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Original research paper

Formation and destruction mechanism as well as major controlling factors of the Silurian shale gas overpressure in the Sichuan Basin, China☆

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Abstract

Taking the Well JY1 and Well PY1 in the Eastern Sichuan Basin as examples, the formation mechanism of shale gas overpressure was studied by using the cross plot of acoustic versus density logging data. During the processes of hydrocarbon generation and the uplifting, the pressure evolution of fluids in shale gas layers was reconstructed by fluid inclusions and PVTSIM software. The major factors controlling the evolution of shale gas overpressure were established according to the study of fracture, the timing of the uplifting, and episodes of tectonic deformation. Our results showed that the main mechanism of overpressure in the Silurian shale gas reservoirs in the Sichuan Basin was the fluid expansion, which was caused by hydrocarbon generation. Since the Yanshanian, the strata were uplifted and fluid pressure generally showed a decreasing trend. However, due to the low compression rebound ratio of shale gas reservoir rocks, poor connectivity of reservoir rocks, and low content of formation water and so on, such factors made fluid pressure decrease, but these would not be enough to make up the effects of strata erosion resulting in a further increase in fluid pressure in shale gas reservoirs during the whole uplifting processes. Since the Yanshanian, the Well PY1 zone had been reconstructed by at least three episodes of tectonic movement. The initial timing of the uplifting is 130 Ma. Compared to the former, the Well JY1 zone was firstly uplifted at 90 Ma, which was weakly reconstructed. As a result, low-angle fractures and few high resistance fractures developed in the Well JY1, while high-angle fractures and many high resistance fractures developed in the Well PY1. In totality, the factors controlling the overpressure preservation in shale gas reservoirs during the late periods include timing of late uplifting, superposition and reconstruction of stress fields, and development of high-angle fractures.

Keywords: Overpressure; Shale gas; Fracture; Preservation condition; Silurian; Sichuan Basin

1. Introduction

The Silurian of Sichuan Basin is one of the best potential targets for shale gas exploration in China, which is also the first shale gas layer for commercial exploitation around the world, excluding North America. The Silurian shale gas has distinct characteristics with its genesis, hydrocarbon, and preservation mechanism. In particular, due to the fact that the Sichuan Basin and its neighboring areas suffered from strongly tectonic reconstruction since the Yanshanian period, the quality of preservation conditions played a key role in shale gas exploration [1,2]. At present, the wells that had been commercially exploited are concentrated within the Sichuan Basin. However, gas reservoirs with high yields have not been found on the basin margins (Fig. 1). Shale gas wells with high yields generally have abnormal high fluid pressure, and gas contents have a good positive correlation with degree of

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overpressure (Fig. 2). Shale gas wells with normal pressure usually have low initial yield, or poor preservation conditions [3−6]. Thus, overpressure is not only the key factor controlling high yields of shale gas but also the major indicator for evaluating preservation conditions.

During the formation and evolution of sedimentary basins, overpressure can be generated from various physical and chemical processes [7−10]. According to the formation processes of overpressure, formation mechanisms of overpressure can be classified into three categories [11]: (1) pressure-generating processes related to the stresses, including disequilibrium compaction (vertical load stress), tectonic stress (lateral compression) and etc; (2) pressure-generating processes induced by volume increase of pore fluids, including hydrothermal pressurization, clay mineral dehydration, hydrocarbon generation, thermal cracking of hydrocarbon, and etc; (3) pressurization induced from fluid flow and buoyancy, including gravity head, buoyancy, and etc. Among them, the mechanisms that solely resulted in a large scale overpressure mainly include disequilibrium compaction, natural gas generation, tectonic compression, and diagenesis.

The burial depth of the Silurian in Sichuan Basin is usually greater than 6000 m, and the corresponding R_O values are more than 2.0%. Thus, the Silurian shale gas should be of thermal origin, and its overpressure mechanisms should cover hydrocarbon generation. In addition, other mechanisms accounting for overpressure formation as well as the means by which the overpressure preserved and destructed have no clear conclusions.

The Jiaoshiba and Pengshui shale gas fields are two of the few commercially-developed gas fields in the Sichuan Basin and its neighboring areas. At present, the Silurian of Jiaoshiba gas field is under overpressure condition, and pressure coefficient ranges from 1.4 to 1.6, whereas the Silurian of Jiaoshiba gas field is under normal pressure condition, with pressure coefficient varying from 0.9 to 1.1. Taking the Well JY1 of Jiaoshiba gas field and Well PY1 of Pengshui gas field in the eastern Sichuan Basin, this paper tries to analyze the overpressure formation and evolution processes, study the formation mechanism of overpressure in shale gas play in the Sichuan Basin, and establish key factors controlling the preservation and destruction of overpressure, providing a useful example for exploration and selection of shale gas targets in the future.

