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Geochemistry and origin of sour gas accumulations in the northeastern Sichuan Basin, SW China

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Abstract

Significant natural gas reserves have recently been discovered in the Lower Triassic oolitic reservoirs from northeastern Sichuan Basin, SW China. In the wake of the December 2003 sour gas well blow-out, this study presents an overview on the petroleum geology and geochemistry of the sour gas accumulations in the study area. Two types of natural gas accumulations were identified in the Lower Triassic oolitic reservoirs, both containing highly mature thermogenic gases, with their hydrocarbon source rocks in Upper Permian strata. Natural gases from the area south of the ancient Kaijiang-Liangping Seaway are generally sweet gases formed as the result of thermal maturation, whereas those discovered from north of the Seaway are products of both thermal maturation and thermochemical sulfate reduction of early accumulated oils in the Feixianguan Formation reservoirs. The proposed origins of the gases are supported by their chemical and stable carbon isotope compositions, as well as the presence or absence of pyrobitumens in the reservoir. The distribution of gas accumulations is controlled predominantly by the combination of lithologic and structural factors. The regional variation in the concentrations of H_2S in the gases appears related to the presence and thickness of anhydrite-bearing evaporitic rocks interbedded or intercalated with the oolitic reservoirs.

1. Introduction

Significant sour gas accumulations have been discovered recently in Triassic reservoirs in the northeastern Sichuan Basin, SW China. The reservoirs occur mostly in the oolitic shoal facies, with mean porosities up to 13–17%. Among the five largest gas pools discovered in the Triassic Feixianguan Formation, each pool contains up to 50 billion cubic meters (or 1.8 trillion cubic feet) of proven gas reserves. The gases are generally dry, containing 70–80% methane, 5–20% H_2S and trace amounts of other gaseous hydrocarbons. Preliminary data presented in several Chinese publications (Jiang et al., 2002; Wang et al., 2002a,b) indicate that the gases were likely derived from thermochemical sulfate reduction (TSR) occurring in the Triassic paleo-oil reservoirs.

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The presence of H_2S in the natural gas not only reduces its economic value, but also increases the health and safety risks from drilling and production to transportation. A sour gas well blow-out in the Luojiazai gas field in northeastern Sichuan Basin occurred in December 2003. This led to a death toll of 233 people, with more than 9000 people being taken to hospital and more than 4000 evacuated. As a result of concerns about the potential reoccurrence of such an event a study was undertaken to improve our understanding of the origin of the sour gas accumulations and to develop predictive tools for evaluating the sour gas risk. This manuscript describes the key geological controls for the gas reservoir and discusses the prevailing geochemical evidence for the origin of the hydrocarbon and non-hydrocarbon gas fluids.

2. Geological setting

The Sichuan Basin is a rhomboid-shaped sedimentary basin on the Yangtze Platform, developed on top of pre-Cambrian metamorphic rocks. This basin, with an area of 190,000 km^2, was filled with 8000–12,000 m of Sinian to Middle Triassic marine carbonates and Upper Triassic to Eocene non-marine clastic rocks. The general geology and petroleum geology of the Sichuan Basin have been studied extensively (e.g., Huang et al., 1995; Wang et al., 1998, 2002a,b; Liu et al., 2001; Yang et al., 2002; Tian et al., 1996).

This study focused on a small area (4000 km^2) east of the ancient Kaijiang-Liangping Seaway in the northeastern part of the Sichuan Basin (Fig. 1). The sediments in the basin have experienced five orogenies, including regional extension during the Caledonian-Hercynian orogenies, a structural transitional phase during the Indosinian – early Yanshanian orogenies and extensive contractions during the late Yanshanian-Himalayan orogenies (Li et al., 2002). Many topographic highs were formed during each of the various stages of basin evolution. The Triassic oolitic shoal facies sediments in the Feixianguan Formation were developed on top of the Kaijiang palaeohigh during the Indosinian orogeny. Subsequent structural adjustments during the Yanshanian-Himalayan orogenies led to three groups of linear structures trending NE–SW, near W–E and NW–SE.

Gas accumulations occur in Carboniferous, Permian, and Lower Triassic strata in the northeastern Sichuan Basin (Fig. 2). The Lower Triassic Feix-

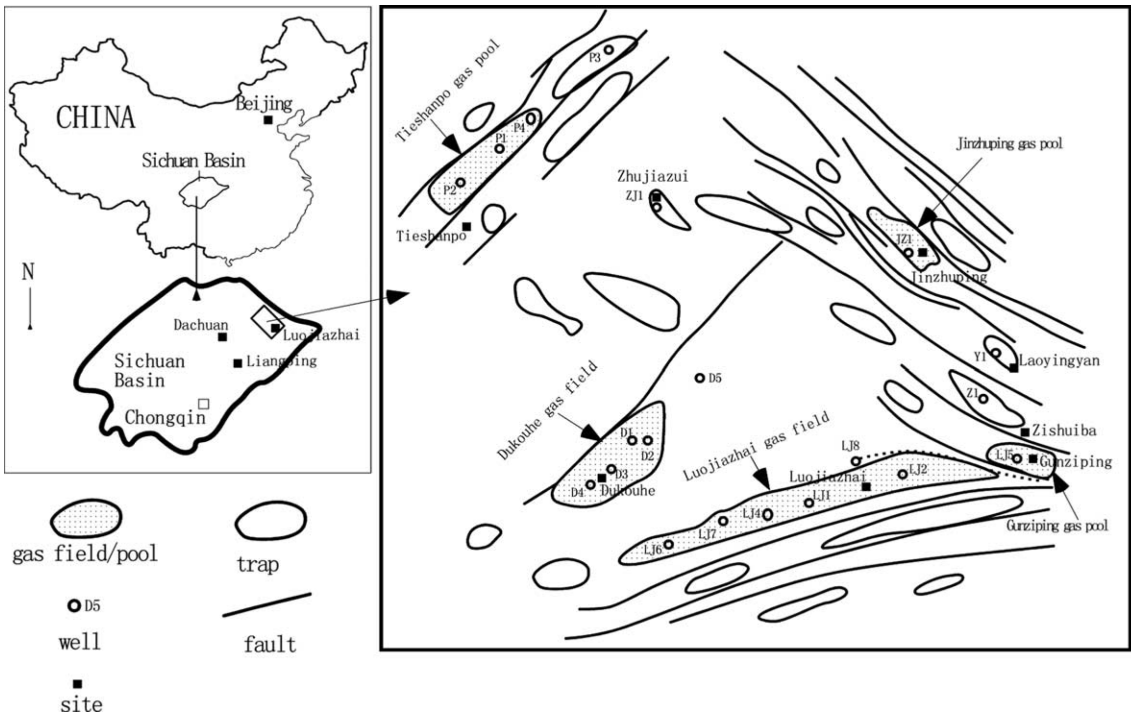

Fig. 1. Map showing the location of the study area.

