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Sedimentary characteristics and depositional model of a Paleocene-Eocene salt lake in the Jiangling Depression, China*

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Abstract We studied the sedimentary characteristics of a Paleocene-Eocene salt lake in the Jiangling Depression through field core observation, thin section identification, scanning electron microscopy, and X-ray diffraction analysis. On the basis of sedimentary characteristics we have summarized the petrological and mineralogical characteristics of the salt lake and proposed 9 types of grade IV salt rhythms. The deposition shows a desalting to salting order of halite-argillaceous-mudstone-mud dolostone-mud anhydrock-glauberite-halite. The relationship among grade IV rhythms, water salinity and climate fluctuations was analyzed. Based on the analysis of the relationship between boron content and mudstone color and by combining the mineralogy and sedimentary environment characteristics, we propose that the early and late Paleocene Shashi Formation in the Jiangling Depression was a paleolacustrine depositional environment with a high salt content, which is a representation of the shallow water salt lake depositional model. The middle Paleocene Shashi Formation and the early Eocene Xingouzui Formation were salt and brackish sedimentary environments with low salt content in a deep paleolake, which represents a deep salt lake depositional model.

Keyword: Paleocene-Eocene; salt lake; salt rhythm; depositional model; Jiangling Depression

1 INTRODUCTION

A continental salt lake is defined as a lake with $w\,(\mathrm{NaCleq}) \geq 3.5\%$ in a narrow sense and $w\,(\mathrm{NaCleq}) \geq 0.3\%$ in a broad sense (Zheng, 1999). Modern salt lakes are present on all continents, and are mainly distributed between 10°–65°N in the Northern Hemisphere and 16°–45°S in the Southern Hemisphere (Zhang, 2000). Different geomorphology and structures lead to different types of salt lakes, such present lakes as Great Salt Lake in Utah, the perennial Zabuye Salt Lake in Tibet, seasonal salt lakes in Mongolia, the Qarham salt lake in Qinghai, and the dry salt lake in Lop Nur of Xinjiang (Spencer et al., 1985; Liu et al., 1998; Zheng and Liu, 2010; Li et al., 2012). Different salt sedimentary sequences occur during the evolution of salt lakes. The abundant types of salt rhythm reveal the paleoclimate changes

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between drought and wet episodes in different periods. The salt rhythm is mainly composed of fine detrital rock from mechanical sedimentation and evaporites and carbonates from chemical sedimentation, which form a rhythmic structure with longitudinal alternate changes (Zhang et al., 2005; Li et al., 2010). Salt-bearing series are developed in the Paleocene-Ecocene Shashi Formation and the Xingouzui Formation in the Jiangling Depression of the Jianghan basin, where the study of salt rhythms and mineralogy has a great significance. Different origins of the salt formation patterns have been proposed, such as the "Sabkha" hypothesis, the "Deep water and deep basin" hypothesis from Schmalz (1969), the "Dry deep basin" hypothesis from Hsu (1972) and the "High mountain and deep basin" hypothesis from Yuan et al. (1983).

The Jiangling Depression is located in the southwest of the Cretaceous-Tertiary Jianghan basin, which is a Mesozoic-Cenozoic fault basin. The basin experiences multi-phase tectonic movements, which form complex basin structures. The Qingshuikou Fault in the east, the Jishansi Fault in the north, the Wenansi Fault in the west and the Gongan-songzi Fault in the south control the formation and development of the Jiangling Depression. The basin has characteristics of north-west zoning and north-east partitioning with the Wancheng Fault as boundary. In the west of the Wancheng Fault there is one depression-one uplift structure and in the east there are two depressions-one uplift-two slopes structures (Lu et al., 2003; Yang et al., 2003) (Fig.1). The Paleocene strata of the Jiangling Depression are composed of the Shashi Formation and the bottom of the lower member of the Xingouzui Formation from downward to upward. The upper member of the Shashi Formation and the lower member of the Xingouzui Formation are developed to the synthesis salt ore, which is mainly composed of rock salt with solid and liquid facies (potassium-rich brine) (Liu, 2013). The salt-bearing strata are very developed in the early Shashi Formation in the Jiangling Depression, as the salt rock layer can be 1 351 m in the Ling2 well, and the rock salt and gypsum layer can be 796 m (Gao, 2013).

We here report our studies of the salt rhythm, mineralogy and sedimentary environment according to core data from the SK3, GK1, B103, SKD1 and ZK0701 wells. Based on previous study results, we discuss in this paper the salt lake depositional model to provide a theoretical basis for the exploration of evaporite, oil and gas.