2. Logging responses to shale gas overpressure

The origin of overpressure in shales includes differential compaction, fluid expansion, tectonic compression, pressure conduction, and so on. According to the statistical results of overpressure basins around the world, two of the common origins include differential compaction and fluid expansion [12]. Different types of overpressure origins have their unique geophysical responses. The overpressure induced by differential compaction has some distinct characteristics such as abnormally high porosity and decreased values of density in logging sets [7]. Fluid expansion can be induced by hydrothermal pressurization, dehydration of clay minerals,

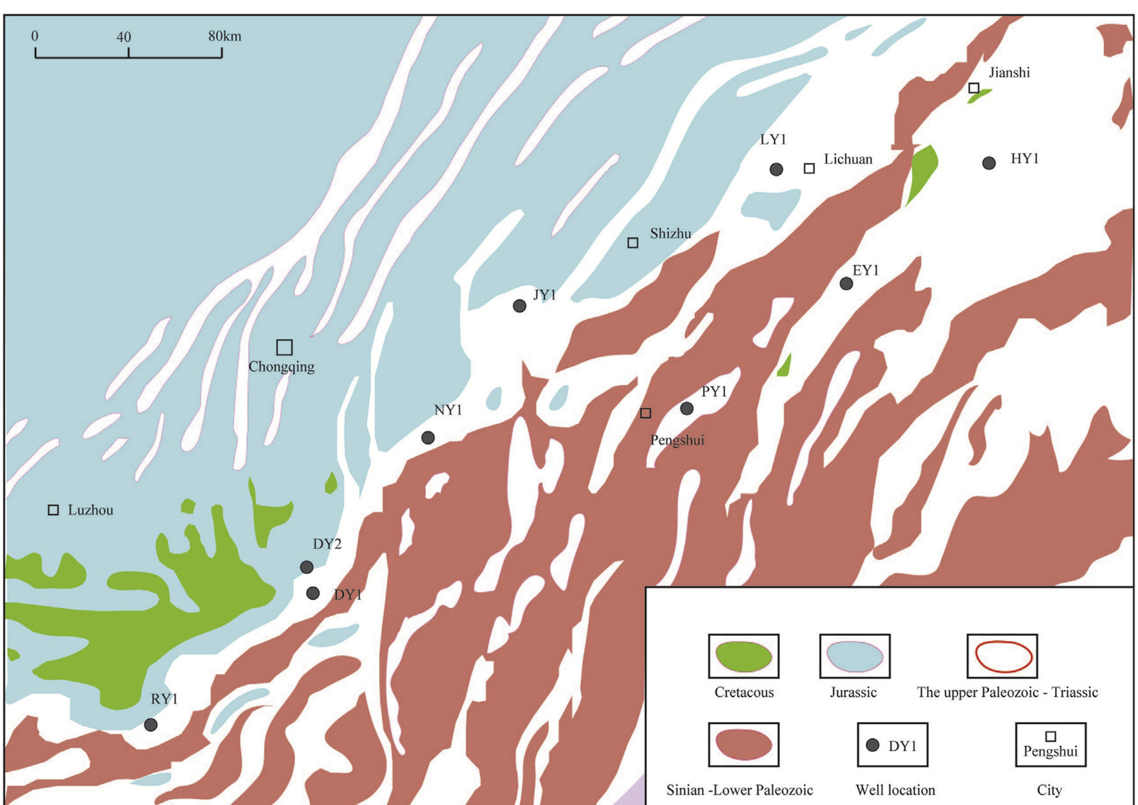

Fig. 1. The distribution map of shale gas wells in the eastern Sichuan Basin.

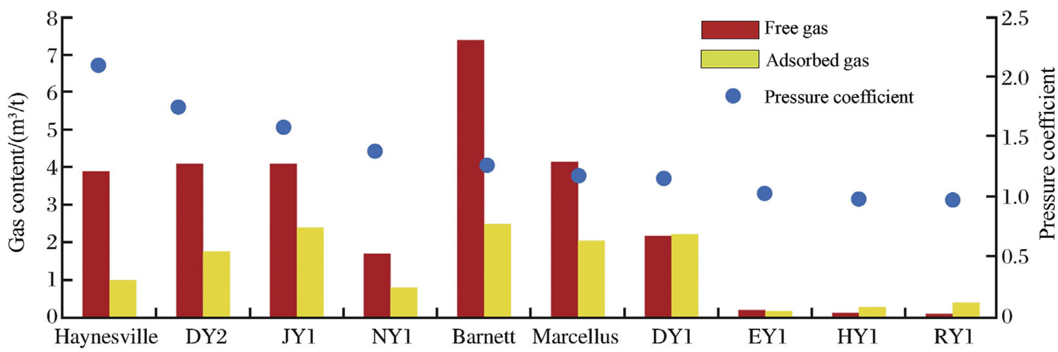

Fig. 2. The relationship between gas content and pressure coefficient in shale gas.

hydrocarbon generation, unloading of the loads, and etc. Among all of them, hydrocarbon generation, especially the cracking of hydrocarbon to gas, is the main reason accounting for overpressure formation [13–16]. Such type of overpressure is shown as low values of acoustic wave velocity in logging sets, but there are no porosity anomalies in the overpressure intervals.

Using the cross plot of acoustic against density logging, various origins of overpressure can be determined (Fig. 3) [7]. In the under-compacted intervals, density and acoustic wave velocity have shown as a consistent trend. The corresponding data are plotted above normal compaction curve. However, since effective stresses of rocks are decreased by hydrocarbon generating overpressure, acoustic wave velocities are shown as decreasing values. Nevertheless, the density of rocks would not have evident changes. Under the overpressure conditions induced by diagenesis of clay minerals or unloading of the loads, the density of rocks increases with the increasing extent of overpressure, meanwhile, acoustic wave velocity will slightly decrease [7,16].

