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Biogenic gas systems in eastern Qaidam Basin

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Abstract

Several giant biogenic gas fields (with proven gas reserves greater than 25 billion cubic meters) have been discovered in recent years in the Sanhu area of eastern Qaidam Basin. This area has an average surface altitude of around 2800 m, and forms the northern segment of the Qinghai-Tibet Plateau. The biogenic gas fields occur mostly within or adjacent to the depocenter of approximately 3400 m of Quaternary sediments. The gas reservoirs, with burial depth generally less than 1900 m, are unconsolidated sandstones with approximately 24–40% porosity, and are interbedded with mudstones containing on average 0.3% TOC. The occurrence of methanogens in the shallow Quaternary sediments appears to depend on both the sedimentary facies and burial depths, thus most of the biogenic gases in the Sanhu area appears to have derived from the source kitchens in the central sag above a biogenic gas floor at the depth around 1800 m. The key gas system elements for the formation of the giant biogenic gas accumulations include (1) secular low surface temperatures and lake water hypersalinity favor the preservation of suitable organic substrates for biogenic methane generation, (2) well-developed sand and mud interbeds, (3) sufficient cumulative thickness of water-saturated mudstones as caprocks, (4) presence of syndepositional anticlines of Pleistocene and later age, (5) a regional hydrogeological system favoring northeastward gas migration, and (6) ongoing dynamic gas migration and accumulation with abundant gas supply.

Keywords: Biogenic gas; Qaidam basin; Natural gas in Chinese basins; Quaternary

1. Introduction

Giant Quaternary biogenic gas fields (i.e. fields with more than 25 billion cubic meters of proven gas reserves) are seldom reported worldwide. In recent years, commercial biogenic gas discoveries have been made in many sedimentary basins in China, including the Sanhu region of the eastern Qaidam Basin (e.g. Pang et al., 2005), Luliang and Baoshan basins in Yunnan (Xu et al., 1999; Dai et al., 1999; Song et al., 1999; Luo, 1999; Wang and Luo, 2000), Baise Basin in Guangxi (Luo et al., 2003), alluvial plain areas along the southeastern coast (Lin et al., 1997, 1999, 2004; Jiang et al., 1997; Lu, 1998; Yan et al., 1998; Chen et al., 2003), Yinggehai and Qiongdongnan basins in the northern continental shelf of South China Sea (He et al., 2002; Huang and Xiao, 2002; Pan et al., 2002), Bohai Bay Basin (Shi, 2002), Subei Basin (Zheng, 1998), Junggar Basin (Liao et al., 2001; J. Wang et al., 2003; Li et al., 2004), Songliao Basin (Zhang et al., 2004) and Hetao Basin in Inner Mongolia (Yang, 2004). However, the Sanhu area of the eastern Qaidam Basin is the only region in China where giant biogenic gas accumulations have been discovered (Pang et al., 2005).

There is still a significant gap in our understanding of the shallow biogenic gas systems in the Sanhu area. This area has an average ground surface altitude of approximately 2800 m above sea level. The high altitude, low surface temperature, high water salinity and high sedimentary rates are considered among the important geographic and geological attributes that are responsible for the accumulation and preservation of gas-source organic matter

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(Gu, 1993; Zhou et al., 1994; Qi et al., 1997; Zhang et al., 2004a, b), and resultant biogenic gases (Guan et al., 1997, 2001; Dang et al., 2003, 2004; Zhu et al., 2003). The very recent dynamic accumulation is believed to be significant for the formation of giant biogenic gas fields in the eastern Qaidam Basin (Qi et al., 1997; Yang et al., 1999; Jin et al., 2002; Xu et al., 2002; Dai et al., 2003; M. Wang et al., 2003; Ma et al., 2004; Xu and Xie, 2004).

The purpose of this manuscript is to review the Chinese literature devoted to shallow biogenic gas systems, with a particular focus on the Sanhu area. This review is intended to provide the first steps toward recognition of specific exploration strategies for shallow biogenic gases with an early generation system.

2. Geological settings

The Qaidam Basin in northwestern China is a large Mesozoic–Cenozoic continental basin, bounded by three major maintain ranges (i.e. Kunlun, Qilian and Altun mountains, Fig. 1). Based on the basement structure and sedimentary covers, this basin can be divided into three first-order structural units: the northern margin fault-fold belt, and the western and eastern depressions. Granite, gneiss and