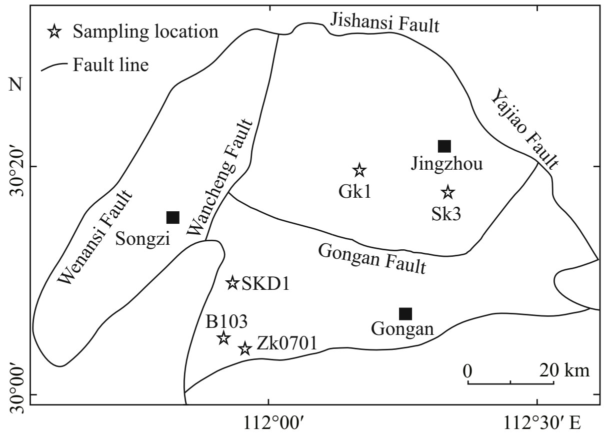

Fig.1 Structural units of Jiangling Depression and the sampling wells map

2 SAMPLES AND METHODS

The samples were collected from the Shashi Formation and the Xingouzui Formation in wells SK3, GK1, B103, SKD1 and ZK0701 of the Jiangling Depression. The petrological and mineralogical characteristics were observed in thin sections under a light microscope. The samples were grinded into 200-mesh for X-ray diffraction, carried out by the China University of Geoscience (Beijing), using a Rigaku D/max-rA12KW rotating anode X-ray diffractometer with Cu as rotor target, a scanning angle 2θ of 3°–70° and a scanning width of 8°/min. The X-ray result was semiquantitatively analyzed by JADE software with the RIR method as analysis principle and standard (Huang, 2006). According to the diffraction results, typical samples were selected for SEM observation to analyze the sample's morphological and energy spectrum in the microscope. Sample analysis was carried out by Institute of Geology, the Chinese Academy of Geological Sciences with a JEOL JSM-5610LV SEM, operated at 20 kV and 1–3 nA.

The boron (B) content in Paleocene-Eocene mudstone, silty mudstone and silty-bearing mudstone was analyzed at the Beijing Research Institute of Uranium Geology. The samples were mainly gray and black in color with a little brown, and homogeneous with pelitic texture and massive structure. For sample preparation the samples were cut by a cutting machine to remove the surface; we selected the hard part without fractures. Then the samples were cut into small chips of 1 cm^3 and washed three times with ultrapure water. The clean non-polluted samples were ground into 200-mesh in an agate grinding bowl for sample analysis. The analytical precision was better than 5% for most elements (Owens et al., 1982; Li