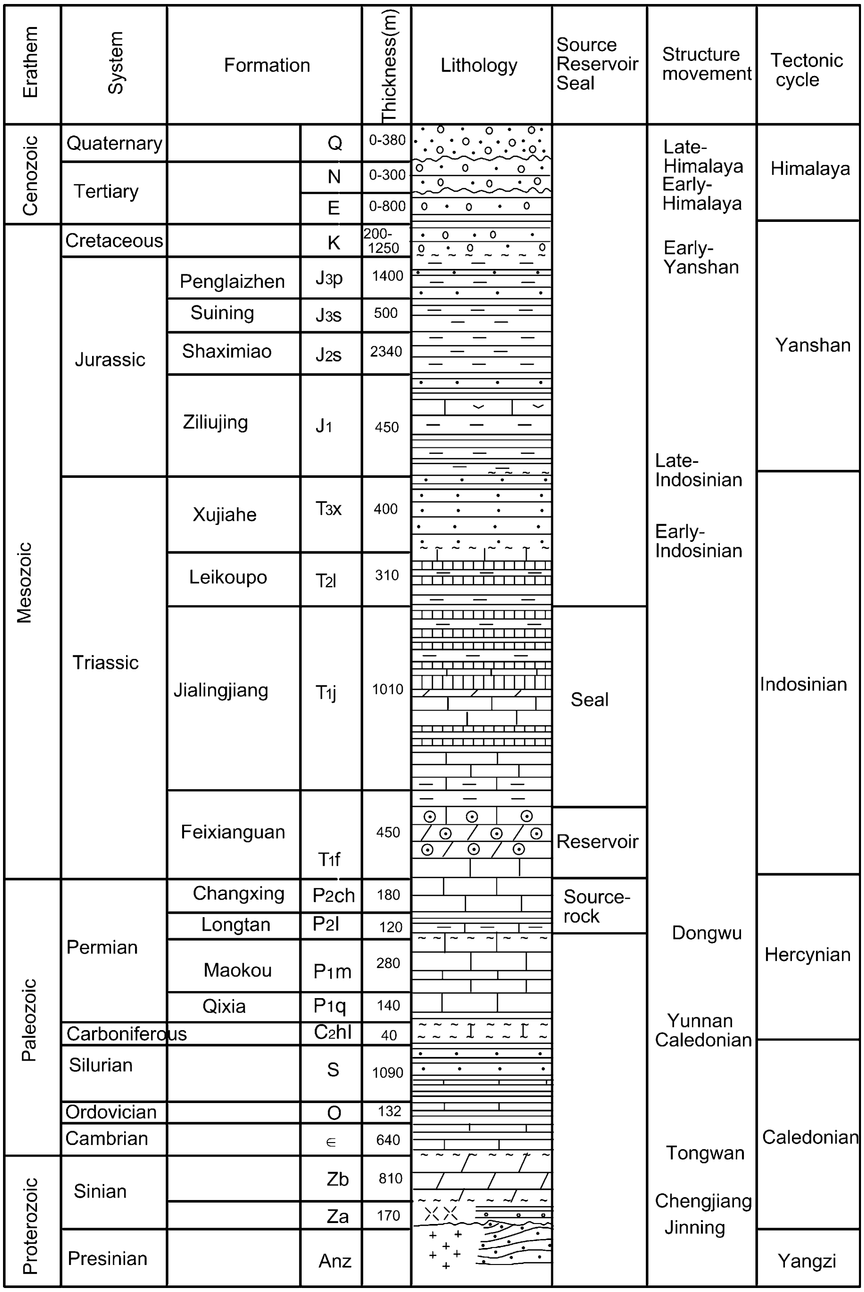

Fig. 2. Stratigraphy of the northeastern Sichuan Basin.

ianguan Formation in the study area lies conformably above the Upper Permian Changxin Formation and below the Lower Triassic Jialinjiang Formation. Due to the influence of the Caledonian orogeny, only 40 m of Middle Carboniferous dolomite was preserved in the study area. The Lower Permian strata are dominated by carbonate rocks formed on a marine platform, whereas the Upper Permian strata consist mainly of transitional marine/non-marine rocks (marlstones, mudstones and coals). The depositional settings during the Early Triassic were generally similar to those in the Late Permian, leading to 400–700 m of sediments in the northern part of the basin and 350–450 m in the study area. The base of the overlying Jialinjiang Formation consists of thin argillaceous limestones and thick limestones.

Wang et al. (2000) proposed a model to describe the sedimentary evolution of the Feixianguan Formation as the development of a marine carbonate platform on top of the Permian Kaiping-Liangping Seaway. Consequently, the Feixianguan Formation is divided into four members, T_1f^4 to T_1f^3 (top to bottom), among which the T_1f^3 to T_1f^1 contain excellent petroleum reservoir rocks deposited in an oolitic shoal facies on the platform margins. The individual oolitic shoal facies can be further divided into three sub-facies, including marginal oolitic shoal, intershoal lagoon and lagoonal-tidal flat. The lithology of the T_1f^1 member is dominated by tight argillaceous-micritic limestones, with little dolomitization. In contrast, the T_1f^2 and T_1f^3 members are composed mainly of loose oolitic dolomite, with large lateral variation in the extent of dolomitization. The top of the Feixianguan Formation (T_1f^4 member) consists of 25–50 m of purplish red, gray purplish thin-layered shale and marlstone, dolomicrite, anhydrite interbeds, which occur relatively stably over a large area.

Five large natural gas accumulations have been discovered recently in the Lower Triassic Feixianguan Formation of the northeastern Sichuan Basin, located in the Luojiazhai, Dukouhe, Tieshanpo, Jinzhuping and Gunzipeng structures, respectively. The gas pay zones are distributed under the regional caprock beds of the Lower Triassic Jialingjiang Formation, and almost all of the gas traps are associated with faults and fractures. Vertically, the highest-quality reservoirs are always within the T_1f^3 to T_1f^1 members. Laterally, reservoir qualities are comparable in four of the five structures, with an average 13–17% porosity. The only exception is observed in the Jinzhuping field where the average porosity is only 4.3%.

3. Geochemistry and likely sources of the sour gas accumulations in the northeastern Sichuan Basin

Thermochemical sulfate reduction (TSR) is thought to take place at temperatures of about 100–140 °C or above with a thermal maturity corresponding to cracking of crude oil to condensate (Trudinger et al., 1985; Sassen, 1988; Machel et al., 1995; Worden et al., 1995; Machel, 1998; Yang and Hutcheon, 2001; Yue et al., 2003). According to previous studies, the minimal temperature for significant TSR to occur varies as a function of such factors as the type of reactive organic compounds, dissolution and diffusion rates of sulfate and reservoir wettability (Machel, 1998). As the thermal regimes of TSR and gas condensate formation from normal thermal maturation overlap, it is usually difficult to differentiate between the two processes. For example, thermal maturation usually leads to a decrease in C_{2+} hydrocarbons and an increase in the $\delta^{13}C$ values of methane accompanied by an increase of H_2S concentration in natural gas (Tissot and Welte, 1984). Similar effects are observed in TSR-affected gas pools (Orr, 1977; Dai, 1985; Sassen, 1988; Machel et al., 1995; Manzano et al., 1997; Shen et al., 1997).

The concentrations of H_2S in the natural gases do not correlate with the present depth of the gas reservoir (Fig. 3), but display a close relationship with the occurrence or absence of anhydrite-rich marlstones interbedded or intercalated with the gas reservoirs (Wang et al., 2002a,b; Jiang et al., 2002). Sour gas accumulations in the northeastern Sichuan Basin occur dominantly in the structures to the north of the ancient Kaijiang-Liangping Seaway (Fig. 1). The concentrations of H_2S in the natural gases produced from the Dukouhe, Luojiazhai, and Tieshanpo fields are 9.81–17.06%, 8.77–13.74% and 10.59–14.20%, respectively (Table 1). The reservoir rocks in these sour gas deposits were deposited mainly in oolitic beaches, back-beach lagoons and tidal flat facies, and contain from a few meters to 35 m of anhydrite-rich marlstones. In contrast, natural gases discovered south of the Kaijiang-Liangping Seaway contain little H_2S. For example, the concentrations of H_2S in the Fuchengzhai and Xingshi regions are 1.66–1.76 and 0.05–0.29 g/m^3, respectively. The depositional environment for most of the gas reservoirs in the Feixianguan Formation was a marine carbonate platform, with little associated marlstones.

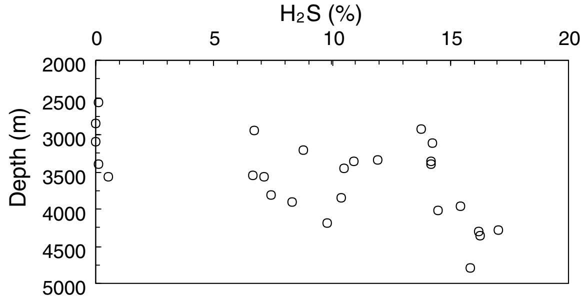

Fig. 3. H_2S concentration in natural gas from the Triassic Feixianguan Formation reservoirs as a function of reservoir depth.

