

Lacustrine algal limestone reservoir in western Qaidam Basin, China

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Abstract Compared to marine carbonate around the world, lacustrine carbonate is relatively scarce. Much less attention has been paid to it. Lacustrine carbonate, a product of mixed deposition of continental clastics and carbonate under special conditions, can be both important source rocks, and oil and gas reservoir rocks. Qaidam Basin is a large salt lake basin on the Tibetan Plateau where oil and gas flow has recently been discovered in lacustrine algal limestone. Study of the algal limestone is a potentially valuable target of exploration, and is of great significance to the exploration and development of mixed carbonate formations.

Keywords Mixed deposition · Lacustrine carbonate · Algal limestone · Pore structure · Oil and gas

Introduction

The Qaidam Basin is not only one of the continental petroliferous basins of in northwestern China and an important component of Tibetan Plateau. It is a basin related to foreland on the northeastern margin of the Tibet Plateau (Zhu 1986; Jia 2005; Zhao and Jia 2012) (Fig 1).

The Qaidam Basin, an inland salt water lake under drought conditions, is generally a low priority for exploration (Harrison et al. 1992; Allegre et al. 1984). Deposition of mixed sediment of clastic depositions and carbonates (including allochemical grains, etc.) formed a variety of mixed sedimentary rocks, which can be found in a

combination of rock layer systems (Guo et al. 2003). Consensus have not yet reached about the origins and classification of the mixed sediment (Feng 1993; Sha 2001; Ma and Liu 2003; Guo et al. 2003; Zhang 2000). The northwestern Qaidam Basin Neogene sedimentary source material mainly came from Altun Mountain, a distant source, forming land facies and lacustrine facies interaction deposition in the western Qaidam Basin. The resulting reservoir rocks are mixed sedimentary rocks, formed by alternating chemical and mechanical effects in arid to semi-arid climatic conditions, and under slightly brackish water to brackish water phases of the lake waters (Tuo et al. 1995; Dang and Zhao 2004; Hanson et al. 2001; Zhang and Shou 2004).

Lacustrine algal limestone material

Lacustrine algal limestone stratigraphy characteristics

According to drilling data, the western Qaidam Basin has undergone Yanshanian and Himalayan tectonic movements since the Mesozoic (Lee 1984; Ulmishek 1984; Ritts 1998; Wu et al. 2003; Zhao 2013), which formed three sedimentary strata sequences (Fig. 2).

In the Paleogene, the depocenter of the basin was in the western Qaidam Basin, then gradually migrated eastward. This process was controlled not only by tectonic movement in the basin evolution process, but also by late structure patterns and distribution (Zhao and Sun 2011).

The development of the sedimentary sequence is strongly governed by the sequence of tectonic movements in the Qaidam Basin. Generally the climate became more arid, and the water more salty. Intermittent or seasonal floods carried fine-grained mud and silt into the lake. This is the main reason for the variation in the vertical rock

