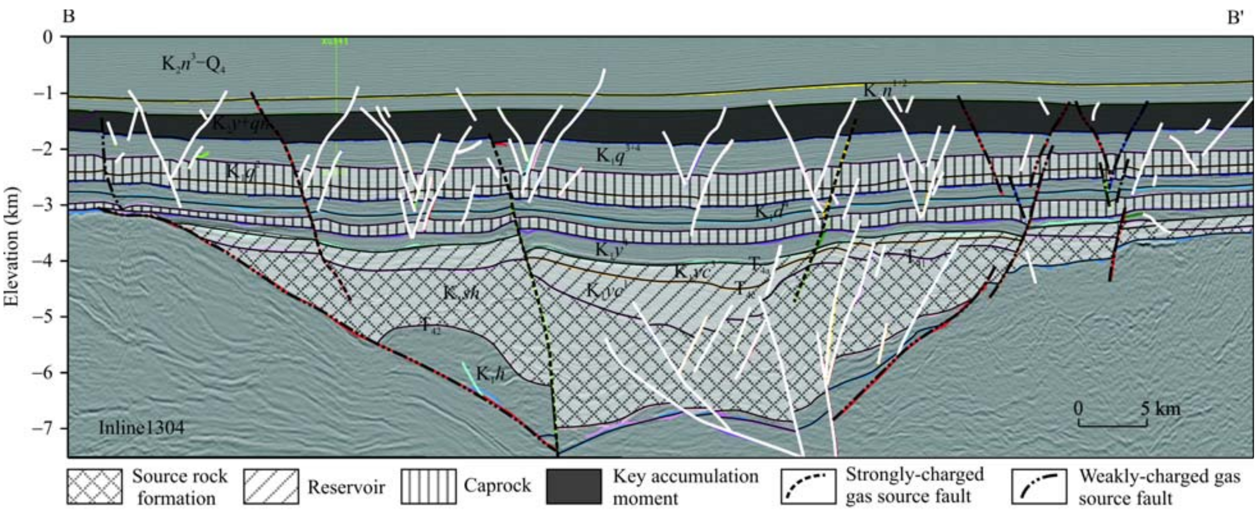

Fig. 7. Deep gas accumulation's source-reservoir-caprock, gas source faults, key accumulation moments in the Xujiaweizi area (for the profile location, see Fig. 6).

in the Qingshankou Fm. to the Yaojia Fm. period; in addition, affected by the distribution azimuth of the geologic structure bodies such as the lower fault system, craters, gentle slopes and bedrock uplifts etc., highly dense fault zones were formed in the T_2 reflection horizon in multiple azimuths.

(2) Xuxi fault controlled the formation and distribution of the Shahezi coal-measure source rocks, and the Xuzhong and Xudong faults controlled the formation and distribution of volcanic reservoirs of the Y1 Member and Y3 Member, respectively. The forming period of the upper fault system matches the period of generating and expulsing plenty of gas from gas source rocks, thus providing channel conditions for large-scale vertical migration of gas through strata. The inversion and deformation of faults were weak as of the late Nenjiang Fm. period and did small destruction to gas accumulations.

(3) A long-term active fault directly connecting gas source rocks with volcanic reservoirs is a strongly-charged direct gas source fault, and a fault not directly connecting gas source rocks with volcanic reservoirs is a weakly-charged indirect gas source fault. The Xuzhong fault controlled the distribution of volcanic reservoirs, and became a strongly-charged direct gas source fault due to strong activities in the period of expulsing plenty of gas from gas source rocks. Therefore, the volcanic reservoir development zones of good physical properties that may be found near the Xuzhong fault are the favorable target zones for future exploration of deep gas accumulations in the Xujiaweizi area.

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