According to lithological, electrical, and physical properties, as well as gas bearing properties, gas-bearing intervals of the Well JY1 and Well PY1 can be divided into three members and five sub-members. There exist five lithological intervals from the bottom up, i.e., carbonaceous siliceous mudstones, carbonaceous mudstones, carbonaceous argillaceous siltstones, carbonaceous calcareous-dolomitic mud shales, and carbonaceous siltstones. High-quality gas-bearing intervals are mainly located within the bottom intervals, such as carbonaceous mudstones and carbonaceous siliceous mudstones. The thickness of the bottom intervals is 38 m in the Well JY1 and 35.5 m in the Well PY1. This study extracted density and acoustic time data of mudstones in two wells in a space of 1 m to make cross plots of acoustic wave velocity against density (Fig. 4). As shown in Fig. 4, the 2nd (carbonaceous mudstones) and 3rd sub-members (carbonaceous siltstones) of the 1st member in the Well JY1 have obvious characteristics of hydrocarbon generating overpressure, while overpressure is not yet to be found in each interval of the Well PY1. The 1st sub-member of the 1st member in the Well JY1 has the highest gas yields, which has a high content of silicon, mostly developed micro-fractures and good physical reservoir properties. However, the 2nd sub-member has a low content of silicon, with characteristics of brittleness, fewer micro-fractures, and poor reservoir connectivity, thus, leading to more understandable hydrocarbon generating overpressure. Similarly, the 3rd member has worse physical reservoir properties than the 2nd member, and the sealing properties of upper and lower strata are good, also displaying as recognizable overpressure. Therefore, the main origin of overpressure in shale gas reservoirs is hydrocarbon generation. The intervals with well-preserved overpressure mainly located within high organic carbon shales which have good sealing properties of upper and lower strata and less of micro-fractures. The decrease of acoustic wave velocity (i.e., acoustic times increase) is the major indicator for fluid overpressure, which is also clearly shown in the Well JY2 and Well JY3 (Fig. 5).

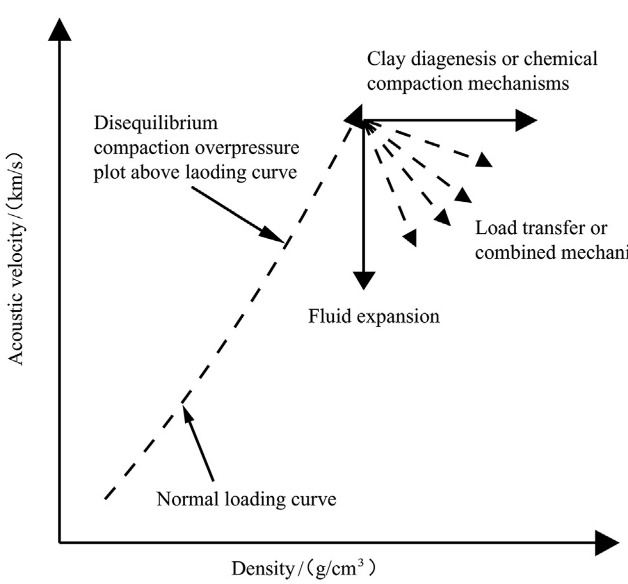

Fig. 3. Classification diagram showing the types of overpressure in the strata [7].

3. Formation processes of shale gas overpressure

3.1. Fluid pressure changes during the cracking of crude oils to gas

It's long been recognized that natural gas generation is the main mechanism for overpressure formation in sedimentary

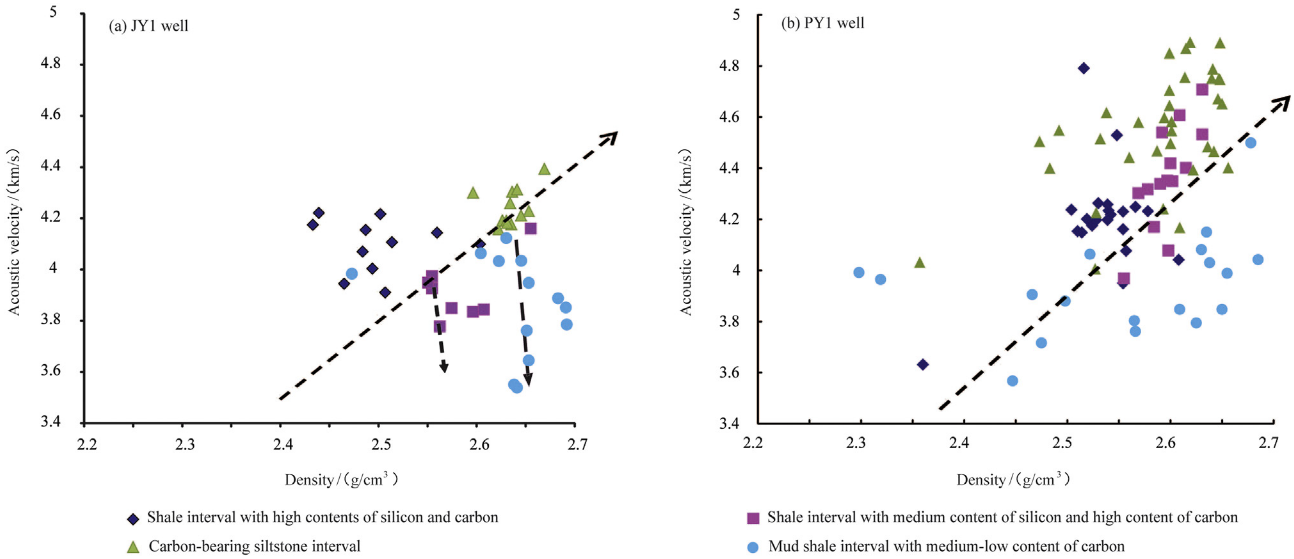

Fig. 4. Discrimination in the origin of the Silurian shale gas overpressure in the eastern Sichuan Basin.

basins. Previous authors made a simulation experiment of hydrocarbon generation. Under standard temperature and pressure conditions, crude oils in a unit volume were fully cracked to gas, and the resulting volume would expand 534.3 times than before. That is, the cracking of 1 vol.% crude oils can result in fluid overpressure within the strata [16]. Within the thin-bedded source rocks or source rocks on the margins of the basin, hydrocarbon will usually migrate to its neighboring reservoirs via micro-fractures during hydrocarbon generation processes. However, apparent overpressure will be formed in the center of the basin, since hydrocarbon generated within the thick-bedded source rocks failed to be expelled out, such as a classic overpressure example in the Bakken shales of the Williston Basin, USA [3]. The thickness of the Silurian mudstones in the Sichuan Basin varies from 50 m to 200 m, in which the thickness of high-quality source rocks is between 10 m and 50 m. Therefore, unsuccessful hydrocarbon expulsion might occur during hydrocarbon generation, and hydrocarbon generating overpressure should be widely formed in the geological past.

