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Organic matter enrichment mechanism in saline lacustrine basins: A review

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Abstract

Organic-rich shale in saline lacustrine basins holds significant importance as a source rock for conventional hydrocarbon exploration and has emerged as a prominent target for unconventional hydrocarbon exploration and development in recent years. Based on in saline lacustrine basins, this paper provides a summary of the organic matter enrichment mechanisms in saline lacustrine basins, considering sedimentary characteristics, biological activities, factors for the organic matter enrichment and consumption, and hydrocarbon generation. The implications for these factors are discussed in relation to the distribution prediction of high-quality lacustrine shale district settings and the exploration and development of shale oil. Saline lacustrine basins undergo distinct evolutionary stages, each corresponding to different sedimentary stages involving carbonate minerals, sulfate minerals, and alkaline minerals. Moreover, these basins exhibit diverse biological types and experience extensive biological activities. The prosperity of organisms and the accumulation of sedimentary organic matter are ensured by halophilic organisms. Organic matter enrichment in saline lacustrine basins is influenced by two main aspects: the primary productivity of organic matter, which is promoted by the proliferation of halophilic organisms, and the efficient preservation of organic matter facilitated by the strong reducing environment resulting from promoted water salinity stratification. The organic matter consumption in saline lacustrine basins involves bacterial sulfate reduction (BSR) in the early stages, thermochemical sulfate reduction (TSR) in the late stages, and dilution of salt minerals with higher depositional rates. of the presence of salt beds and saline minerals positively influences hydrocarbon generation and expulsion in organic-rich shale within saline lacustrine deposition. Consequently, continental saline lacustrine basins in China offer favorable conditions for the formation of organic-rich shale and present broad prospects for for the exploration of shale oil and gas resources.

Keywords

Biological activities, Consumption of organic matter, Enrichment of organic matter, Saline lacustrine basins, Shale oil

1 INTRODUCTION

Source rocks associated with evaporation and saltwater are widely distributed globally, encompassing numerous renowned marine and continental basins (Warren, 2016; Figure 1). Those organic-rich shales, that formed under a saline backdrop, serve as crucial source rocks for conventional and unconventional hydrocarbon exploration and development in recent years (Jin et al., 2006). A saline lacustrine basin is characterized by a lake basin with salinity levels exceeding 1‰, typically resulting from a higher rate of water evaporation compared to water influx (Jiang et al., 2004). The presence of Ca-Mg carbonate minerals often marks the initiation of a saline lacustrine basin. With the increasing lake water salinity, minerals such as sodium carbonate, sulfate, and chloride are also deposited. From the Permian to the Paleogene periods, there are numerous saline lacustrine basins and strata developed in China (Figure 2). In the 1980s, the interbedding of evaporites and source rocks was discovered in the Jianghan Basin, while the Dongpu Depression of Bohai Bay Basin revealed the coexistence of extensive salt rocks and shale (Jiang, Sheng, & Fu, 1988; Jin & Huang, 1985). In recent years, significant advancements have been made in the exploring and developing the continental shale oil in China, shedding light on the mixed deposition and interbedded relationships between high-quality shale and salt minerals (Zhi et al., 2016, Zeng et al., 2017). This indicates the crucial role of saline lacustrine basins in the formation of organic-rich shale. However, the mechanism of organic matter enrichment in the saline lacustrine basins remains unclear. Based on previous research findings and involved the development characteristics of organic-rich shale in Jianghan Basin, this paper aims to elucidate the mechanism of organic matter enrichment in a saline lacustrine basin. The investigation encompasses hadrochemical conditions, sedimentation, biological activities, organic matter enrichment and consumption, aiming to provide a theoretical foundation for the development and prediction of high-quality shale in continental lacustrine basins, as well as shale oil exploration and development.