While the concentrations of CO_2 in the natural gases correlate well with those of H_2S (Table 1), the H_2S and CO_2 rich gases in the Feixianguan Formation are generally dry, with a dryness range of 0.9970–0.9998. The concentrations of methane range from 75% to 90%, whereas the C_{2+} gaseous hydrocarbons account for only 0–0.15%. On the other hand, the H_2S and CO_2 poor gases in the Jialingjiang Formation also show extremely high dryness (0.9935–0.9988), consistent with the high thermal maturity of the natural gases in the northeastern Sichuan Basin. Fig. 4 indicates the variation in the H_2S concentration as a function of the C_1/C_{2+} value in the gas, which shows that the H_2S rich gases are relatively depleted in C_{2+} hydrocarbons. The result provides strong support for the origin of these gases from both thermal maturation and thermochemical sulfate reduction (TSR) (Peters and Fowler, 2002; Wang et al., 2002a,b; Cai et al., 2002).

As shown in Table 2 and Fig. 5, the $\delta^{13}C$ values of methane and ethane in the H_2S-rich gases of the Feixianguan Formation reservoirs are 3–4‰ higher than those with little H_2S, an effect previously attributed to TSR and thermal maturation (Krouse et al., 1988; Worden et al., 1996; Cai et al., 2002). For example, the $\delta^{13}C$ values of methane in the sour gases discovered in the Hetianhe gas field of the Tarim Basin in northwester China are 1–3‰ higher than those of related sweet gases. Similar isotopic effects were observed for gasoline range hydrocarbons (Rooney, 1995; Whiticar and Snowdon, 1999).

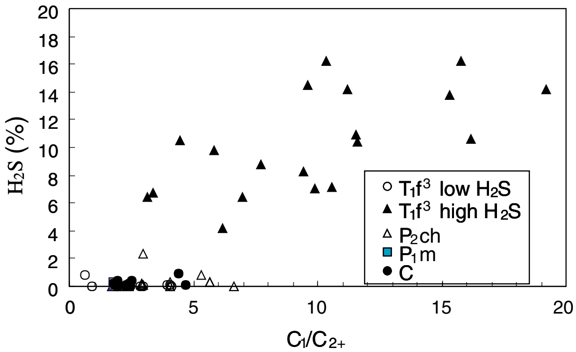

Fig. 4. H_2S concentration in natural gas from the Triassic Feixianguan Formation reservoirs as a function of C_1/C_{2+} ratio of the gas.

In the region south of the Kaijiang-Liangping Seaway of the northeastern Sichuan Basin, thermal maturation is probably the main factor controlling the hydrocarbon distribution in the various gas pools. Although the paleo-temperatures at the top of the Feixianguan Formation had reached over 160 °C at the end of Jurassic time (Table 3), these reservoirs are sweet (<1% H_2S) and hence TSR has not occurred to any significant extent. In contrast, gas pools distributed to the north of the Kaijiang-Liangping Seaway in the study area are sour (Table 1), and therefore, the present hydrocarbon

Table 1
Chemical compositions of the natural gases in the northeastern Sichuan Basin

Gas field	Well	Strata	Depth (m)	CH_4 (%)	C_2H_6 (%)	C_3H_8 (%)	H_2S (%)	CO_2 (%)	Remark
Dukouhe	D1	T_1f	4306–4354	82.70	0.04	0.04	16.21	0.46	High H_2S (>1%)
Dukouhe	D2	T_1f	4362–4385	78.74	0.04	0.01	16.24	3.29	
Dukouhe	D3	T_1f	4272–4342	73.71	0.06	0.05	17.06	8.27	
Dukouhe	D4	T_1f	4191–4220	83.73	0.06	0	9.81	5.03	
Tieshanpo	P1	T_1f	3400–3460	78.38	0.05	0.02	14.19	6.36	
Tieshanpo	P2	T_1f	4022–4162	80.79	0.03	0.02	10.59	7.22	
Tieshanpo	P4	T_1f	3365–3395	76.90	0.04	0	14.20	7.62	
Luojiazhai	LJ2	T_1f	3211–3286	84.68	0.08	0.03	8.77	5.44	
Luojiazhai	LJ5	T_1f	2932–2997	76.66	0.05	0	13.74	8.93	
Luojiazhai	LJ7	T_1f	3856–3956	81.37	0.07	0	10.41	6.74	
Shuanglong	SHU16	T1j	3121–3138	99.09	0.35	0.03	0.02	0.14	Low H_2S (<1%)
Fuchengzhai	CH22	T_1f	3024–3040	98.63	0.24	0.01	0.11	0.08	
Xinshi	X9	T_1f	3112–3224	97.46	0.37	0.05	0.02	0.13	
Tieshan	TS4	P2	3098–3102	98.32	0.23	0.01	0.26	0.41	
Huangcaoxia	C16	P2	2000–2008	98.48	0.31	0.02	0.09	0.17	
Huangcaoxia	C6	P1	2526–2614	98.36	0.49	0.05	0.17	0.04	
Yunanchang	YUN6	C_2hl	4592–4642	97.3	0.41	0.02	0.08	0.59	
Dukouhe	D4	C_2hl	5227	97.83	0.20	0.01	0.10	1.00	
Tieshan	TS2	C_2hl	4077–4118	97.02	0.21	0.01	0.93	0.89	

Table 2
Stable carbon isotopic compositions of the Feixianguan Formation gas pools in northeastern Sichuan Basin

Gas field	Well	Strata	Depth (m)	$\delta^{13}C_1$ (‰)	$\delta^{13}C_2$ (‰)	Remarks
Tieshanpo	P1	T_1f	3430	−30.1		High H_2S
Tieshanpo	P2	T_1f	4105	−29.5		
Dukouhe	D4	T_1f	4215	−29.8	−32.4	
Luojiazhai	LJ6	T_1f	3960	−30.4		
Luojiazhai	LJ7	T_1f	3910	−31.5	−29.4	
Tieshan	TS11	T_1f	2890	−33.0	−35.2	Low H_2S
Tieshan	TS13	T_1f	2991	−33.0	−34.7	
Fuchengzhai	C16	T_1f	2616	−33.5	−37.4	
Fuchengzhai	C22	T_1f	3032	−33.8	−36.5	

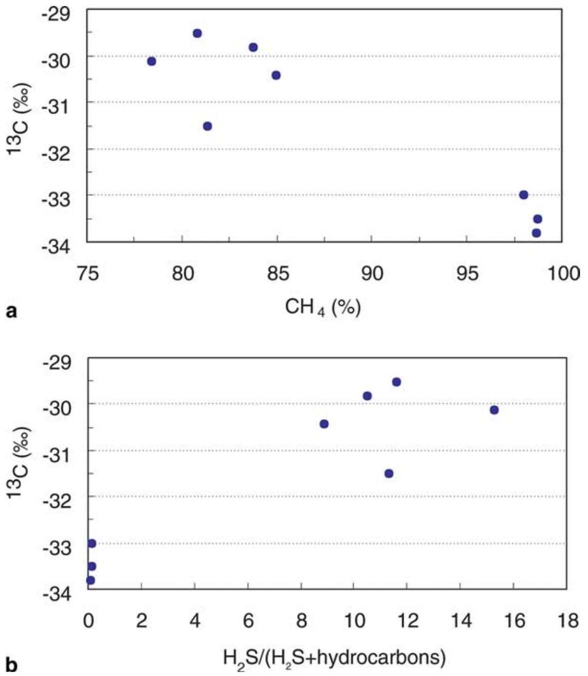

Fig. 5. Relationship between $\delta^{13}C$ values for methane and proportions of H_2S in the gas.

distribution probably reflects both thermal maturation and TSR effects. This is supported by the large variation in the C_2/C_3 ratio associated with a relatively narrow range in the C_1/C_2 ratio for both sweet and sour gas accumulations in the study area (Fig. 6). Similar gaseous hydrocarbon distributions are considered typical of thermogenic gases derived from oil cracking (Schenk et al., 1997; Waples, 2000; Prinzhofer and Huc, 1995; Zhao et al., 2001a,b, 2002).