Regarding the degree of overpressure generated from oil to gas cracking, previous authors made systematic studies for conventional gas fields by using the paleopressure reconstruction of fluid inclusions and PVT simulation. Yuan et al. [17] reconstructed the paleopressure of the Sinian reservoirs in the Weiyuan and Anyue gas fields by using fluid inclusion method. They then suggested that fluid pressure coefficient of the Sinian reservoirs had exceeded 2.0 during gas charging. Liu et al. [18,19] and Tian et al. [20] made a PVT simulation for fluid pressure variations during the cracking of the Changxing crude oils in the Puguang gas field of Sichuan Basin. The results showed that reservoir fluid pressure coefficient would exceed 2.2 numerable times during oil to gas cracking processes if oil saturation of reservoirs was 100%. The overpressure would make gas reservoirs leak. During the cracking of oil reservoirs to gas reservoirs, the overpressure

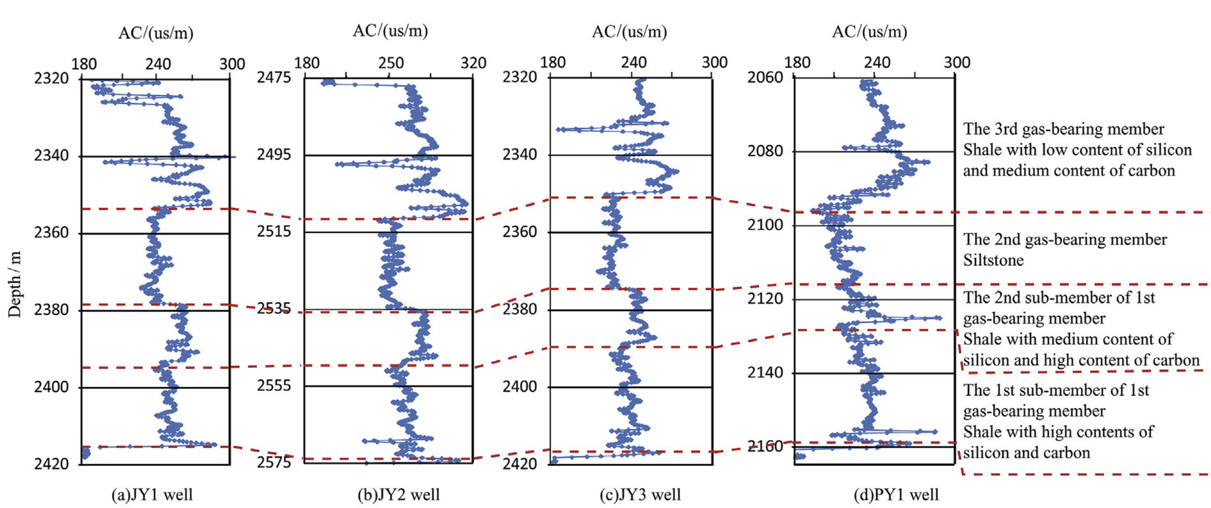

Fig. 5. Acoustic logging responses to overpressure in various intervals in the Jiaoshiba and Pengshui areas.

had been formed, which is evidenced by high-density methane of fluid inclusions in reservoirs.

Compared to conventional gas reservoirs, shale gas reservoirs have tighter reservoir rocks that possess low porosity and poor connectivity. Thus, fractures derived from overpressure will inevitably form for several times during the cracking processes of oil to gas, hence, leading to hydrocarbon expulsion. Under the condition of unsuccessful hydrocarbon expulsion, the formation of organic pores and micro-fractures can increase the reservoir spaces. Since precise time and volume of hydrocarbon expulsion during hydrocarbon generation of source rocks fail to be counted, the degree of continued overpressure cannot be estimated after the end of widespread hydrocarbon generation. However, the highest reservoir pressure will not exceed 0.85 times of the weight of overlying rocks according to the limits of rock fracture [19], which is equivalent to pressure coefficient of 2.0 in the Sichuan Basin. Gao et al. [21] analyzed the Laser Raman peak shift of high-density methane inclusions in quartz veins in the bottom of the Silurian in Well JY1, and the minimum trapping pressure of inclusions was calculated, i.e., 114−130 MPa. Combined with burial history of the Well JY 1, previous fluid pressure coefficient of this well varied from 1.58 to 1.81. The homogenization temperature of aqueous inclusions coexisted with pure gaseous methane was greater than 216 °C, which should be formed during the periods of maximum burial depth of the Silurian. It basically represented the fluid overpressure conditions in the Silurian shales before the uplifting.