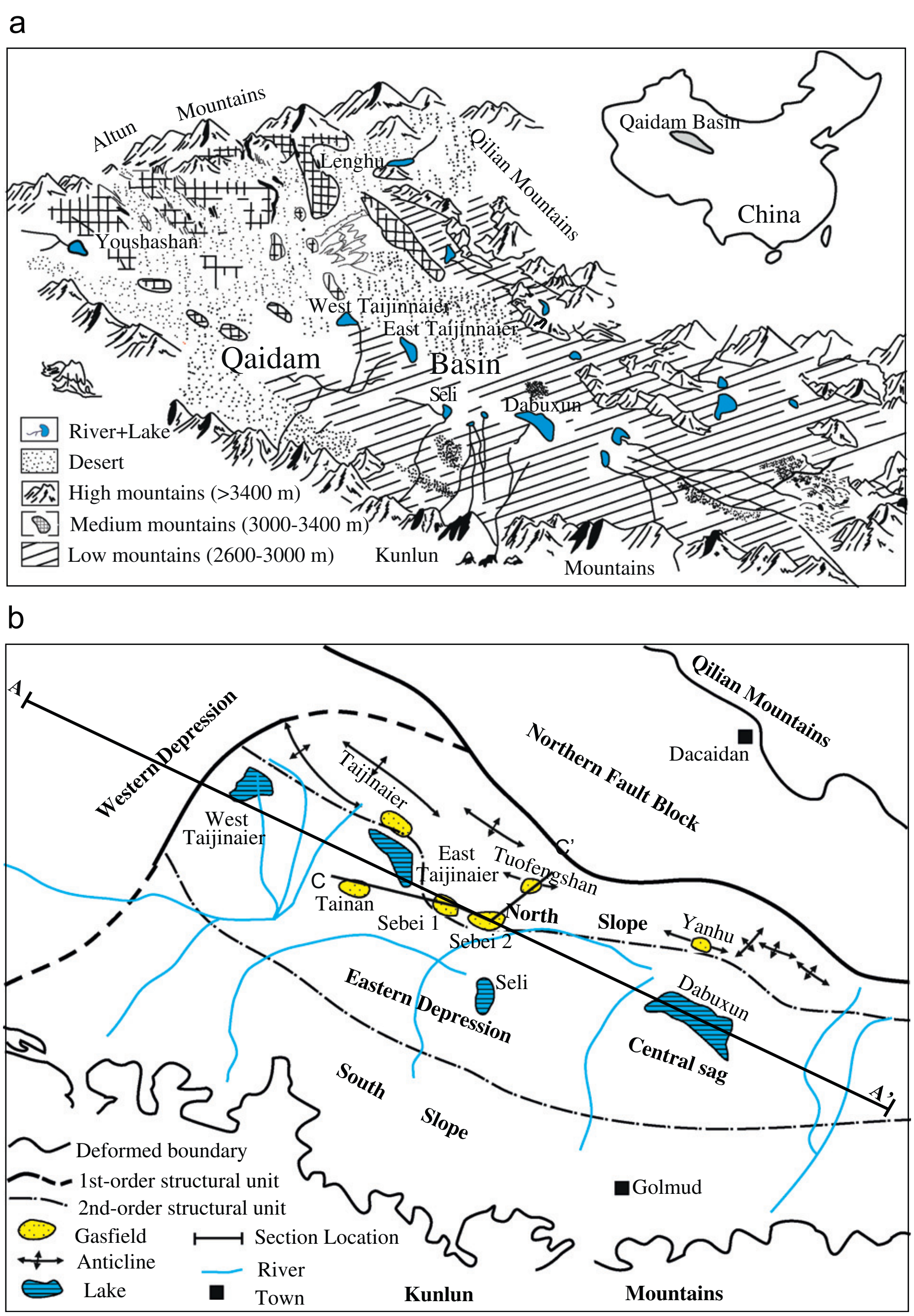

Fig. 1. (a) Geographic location of the Qaidam Basin and (b) the division of structural units in the central and eastern Qaidam Basin.

green schist occur in the basement of the eastern and western depressions. Weakly metamorphosed Paleozoic carbonates are also present in most areas of the basin, with the exception of the eastern depression and the Kunlun piedmont zone that contains igneous rocks (Zhai, 1990).

It is this difference in basement composition that resulted in the structural response in different parts of the basin to the north-south compression. The evolution of the Qaidam Basin has experienced three major stages: the piedmont fault depression stage in the Mesozoic, the unified depression stage in the Tertiary, and the cyclic folding in the center and west but subsiding depression in the east in the Quaternary. At the end of the Pliocene, the intense northward subduction of the Indian Plate led to significant elevation of the central and western Qaidam Basin, while the Sanhu area in the east remained relatively stable and formed a large inland lake in the Quaternary. Since the Holocene, the eastern depression has uplifted as part of the re-upheaval of the Qinghai-Tibet Plateau, with the depocenter being shifted eastward, and the development of the large-scale lake basin then terminated (Zhai, 1990; Huang et al., 1996; Jin et al., 1999, 2002; Hanson et al., 2001; Xia et al., 2001).

With the eastward shift in depocenter, fluvial-lacustrine sediments were deposited in the Sanhu area (Fig. 2). The thickness of the Quaternary sediments is up to 3400 m and mostly in the range of 1500–2000 m, with the mean past sedimentary rate around 0.6–0.7 mm per year. In the early Pleistocene fluvial-deltaic sediments were deposited with abundant terrestrial debris. The development of the lake basin reached its climax by the middle Pleistocene, with the deposition of dominantly deepwater fine-grained argillaceous sediments. In the late Pleistocene, the Sanhu area was continuously elevated due to the influence of the Quaternary neo-tectonic movement. As the climate became drier, the lake shrank with waters becoming shallower and saltier. In the Holocene, the lake dried out as the whole Qaidam Basin was elevated (Table 1).

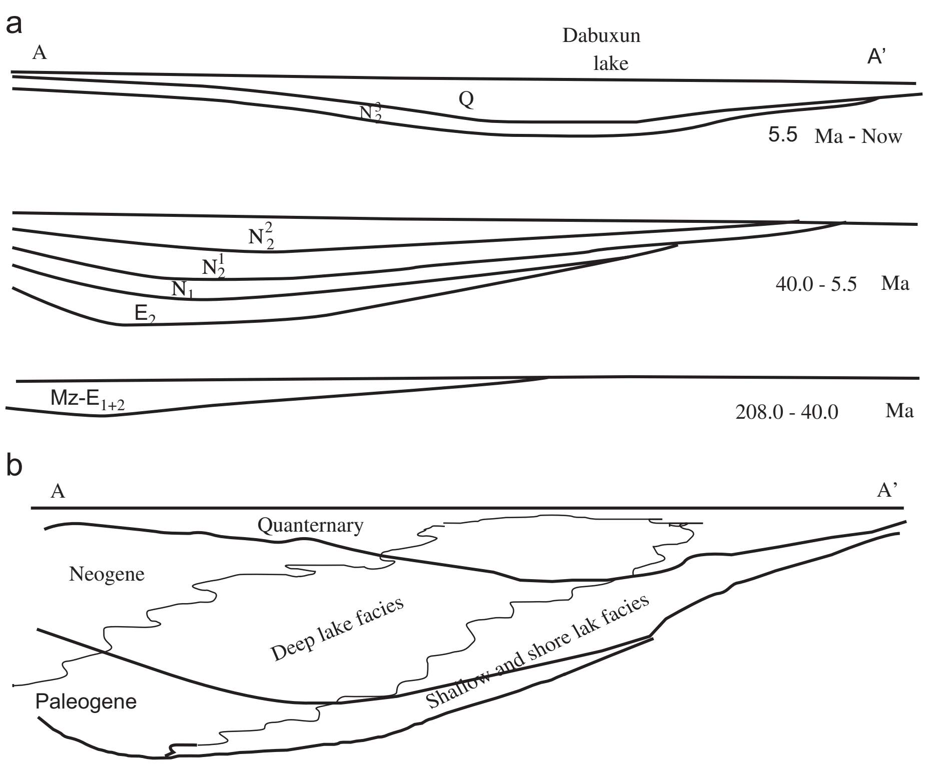

Fig. 2. (a) Schematic cross section showing the shift in depocentres as a function of geological time; and (b) variation in sedimentary facies in eastern Qaidam Basin. See Fig. 1 for the location of the cross section.

Table 1
Quaternary stratigraphy in the Sanhu area, Qaidam Basin

Stratigraphic system		Average thickness (m)	Sedimentary facies
Q			
Holocene	Yanqiao Fm. (Q_4)	20	Saline lake/kavir
Pleistocene			
Upper	Dabuxun Fm. (Q_3)	80	Lacustrine bog/saline lake
Middle	Qigequan Fm. (Q_{1+2})	1700	Shallow to semi-deep water lacustrine
Lower			

The Qigequan Formation (Q_{1+2}) is the main Quaternary stratum in the Sanhu area (Table 1), with a maximum thickness of 3200 m and an average thickness of 1700 m. Based on seismic reflectance features, this formation can be divided into 14 units (K0-K13, from top to base). All of the gas pays discovered in the Sanhu area are within this formation, which are grouped into four payzones (Fig. 3).