Establishing a common source for all of the sampled gaseous hydrocarbon pools would eliminate source variation as a factor influencing the H_2S concentrations in the study area. However, because of the nature of the samples, establishing the source(s) is not easy. Several correlation parameters, e.g., sulfur carbon isotopic compositions and sulfur concentrations used in previous studies are not applicable in this study, as they can be altered by TSR. Geochemical alteration of oils and condensates by thermal maturation in the study area may have reduced the absolute concentrations of biomarkers in these hydrocarbon fluids. However, the terpane and sterane distributions in the solvent extracts of the sour

Table 3
Temperatures reached by the top of the Feixianguan Formation at present and at the end of Jurassic time

Structure name	Present temperature (°C)	Paleo-temperature (°C)
Luojiazhai	72–101	172–209
Dukouhe	95–105	188–206
Tieshanpo	76–91	165–179
Jingzhuping	64	160
Gunzhiping	66	165
Zhujiazui	121	223
Yuexichang	98	196
Laoyingyan	61	166

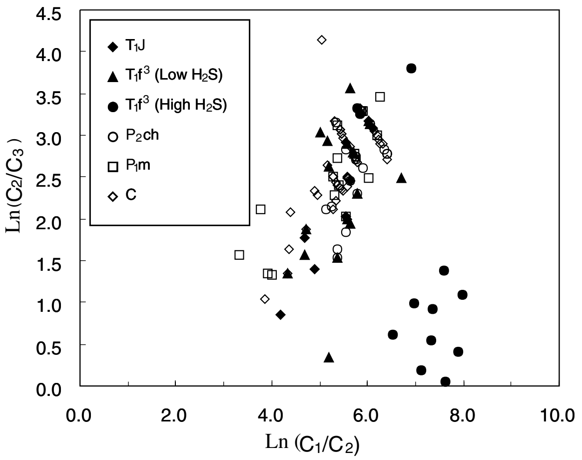

Fig. 6. Correlation of C_1/C_2 and C_2/C_3 ratios for natural gases from the eastern Sichuan Basin.

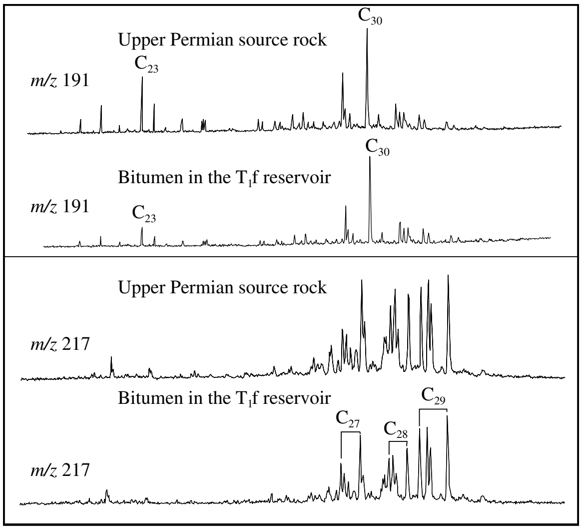

Fig. 7. m/z 191 and 217 mass fragmentograms showing the excellent correlation of the reservoir bitumens in the Feixianguan Formation with Upper Permian source rocks in the Changxing Formation.

gas reservoirs in the Triassic Feixianguan Formation correlate well with those in the coal – marine micritic limestones of the Upper Permian Changxing Formation (Fig. 7), indicating a possible genetic relationship, although the possibility of migration-contamination that may have compromised the biomarker data cannot be excluded (Huang et al., 1995; Wang et al., 1998; Yang et al., 2002).

4. Pyrobitumens in the Triassic Feixianguan Formation

Reservoir bitumens have been studied extensively in China (e.g., Jin et al., 1997; Sun and Yan, 1998; Wu et al., 1999; Liu et al., 2000; Xie et al., 2002a,b). The dominant form of solid bitumens observed from the oolitic reservoirs in the Lower Triassic Feixianguan Formation in northeastern Sichuan Basin is microscopic pyrobitumen closely associated with elemental sulfur and anhydrite nodules with clear replacement by calcite (Wang et al., 2002a,b). Detailed examination of the spatial relationships between the pyrobitumen and reservoir fabric/porosity structure provides additional evidence for the origin of pyrobitumens from TSR reactions in the palaeo oil reservoirs.

Petrographic thin section data reveal that pyrobitumens in the Feixianguan Formation reservoir rocks occur mainly in three different forms: as the filling of intercrystal and intergranular pores, as the particulate or spheric fills for spaces vacated by pressure dissolution, or as elongated fills for dissolution veins or vein networks.

Locally, the abundance of pyrobitumen in a rock also changes with reservoir lithology, with the highest concentrations being observed in the irreducible oolitic dolostone (0.2–2.3%, with an average of 1.33%). It is followed by spar oolitic dolostone (0.1–2.5%, average 0.59%), fine-middle spar dolostone (0.1–1.2%, average 0.36%), fine dolostone (average 0.16%) and spar dolostone (average 0.1%). Thus, the abundance of pyrobitumens is primarily a function of the effective porosity of the rock, because the dominant storage spaces for the natural gas in the Feixianguan Formation of the study area is the intercrystal oolitic dolostone (Ran et al., 2002).

Laterally, on a regional scale, the abundance of the pyrobitumen decreases slightly from Luojiazhai, and Dukouhe fields to the Tieshanpo Field, as the proven gas reserves change from 58 (Luojiazai Field), 27 (Dukouhe Field), to 32 billion cubic meters (Tieshanpo Field).

Vertically, the abundance of pyrobitumen in the rock shows large variation (Fig. 8a). As the pyrobitumens tend to distribute in payzones that have good porosity (Fig. 8b and c), there appears to be a linear correlation between the daily gas production from an individual payzone and the percentage of the pyrobitumen it represents in the combined pyrobitumen reserves from all of the payzones within the Feixianguan Formation (Fig. 9). As both the natural gas and pyrobitumen are TSR products of the early-accumulated oil, the presence of abundant pyrobitumen in the sour gas payzones does not appear to have any adverse effect on the reservoir quality.

5. Models for oil and gas generation, entrapment and thermochemical sulfate reduction in the oolitic reservoirs of the Lower Triassic Feixianguan Formation

Several attempts have been made to determine the timing for oil and gas entrapment and thermochemical sulfate reduction in the oolitic reservoirs of the Lower Triassic Feixianguan Formation from northeastern Sichuan Basin, using reservoir fluid inclusions, autogenous illite and paleo-oil–water contact (Zhao, 2001; Zhao, 2002a,b; Gao and Huang, 2002). The basic approaches are

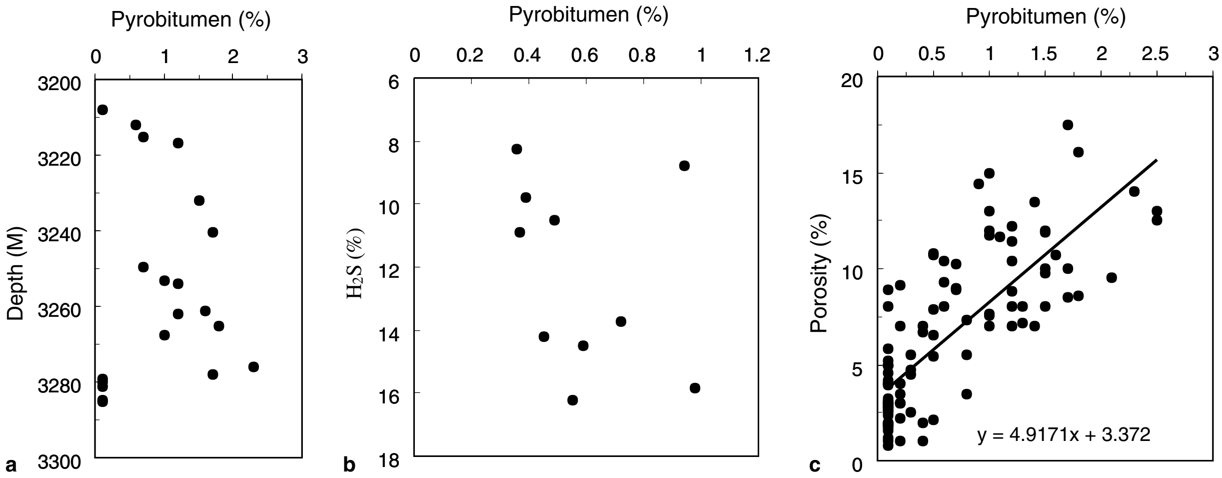

Fig. 8. Pyrobitumen contents in the Feixianguan Formation reservoirs as a function of reservoir depth (a) and variation in the pyrobitumen content with H_2S concentration (b) and reservoir porosity (c).