3.2. Fluid pressure changes during the uplifting

During the uplifting, the decrease of temperature and pressure resulted in a fluid shrinkage and rebound of rock pore volume, respectively. Stressing on the tectonic uplifting leads to the formation of abnormal low pressure when the pores contain formation water and crude oils since they both have greater expansion coefficients. However, since gas are mainly enriched in the organic pores and formation water rarely occurs in the organic pores in the Silurian shale gas reservoirs [22], the effect of formation water shrinkage caused by decreased temperature during the uplifting on reservoir spaces of shale gas could be ignored. In addition, the elastic modulus of shales is 4000−5500 MPa according to the Log interpretation, and the Poisson ratio is said to be 0.22−0.26. Thus, the compression coefficient ($\beta r = 3*(1\text{-}2v)/E$) of whole rocks is 0.00042−0.00026 MPa^{-1}. Setting rock density as 2.5 kg/m^3, the volume of rocks expanded by 1.9%−3.1% than before when the strata were uplifted by 4000 m. Thus, this proves that the effect of fluid shrinkage and rebound of rock pore volume on reservoir spaces is very weak. However, the decrease in pressure will result in a gas expansion during the uplifting. Meanwhile, pressure coefficient of gas reservoirs will relatively increase due to the unloading of overlying loads. Therefore, there are uncertainties on the changes of fluid pressure and pressure coefficient during the uplifting of shale gas reservoirs.

This paper assumes that the Silurian shale gas reservoirs are all filled with methane gas. Taking three volume increased factors (i.e., temperature decreases, pressure decreases, and pore rebound) into consideration, this paper reconstructed the changes of fluid pressure and pressure coefficient of the Well JY1 and Well PY1 during the uplifting by using the PVTSIM 2.0 software according to the real status of gas (Due to high pressure of formation fluids, there remain several errors on the ideal gas equation.). This paper assumed that the porosity remained unchanged during simulation, and mutual transformation between free gas and adsorbed gas within shales and the diffusion of gas would not be considered. Since initial pressure coefficient could not be quantitatively determined, two initial states of gas reservoirs, i.e., normal pressure and overpressure, were selected for the simulation study. The pressure coefficient of initial gas reservoirs is 1.0 and 1.7, respectively. The results of pressure reconstruction are as shown in Fig. 6 and Fig. 7.

As shown in Figs. 6 and 7, absolute values of fluid pressure during the uplifting showed a decreasing trend regardless of normal or overpressure gas reservoirs. However, pressure coefficients of the fluids increased because of erosion of the overlying strata. Well JY1 and Well PY1 were uplifted to the current depth as a state of normal gas reservoirs, and the corresponding pressure coefficients were 1.7 and 1.8, respectively, which were greater than current pressure coefficients of

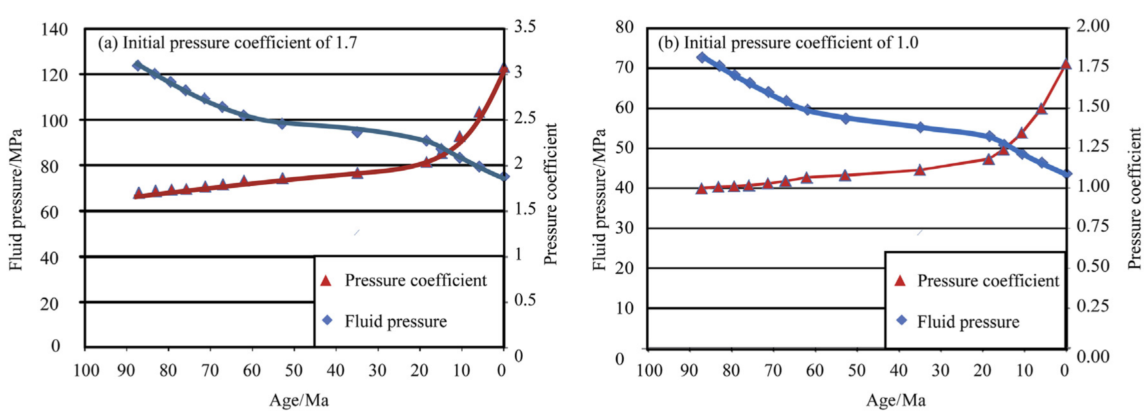

Fig. 6. Changes in fluid pressure in the Well JY1 during uplifting.

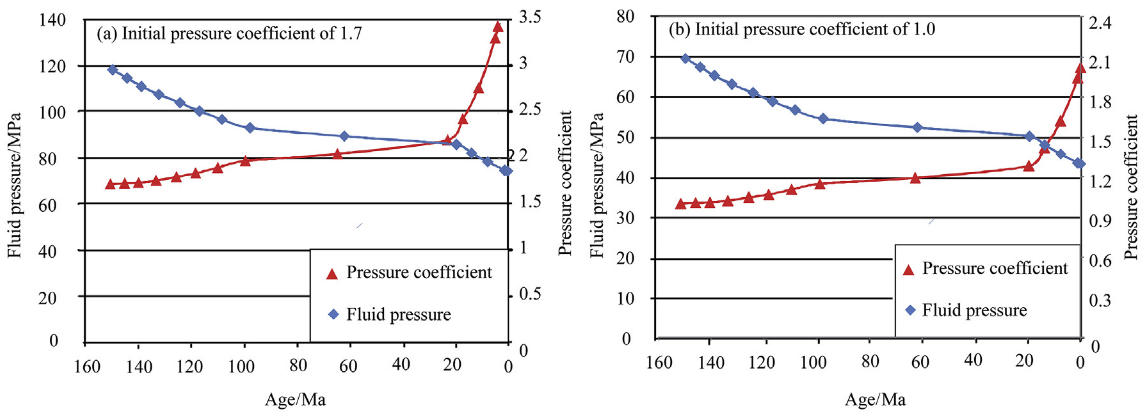

Fig. 7. Changes in fluid pressure in the Well PY1 during uplifting.

gas reservoirs. However, fluid pressure had not yet reached the fracture limit of rocks during the whole processes. The main ways for pressure release of gas are diffusion or tectonic fracturing. If gas reservoirs were uplifted as the state of overpressure, fluid pressure coefficient could exceed 2.0 after gas reservoirs being uplifted by 2000–3000 m. Meanwhile, the rocks were broken up because of overpressure, finally leading to the release of pressure. The difference is that the pressure of Well JY1 was not completely released. So far a portion of overpressure has been preserved, while Well PY1 has shown as a state of normal pressure because of complete release of pressure and loss of large amounts of free gas.