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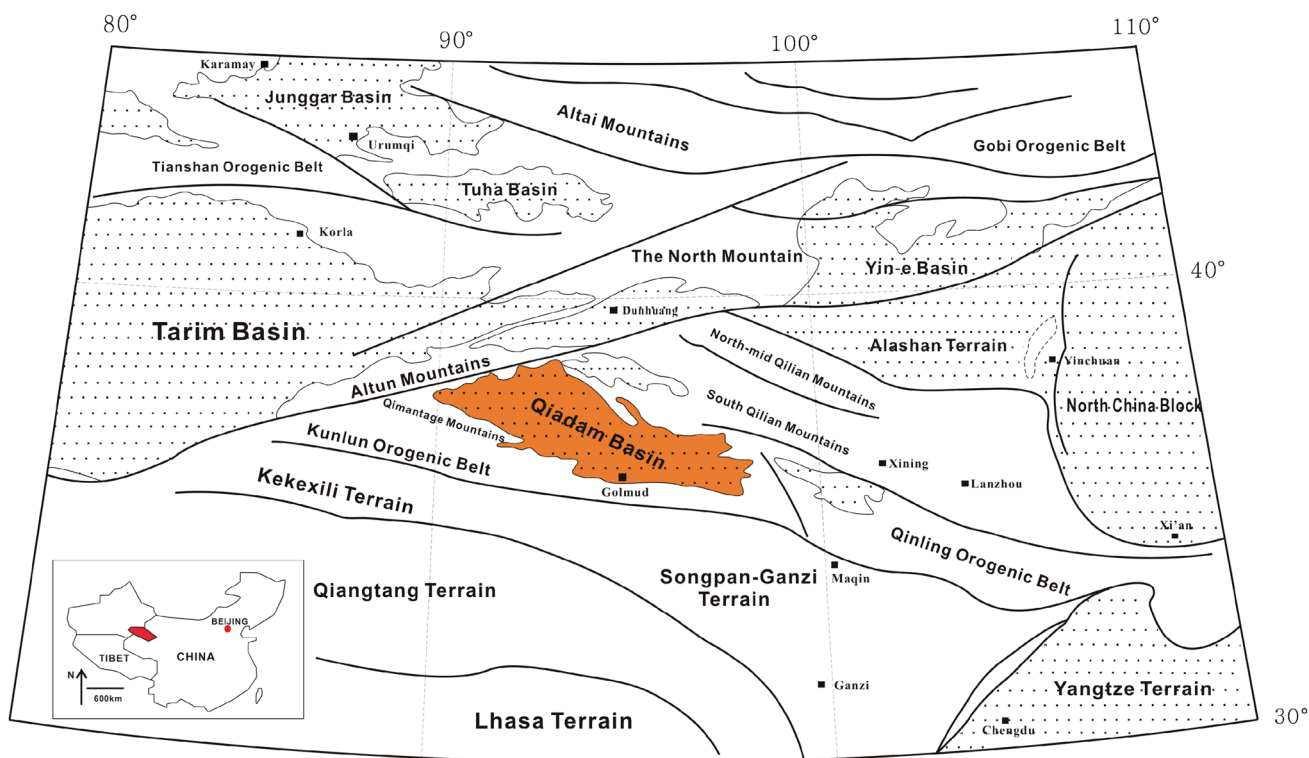


Fig. 1 Tectonic background and location map of the Qaidam Basin, a relatively unstudied frontier basin on the northeastern margin of the Tibetan Plateau