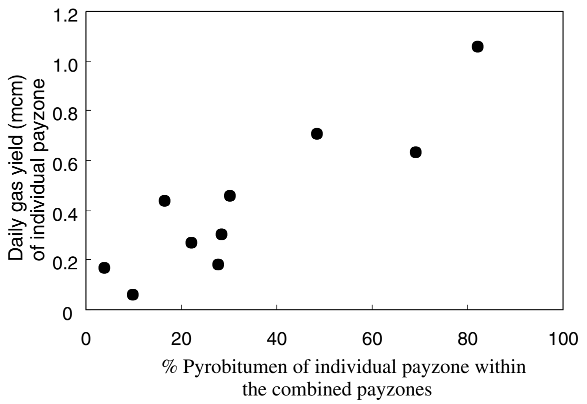

Fig. 9. Increase in the proportion of pyrobitumen produced with increasing single-well daily gas yield.

similar to those described earlier (Haszeldine et al., 1984; Karlsen et al., 1993; Lee et al., 1985; Hogg et al., 1993).

The sour gas traps are largely controlled by combined lithologic (oolitic beach deposit) and structural factors. Although the traps were structurally formed during the Himalayan orogeny, the oolitic reservoir rocks in the Feixianguan Formation were formed on the Kaijiang paleo-topographic highs during the Indosinian orogeny. As shown by a representative 1-D burial history model in Fig. 10, the only possible hydrocarbon source rocks in the Upper Permian strata of the study area entered the conventional oil window at the Late Triassic era. This indicates that the earliest possible time for the formation of the gas accumulations in this area had to be after this time. The homogenization temperature data obtained for the hydrocarbon inclusions in the Feixianguan Formation reservoir rocks range from 100 to 200 °C. Using a palaeogeothermal gradient of 2.8 °C/100 m, the reservoir rocks were buried to approximately 2600–6500 m when the hydrocarbon fluids were trapped during the Middle to Late Jurassic (Fig. 10). As most of the gas pools are located above the Upper Permian hydrocarbon source rocks, faults and fractures appear to have played a significant role in controlling the oil and gas distribution in the study area. The key geological elements and events for the petroleum systems in the study area are shown in Fig. 11.

The high quality oolitic gas reservoirs in the Feixianguan Formation were formed initially as the result of near-surface dolomitization and modified later by burial dissolution processes. Burial dissolution occurred at three different diagenetic stages, associated with different organic thermal maturation reactions and products. The first stage corresponded to conventional oil window for the Upper Permian source rocks, which was reached near the end of the Triassic to Middle Jurassic time. Primary expulsion from the Upper Permian source rocks provided not only hydrocarbons to fill Feixianguan Formation reservoirs, but also organic-rich aqueous solutions to dissolve some of the oolitic rock matrix. The second dissolution stage took place when the liquid hydrocarbons accumulated in the Feixianguan Formation reservoirs began to crack into gas at the end of the Middle Jurassic, as the result of thermochemical

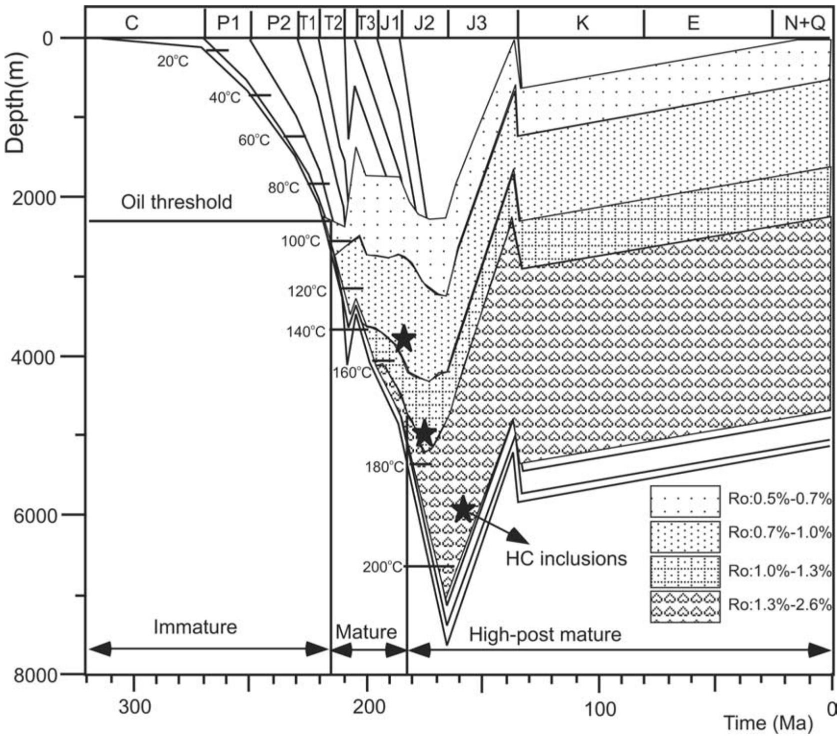

Fig. 10. Burial history curves for the Triassic Feixianguan Formation in the northeastern Sichuan Basin.

sulfate reduction under elevated subsurface temperatures. As the oolitic reservoirs are enriched in anhydrite, the resultant H_2S was extremely corrosive to the carbonate minerals in the reservoir. The last stage of dissolution occurred during the Himalayan orogeny, when the Feixianguan Formation was folded and uplifted, resulting in numerous microfractures. Dissolution along fractures in fine-grained micritic limestone and micritic dolostone often led to small veins or karst caves.

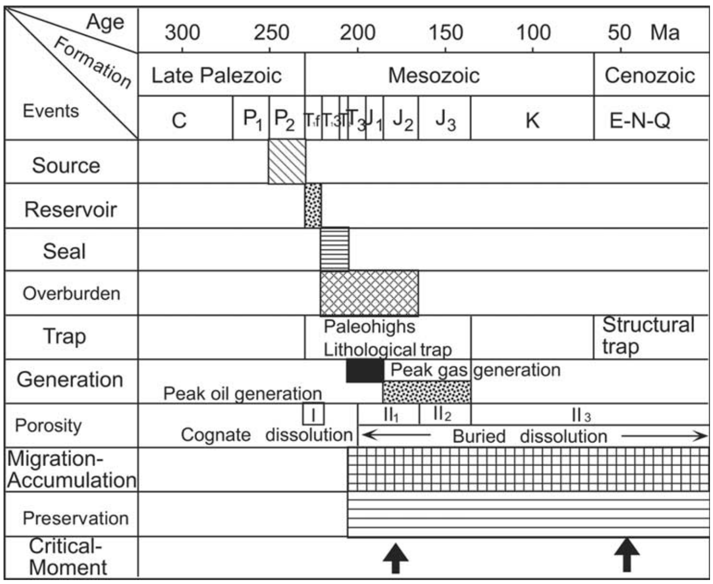

Fig. 11. Petroleum system chart for the Triassic oolitic gas reservoirs in the northeastern Sichuan Basin.