2 SEDIMENTARY CHARACTERISTICS OF THE SALINE LACUSTRINE BASIN

Figure 2 illustrates the wide distribution of source rocks within China's saline lacustrine basins, spanning various geological periods. During the Permian period, the Junggar Basin and Santanghu Basin developed a semi-enclosed saltwater lake sedimentary environment under the compressive tectonic background (Du et al., 2020). Notably, two sets of high-quality source rocks were formed within the Fengcheng and Lucaogou Formations (Fan et al., 2021; He et al., 2021; Su et al., 2019). During the Cretaceous period, the Yin'e Basin and Erlian Basin experienced a brackish water to saltwater lake sedimentation in faulted depression settings, giving rise to high-quality source rocks within Bayingebi Formation. (Yu et al., 2021; Zhang et al., 2020). In the

Paleogene period, the development of China's saline lacustrine basin reached its peak, resulting in the formation of high-quality source rocks. The Bohai Bay Basin harbored such source rocks within the Shahejie Formation and Kongdian Formation, while the Subei Basin contained them within the Funing Formation. The Qaidam Basin exhibited high-quality source rocks within the Ganchaigou Formation and Dameigou Formation, whereas the Nanxiang Basin contained them within the Hetaoyuan Formation. Lastly, the Jianghan Basin featured high-quality source rocks within the Qianjiang Formation and Xingouzui Formation (Li et al., 2021; Song et al., 2019; Wang et al., 2020; Zhang et al., 2019; Zhou et al., 2020).

In contrast to the relatively stable chemical composition found in the present-day marine environment, the composition of ions in the continental lacustrine basin water is complex and diverse. These ions originate from various sources, including atmospheric water, surface runoff water, transgressive residual water, and deep hot brine. Typically, the concentration of original salts in lake basins is relatively low, and the formation of saline lacustrine basin necessitates a combination of closed water bodies and strong concentration processes.

Under arid climate conditions, the evaporation of lake water surpasses the replenishment of rainfall or river water, resulting in the gradual shrinkage of the lake basin, salinization, and the deposition of corresponding salt minerals (Du et al., 2020; Wang et al., 2021; Yuan, 2019). Deep brine, which is rich in salt substances, contributes to the increased concentration of salts in lake basin water. Consequently, salt minerals are deposited, even without a high initial water concentration (Wu et al., 2017).

The composition of ions in saline lacustrine basin varies, leading to the deposition of different salt minerals during the process of evaporation and concentration. As the concentration and salinity in saline lacustrine basin increase, the initial precipitates are typically Ca-Mg carbonate minerals. In addition, based on the ratio of Ca^{2+} to Mg^{2+} in the brine, various minerals such as low magnesium calcite, high magnesium calcite, aragonite, and dolomite may form. This marks the primary stage of salinization in the lake (Figure 3; Warren, 2016). Representative strata illustrating this process include the Shahejie Formation in Dongying Sag of Bohai Bay Basin (Figure 4A) and 7th member of Dameigou Formation in Yuqia Sag of Qaidam Basin. These formations are characterized by the presence of mudstone and calcareous mudstone (Bai et al., 2021; Wang et al., 2019; Zhang et al., 2019). The subsequent deposition of minerals is determined by the ratio of Ca^{2+}, Mg^{2+}, and HCO^{3-} (Figure 3; Warren, 2016). When $(Ca^{2+}+Mg^{2+}) \gg HCO^{3\ -}$, the excess Ca^{2+} and Mg^{2+} ions, following the deposition of Ca-Mg carbonate minerals, combined with sulfate ions to precipitate aboundant sulfate minerals, including gypsum and glauberite (Figure 4B1-B4). This stage is characterized by the process of sulfate brine, representing the process of seawater concentration sequence.

An example of such a stratum is the Xingouzui Formation in Jianghan Basin (Figure 4A), which exhibits the development of three main lithological associations. The first association comprises argillaceous dolomite and dolomitic mudstone, reflecting the sedimentary characteristics during the early stage of salinization. The second association consists of interbedded argillaceous dolomite, dolomitic mudstone, and layered glauberite, indicating a further increase in water salinity. The third association features a pure glauberite section and locally visible salt rock, exemplifying the sedimentary characteristics of late-stage salinization. When $HCO_3^- \gg Ca^{2+} + Mg^{2+}$, the brine exhibits a carbonate type. During the deposition stage of Ca-Mg carbonate minerals, Ca^{2+} and Mg^{2+} become depleted. At this time, the excessive HCO_3^- combines with Na^+ to form alkaline minerals, typically without the formation of gypsum and other sulfate minerals. An example of such a stratum is the Lower Permian Fengcheng Formation in the Mahu Sag of Junggar Basin. The sedimentary period of the Fengcheng Formation was characterized by frequent volcanic activities, which promoted the the high partial pressure of CO_2 in the atmosphere. Consequently, a large amount of CO_2 dissolved in the sedimentary water, resulting in the formation of HCO_3.The Fengcheng Formation showcases a complete alkaline lake sedimentary sequence (Figure 4A). In the first member of Fengcheng Formation, mudstone and dolomite were the primary minerals, with localized deposition of sodium carbonate minerals. As water salinity increased, the second member witnessed the emergence of numerous alkaline minerals, including reedmergnerite, shortite, eitelite, wegscheiderite and nahcolite (Figure 4C1-C4). Gradually, the content of dolomite and alkaline minerals decreased during the third member of Fengcheng Formation, indicating a weakening alkaline lake environment. (Cao et al., 2020).