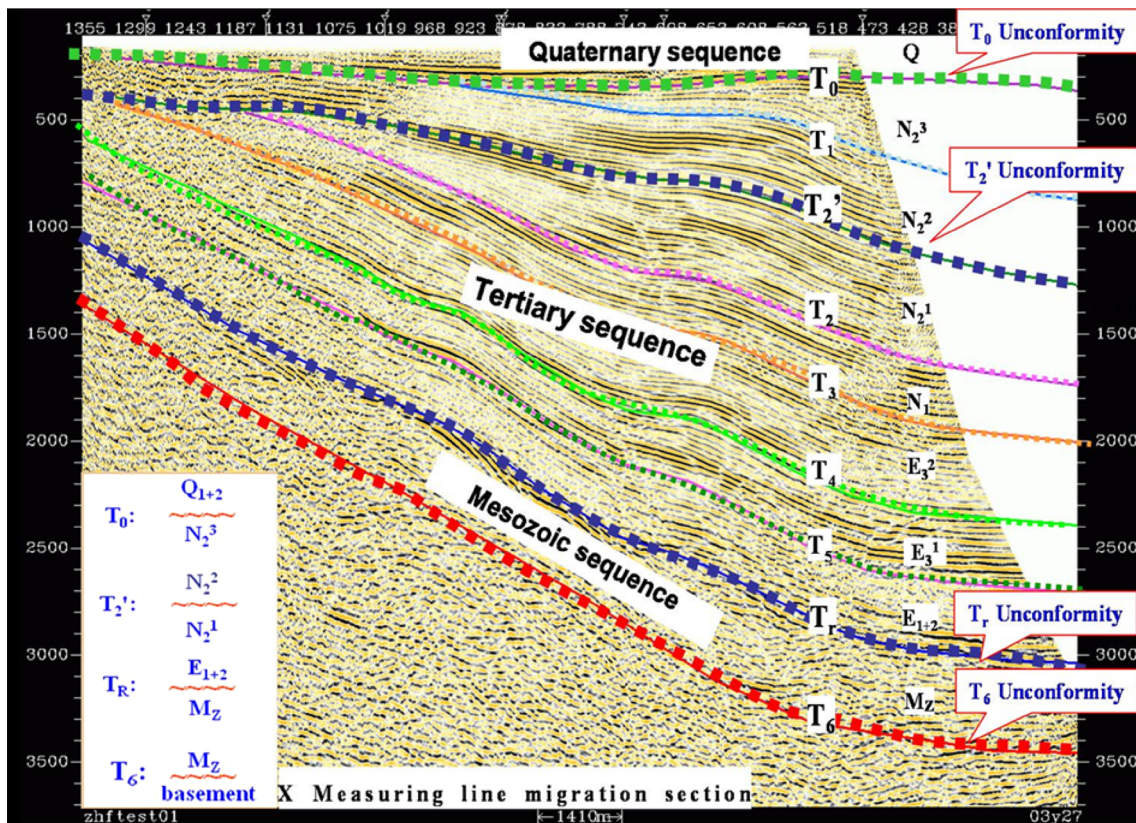


Fig. 2 Seismic section interpretation and stratigraphic framework in the western Qaidam Basin showing the formation of four regional unconformities and the corresponding three sedimentary sequences

Table 1 Mesozoic and Cenozoic chronostratigraphic framework in western Qaidam Basin

Era	Age	Epoch	Formation	Code	
Cenozoic	Quaternary	Holocene	Hubuxun	Q ₄	
		Pleistocene	Qigequan	Q ₁₊₃	
	Neogene	Pliocene	Shizigou	N ₂ ³	
			Upper Youshashan	N ₂ ²	
		Lower Youshashan	N ₂ ¹		
		Miocene	Upper Gancaigou	N ₁	
	Paleogene	Oligocene	Lower Gancaigou	E ₃	
			Eocene	Lulehe	E ₁₊₂
	Mesozoic	Cretaceous	Late Cretaceous		K ₂
			Early Cretaceous	Quyagou	K ₁
Jurassic		Late Jurassic	Hongshigou Chaishiling	J ₃	
		Mid Jurassic	Dameigou Xiaomeigou	J ₂	
Early Jurassic		Huxishan	J ₁		

sequence. The Neogene is divided into six units from the bedrock upwards (Table 1) (Wang and Coward 1990).

Lacustrine algal limestone types and distribution

On the basis of well core observation and single well analysis, the Neogene sedimentary facies in the western Qaidam Basin (Table 2) (Fig. 3) is comprised of lacustrine algal limestone of the shallow lake subfacies (Peters and Cassa 1994).

Shallow lake subfacies is the belt between the lowest lake water surface (dry season) and the wave base (Peters and Cassa 1994; Hendrix et al. 1992). The hydrodynamics are mainly waves and lake flow. Here the microfacies include: algal mounds, microfacies containing algal laminated limestone, algal limestone mass and algal micrite lithofacies. The lithofacies of lake bay microfacies is composed of micrite, marl, mudstone and shale. Shallow shoal microfacies includes many types of limestone lithofacies (Table 2).