In the study area, the evolution of the oolitic sour gas accumulations in the Feixianguan Formation can be described using two different models. Most of the gas traps were formed by combined lithologic/structural controls (e.g., in the Luojiazhai, Dokouhe, Tieshanpo and Gunziping fields), but only small amounts of gases are trapped because of structural factors (e.g., the Jinzhuping Field). As illustrated in Fig. 12a, the formation of the lithologic-structural sour gas accumulations in the

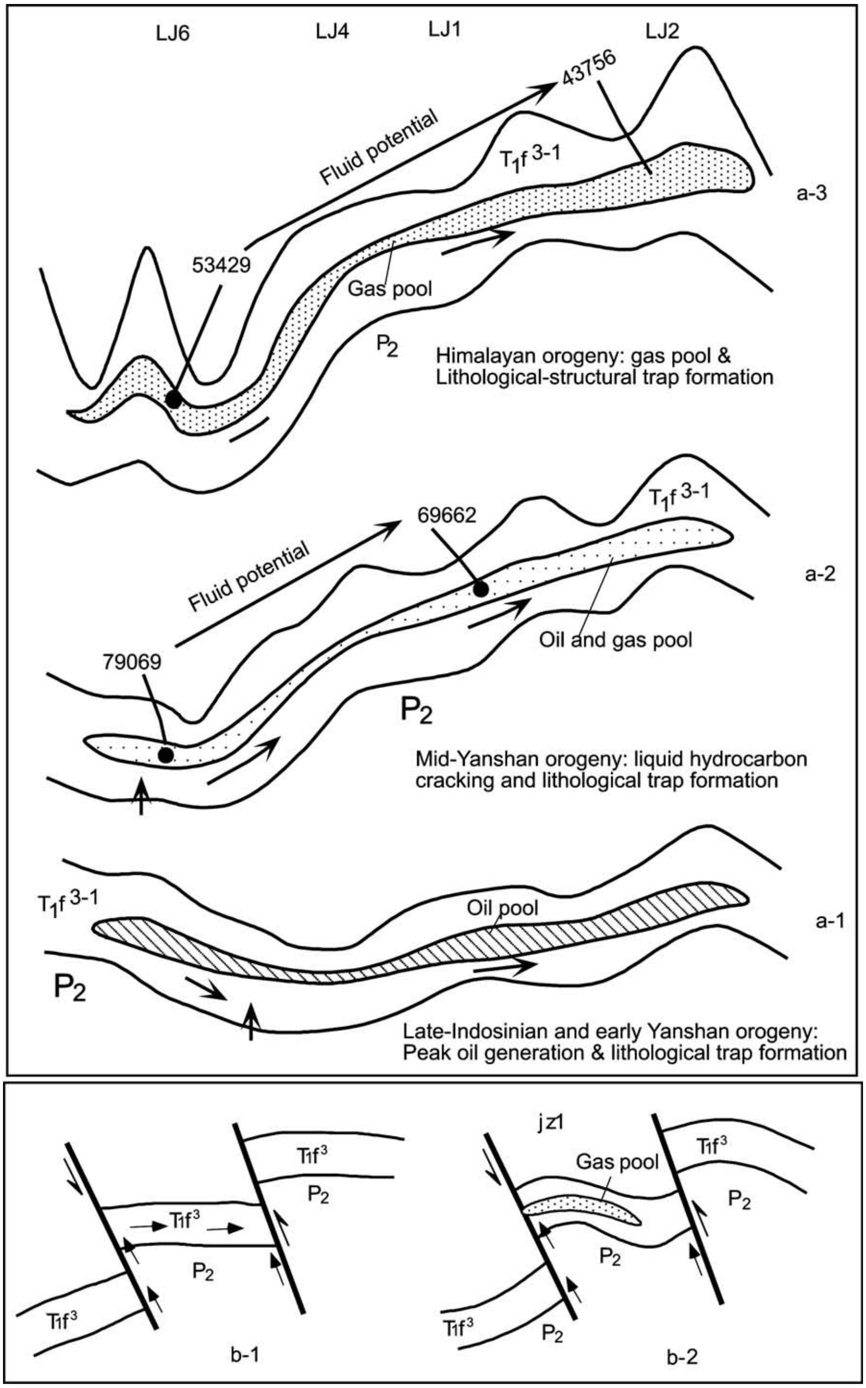

Fig. 12. Structural evolution of the Luojiazai (a-1 to a-3) and Jinzhuping gas fields (b-1 and b-2).

Table 4
Relationship among the structural position of the top of the Feixianguan Formation tectonic framework, reservoir quality and single well daily gas production

End of Triassic	End of Jurassic	Present day	Reservoir quality	Gas yield	Representative wells
Paleo-high	Paleo-high	Structural high	Well developed oolitic reservoirs	High (0.2–1.0 mcm)	LJ6, LJ7, LJ1, LJ2, LJ5; D1, D2, D3, D4; P1, P2, P4
			Poor reservoirs	Low (<0.1 mcm)	JZ1
Paleo-high	Paleo-sag	Structural sag	Good	Water well	D5, LJ8, ZJ1, Z1
Paleo-sag	Paleo-high	Structural high	Good but thin payzones	Low (<0.02 mcm)	LJ4
			Poor reservoir	Dry well	P3,Y1