3 BIOLOGICAL ACTIVITY OF THE SALINE LACUSTRINE BASIN

3.1 Biological species

Previous studies initially suggested that that high salinity environments were unfavorable for the survival of organisms. However, further research has revealed that biomass in these environments may not be reduced and can even be higher. The predominant organisms found in high salinity environments include microeukaryotes, halophilic bacteria and haloarchaea. For example, various algal groups, particularly diatoms, are consistently found in Qinghai Lake throughout the year (Yao et al., 2011), and halophilic bacteria and *Dunaliella* are commonly observed in large salt lakes in the United States (Baxter & Zalar, 2019). Significantly, extensive evidence of biological activities has been discovered in the source rock development strata of the saline lacustrine basins. For instance, in the organic-rich shale of the 7th member of the Dameigou Formation in Qaidam Basin, numerous biological fossils and algal bodies suspected resembling coccolithophores have been found, along with a substantial amount of biogenic apatite (Figure 5A-F). Zhang et al. (2019) identified organic-rich shales of Shahejie Formation in Dongpu Sag of Bohai Bay Basin by optical microscopy and scanning electron microscopy, and found many dinoflagellates, cyanobacteria, green algae and charophytes. Xia et al. (2022) confirmed the presence of *Dunaliella* in the shale of Fengcheng Formation in the Mahu Sag, Junggar Basin using organic geochemical indicators such as the C_{28}/C_{29} sterane ratio and β-carotene index.

3.2 Biological survival mechanism

Organisms in a salt lake require abundant nutrients for their survival. In high salinity environments, nitrogen and phosphorus compounds are crucial nutrients that promote the phytoplankton proliferation. A salinity increasing in evaporative environments, nutrients become more concentrated. Therefore, even a slight increase in nutrient availability in saline environments can trigger a bloom of phytoplankton bloom (Jiang et al., 2004). Particularly in alkaline lake water with high pH levels, the presence of abundant CO_2, molybdenum (Mo), and phosphorus (P) elements greatly facilitates biological reproduction (Li et al., 2021). In a saline environment, organisms face a significant challenge posed by osmotic pressure resulting from elevated salinity levels. Under normal circumstances, cells tend to lose water and ultimately succumb to the detrimental effects of such high osmotic pressure. However, organisms inhabiting lacustrine basins have evolved two distinct mechanisms to effectively maintain stable osmotic pressure and thrive in this challenging environment.

The first mechanism is referred to as the internal salt mechanism, which involves the accumulation of substantial quantities of potassium ions (K^+) within cells until the intracellular reaches equilibrium with the concentration of ions (Na+) present in the surrounding environment. These accumulated K^+ ions facilitate the positioning of acidic amino acid residues on the surface of proteins and enzymes, leading to the formation of water layers that effectively prevent the collision and agglutination of macromolecules. This protective mechanism ensures that cells can carry out their normal physiological functions unhindered. It is particularly well-suited for halophilic microorganisms that require continuous survival in high salinity conditions. The second is mechanism is known as the compatible solute mechanism. Compatible organic solutes are small molecules, such as glycerol, that readily dissolve in water and do not negatively interfere with the enzymatic activity within cells. Some of these solutes are synthesized within the cells themselves, while others are absorbed from the surrounding environment. Importantly, compatible organic solutes can be adjusted in response to the salinity of the external environment. This adaptability makes them particularly suitable for organisms residing in environments characterized by frequent fluctuations in salinity levels. Through the utilization of these mechanisms, including the internal salt mechanism and the employment of compatible solutes, organisms in saline environments can effectively mitigate the adverse effects of high osmotic pressure and thrive in extreme conditions (Han Shuaibo, 2021; Strahl & Greie, 2008).