Algal limestone analysis results

Algal limestone lithology analysis results

The western Qaidam Basin is mainly algal limestone lithology, including algal laminated limestone, algal clump

Table 2 Typical Sedimentary microfacies in western Qaidam Basin

Subfacies	Microfacies	Lithofacies	Color of mudstone	
Fan delta front	Distributary channel	Sandstone	Mulberry	
	Mouth bar	Siltstone		
	Distal bar–sheet sand	Siltstone		
	Interdistributary bay	Mudstone		
	Share lake	Sand flat	Sandstone	Purple
		Sand mud flat	Muddy siltstone	Brown
Mud flat		Mudstone	Red	
Shallow lake	Plaster floor	Marl	Flesh	
	Grey flat	Micrite	Gray	
	Algal mound	Algal laminated limestone		Dark gray
				Gray
				Dark gray
	Bay	Algal limestone-mass		Gray
				Dark
				Algal micrite
				Micrite
	Shoal	Algal micrite		Marl
			Shale	
			Mudstone	
	Limestone particle			

limestone and algal micrite limestone (Fig. 4). Observation of the core from the western Qaidam Basin well shows that the surface of algal limestone has dissolution porosity, growth formation, good oil-bearing nature, multi-layer, and large total thickness (Table 3).

Pure carbonates or pure siltstone or pure mudstone have not been found. Lithologies include algal micrite, algal clump limestone, silty mudstone and gray matter and other siltstone, showing this deposition is the combined result of mechanical and bio-chemical processes.

Algal limestone properties analysis results

Algal limestones in western Qaidam Basin show an average porosity of 6.9 %, and an average permeability of 1.353 mD (Fig. 5), which are better than other types of reservoirs.

Algal limestone pore structure analysis results

Porosity in the reservoir rocks include pores and fissures. To find out pore size, shape, degree of development and interconnection, mercury analysis is the most common and most effective method. In the study of carbonate reservoirs, pore structure is especially important for oil