Spore-pollen assemblages and geomagnetic dating data indicate several alternating cold and dry–warm and humid climate cycles in the past 3 Ma (Zhai, 1990). Ostracode fossils reveal at least five alternating fresh and saline fossil zones within the Quaternary deposits (Yang, 1981). More recent investigations suggest that the alternation of different climates in the Quaternary in the Qaidam Basin was probably far more frequent than previously thought, as there is evidence for at least 30 alternation cycles within the past 1.87 Ma (Kang et al., 2003). The Sanhu area has been the Quaternary depocenter, with the sediments consisting mainly of mudstone and sandy mudstone intercalated with siltstone, argillaceous siltstone and carbonaceous mudstone. However, the organic richness in these Quaternary sediments is relatively low, with little organic matter ($<0.1\%$ TOC) in sandstones, an average 0.3% TOC in argillaceous mudstones (Gu, 1993), and occasionally up to 19% in carbonaceous mudstones (Zhou et al., 1994; Xu and Xie, 2004).

3. Gas system description

3.1. Gas geochemistry and early gas generation

The critical moment of gas generation, migration and accumulation is an important characteristic for unconventional biogenic gas systems. Geochemical data of gases in Quaternary reservoirs clearly demonstrate that the gases are of biogenic origin and were formed by breakdown of organic matter by anaerobic bacteria. The gases are dominated by methane (mostly $>99.9\%$ by weight), with minor C_{2+} hydrocarbons, N_2 and CO_2 (all below 1%). The $\delta^{13}C$ values of methane in these gases range from $-68.51‰$ to $-65.00‰$. Both these characteristics are typical of biogenic gas. Biogenic gas can form in saline and freshwater environments by microbial action either through carbon dioxide reduction or acetate fermentation. The δD values of methane in these gases range from $-227.55‰$ to $-221.94‰$, much higher than those generated from acetate fermentation. Thus, these biogenic gases are probably produced during carbon dioxide reduction (Schoell, 1980; Xu and Xie, 2004; Pang et al., 2005).

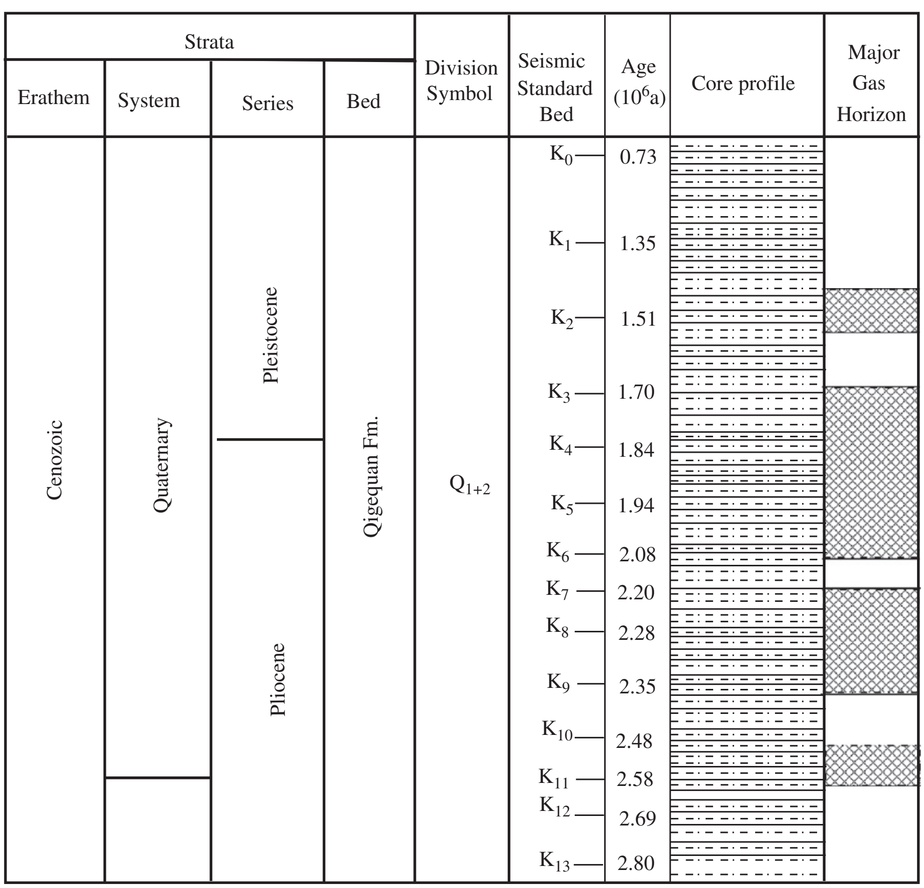

Fig. 3. Stratigraphic column of the Quaternary Qigequan Formation in the Sanhu area, Qaidam Basin (based on data from the Sezhong 6 and Sesheng 1 wells).

3.2. Gas source bed attributes

Quaternary strata in the Sanhu area are characterized by inland evaporitic lacustrine sediments, with low organic content. The cumulative thickness of the Quaternary lacustrine dark mudstones is up to 2500 m with an average of 1200 m, accounting for about 70% of the sedimentary column. These mudstones contain on average only 0.3% TOC due to the optimum sedimentation and burial rate in the Quaternary (up to 1.2 mm/year with an average of 0.65 mm/year). The organic input is predominately from terrigenic herbaceous and low shrubbery plants, relatively rich in cellulose, hemicellulose, and carbohydrates such as starch, fat and pectin. As the average geothermal gradient in this area is only about 25 °C/km, the Quaternary sediments have been exposed to less than 70 °C, with the measured vitrinite reflectance values for shallow sediments with burial depth less than 2000 m being far below 0.5% Ro (Gu, 1993; Qiu, 2001).

How could the Quaternary deposit with such a low TOC content be the effective source rocks for the bioigenic gases? In contrast to conventional thinking, mass balance calculations (Clayton, 1992) suggest that the amount of TOC needed for biogenic gas is not very large, and allowing for 10% conversion, sediments containing greater than 0.2% TOC can potentially generate a free gas phase. In addition to the moderate burial rate, the specific climate and depositional environment in the area may have also played an important role in the preservation of the generated biogenic gases. In the early and middle Pleistocene, the rise of the Qinghai-Tibet Plateau led to widespread occurrence of glaciers in the southern and northern margins of the basin, i.e. in the Kunlun and Qilian mountains. The dry and cold climate in the Sanhu area resulted in extremely low temperature and high salinity in the column of the lake water, with the contents of xerophile and halobiont increasing relative to the aquatic organisms (Fig. 4). Therefore, the presence of permafrost could result in both the monotony of organic species and the slow degradation of the primary organic matter both in water columns and in shallow subsurface, as indicated by the presence of large amounts of well-preserved plants in sediments. This provided methanogens with sufficiently available substrates in subsequent diagenesis (Dang et al., 2003). When the sediments are buried to some depth and reach the optimal temperatures for methanogens to thrive, the dilution of water salinity by groundwater infiltration would greatly facilitate the flourish of the methanogens in shallow sediments and hence the generation of large quantities of biogenic methane.