4 ORGANIC MATTER ENRICHMENT OF THE SALINE LACUSTRINE BASIN

4.1. Biological bloom and primary productivity

As salinity increases in saline lacustrine basins, there is a significant decrease in the number of species present. However, organisms that are adapted to specific salinity ranges can proliferate in these environments, benefiting from reduced competition for nutrients and living space, as well as the absence of predators. When the salinity of lake basin water changes and falls outside the optimal range for these organisms, a large number of these organisms will die (Figure 6). Barbe et al. (1990) conducted a study on seawater with different salinities in coastal areas, revealing that different salinity levels lead to the production of distinct groups of organisms.. For instance, when seawater salinity rises from 60‰ to 140‰, salt-tolerant organisms such as diatoms, green algae and cyanobacteria flourish. As the salinity further increases to around

300‰, the brine shrimp (*Artemia*), *Dunaliella*, halophilic archaea and eubacteria dominate (Figure 6A). It's important to note that the development of organisms in saline environments is influenced not only by salinity but also by factors such as light, temperature, nutrient availability. The aqueous conditions of lakes are highly sensitive to changes in structure, climatic, and source-related factors (Deng et al., 2020). Consequently, the salinity of lake basin water can undergo significant changes, ranging from freshwater to hypersaline conditions. These fluctuations, combined with other factors, can trigger sudden flourishing of certain species (biological blooms) followed by rapid die-offs (organic matter enrichment) (Figure 6B, 6C). Algae and bacteria involved in these processes are often rich in lipids, and their autolysis can directly contribute to the generation of hydrocarbons, thereby influencing the early stages of organic-rich shale formation (Guo, 1998).In the investigation of source rocks in saline lacustrine basins, has been observed that laminations are commonly developed, consisting of carbonate laminae, clay laminae and organic laminae (including algal laminae and biological fossil laminae) (Figure 7). Zheng et al. (1985) conducted research on Zabuye Salt Lake in Tibet and found that halophilic bacteria and algae are distributed extensively, forming organic matter enrichment layers of 1-2 cm thickness after their death. Zeng et al. (2017) proposed that fine organic laminae are generated by the extensive growth of benthic microbial communities during periods of nutrient abundance and high water salinity.Zhao et al. (2019) studied the laminated shale of the Shahejie Formation in Dongying Sag using astronomical cycle theory and concluded that these laminated shales represent annual laminae primarily influenced by seasonal climate variations. Drawing from these investigations, it is hypothesized that the organic matter laminae observed in organic-rich shale within saline lacustrine basins may serve as a record of biological blooms that have adapted to specific water salinity conditions. These laminae provide valuable insights into the dynamics of past ecological processes within these environments.

4.2. Water stratification and organic matter preservation

Previousresearch has indicated that when a lake reachesa certain depth, the water column undergoes stratification due to variations in density and gravity. The denser high salinity water occupies the bottom of the lake basin, while the less dense low salinity water resides at the surface, with the halocline separating the two layers. The surface water benefits from contact with the atmosphere, , resulting in higher oxygen levels, and light penetration supports photosynthesis. Algae in the surface water exhibit the highest productivity and contribute the most to organic matter production, followed by bacteria near the halocline (Figure 7A). In the deep water of the lake basin, limited exchange occurs between the oxygenated surface water and the deep water due to the presence of the halocline. Consequently, the bottom water is characterized by a stagnant, anoxic, and strongly reducing environment (Figure 7A). The stratified water structure of the saline lacustrine basins provides favorable conditions for the preservation of organic matter (Jin et al., 2008), thus promoting the formation of high-quality source rocks.Based on available data, the preservation efficiency of marine organic matter in the modern shallow open oxygenated oceans is estimated to be approximately 0.1%

(Menzel & Ryther, 1970), In contrast, in the anoxic Black Sea, the preservation efficiency is around 4% (Warren, 2016). Notably, in high-salinity lakes with density-stratified water bodies, the preservation efficiency of organic matter can reach a remarkable 85% (Hite & Anders, 1991). Comparing two modern lake basins, namely the mesotrophic Qinghai Lake and the eutrophic Turkana Lake, both characterized by brackish water environments, reveals interesting differences. Despite Turkana Lake having relatively high nutrient levels and surface productivity, the average organic matter content in the lake's bottom is only about 0.6%. In contrast, Qinghai Lake, with its stratified water conditions, exhibits an average organic matter content of 2.29% in the bottom sediments. These findings highlight the significance of water stratification and strong reduction preservation conditions in the bottom sediments for the enrichment of organic matter in high-salinity lakes.