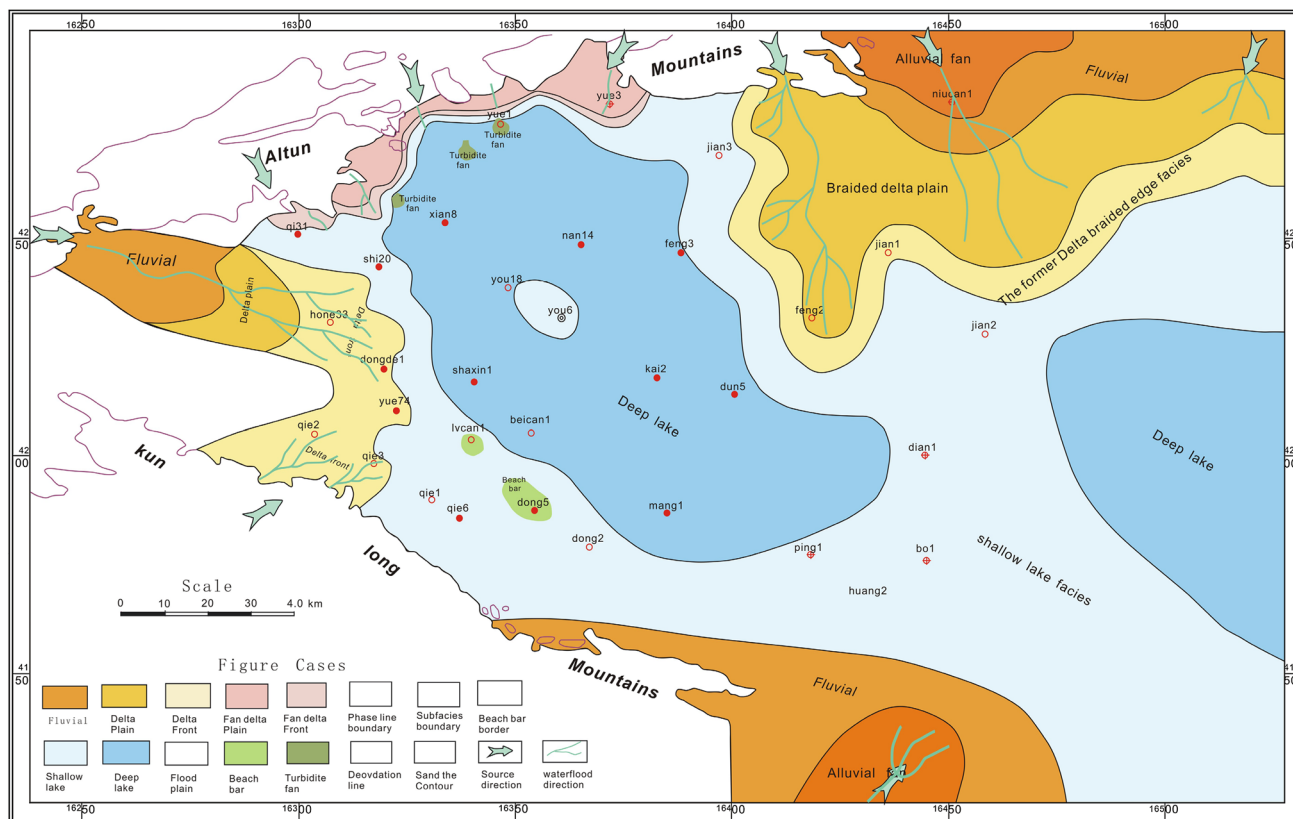


Fig. 3 Sedimentary facies of the Miocene in the western Qaidam Basin. Paleogene facies in the western region of Ganchaigou (N1), Qaidam Basin. Ancient structural higher location would be suitable for the growth of algae and benthic animals. Along with the change in seasons, the influx of clastic material was intermittent. When the influx was low, fairly clear water was ideal for the growth of algae and benthic animals, which formed biogenic limestone. When the influx was plentiful, the water was muddy, which was not conducive

to the growth of algae and benthic animals, and biogenic limestone was not likely to form. Instead with the influx of debris, the amount of energy and environmental input results in other types of rocks. Algae and benthic animals mound facies developed in the high part of the shallow lake facies. On the side of semi-deep lake, strong waves and lake current caused strong agitation of water and higher energy, which would help the growth of algae and benthic animals

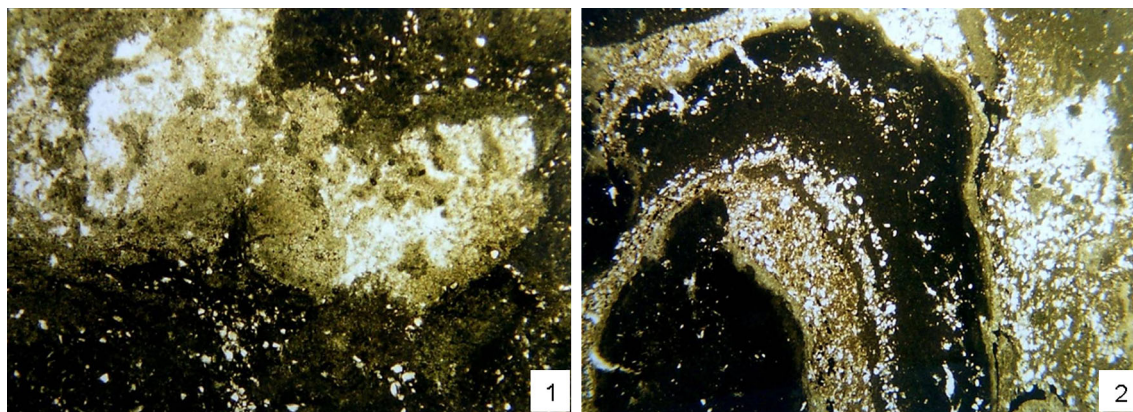


Fig. 4 Photomicrographs of algal limestone reservoir in western Qaidam Basin. **1** Feng 3 Well, 2,772.8 m, algal laminated limestone, orthogonal polarization, $\times 100$, $\phi = 6\%$, $K = 0.023 \times 10^{-3} \mu\text{m}$. **2**