4. Preservation and destruction mechanism of shale gas overpressure

The Well PY1 and Well JY1 in the eastern Sichuan Basin share similar hydrocarbon accumulation conditions and hydrocarbon generating processes. Not to mention fluid overpressure should have taken place during the past, while preservation status of overpressure in both wells significantly varies at present. Such variations are mainly affected by the following three factors.

4.1. Vertical and lateral sealing of overpressure compartment

Shale gas reservoir is a kind of non-continuous and self-sealing fluid system [23]. Under the favorable sealing conditions in the vertical and lateral positions, overpressure fluid compartment can be formed. High-quality shale interval in the Well JY1 is overlaid by nearly 100 m of shales and siltstones, which has high breakthrough pressure with the measured values ranging from 20 to 40 MPa. It has a capability for sealing overpressure gas. The bottom of shale interval is sealed by the Ordovician Linxiang Formation tight marls, which have better-sealing properties than the upper part of mudstones, thus, leading to a better vertical sealing condition in the Jiaoshiba area. The shape of the Jiaoshiba structure is a box-shaped anticline. Laterally, the pores cannot be connected with each other and fluid pressure cannot be transferred to each other; this results in the lack of fluid migration forces. Moreover, vertical destructive fractures are less developed. Thus, the lateral sealing condition of the Well JY1 zone in the lateral is favorable. The Well PY1 and Well JY1 share similar sealing layers at the top and bottom which have good sealing properties. However, the Well PY1 is located on the flank of the syncline, and the Silurian was exposed on the surface along the side-inclined direction. The Silurian shale intervals have large amounts of bedding fractures. Due to the higher permeability of shales along the bedding direction and larger diffusion coefficient, shale gas can easily dissipate along bedding fractures.

4.2. Development degree and opening of fractures

Undoubtedly, development of fractures is one of the major factors controlling the loss of shale gas. According to core observation and image logging interpretation of the Well JY1 and Well PY1 (Fig. 8), two types of fractures (i.e., high conductive fractures and high resistance fractures) are developed in both wells. High conductive fractures are mainly composed of unfilled and opened fractures that easily lead to gas leakage. The dip angle of high conductive fractures in the Well JY1 is relatively small, mainly ranging from 30° to 50°, whereas the dip angle of high conductive fractures in the Well PY1 is larger, mainly varying from 80° to 90°. Such high resistant fractures are filled with minerals, which were formed by early tectonic movement. High resistant fractures have been found to be well developed in the Well PY1, but less developed in the Well JY1, suggesting that the effects of early tectonic movement on the Well PY1 are evident. Gas leakage might take place before the filling of fractures. Even if fractures were filled, there exists a larger risk for gas leakage. Since the whole fractures can be hardly filled with lately-formed minerals, some fractures still occur among the lately-formed minerals, and their sizes are larger than those of rock pores. In addition, the strike of boundary fault of the Jiaoshiba anticline (Well JY1 zone) is NEE, which is vertical to EW compression stresses at present. Thus, the sealing condition of boundary faults is favorable. However, the strike of the Sangtuoping syncline (Well PY1 zone) is NE, which is

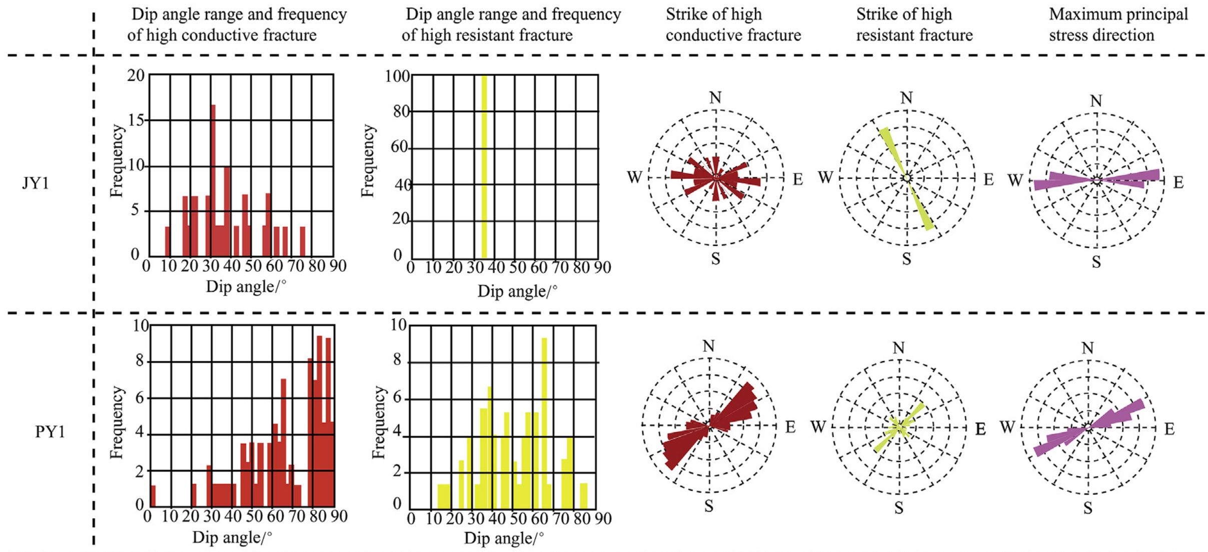

Fig. 8. Development characteristics of fractures in the Well JY1 and Well PY1.