5 ORGANIC MATTER CONSUMPTION OF THE SALINE LACUSTRINE BASIN

According to the research conducted by Jiang et al. (2004), it has been observed that during the development, evolution, and sedimentation of the saline lacustrine basin, the early stages characterized by Ca-Mg carbonate sedimentation exhibit organic matter enrichment that is approximately three orders of magnitude higher compared to the later stages characterized by sulfate and halide sedimentation. In China, source rocks formed under a typical sulfate saline lake setting also exhibit low organic matter content, indicating that the late evolution of the saline lacustrine basins may not be favorable for organic matter enrichment. This reason phenomenon could be attributed to factors such as sulfate reduction during early diagenetic stage and the deposition rate of salt rock.5.1. Bacterial sulfate reduction (BSR)

In anoxic environments, sulfate-reducing bacteria (SRB) utilize sulfate ions (SO_4^{2-}) as electron donors to metabolize organic matter at temperatures below 60-80℃. During this process, sulfate is reduced to H2S gas or further forms pyrite (Strauss, 1999). Reeburgh (1980) suggested that microbial sulfate oxidation of organic matter is more pronounced compared to other oxidants such as oxygen, nitrate, and metal oxides. Kelts (2015) indicated that the efficiency of sulfate oxidation of organic matter in lakes primarily depends on sulfate concentration. For instance, in Vechten Lake, which has a sulfate concentration of approximately 15g/m3, around 25% of the sedimentary organic matter is degraded annually. Bacterial sulfate reduction (BSR) leads to the enrichment of residual sulfate relatively higher δ34S values (Wang et al., 2014). Canfield et al. (1996) reported a sulfur isotope fractionation range of 4‰ ~ 46‰, resulting from BSR, with an average of 21‰. However, in the absence of sulfate-reducing bacteria, the δ34S value of sulfate in lake basin water is significantly lower, approximately 20‰ (Zhang et al., 2010). Xiao et al. (2020) found that the difference of δ34S value between H2S produced after BSR and the original SO_4^{2-} ranged from -15‰ and -30‰. Sulfur isotope analysis of organic-rich shale in Xingouzui Formation, Jianghan Basin indicated that the δ34S values of the original SO_4^{2-} and the generated H2S were 26.4 ~ 40.1‰ and 12.0～32.0‰ respectively. The difference of δ34S between generated H2S and original SO_4^{2-} ranges from -27.0 to -19.5‰ (Xiao et al., 2020). These findings highlight the significant impact of BSR on the consumption of sedimentary organic matter, which aligns with the relatively high sulfate content and low abundance of organic matter observed in the Xinguozui Formation shale in the Jianghan Basin (Li et al., 2021, 2022).5.2. Thermochemical sulfate reduction (TSR)

During the later stage of diagenesis, a process called thermochemical sulfate reduction (TSR) occurs when the burial temperature a specific range and there is sufficient contact between sulfate and organic matter. Previous studies have indicated that TSR typically occurs at temperatures between 100~200°C, which coincides with the formation temperature of light oil and condensate (Bildstein et al., 2001). In the lower member of the Xingouzui Formation in the Jianghan Basin, shale sections can be distinguished into three high total organic carbon (TOC) sections and two low TOC sections (Figure 8A). The high TOC sections consist mainly of dolomitic mudstone, while the low TOC sections comprise numerous thinly thin layered glauberite ($Na_2Ca(SO_4)_2$) and dolomitic mudstone interbeds (Figure 8A, 8B). The organic-rich shale in the Xinguozui Formation in Jianghan Basin has reached mature stage, as indicated by a vitrinite reflectance (Ro) is 0.7-1.2%, corresponding to the stage of significant hydrocarbon generation. In the shales of Xingouzui Formation, glauberite frequently occurs as interbeds with organic-rich shales, exhibiting high sulfate content and directcontact with organic matter. These conditions are conducive to TSR, which contributes to the consumption of organic matter and aligns with the relatively low abundance of organic matter observed in the Xingouzui Formation shale (Li et al., 2021, 2022). Additionally, significant pyrite mineralization is present in the shales of Xingouzui Formation, with pyrite particle sizes averaging around 5 microns, some of which are associated with organic matter (Figure 8C). Wang et al. (2015) proposed that pyrite is a product of TSR. In summary, thermochemical sulfate reduction (TSR) during late diagenesis period of saline lacustrine shale represents another important mechanism for organic matter consumption and abundance reduction.