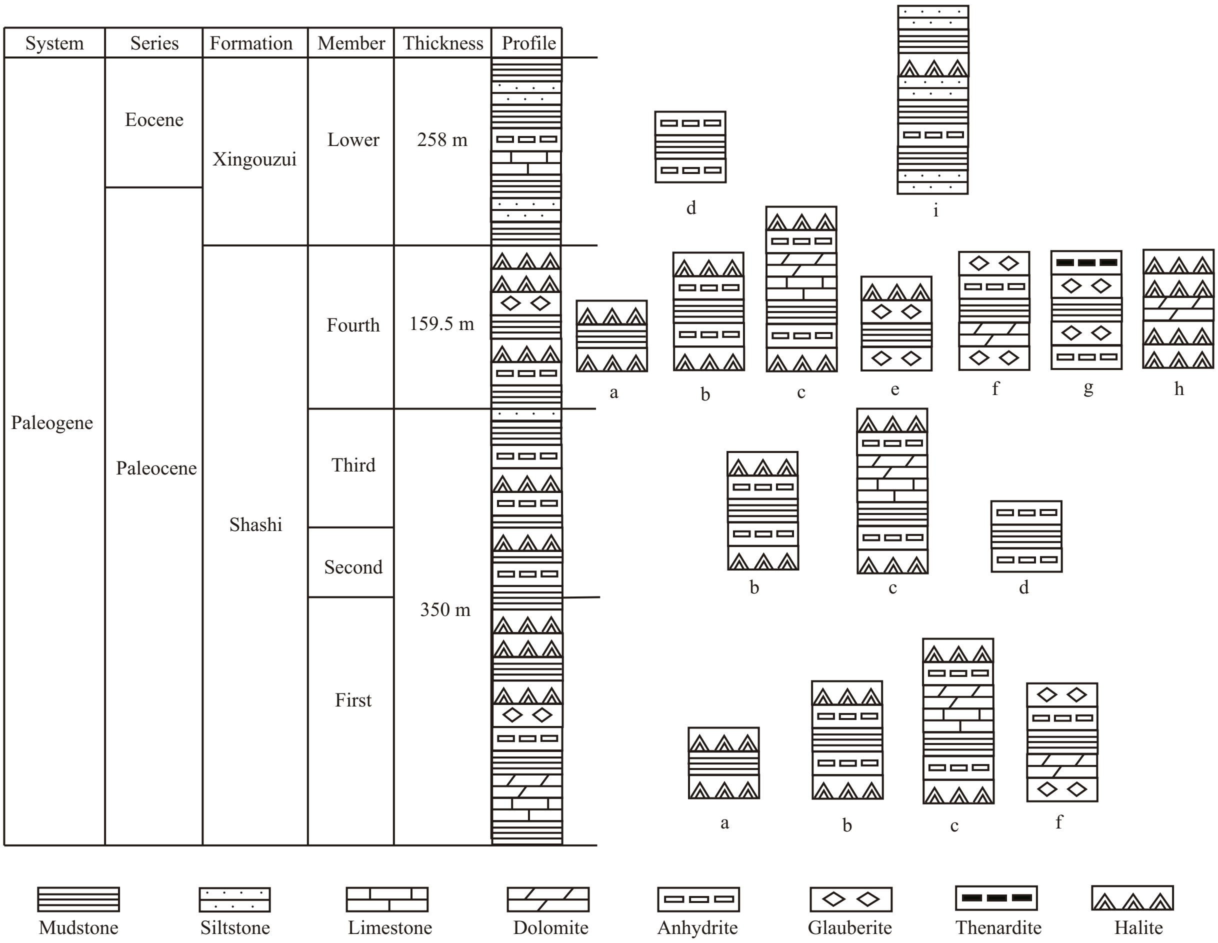

Fig.2 Grade IV salt rhythm types in Paleocene-Eocene Jiangling Depression

The characters (a–i) mean rhythm types.

and Li, 1988). The instrument version was HR-ICP-MS Element I.

3 RESULTS AND DISCUSSION

3.1 The type and characteristics of the rhythm

The Paleogene salt-bearing formation in the Jiangling Depression is located at the Shashi Formation and the base of Xingouzui Formation, and is mainly composed of detrital rock, evaporite and carbonate rock. Due to the sedimentary environment and tectonic movement, the salt layers in different regions have different sequence structures. The petrology and mineralogy in the core sections show that the rock in the region is composed of 2 to 3 mineral types. To reveal the rhythm of salt sedimentation, this study defines the major mineral of the rock as a basic unit of the rhythm. The studied strata thus have 7 basic units: salt rock, glauberite, anhydrock, thenardite, dolomite, limestone and mudstone, which form the overall salt rhythm profile.

A grade IV rhythm is the basic unit of the salt series, which represents slight fluctuations of climate and fresh water supply. According to the salt rhythm division principle of Liu and Chen (1987) and Zhang et al. (2005), based on fine description of the well core, we here propose 9 types of grade IV rhythm (Fig.2).

The early stage of Shashi Formation was a process of water salinization, and 4 rhythm types (Fig.2a–c, f) appeared. Figure 2a depicts two basic units, which are relatively simple. After halites precipitated, the water was desalted and then mudstones precipitated, and finally halites appeared again because of water salinization, caused by rapid desalination and evaporation of brine. Figure 2b and 2c show three basic units composed of a halite-anhydrock-mudstone rhythm and an anhydrock-halite rhythm with thin intervals of dolostone and limestone. This is common in the study region and is caused by rapid desalting and slow evaporation. There is no halite layer present in Fig.2f with only glauberite, dolostone and mudstone and anhydrock-glauberite; the desalting and evaporation in the salt lake occurred equally. In this stage the halite thickness can range from several meters to 20–30 m.

The water was desalted gradually from the middle Shashi Formation, which produced three rhythm types (Fig.2b–d), the rhythm shown in Fig.2d being most common. The halite thickness decreases to 3–5 m, which reveals that the injection of freshwater increased gradually while evaporation was decreasing and was of short duration.

The water in late Shashi Formation gradually became saline, which produced three rhythm types (Fig.2e, g, h) in addition to the rhythm type seen in the early Shashi Formation. Although the rhyme combination is different in the three rhythms, they all show rapid desalting and evaporation characteristics of brine in a salt lake. The occurrence of thenardite represents intense evaporation of brine in a salt lake. The halite in this section can be more than 10 m thick and up to 64 m.

The water in early Xingouzui Formation desalted gradually, and this resulted in sandstone and mudstone interbedded with thin sections of halite and anhydrock (Fig.2i). The rhythm shown in Fig.2d occurs occasionally.

3.2 Mineral characteristics of individual layers

The evaporite minerals developed in the Jiangling Depression include anhydrite, glauberite, thenardite and halite. The mineralogical characteristics were studied by field core observations, thin section authentication, X-ray diffraction and scanning electron microscopy.