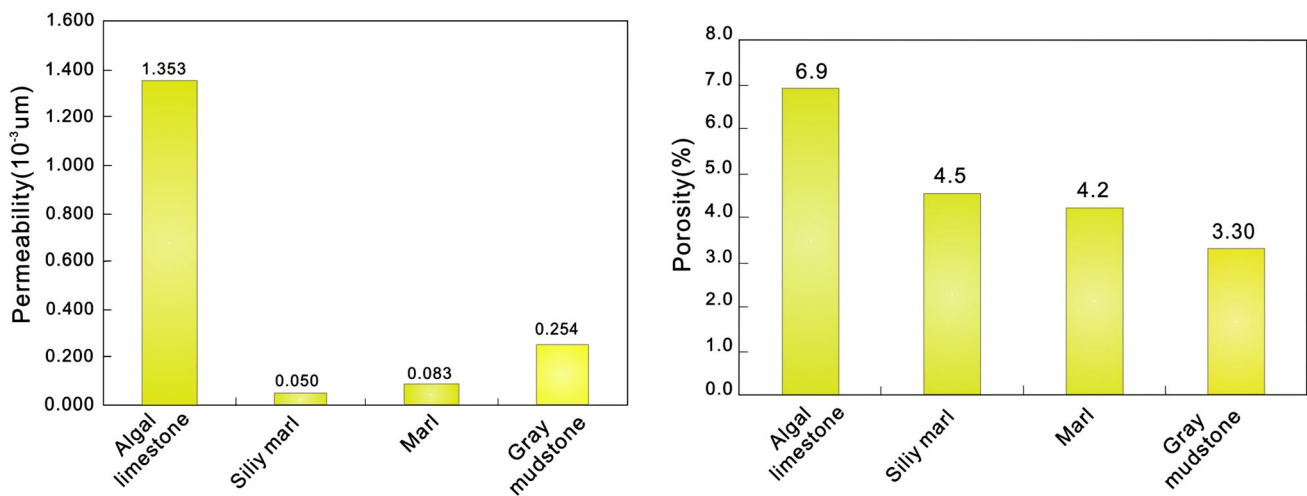
Feng 3 Well, 3,017.8 m, algae clump limestone, orthogonal polarization, $\times 100$, $\phi = 13.1\%$, $K = 17.5 \times 10^{-3} \mu\text{m}$

and gas information. Common parameters involved are displacement pressure and the largest connected pore throat radius.

In the western Qaidam Basin algal limestone reservoir, displacement pressure ranges from 0.69 to 8.966 MPa, with most values >1 MPa. The largest connected pore

Table 3 Physical properties of the Algal limestone samples from western Qaidam Basin

No.	Depth (m)	Lithology	Porosity (%)	Permeability (md)	Displacement pressure (MPa)	The largest connected pore throat radius (μm)
2	2,772.8	Algal limestone	6.0	0.023	1.034	0.711
12	3,017.6	Algal limestone	4.4	0.029	1.379	0.533
15	3,017.8	Algal limestone	13.1	17.5	0.69	1.065
17	3,019.1	Algal limestone	10	1.1	0.69	1.065
25	3,017.7	Algal limestone	5.4	0.31	8.966	0.082
27	3,017.9	Algal limestone	8.2	0.87	3.103	0.237

**Fig. 5** Histogram of average permeability and porosity by rock type in western Qaidam Basin**Table 4** Classification of pore structure for the carbonate reservoir in western Qaidam Basin

Type of pore structure	The largest connected pore throat radius (μm)	Porosity (%)	Permeability (md)	Evaluation		
Coarse porosity Large throat	>10	Big throat	>12	Coarse porosity	>10	Best
Middle porosity Middle throat	2–0.5	Middle throat	12–6	Middle porosity	10–0.25	Better
Fine porosity Small throat	0.5–0.04	Small throat	6–2	Fine porosity	0.25–0.02	Good
Fine porosity Micro throat	<0.04	Micro throat	<2	Fine porosity	<0.02	Poor

throat radius falls in the range of 0.082–1.065 μm , most are <1 μm (Table 4). About 17 samples show a smaller displacement pressure and larger pore throat radius (Fig 6).