Therefore, the secular cryogenic climate and the hypersalinity of the lake waters may have been critical factors, not only for the effective preservation the nutrients and primary organic matter but also for the delay in peak biogenic gas generation in the Sanhu area.

3.3. Gas reservoirs and caprocks

Quaternary reservoir beds are well developed in the Sanhu area, with the arenaceous rocks (sand sheets and small sand bars) amounts to about 16–28% of the sedimentary column. The reservoirs are lithologically dominated by silty clasolite, with siltstone and argillaceous siltstone accounting for over 90%. Occasionally, fine-grained sands and oolith occur in some localities in reservoir intervals. The sand sheet clasolite has excellent horizontal connection and stable occurrence, commonly attributed to flood land deposit or eolian sands (Sun et al.,

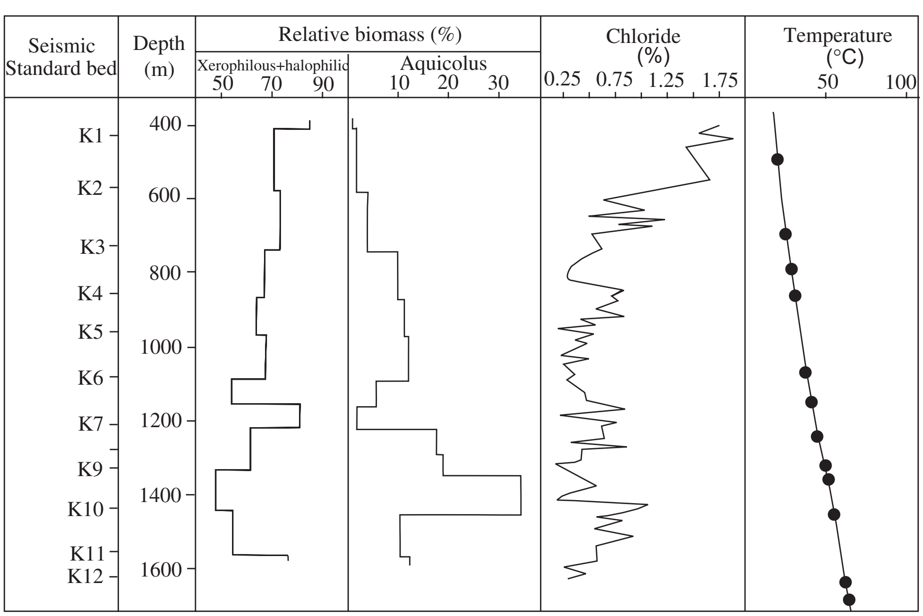

Fig. 4. Reconstructed land and aquatic plant assemblages, lake water salinity and present-day temperature of the Quaternary sediments in the Sanhu area. Chloride percentage was measured from the mud samples in the canned cuttings. As freshwater was used for drilling, the vertical variation in the chloride percentage gives a proxy to changes in paleosalinity.

2003). The reservoirs are typically of small single-bed thickness (mostly 1–3 m but up to 6 m for sand bars) that may be vertically stacked (over 120 beds in the lower Pleistocene). Stacked reservoirs have large cumulative thickness (up to 200–300 m), high vertical heterogeneities, and good horizontal connectivity.

Fig. 5 demonstrates the variation in porosity and permeability as a function of burial depth for arenaceous and argillaceous rocks in the Sanhu gasfield area. Vertically, porosity and permeability for both arenaceous and argillaceous rocks decrease with increasing depth, indicating the compaction effect. Due to the weak compaction, primary pores are well developed in these largely unconsolidated rocks, with the effective porosity ranging from 25% to 40%. Although theoretically both arenaceous and argillaceous rocks can act as gas reservoir rocks, no mudstone and arenaceous mudstone in this area have produced commercial gas flows in this area, nor does an electric log interpretation show a gas pay in the mudstone intervals.

There is a large difference in the permeability between the Quaternary sandstones and mudstones in the Sanhu area, and this has likely played a significant part in the formation of the relative gas caprocks. As shown in Fig. 5, the permeability of argillaceous rocks is commonly less than 3 mD, whereas the arenaceous rocks often show values greater than 10 mD. The permeability difference in adjacent sandstone and mudstone beds can be up to two orders of magnitude. It is this difference that makes sandstone and siltstone good gas reservoirs but mudstone and argillaceous rock caprocks. It is worth mentioning that salt-bearing sediments occur in the shallow depth of the Sanhu area. However, drilling results show that most of the main gas horizons are not distributed in the area where salt-bearing sediments are present in shallower strata. As the gas yields generally increase with reservoir depth (Fig. 6), this suggests that the decrease in mudstone caprock permeability not the presence of salt layers may be a key geological control.

Although mudstones undoubtedly act as the gas caprock in the Sanhu area, it is very useful to pay attention to the effect of the individual mudstone bed thickness, the total number of mudstone beds above a particular reservoir, and water saturation on the seal capacity of a given caprock. Laboratory experiments on samples taken from the Sanhu area show that the measured breakthrough pressures for a 6 and a 23 cm mudstone core are 1.9 and 6.0 mPa, respectively. Thus, thicker mudstones possess stronger seal capability. Data determined for the two mudstone cores and different sand-mud association under different water saturations (Fig. 7) show that, for any given water

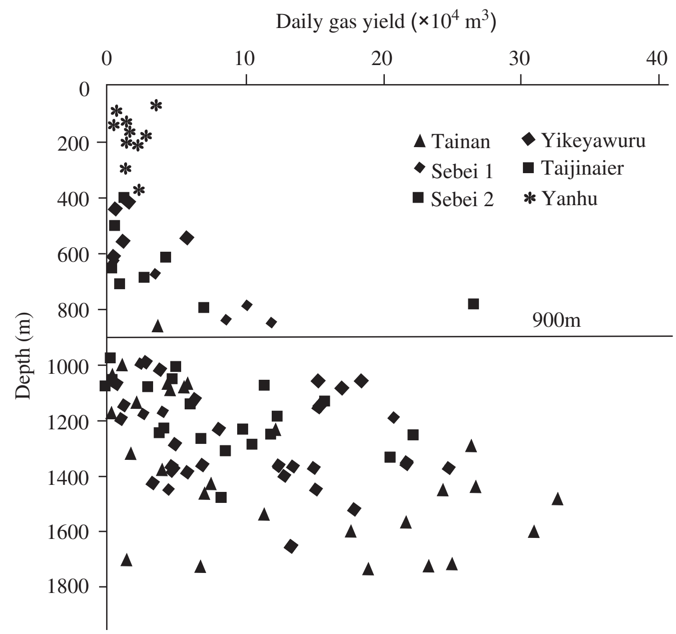

Fig. 6. Daily gas yields as a function of reservoir depth in the Sanhu area.