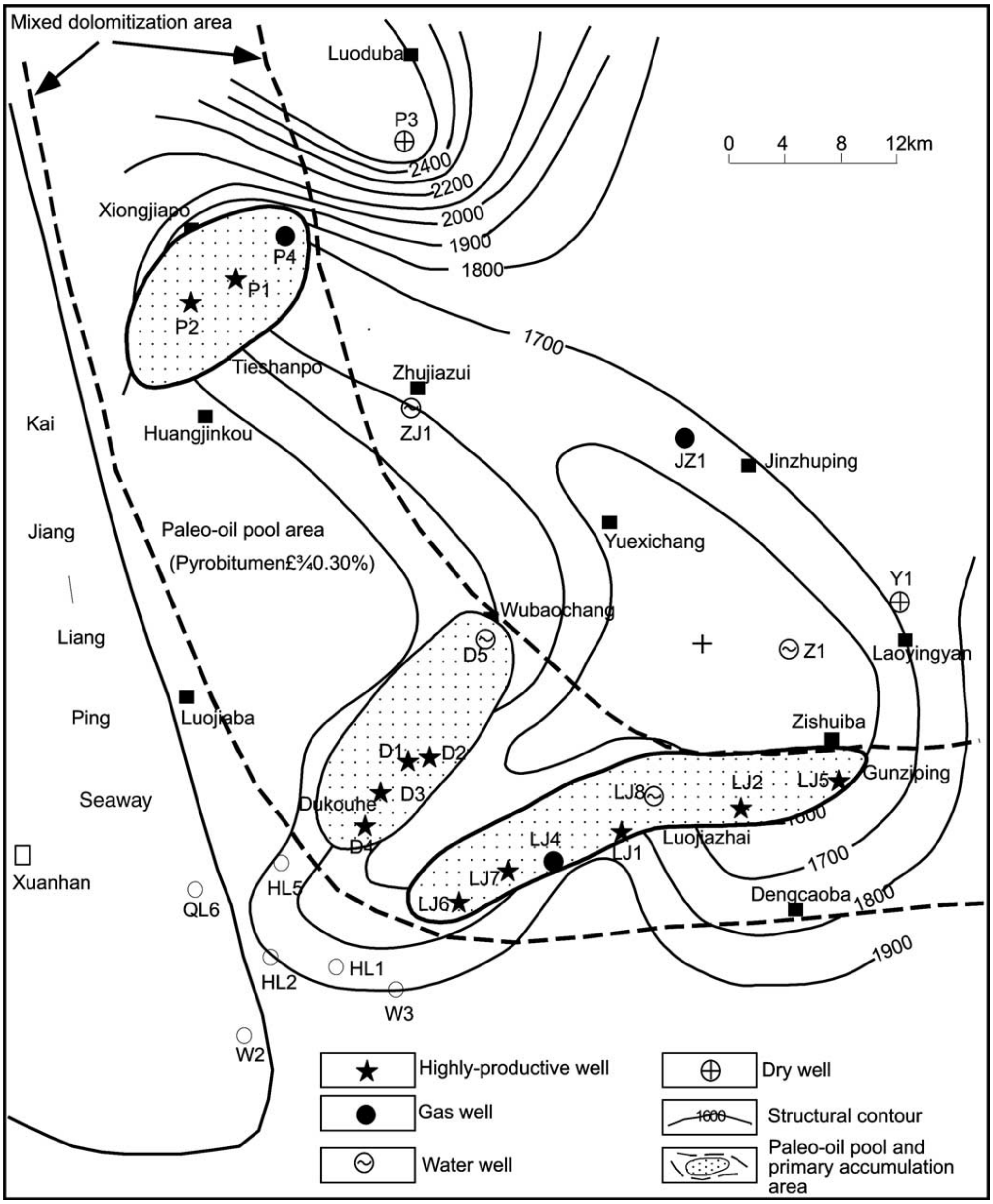

Fig. 13. Structural contour of the top of the Feixianguan Formation at the end of Late Triassic time and the likely locations of the paleo-oil traps.

Luojiazhai Field have experienced at least four different stages. (1) Deposition of oolitic sediments occurred in Early Triassic and subsequent dolomitization led to excellent primary reservoir porosities. (2) Upper Permian derived liquid hydrocarbons migrated upwards via faults into the Feixianguan Formation during the late Indosinian to early Yanshan orogeny. As this predated the formation of structural traps, the hydrocarbon fluids moved laterally within the continuous oolitic beds easterly, and eventually accumulated near the paleo-topographic highs (Fig. 12a-1). (3) Accumulation of liquid hydrocarbons in the oolitic reservoirs continued until the mid Yanshan orogeny. With increasing burial, liquid hydrocarbons in the reservoir cracked gradually to gas and interacted with sulfate to produce H_2S, thus turning the original oil pool into a sour gas accumulation (Fig. 12a-2). (4) Following extensive folding and uplift, structural traps were finally formed during the Himalayan orogeny, resulting in gas redistribution within the lithologic-structural traps (Fig. 12a-3). Drilling results summarized in Table 4 indicate that wells with high gas yields (e.g., LJ2, P2 and D1) are generally drilled on inherited paleo-topographic highs, but water wells are often encountered in locations that have experienced structural inversions. On the other hand, the structural gas traps in the Jingzhuping Field were formed rather late (Fig. 12b). It appears that no hydrocarbon accumulation occurred because of the poor reservoir porosity before the Mid Yanshan orogeny (Fig. 12b-1). Both the structural traps and secondary reservoir porosities (fractures and fissures) were formed during the late Yanshan-Himalayan orogeny (Fig. 12b-2).

Fig. 13 is a reconstructed paleo-structural map for the top of the Lower Triassic Feixianguan Formation at the end of Triassic time, together with the likely locations of the paleo-oil accumulations that were determined based on the current sour gas pools and reservoir pyrobitumens. The area between the two dashed lines on the map indicates the dolomitization zone within the oolitic reservoirs of the Feixianguan Formation, where the mean porosities range from 7% to 10%.

6. Conclusions

Results obtained from this study demonstrate the presence of two types of natural gas accumulations in the Lower Triassic oolitic reservoirs of the northeastern Sichuan Basin, SW China. Both types contain highly mature thermogenic gases, with the hydrocarbon source rocks in the Upper Permian strata. Natural gases from the area south of the ancient Kaijiang-Liangping Seaway are generally sweet gases formed as the result of thermal maturation, in contrast to those sour gases discovered north of the seaway that were clearly products of both thermal maturation and thermochemical sulfate reduction of early accumulated oils in the Feixianguan Formation reservoirs. The origins of the gases are supported by their chemical and stable carbon isotope compositions, as well as the occurrence of pyrobitumens in the reservoir. The distribution of the gas accumulations is controlled dominantly by the combination of lithologic and structural factors, and the regional variation in the concentrations of H_2S in the gases is clearly related to the presence and thickness of anhydrite-bearing evaporitic rocks interbedded or intercalated with oolitic reservoirs.

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References

Cai, C.F., Worden, R.H., Wang, Q.H., 2002. Chemical and isotopic evidence for secondary alteration of natural gas in the Hetianhe Field, Bachu Uplift of the Tarim Basin. Organic Geochemistry 33, 1415–1427.

Dai, J.X., 1985. The distribution, classification and origin of H_2S-bearing gases in China. Acta Sedimentologica Sinica 3 (4), 109–120 (in Chinese).

Gao, G., Huang, Z.L., 2002. Hydrocarbon fluid inclusions in reservoir rocks and gas accumulation processes in the Pingluoba Gasfield. Acta Sedimentologica Sinica 20 (1), 156–159 (in Chinese).

Haszeldine, R.S., Samson, I.M., Cornford, C., 1984. Dating diagenesis in a petroleum basin, a new fluid inclusion method. Nature 307, 354–357.

Hogg, A.J.C., Hamilton, P.J., Macintyre, R.M., 1993. Mapping diagenetic fluid flow within a reservoir: K–Ar dating in the Alwyn area (UK North Sea). Marine and Petroleum Geology 10, 279–294.

Huang, J.Z., Chen, S.J., Song, J.R., 1995. Source Rock Distribution and Thermal Evolution of the Marine Carbonate Sequence in the Sichuan Basin. PetroChina Southwest Petroleum Company, Chengdu, p. 230 (in Chinese).

Jiang, X.F., Xu, R.F., Huang, J.Z., 2002. Characteristics of hydrogen sulfide distribution in the Feixianguan Formation gas reservoirs in eastern Sichuan. Natural Gas Industry 22 (2), 24–27 (in Chinese).

Jin, K.L., Liu, D.M., Tu, J.Q., 1997. Organic Petrology – A Case Study of the Tarim Basin. Seismic Press, Beijing, p. 234 (in Chinese).

Karlsen, D.A., Nedkvitne, T., Larter, S.R., 1993. Hydrocarbon composition of authigenic inclusions: application to elucidation of petroleum reservoir filling history. Geochimica et Cosmochimica Acta 57, 3641–3659.

Krouse, H.R., Viau, C.A., Eliuk, L.S., Ueda, A., Halas, S., 1988. Chemical and isotopic evidence of thermochemical sulfate reduction by light hydrocarbon gases in deep carbonate reservoirs. Nature 333, 415–419.

Lee, M., Aronson, J.L., Sayin, S.M., 1985. K–Ar dating of Rotliegendes sandstone, Netherlands. American Association of Petroleum Geologists Bulletin 68, 1381–1385.

Li, Z.Q., Ran, L.H., Cheng, G.S., 2002. Geological models of steep gas-bearing structures in eastern Sichuan. Journal of Chengdu University of Technology 29 (6), 605–609 (in Chinese).

Liu, L.F., Zhao, J.Z., Zhang, S.C., 2000. Genetic types and characteristics of the Silurian asphaltic sandstones in the Tarim Basin. Acta Petrolei Sinica 21 (6), 12–17 (in Chinese).

Liu, X.Y., Zhao, D.L., Zheng, B., 2001. History, status and trend of research on oil and gas reservoir formation. Henan Petroleum 15 (3), 10–14 (in Chinese).

Machel, H.G., Krouse, H.R., Riciputi, L.R., 1995. The Devonian Nisku sour gas play, Canada – a unique natural laboratory for study of thermochemical sulfate reduction. In: Vairavamurthy, M., Schoonen, M.A.A. (Eds.), Geochemical Transformations of Sedimentary Sulfate. American Chemical Society Symposium Series, vol. 612, pp. 439–454.