3.2.1 Anhydrite

This mineral has the following characteristics: grayish white, white or red; semitransparent with a weak oily luster; massive and fibrous aggregates with six kinds of structures, including massive, lamellar, scattered, lentiod and vein. Anhydrite in a massive structure often represents more than 90% in purity with a thicknesses of 4–20 cm, small amounts of mudstone and siltstone in a micro-fine grain structure (Fig.3a). Lamellar anhydrite is laminated, alternating between anhydrite laminate and brown-red, grayish-green mudstone (Fig.3b). Scattered anhydrite (0.5–3 mm) occurs in mudstone with no directing property (Fig.3c). White vein anhydrite occurs in gray mudstone fractures (Fig.3d). The fissures show high angles up to 90° and widths of 2–30 mm. Cloddy anhydrite (1×3 cm to 3×5 cm) is developed in mudstone (Fig.3e) with cleavages visible under the microscope (Fig.3f).

3.2.2 Glauberite

This mineral is gray white, gray brown, micro- to macro-crystalline (0.5–4 cm), semitransparent with a weak waxy luster and a euhedral to subhedral texture. The mineral is mainly in clintheriform or schistose shape with some granulous, massive and petaloid aggregation (Fig.3g). Glauberite mainly occurs in thin stratified structures where scattered clintheriform glauberite developed in mudstone (Fig.3h). The mineral has a good crystal form under polarizing microscopy and SEM (Fig.3i, j).

3.2.3 Thenardite

This mineral is colorless, white, transparent to semi-transparent, microcrystalline with a glassy luster, and massive aggregation (Fig.3k). It is lamellar with individual thicknesses of 0.51–1.96 m and found at a depth of 181.81–329.57 m, which is in late Shashi Formation in the south of the Jiangling Depression.

3.2.4 Halite

It is mainly colorless and flesh pink, has a glassy luster on a fresh surface, microcrystalline to coarse grained with thick layers, and cubic, massive, fibrous or acicular subhedral-anhedral texture. The halite becomes darker with increasing shale content (Fig.3l). Vein halite has filled-in mudstone fissures (Fig.3m) with a little of sylvinite in halite (Fig.3n).

3.2.5 Dolomite

The mineral is mainly gray dolomicrite (Fig.3o) with a thickness of 0.5–50 cm, which is often symbiotic with anhydrite or glauberite. The mineral is mainly developed in the Shashi Formation and the early Xingouzui Formation in the southwest of the Jiangling Depression.

3.3 Characteristics of the depositional environment

Mudstone color can reveal the depositional environment. A reduced color such as a gray and dark gray color represents a semideep-deep lake environment in a moist climate, while oxidation colors such as purple red, red, brown red and mixed colors represent land and shore environment in a dry climate. An intermediate color such as greyish-green and green colors represents a shore-shallow lake