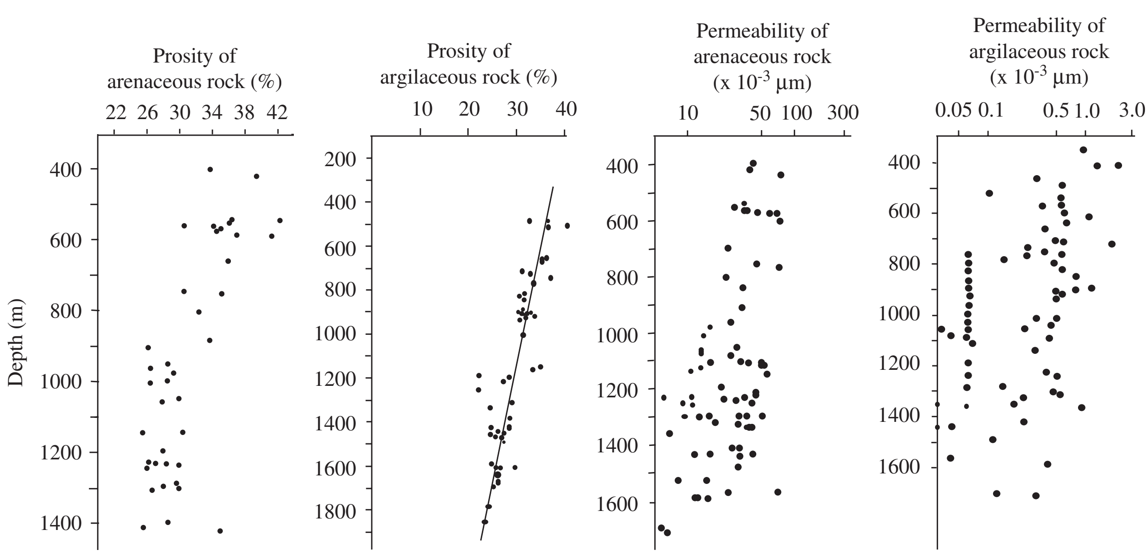

Fig. 5. Change in petrophysical properties of the arenaceous and argillaceous sediments in the Quaternary strata of the Sanhu area.

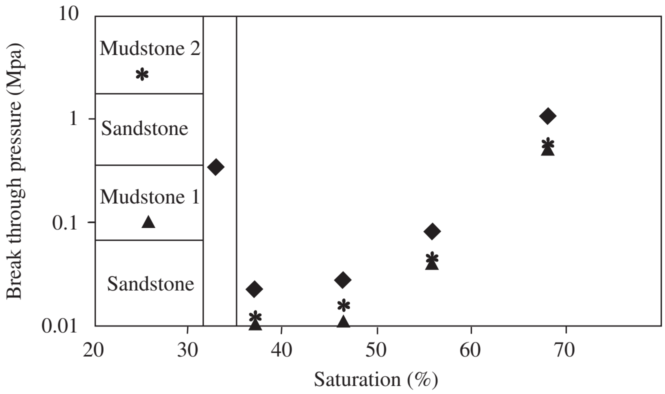

Fig. 7. Experimental data showing the relationship between water saturation and breakthrough pressure for the mudstone and sand-mud samples collected from the Sanhu area.

saturation, the total seal capacity of the two mudstone caprocks equals to that of a single mudstone bed with the cumulative thickness of both mudstone beds, whereas the mudstone breakthrough pressure increases exponentially with increasing its water saturation. Therefore, mudstone in deep strata has higher seal capacity not only because of the decrease in its permeability but also the presence of overlying mudstones. Thus, it is not difficult to explain why most commercial gas payzones in the Sanhu area occur in strata greater than 900 m. The high water saturation of the Quaternary strata is also important for the porous mudstones in this area to act as flow barriers for gas migration.

In addition, high gas concentration in the mudstone was also proposed as a possible sealing mechanism in this area (Zhang et al., 2004), where the high gas concentration in the mudstone could potentially inhibit or slacken the upward diffusion of methane from the underlying strata. This proposal has some merit when the gases are largely in solution. However, if the high gas concentration in the mudstone involves free gas as most caprocks do, this would significantly reduce the water saturation in the mudstone and thus its gas sealing capacity. As high gas concentration has not been encountered in the mudstones from the study area, it remains to be determined how much this proposed mechanism has contributed to the seal integrity of mudstone caprocks in the Qaidam Basin.

3.4. Syndepositional anticlines and gas traps

The Sanhu area has experienced relatively mild tectonic movement since the early Neogene, compared to other areas in the Qaidam Basin. The development of several large syndepositional anticline structures in this area has provided ideal habitats for giant biogenic gas accumulations. The continuously upwarping of the Qinghai-Tibet Plateau in the Quaternary under persistent compressional stress field resulted in the formation of several low-amplitude syndepositional anticline structures near the Quaternary depocenter in the Sanhu area, with the dip angle being usually less than 2° and closure less than 100 m. As the amplitude of the anticlines decreases gradually from the older to younger strata, these structures are characterized by thinning near the top and thickening along the flank, an increase in dip angle and structural closure but a decrease in closure area from the shallow to deep strata (Gu, 1993).

Fig. 8 shows a structural section across the major gas fields in the Sanhu area. The K9 seismic reflection surface in the Sebei 1 field has a 75 m of structural amplitude. However, no unified gas–water contact can be recognized across the section. Instead individual gas pays show separate gas–water contacts that are commonly controlled by the lithology of interbedded strata, as observed in the northern Great Plains of Alberta, Saskatchewan and Montana (Shurr and Ridgley, 2002). Thus, structural traps have played an important part in controlling the gas accumulation in the Sanhu area (Ma et al., 2004).

3.5. Critical moment

The timing of events in a petroleum system can be described using a standard chart such as the one proposed by Magoon and Dow (1994). The chart format was modified by Shurr and Ridgley (2002) for unconventional biogenic gas systems by not including events such as deposition of seal and overburden rock and trap formation. The time of gas generation, migration and accumulation is of particular importance in understanding the accumulation mechanisms involved in the formation of the giant biogenic gasfieds in the Sanhu area.

As discussed earlier, early generation occurs shortly after deposition of the Quaternary source and reservoir rocks (Pang et al., 2005). Generation, migration and accumulation occur continuously during deposition of the source and reservoir rocks and may continue into the postdepositional history of the system. As a result, the critical moment approximately corresponds to the deposition of source and reservoir rock and subsequent burial by overburden deposition. Because the deposition of the Qigequan Formation and overburden sediments in the Sanhu area has occurred within the past 1.8 Ma, gas systems under the investigation represent a truly young generation system. However, more geochemical constraints are still needed to resolve the issue of early versus late gas generation.