Controlling factors of algal limestone

The main controlling factors of the algal limestone reservoir include: sedimentary microfacies, faulting, dissolution along faults and dissolution of organic acids.

The main reservoir space in western Qaidam Basin is made up of a variety of dissolved pores, with evidence of exposure and meteoric water leaching. These dissolved pores are most likely formed due to dissolution over burial time. On the other hand, the western Qaidam Basin has many small faults, which provide channels for the invasion of fresh water, making up a relatively open system. Therefore, pores in algal limestone, algal micrite and shale gray micritic were formed mainly by dissolution along

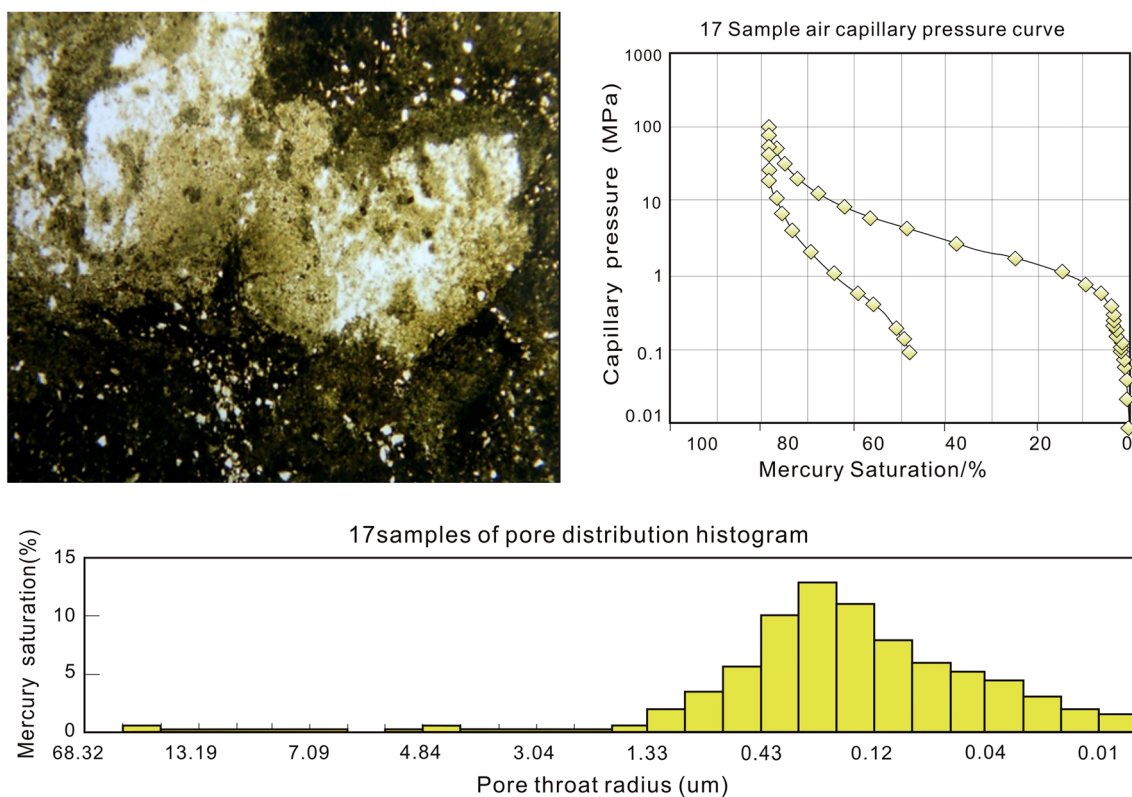


Fig. 6 Pore structure analysis for algal clump limestone in western Qaidam Basin

small faults. In addition, the dissolution of organic acid also played a role in the pore formation.

Conclusions

The algal limestone includes mainly algal laminated limestone, algal clumps and algal micrite limestone in the western Qaidam Basin. The sedimentary environment here was primarily the lakeshore and shallow lake. Algal limestone analysis results indicated a good reservoir rock, which may be an important exploration target for the Qaidam Basin.

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