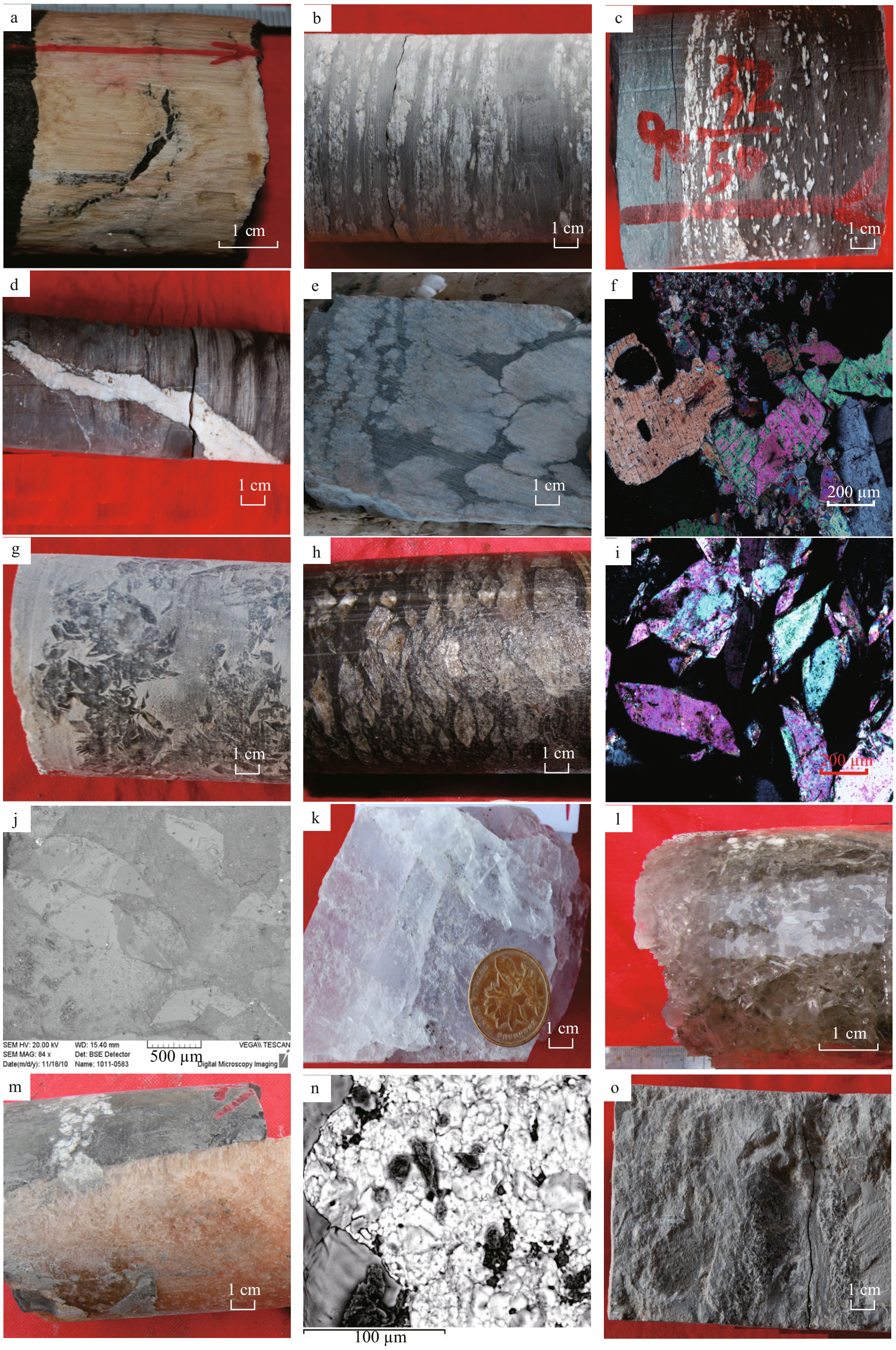

Fig.3 The salt mineralogical characteristics in Paleocene-Eocene Jiangling Depression

a. light red massive anhydrite, fibrous, well GK1, 3 549.13–3 549.63 m; b. white lamellar anhydrock, well ZK0701, 320.76–321.54 m; c. white scattered anhydrock, well SKD1, 1 846.46–1 846.58 m; d. white vein anhydrock, well SKD1, 2 051.42–2 051.60 m; e. Cluster-massive anhydrock, well SKD1, 1 058.10–1 058.21 m; f. Photomicrographs of h., cross-polarized light; g. petaloid glauberite well ZK0701, 310.9 m; h. flake glauberite, well B103, 667.84 m; i. Photomicrographs of h, cross-polarized light; j. SEM microphotograph of h; k. transparent thenardite, well ZK0701, 272.91 m; l. transparent halite, granular, well SK3, 3 728.87 m; m. flesh red vein halite, well B103, 593.49 m; n. SEM microphotograph of l, white is sylvine, gray is halite; o. gray micritic dolomite, well ZK0701, 302.78 m.

Table 1 Rare elements analysis in Paleocene-Eocene mudstone in the Jiangling Depression

Formation	Lowest ω (B)/10^{-6}	Highest ω (B)/10^{-6}	Average ω (B)/10^{-6}	Lake type	Samples	
Early Xingouzui	85	325	198	Brackish	15	Mainly mudstone, no or little siltstone and halite, little dolomite and calcite
Late Shashi	185	842	483	Salt lake	22	Mainly halite, small amount of glauberite and dolomite, little mudstone and calcite
Middle Shashi	102	455	324	Saltwater lake	18	Mainly gypsum and dolomite, small amount of halite, little mudstone, glauberite and calcite
Early Shashi	165	803	452	Salt lake	17	Mainly halite, small amount of glauberite and dolomite, little mudstone and calcite

environment in a relatively dry climate (Hao and Li, 1984; Wang et al., 2012a, b). The mudstone in the late and early Shashi Formation mainly shows oxidation color and the mudstone in the middle Shashi Formation and early Xingouzui Formation mainly shows reduced color.

The paleosalinity in the paleo-lake is fluctuant, which reveals the relative changes of lake level (Yi et al., 2009). The B content in sedimentary rock is closely correlated with salinity in the paleo-lake. The study on continental salty lakes shows that salt lakes and marine deposits cannot be distinguished by B content. There is linear relationship between B content and water salinity (Couch, 1971; Sun et al., 1998; Barth, 2000; Warren, 2010), in which the B content increases with salinity. Different clay minerals have different ability to absorb B, illite having the strongest absorption ability and kaolinite the weakest (Walker and Price, 1963; Walker, 1968). X-ray diffraction results of Paleocene-Eocene mudstone in the Jiangling Depression reveal that the clay mineral is mainly illite in the rock with little kaolinite. Therefore, the B content in Paleocene-Eocene mudstone in the Jiangling Depression is mainly caused by the absorption of illites.