3.6. Dynamical biogenic gas accumulations

As shown in Fig. 6, the main gas payzones in the Sanhu area occur in 900–1800 m below the surface, and the gas reserves increase with increasing reservoir depth. The maximum thickness of the Quaternary sediments in the Sanhu area exceeds 3000 m, and the syndepositional anticlines extend well below 1850 m in the Sebei 1 and Tainan fields (Fig. 9). However, it is still not fully

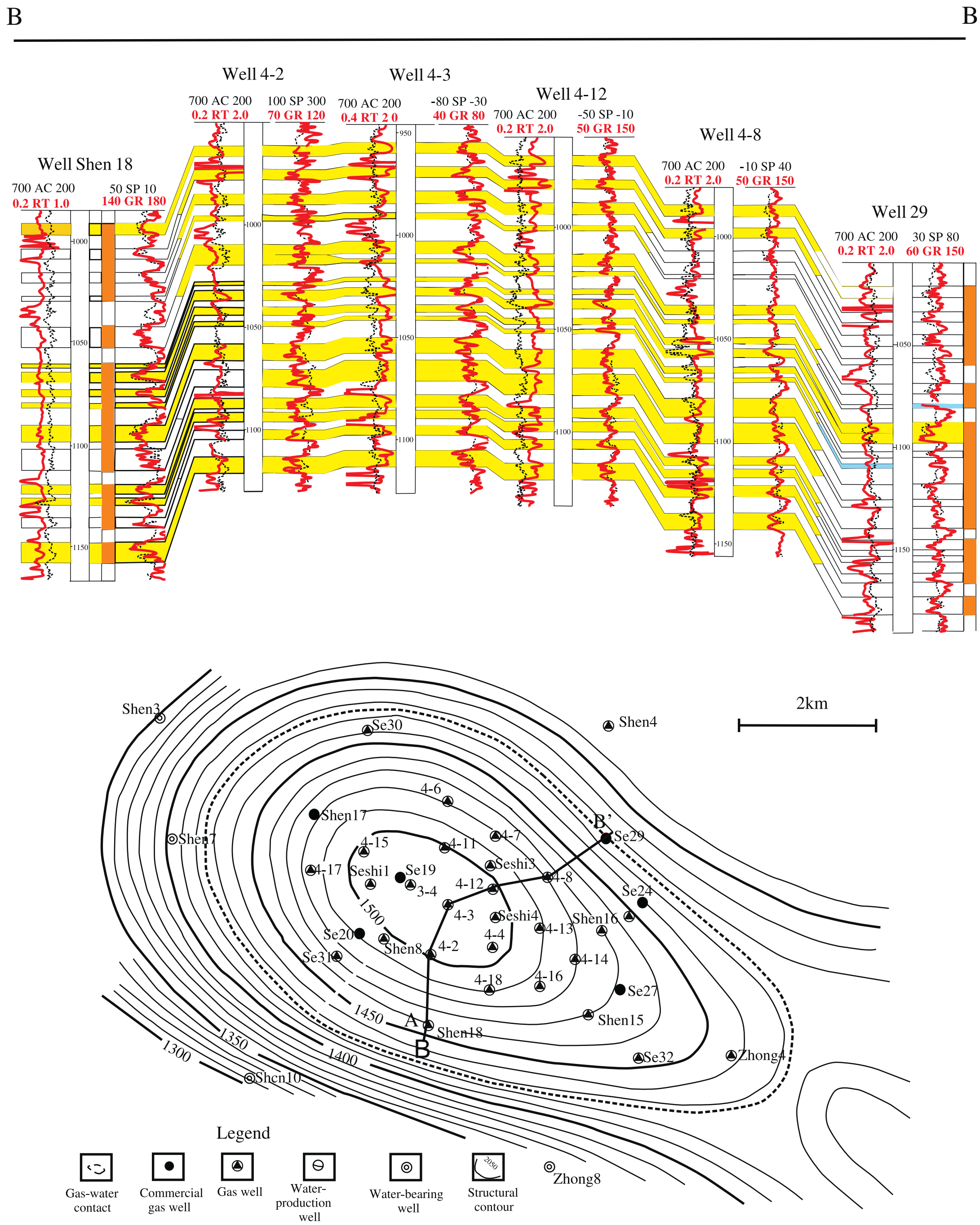

Fig. 8. Typical wireline logs of the biogenic gas reservoirs (a) and the structural contour map of the K9 seismic reflectance surface in the Sebei 1 gasfield (b).

understood why no biogenic gas pool is present in reservoirs below 1800–1850 m.

Interestingly, the temperature range of the gas payzones corresponds to the optimal temperatures for methanogens to thrive and generate methane (35–65 °C, Fig. 4). As shown in Fig. 10, methanogens and symbiotic bacteria occur mainly in sediments above 2000 m, whereas sulfate-reducing bacteria are present only very shallow sediments. Fermentation bacteria and cellulose decomposing bacteria account for the majority of the microbial populations in the Quaternary sediments. Methanogens occur in sediments with burial depth less than 1800 m (<75 °C). Results obtained by Deng et al. (1996) indicate a general decrease in bacterial accounts below 1500 m.

Reconstruction of the burial history in the Sanhu area indicates that methanogenesis should have occurred in the sediments currently within the 1800–3000 m interval when they were in shallow burial. Syndepositional anticlines had probably existed then, leading to early biogenic gas accumulation. With increasing burial, these early gas

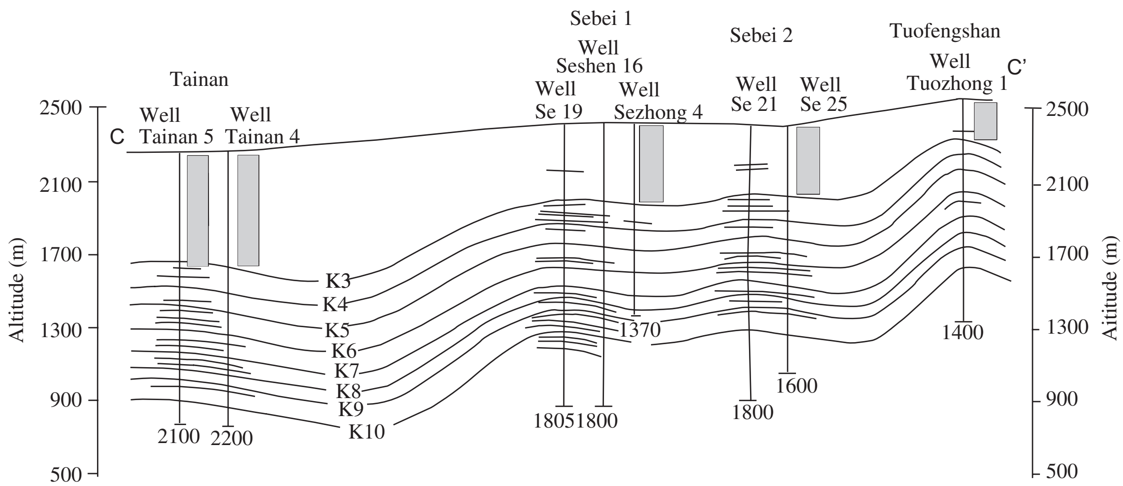

Fig. 9. Schematic cross section showing the main gas payzones in the Sanhu area. See Fig. 1 for the location of the cross section.