Machel, H.G., 1998. Gas Souring by thermochemical sulfate reduction at 140°C: discussion. American Association of Petroleum Geologists Bulletin 82, 1870–1873.

Manzano, B.K., Fowler, M.G., Machel, H.G., 1997. The influence of thermochemical sulfate reduction on hydrocarbon composition in Nisku reservoirs, Brazeau River area, Alberta, Canada. Organic Geochemistry 27, 507–521.

Orr, W.L., 1977. Geologic and geochemical controls on the distribution of hydrogen sulfide in natural gas. In: Campos, R., Goni, J. (Eds.), Advances in Organic Geochemistry, Proceedings of the 7th International Meeting on Organic Geochemistry, Enadisma, Madrid, pp. 571–597.

Peters, K.E., Fowler, M.G., 2002. Applications of petroleum geochemistry to exploration and reservoir management. Organic Geochemistry 33, 5–36.

Prinzhofer, A.A., Huc, A.Y., 1995. Genetic and post-genetic molecular and isotopic fractionations in natural gases. Chemical Geology 126, 281–290.

Ran, L.H., Chen, G.S., Zhang, J., 2002. Distribution and exploration potential of the oolitic beach reservoirs in the Feixianguan Formation of northeastern Sichuan Basin. China Petroleum Exploration 7 (1), 46–55 (in Chinese).

Rooney, M.A., 1995. Carbon isotope ratios of light hydrocarbons as indicators of thermochemical sulfate reduction. In: Grimalt, J.O., Dorronsoro, C. (Eds.), Organic Geochemistry: Developments and Applications to Energy, Climate, Environment and Human History. AIGOA, Donostia-San Sebastian, pp. 523–525.

Sassen, R., 1988. Geochemical and carbon isotopic studies of crude oil destruction, bitumen precipitation and sulfate reduction in the deep Smackover Formation. Organic Geochemistry 12, 351–361.

Schenk, H.J., di Primio, R., Horsfield, B., 1997. The conversion of oil into gas in petroleum reservoirs. Part 1: comparative kinetic investigation of gas generation from crude oils of lacutrine, marine and fluviodelaic origin by programmed-temperature closed-system pyrolysis. Organic Geochemistry 26, 467–481.

Shen, P., Xu, Y.C., Wang, J.J., 1997. Sulphur isotopic compositions of hydrogen sulphides in natural gases and sedimentary controls. Acta Sedimentologica Sinica 15 (2), 216–219 (in Chinese).

Sun, Y.S., Yan, F., 1998. Microfluorescence characteristics and timing of hydrocarbon expulsion of the Ordovician source rocks in the Tazhong region of the Tarim Basin. Xinjing Petroleum Geology 19 (1), 14–17 (in Chinese).

Tian, S.C., Chen, J.Y., Zhang, S.L., 1996. Dynamic system for petroleum trap formation. Petroleum Explorationist 1 (2), 35–42 (in Chinese).

Tissot, B.P., Welte, D.H., 1984. Petroleum Formation and Occurrence. Spinger-Verlag, Berlin, Heidelberg, New York, Tokyo, pp. 313–319.

Trudinger, P.A., Chambers, L.A., Smith, J.W., 1985. Low temperature sulfate reduction: biological versus abiological. Canadian Journal of Earth Sciences 22, 1910–1918.

Wang, Y.G., Liu, H.Y., Wen, Y.C., 1998. Upper Permian Reef Reservoirs and Drilling Targets in Eastern Sichuan Basin. PetroChina Southwest Petroleum Company, Chengdu, p. 145 (in Chinese).

Wang, Y.G., Yang, Y., Wen, Y.C., et al., 2000. The study on the gas pool forming of Changxing group and Feixianguan group and its prediction for exploitation objects evaluation in the northeast of Sichuan basin, the west-south branch cooperation, Petrochina.

Wang, X.Z., Zhang, F., Ma, Q., 2002a. Characteristics of reef and bank sediments and fluctuation of sea-level during the deposition of Lower Triassic Feixianguan Formation in eastern Sichuan Basin. Acta Sedimentologica Sinica 20 (2), 249–254 (in Chinese).

Wang, Y.G., Dou, L.R., Wen, Y.C., 2002b. Origin of H_2S in the Triassic Feixianguan Formation gas pools, northeastern Sichuan Basin, China. Geochimica 31 (6), 517–523 (in Chinese).

Waples, D.W., 2000. The kinetics of in-reservoir oil destruction and gas formation: constraints from experimental and empirical data, and from thermodynamics. Organic Geochemistry 31, 553–575.

Whiticar, M.J., Snowdon, L.R., 1999. Geochemical characterization of selected Western Canada oils by C_5-C_8 Compound Specific Isotope Correlation (CSIC). Organic Geochemistry 30, 1127–1161.

Worden, R.H., Smalley, P.C., Oxtoby, N.H., 1995. Gas souring by thermochemical sulfate reduction at 140 °C. American Association of Petroleum Geologists Bulletin 79, 854–863.

Worden, R.H., Smalley, P.C., Oxtoby, N.H., 1996. The effect of thermochemical sulfate reduction upon formation water salinity and oxygen isotopes in carbon gas reservoirs. Geochimica et Cosmochimica Acta 60, 3925–3931.

Wu, Z., Yang, Y.C., Wang, X.H., 1999. Estimation of original bitumen quantities in the Lower Ordovician strata of Ordos Basin. Natural Gas Industry 19 (6), 14–17 (in Chinese).

Xie, Z.Y., Hu, G.Y., Li, J., 2002a. Validity in the identification of Ordovician source rocks in the Ordos Basin using laboratory simulation experiments. Petroleum Exploration and Development 29 (2), 29–32 (in Chinese).

Xie, Z.Y., Jiang, Z.S., Zhang, Y., 2002b. Whole rock pyrolysis and application in the evaluation of source rock. Acta Sedimentologica Sinica 20 (3), 510–514 (in Chinese).

Yang, C., Hutcheon, I., 2001. Fluid inclusion and stable isotopic studies of thermochemical sulphate reduction from Burnt Timber and Crossfield East gas fields in Alberta, Canada. Bulletin of Canadian Petroleum Geology 49 (1), 149–164.

Yang, J.J., Wang, Y.G., Wang, L.S., 2002. The origin of natural gases in the Changxing and Feixianguan formations of eastern Sichuan Basin. Acta Sedimentologica Sinica 20 (2), 349–353 (in Chinese).

Yue, C.T., Li, S.Y., Ding, K.L., 2003. Laboratory simulation on thermochemical sulfate reduction of methane with solid calcium sulfate. Geochimica Acta 32 (6), 601–605 (in Chinese).

Zhao, J.Z., 2001. Timing of marine petroleum accumulations in the Tarim Basin using paleo-oil/water and gas–water contact. Petroleum Exploration and Development 28 (4), 53–58 (in Chinese).

Zhao, M.J., 2002a. Origin of natural gases from the Hetianhe Gasfield. Geological Review 48 (5), 480–486 (in Chinese).

Zhao, J.Z., 2002b. Hydrocarbon inclusion analysis: application in geochronological study of hydrocarbon accumulation. Geology and Geochemistry 30 (2), 83–89 (in Chinese).

Zhao, M.J., Zhang, S.C., Liao, Z.Q., 2001a. Gas generation from oil cracking and its significance in gas exploration. Petroleum Exploration and Development 28 (4), 47–49 (in Chinese).

Zhao, M.J., Zeng, F.G., Qin, S.F., 2001b. Two types of thermogenic gases in the Tarim Basin. Natural Gas Industry 21 (1), 35–39 (in Chinese).

Zhao, J.Z., Pang, W., Wu, S.B., 2002. Geochronology and characteristics of marine hydrocarbon accumulation in the Tarim Basin. Chinese Journal of Geology 37 (Suppl.), 81–90 (in Chinese).