Fresh water and salt water deposition can be distinguished by B content (Xiao et al., 1992; Vengosh et al., 1995; Meng et al., 2014), in which B a content $<20\times10^{-6}$ represents fresh water; (20×10^{-6})–(60×10^{-6}) represents less brackish water; (60×10^{-6})–(200×10^{-6}) represents brackish water; $(200\times10^{-6}\times10)$–$(400\times10^{-6})$ represents salt water; B content $>400\times10^{-6}$ represents salt lake environment (Walker and Price, 1963; Walker, 1968; Couch, 1971). According to the relationship between B content and water salinity, the B content of 72 samples was analyzed (Table 1). Based on B content, the general tendency of salinity in Paleocene-Eocene mudstone in the Jiangling Depression is salt-fresh-salt-fresh. The lake in the early and late Shashi Formation was a salt lake; the lake in the middle Shashi Formation was a salt water lake, and the lake in the early Xingouzui Formation contained brackish water. The depositional environment has a close relationship with the lithology, in which dark mudstone and dolomite-bearing mudstone is deposited in a brackish or fresh environment with low salt content; argillaceous dolomite, argillaceous gypsum, dolomite and argillaceous glauberite is deposited in a salt environment; salt rock, such as halite, thenardite, sylvine, glauberite and argillaceous dolomite is deposited in a brine environment.

The Paleocene-Eocene in east China was a typical subtropical arid and semi-arid climate (Ye, 1992). The arid climate of the land is related with the uplift of the Qinghai-Tibet plateau (Wang and Xiang, 2001; Fang et al., 2007a, b). Under the tectonic background and arid climate, the water in the early Shashi Formation was gradually evaporated and the lake became salty, so that halite, gypsum, glauberite and carbonate was deposited in the lower Shashi Formation. Halite is mainly distributed in the middle region of the Jiangling Depression with little halite deposited in the lower plate of the Wancheng Fault in the northwest (Fig.4a). In the middle Shashi Formation, the Jiangling Depression is further depressed and settled, which caused the lake to deepen and the lake surface to widen. With desalting of the water, the halite deposition area decreased, the sulfate such as anhydrock and glauberite, terrigenous materials increased and sand-mudstone deposition increased (Fig.4b). In the late Shashi Formation, because of the persistent dry climate, the water was evaporated gradually and abundant halites precipitated. A thick section of thenardite and glauberite (Zheng et al., 1998) was deposited and moved toward the southwest (Fig.4c). In the early Xingouzui Formation, the large fault of Neijiangkou