parallel to current stresses or it is intersected at a low-angle, leading to a poor sealing condition of boundary faults. Therefore, multi-episodes of fractures had taken place in the Well PY1 zone, and high-angle fractures well developed. The opening of boundary faults is robust. This is the main reason accounting for poor preservation condition of shale gas in this area.

4.3. Timing and intensity of tectonic reconstruction

The Jiaoshiba and Pengshui areas belong to different tectonic units, and they are separated by the Qiyueshan fault. There are obvious differences in the timing of uplifting and deformation between both areas, which are demonstrated by simulation results of thermal history obtained from apatite fission track (Fig. 9). The timing of late uplifting in the Pengshui area is about 130 Ma, while the timing of initial uplifting is about 90 Ma. The difference is 40 Ma. The early uplifting implies that shale gas reservoirs are more likely to be affected by lately tectonic movement since differential stresses are more obvious in shallow-buried zones. According to deformation of the strata in the Enshi area located in the northern of Pengshui syncline, this area had suffered from at least three episodes of tectonic movement since the late Jurassic. Before the late Cretaceous, tectonic compression made this area to be formed as trough-like structures. During the late Cretaceous, the tectonic extension made it possible for clastic materials to be deposited in local areas. After that, the upper Cretaceous was folded through re-compression during the Himalaya period [24,25]. The previously-formed fractures reactivated as a result of the change of stress fields that was caused by several episodes of tectonic movement. Principally, after intensive erosion during the late Jurassic-Early Cretaceous, the regional extension can lead to the opening of previously-formed faults or make their sealing conditions worse during the late Cretaceous. Therefore, another major reason accounting for poor preservation condition of shale gas in the east areas of Qiyueshan fault is that this area suffered from multi-episodes of reconstruction of stress fields with various directions after the shale gas strata were uplifted to near surface.

5. Conclusions

(1) The Silurian shale gas overpressure in the Sichuan Basin is mainly developed in the organic-rich intervals with less micro-fracture, which is a comprehensive reflection of multiple single overpressure systems in a unit of organic

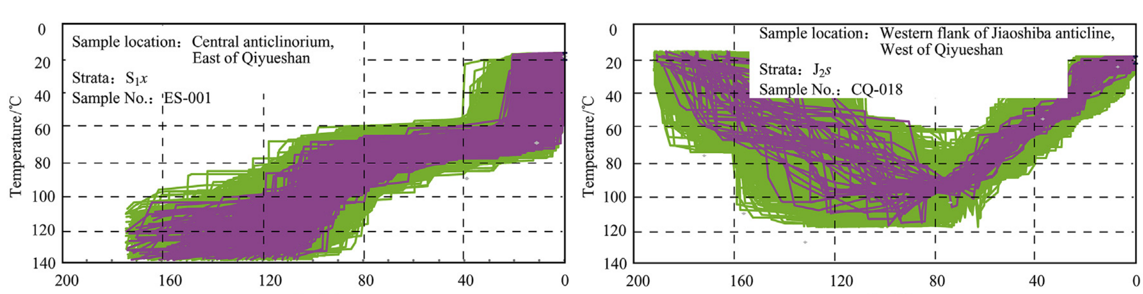

Fig. 9. AFT curves showing the timing of erosion and uplifting in the Jiaoshiba and Pengshui areas (See Fig. 1 for the location of samples).

pores. Acoustic time anomaly is the important indicator for overpressure. The fluid expansion is the main mechanism for the formation of shale gas overpressure.

(2) Shale gas reservoirs are very tight and the rebound rate of pores is low. Although the absolute value of fluid pressure of gas reservoirs decreases during the uplifting, simultaneously, the relative pressure increases. This type of fluid overpressure is the vital reason accounting for generation of micro-fractures and keeping the opening status in shale gas.

(3) The key factors controlling shale gas preservation in the Sichuan Basin and its peripheral areas include the lateral sealing of shale gas reservoirs, the density of high-angle fractures, the opening status of fractures, as well as episodes of tectonic activities since the Yanshanian and the timing of initial uplifting.

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Conflict of interest

The authors declare no conflict of interest.

References

[1] Zhigang Wang, Breakthrough of Fuling shale gas exploration and development and its inspiration, Oil Gas Geol. 36 (1) (2015) 1–6.

[2] Fang Hao, Huayao Zou, Yongchao Lu, Mechanisms of shale gas storage: implications for shale gas exploration in China, AAPG Bull. 97 (8) (2013) 1325–1346.

[3] Xunsheng Guo, Rules if two-factor enrichment for marine shale gas, Southern China-understanding from the Longmaxi formation shale gas in Sichuan basin and its surrounding area, Acta Geol. Sin. 88 (7) (2015) 1209–1218.

[4] Tonglou Guo, Ruobing Liu, Implications from marine shale gas exploration breakthrough in complicated structural area at high thermal stage: taking Longmaxi Formation in Well JY1 as an example, Nat. Gas. Geosci. 24 (4) (2013) 643–651.