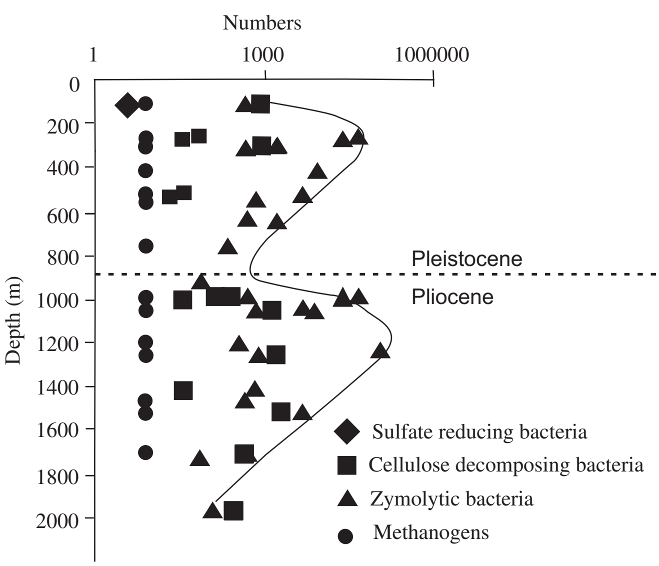

Fig. 10. Variation in the bacterial counts in the Quaternary sediments from the Sanhu area as a function of burial depth.

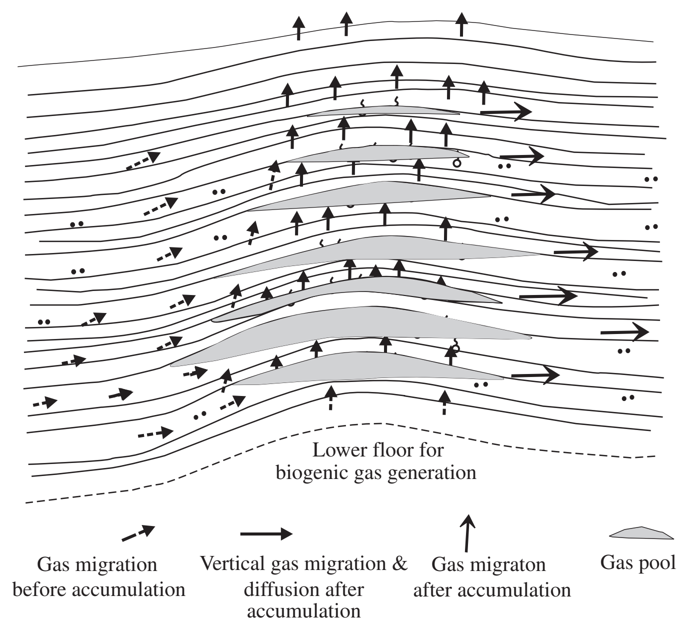

Fig. 11. Schematic cross section of the Sebei 1 gas field showing the dynamic process of biogenic gas migration and accumulation.

accumulations may have been destroyed due to the gas leakage to shallower strata.

As there is a large amount of dissipated biogenic gases in the Quaternary strata, the gas accumulation in the Sanhu area is a dynamic process. The Quaternary sediments in the Sanhu area are characterized by high porosity and high permeability due to their weak diagenesis, which results in relatively low sealing capacity of the caprocks. As shown in Fig. 11, the present-day maximum depth of gas payzones in the Sebei 1 gasfield is 1680 m with an estimated gas reserve around 2.7 trillion cubic meters (tcm). Although low-amplitude structure exists in the sediments around the 1800 m interval, no biogenic gas is present in this deep structure. As there is no reason why no biogenic gas was generated and accumulated in this interval when the sediments were in shallower burial, the lack of biogenic gas in the deeper reservoirs can only be explained by the dynamic process involved in the biogenic accumulation. Using an average deposition rate of 650 m/Ma in the study area, it can be easily estimated that the increase in burial depth from 1680 to 1800 m took only about 0.18 Ma. As the diffusion rate of methane is relatively rapid, this implies that a gas pool with 2.7 tcm gas reserve at around 1680 m depth has been exhausted within less than 0.18 Ma due to diffusion. The fact that giant gas fields are formed in the Sanhu area in spite of such a high methane diffusion rate suggests the presence of incessant and ample biogenic gas supply from the present gas kitchen. Therefore, the formation of biogenic gas accumulations in the Sanhu area can be attributed to ample supplies of synchronous biogenic gases during a dynamic accumulation-diffusion process (Fig. 11; Dai et al., 2003).

3.7. Source kitchens and gasfield distribution

Sufficient gas supply is a prerequisite for the formation of gas pools and giant gas fields (Dai et al., 2003), and gas source is also important for the formation of biogenic gas fields in the Sanhu area. However, it may be inappropriate, and sometimes misleading, to assess the biogenic gas source potential of a given source rock using the same parameters or approaches as those for the thermogenic gas. For example, the TOC content may not necessarily a good parameter for this purpose (Clayton, 1992; Zhou et al., 1994; Gu, 1993; Qi et al., 1997; X. Zhang et al., 2004a, b). As the biogenic gas potential appears to be related directly to methanogenesis (Ding et al., 1995; Xia and Bai, 2004), a comparison of the relative abundance of methanogens in sediments may provide a means for assessing the relative location of the biogenic gas source kitchens for specific gas pools. In a recent investigation, canned cutting samples were systematically collected from two exploration wells in the Sanhu area, and the samples semi-quantitatively analyzed for methanogens following the analytical procedures presented by Schouten et al. (2001). As shown in Fig. 12, one of the wells (XS 3-4) is located in the Sebei 1 structural belt along the north slope of the Sanhu Depression, while the other well (SN 2) in the central sag. The Quaternary sediments penetrated by the XS 3-4 well were deposited in near-shore to shallow lacustrine facies, whereas those encountered in the SN 2 well are dominated by semi-deep water lacustrine sediments near the depocenter (Dang et al., 2004).

The relative abundances methanogens in the Quaternary sediments (Fig. 12) generally decrease with increasing burial in the XS 3-4 well, while those in the SN 2 well first increase in the shallow depth and then decrease drastically. The absence of a shallow zone where the methanogen abundance increases with increasing depth may be partially related to small uplift and possible erosion associated with the formation of the syndepositional anticlinal structures. Nevertheless, the maximum methanogen abundance appears to occur in sediments above 1300 m. The high abundance of methanogens in the SN 2 well near the central sag relative to those in the XS 3-4 well indicates that the main biogenic gas kitchen in the Sanhu area is located close to the depocenter of the lake basin, with the main effective source rocks in the 500–1300 m interval.