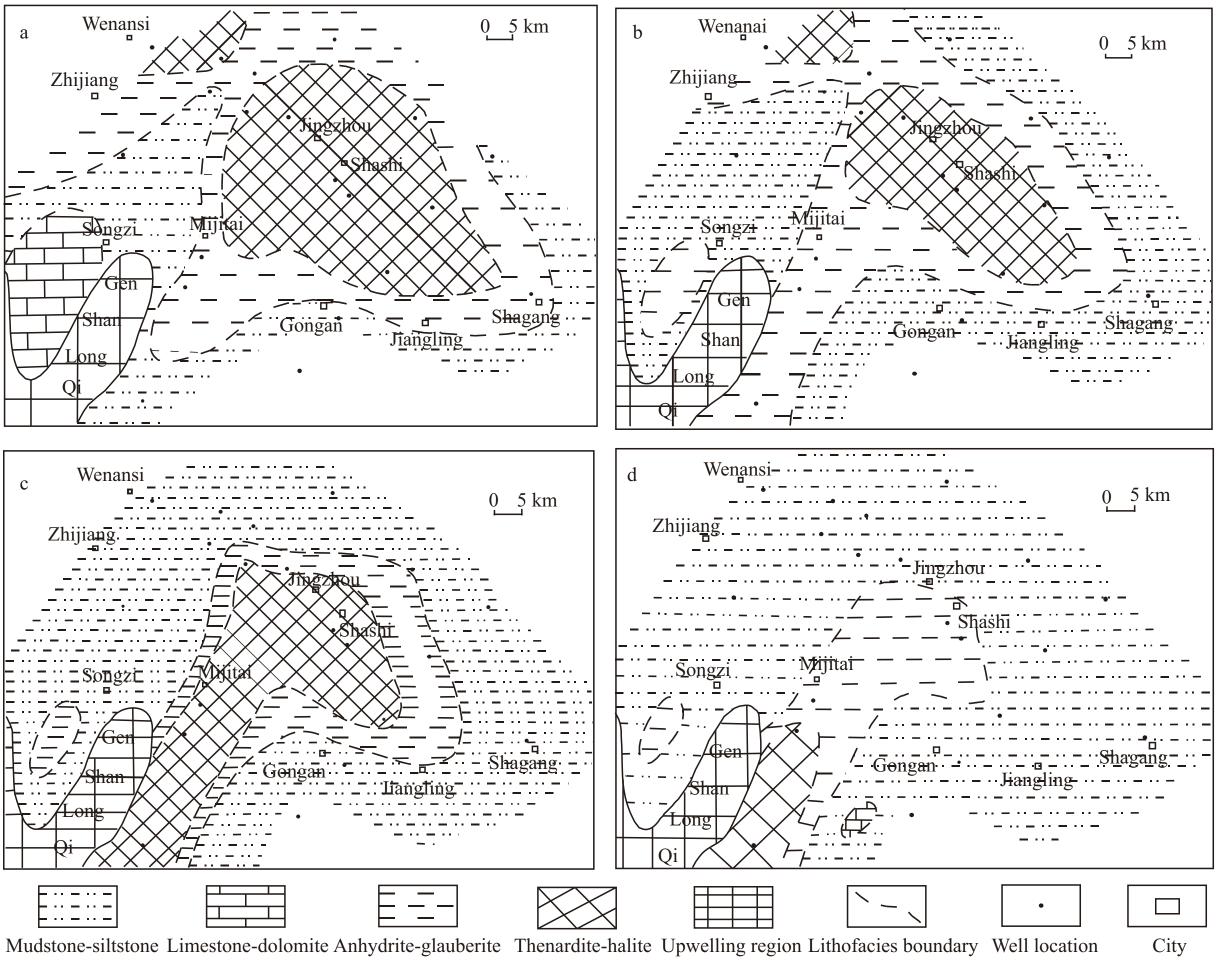

Fig.4 Sedimentary facies map of the Shashi Formation and Xingouzui Formation in the Jiangling Depression (after Research Institute of Jianghan Oilfield, 2010)

a. early Shashi Formation; b. middle Shashi Formation; c. late Shashi Formation; d. early Xingouzui Formation.

and Wancheng in the Jiangling Depression was still active and caused lake transgression. A set of dark mudstone of lake facies was deposited with mudstone and gypsum interbedded. A small amount of halite occurs with decreasing thickness and moved toward the southwest (Fig.4d). Afterward, mainly clastic rock was deposited.

3.4 The depositional model

The Jiangling Depression is a typical fault depression basin with monocline and half graben developed in the depression, which is controlled by basement rift (Liu et al., 2008). The basin settled gradually and closed well. The active volcanic activity provides abundant mineral substance. The coupling of paleoclimate, structure and source is favorable for the deposition of salt and sylvite. According to the paleo-tectonic setting, paleotopography, paleoclimate, sedimentary characteristics and sedimentary environment (Caus et al., 1997; Lüning et al., 2004; Martius et al., 2012), there are two kinds of depositional models in the Shashi Formation and Xingouzui Formation.

3.4.1 The shallow salt lake-dry salt lake model

In the early and late Shashi Formation, during hot and arid conditions, the lake water was evaporated and became salty, mainly developing gypsum-salt facies of salt lake and mud-gypsum facies in the shore-shallow lake (Fig.5). Thick sections of gypsum rock, glauberite and halite were deposited with oxidation red mudstone in shallow water. The early Shashi Formation has characteristics of rapid desalting and slow evaporation, which leads to several types of salt rhythm. The late Shashi Formation has more characteristics of rapid desalting and slow evaporation, but with more abundant types of salt rhythms, indicating more frequent climate changes. The condensed brine was aggregated in the most favorable secondary depression and evaporite was deposited. Some brine permeated into Cretaceous sandstone along the deep fracture and layer. Meanwhile, the meteoric water, surface runoff and deep flow provided the supplies of ore-forming materials. In the process of flow movement, the leaching of evaporite in ancient strata brings richly saline materials. In the Paleocene, volcanic activity provided a favorable heat source and mineral substance. In the final stage of salt evolution, under the coupled multi-factors, sylvite ore could be formed in a favorable secondary depression.