[5] Haikuan Nie, Xuan Tang, Ruikang Bian, Controlling factors for shale gas accumulation and prediction of potential development area in shale gas reservoir of South China, Acta Pet. Sin. 30 (4) (2009) 484–491.

[6] Dazhong Dong, Caineng Zou, Hua Yang, Yuman Wang, Xinjing Li, Gengsheng Chen, Shiqian Wang, Zonggang Lv, Yongbin Huang, Progress and prospects of shale gas exploration and development in China, Acta Pet. Sin. 33 (Suppl. 1) (2012) 107–114.

[7] S. O'Conner, R.E. Swarbrick, R.W. Lahann, Geologically driven pore fluid pressure models and their implications for petroleum exploration. Introduction to thematic set, Geofluids 11 (4) (2011) 343–348.

[8] B.A. Eaton, Graphical method predicts geopressures worldwide, World Oil 183 (6) (1976) 51–56.

[9] Xiaowen Guo, Sheng He, Lunju Zheng, Zhenzhen Wu, A quantitative model for the overpressure caused by oil generation and its influential factors, Acta Pet. Sin. 32 (4) (2011) 637–644.

[10] Guanghui Yuan, Yingchang Cao, Zhenzhen Jia, Yanzhong Wang, Tian Yang, Research progress on anomalously high porosity zones in deeply buried clastic reservoirs in petroliferous basin, Nat. Gas. Geosci. 26 (1) (2015) 28–42.

[11] M.J. Osborne, R.E. Swarbrick, Mechanisms for generating overpressure in sedimentary basins: a reevaluation, AAPG Bull. 81 (6) (1997) 1023–1041.

[12] M.R.P. Tingay, R.R. Hillis, R.E. Swarbrick, C.K. Morley, A.R. Damit, Origin of overpressure and pore pressure prediction in the Baram Delta Province, Brunei, AAPG Bull. 93 (1) (2009) 51–74.

[13] M. Tingay, R. Hillis, R. Swarbrick, A.R. Damit, "Vertically transferred" overpressures in Brunei: evidence for a new mechanism for the formation of high magnitude overpressures, Geology 35 (11) (2007) 1023–1026.

[14] R.W. Lahann, R.E. Swarbrick, Overpressure generation by load transfer following shale framework weakening due to smectite diagenesis, Geofluids 11 (2011) 362–375.

[15] H.D. Hedberg, Relation of methane generation to undercompacted shales, shale diapirs, and mud volcanoes, AAPG Bull. 58 (4) (1974) 661–673.

[16] C. Barker, Calculated volume and pressure changes during thermal cracking of oil to gas in reservoirs, AAPG Bull. 74 (8) (1990) 1254–1261.

[17] Haifeng Yuan, Guosheng Xu, Guozhi Wang, Min Mao, Jiaju Liang, Phase evolution during hydrocarbon accumulation and exploration prospect for Sinian reservoirs in Central Sichuan Basin, China, J. Chendu Univ. Technol. Sci. Technol. Ed. 36 (6) (2009) 662–668.

[18] D.H. Liu, X.M. Xiao, J.K. Mi, X.Q. Li, J.K. Shen, Z.G. Song, P.A. Peng, Determination of trapping pressure and temperature of petroleum inclusions using PVT simulation software-a case study of Lower Ordovician carbonates from the Lunnan Low Uplift, Tarim Basin, Mar. Petroleum Geol. 20 (1) (2003) 29–43.

[19] Dehan Liu, Xianming Xiao, Hui Tian, Jiagui Shen, Methodology and results of dynamic and thermodynamic simulation for oil-cracked gas pool of Puguang, Nat. Gas. Geosci. 21 (2) (2010) 175–184.

[20] H. Tian, X.M. Xiao, W.T. Ronald, Y.C. Tang, New insights into the volume and pressure changes during the thermal cracking of oil to gas in reservoirs: implications for the in-situ accumulation of gas cracked from oils, AAPG Bull. 92 (2) (2008) 181–200.

[21] Jian Gao, Sheng He, Jizheng Yi, Discovery of high density methane inclusions in Jiaoshiba shale gas field and its significance, Oil Gas Geol. 36 (3) (2015) 472–480.

[22] Chaohe Fang, Zhilong Huang, Qiaozhi Wang, Dewen Zheng, Honglin Liu, Cause and significance of the ultralow water saturation in gas-enriched shale reservoir, Nat. Gas. Geosci. 25 (3) (2014) 471–476.

[23] Yu Zhang, Jianping Yan, Xiangjuan Jia, Yanfang Li, Deyong Shao, Ping Yu, Tongwei Zhang, The pore size distribution and its relationship with shale gas capacity in organic-rich mudstone of Wufeng-Longmaxi formation, Sichuan Basin, Nat. Gas. Geosci. 26 (9) (2015) 1755–1762.

[24] Lianfu Mei, Shaoqian Liu, Jiguang Tang, Chuanbo Shen, Yuanfang Fan, Mesozoic intracontinental progressive deformation in Western Hunan Hubei Eastern Sichuan provinces of China: evidence from apatite fission track and balanced cross section, Earth Sci. J. China Univ. Geosci. 35 (2) (2010) 161–174.

[25] Erchie Wang, Kai Meng, Zhe Su, Qingren Meng, Jean J. Chu, Zhiliang Chen, Gang Wang, Xuhua Shi, Xinquan Liang, Block rotation: tectonic response of the Sichuan basin to the southeastward growth of the Tibetan plateau along the Xianshuihe-Xiaojiang fault, Tectonics 33 (5) (2014) 686–718.