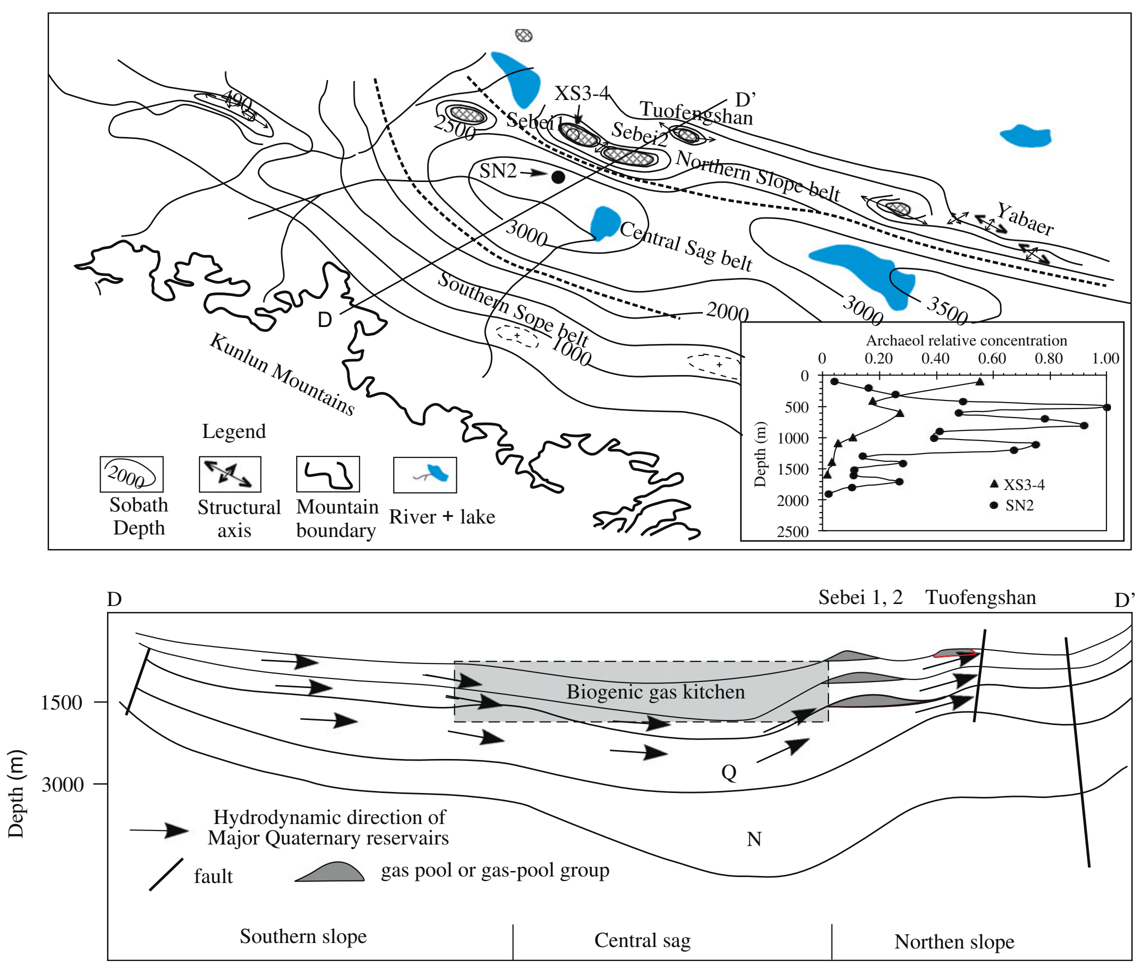

Fig. 12. Schematic map (a) and cross section (b) showing the hydrodynamics and gas migration direction in the Quaternary reservoirs in the Sanhu area; (c) variation in the relative abundance of archaebacteria in the Quaternary sediments collected from the two exploration wells.

The migration of biogenic gases generated in the central sag and eventual entrapment in the structural traps along the North Slope is clearly hydrogeologically controlled. The Sanhu area is located in a topographic low to the north of the Kunlun Mountains. Ground water originating in the mountains in the south permeated into the porous Quaternary strata. Superfluous waters also formed surface rivers and converged into lakes in the subsiding zones (M. Wang et al., 2003). Faults cut through the Quaternary strata on the north side of the North Slope. However, the surface altitudes of these faults are much lower than those of the hydrologic heads in the front range of the Kunlun Mountains, leading to northeastward groundwater flows that are indicated southward tilted gas–water contact (Fig. 12). This groundwater recharge not only brings nutrients to the Quaternary strata, but also increases the water saturation of the Quaternary loose sands and muds and thus sealing capacity by complete immergence in waters. When the high-flux waters pass through the biogenic gas generative zones, gases are often carried away in the form of aqueous solution. These gases are later released to form gas accumulations in updip structural traps due to pressure decrease or salinity increase.

Because the groundwater has always flowed north-easterly in the Sanhu area (from the South Slope, through the Central Sag, to the North Slope), the North Slope has naturally become an favorite area for gas accumulation. This is why all the gasfields discovered up to now in this area are distributed along the North Slope. As the Sebei and Tainan fields are located either near or within the gas kitchen in the central sag and the relatively deep burial also improves the seal capacity of the caprocks, they have formed giant gas accumulations. In contrast, Tuofengshan and Yanhu gasfields are located far away from the main gas kitchens in the areas (Fig. 1), and lack of sufficient gas supply when compounded with the poor caprocks due to shallow burial results in only small gas accumulations.

Therefore, the formation and occurrence of biogenic gasfields in the Sanhu area of the Qaidam Basin is not only controlled by the scale and locality of the gas kitchens, but also is closely related to the seal capacity of the caprocks, the location of structural/stratigraphic traps, and the hydrogeological regime of the groundwater systems.

4. Conclusions

The giant biogenic gas accumulations in the Sanhu area of the eastern Qaidam Basin belong to the young generation system of the unconventional shallow gases. They represent biogenic gases formed in the Quaternary sediments above the biogenic floor around 1800–1900 m, primarily through carbon dioxide reduction. Methanogenesis in the Sanhu area occurs mostly in the temperature range around 35–65 °C, with the dominant biogenic gas kitchen being the central sag to the south of the gas fields. The low surface temperature and high salinity of lake waters have provided excellent conditions for the preservation of organic substrates for gas source rock. Interbedded porous sandstones and mudstones have provided ample gas storage spaces while the accumulation of thick water-saturated mudstone beds has enhanced the seal capacity of the caprocks. The presence of syndepositional anticlinal traps since the Pleistocene is also critical for the formation of the giant biogenic gasfields. Early generation begins to form shortly after deposition, and generation, migration and accumulation may be simultaneously over a short period of time. As a consequence, the biogenic gas accumulation is best described as a dynamic system, largely influenced by the prevailing regional hydrogeological groundwater flow. The giant biogenic gasfields occur most likely near or within the main gas source kitchens with relatively deep burial of source-reservoir-caprock, being controlled by structural-facies changes.

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