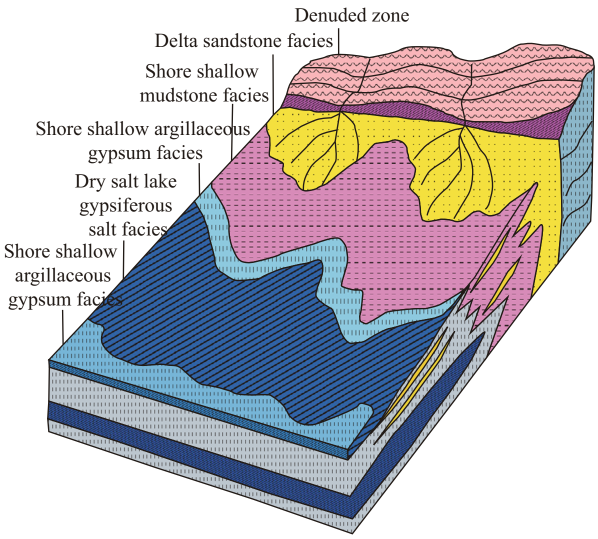

Fig.5 The salt lake depositional model in the early and late Paleocene in the Jiangling Depression (after Research Institute of Jianghan oilfield, 2010)

3.4.2 The salt lake-brackish water lake

In the middle Shashi Formation and early Xingouzui Formation, because of climate and structure, lake water was desalted to salt-brackish water, in which a set of dark mudstone and siltstone was deposited with little gypsum and halite (Fig.6). This reveals that the lake water was deep with abundant terrigenous materials, which developed sand-mudstone deposition on the margin of the basin with gypsum being deposited toward the center of the basin. The rhythm is relative simple with mainly argillaceous-mudstone-argillaceous rhythm. The climate at that time was warm and humid with weak and short evaporation.

4 CONCLUSION

Our studies of the sedimentary characteristics and depositional model in the Paleocene-Eocene salt lake in the Jiangling Depression have led to the following conclusions:

1) The sediments in the Paleocene-Eocene salt lake in the Jiangling Depression include halite, thenardite, sylvine, glauberite, anhydrite, limestone, dolostone, sandstone, conglomerate and mudstone;

2) Nine types of rhythms were identified. The deposition shows a desalting-salting order of halite-argillaceous-mudstone-mud dolostone-mud anhydrock-glauberite;

3) The early and late Paleocene was a salt lake depositional environment with high salt content and a shallow paleolake, which represents a shallow water

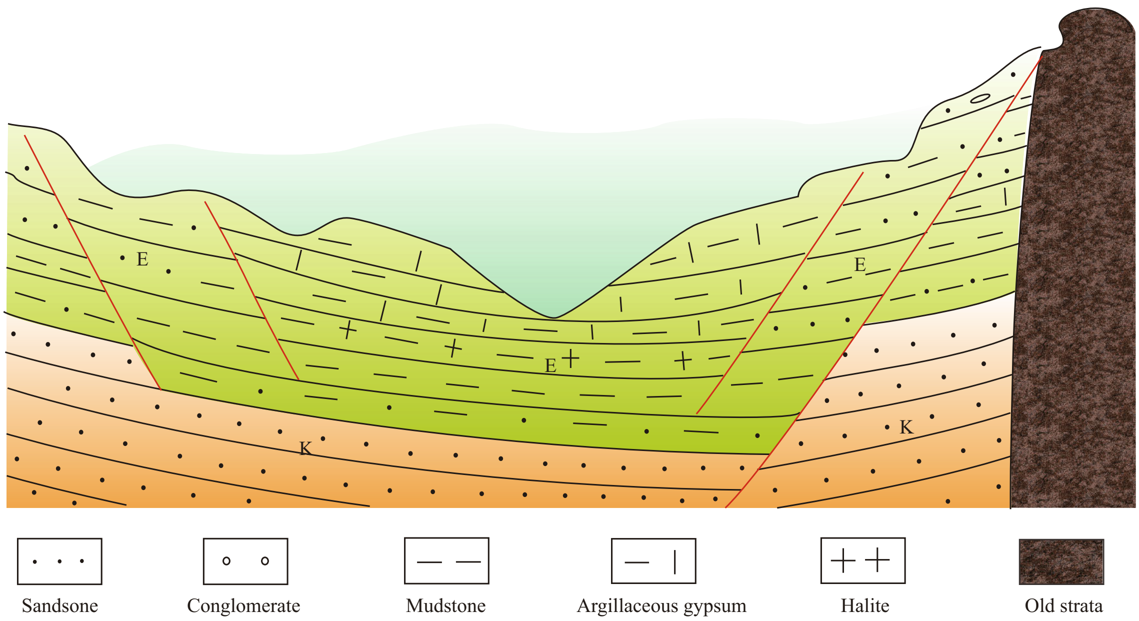

Fig.6 The deep-semideep lake depositional model in early Eocene in Jiangling Depression

salt lake depositional model. The middle Shashi Formation in the Paleocene in the Jiangling Depression and the early Xingouzui Formation in the Eocene was a salt and brackish sedimentary environment with low salt content and a deep paleolake, representing a deep salt lake depositional model.

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