5.3. Deposition rate

The deposition rate plays a significant role in the enrichment of organic matter (Figure 9). When the deposition rate is low, organic matter will remains exposed to an oxidation environment for an extended period, increasing the likelihood of complete consumption by oxidation, which is unfavorable for organic matter preservation (Henrichs & Reeburgh, 1987). As the deposition rate increases, organic matter experiences a shorter time in oxygenated water, enhancing its preservation (Müller & Suess, 1979). However, when th deposition rate is excessively fast, inorganic minerals are rapidly deposited in sediments, resulting in limited organic matter being diluted by a large number of inorganic minerals. This situation hampers the organic matter preservation (Ibach, 1980). Tyson (2001) suggested that the critical threshold for excessive deposition rate of marine organic matter enrichment is 5 cm/ka. Ding et al. (2017), in their study of the Tenger Formation in the Erlian Basin, also identified 5 cm/ka as the critical threshold for excessive deposition rate in organic matter enrichment.According to Jiang et al. (2004), the deposition rates of the Qianjiang Formation in the Qianjiang Sag of the Jianghan Basin and the Shahejie Formation in the Dongpu Sag of Bohai Bay Basin, both with a sulphate-type salt lake sedimentary background, are 32 cm/ka and 29 cm/ka, respectively (Table 1), significantly higher than the critical threshold deposition rate (Figure 9A). Hofman et al. (1993) pointed out that the deposition rate of anhydrite was 156.2 cm/ka, while of salt rock was 3030 cm/ka, thereby increasing the dilution effect of inorganic minerals on organic matter. Furthermore, in the later stages of the evolution of the saline lacustrine basin evolution, the water density increases, making it difficult to for organic matter to settle rapidly and rendering it more susceptible to oxidation. Hence, higher deposition rate in the late stage of saline lacustrine evolution lead to a dilution effect on organic matter, which is unfavorable for its enrichment. Thus understanding aligns with the relatively high content of salt minerals and low abundance of organic matter observed in the shales of the Xingouzui Formation in the Jianghan Basin (Li et al., 2021, 2022).

6 HYDROCARBON GENERATION OF ORGANIC MATTER IN THE SALINE LACUSTRINE BASIN

The salt minerals in saline lacustrine basins exists in two primary forms: giant thick gypsum salt beds formed through long-term deposition in saline lake environments and thin beds of salt rock interbedded with mud shale s. Both have important effects on the hydrocarbon generation and evolution of source rocks (Carroll & Bohacs, 2001; Qi et al., 2021). The giant thick gypsum salt beds exhibit high thermal conductivity, typically 2~3 times that of sand and mudstone (Qiu et al., 2004). This characteristic facilitates the transfer of deep heat to the shallow regions. In the Shahejie Formation of the Dongpu Sag in the Bohai Bay Basin, the strata adjacent to the upper part of the gypsum salt beds exhibit significantly higher temperatures compared to areas without gypsum salt layers at the same depth. Conversely, the strata below the gypsum salt layer show notably lower temperatures than areas without gypsum salt beds at the same depth. This observation indicates the efficienct heat conduction of gypsum salt beds. (Li, 2018), which promotes the hydrocarbon generation in overlying source rock. Chen et al. (2018) conducted a comparative study on the influence of different thickness of gypsum salt beds on the hydrocarbon generation threshold of source rocks. They concluded that a minimum thickness of 50 meters of gypsum salt beds is necessary to impact the hydrocarbon generation of source rocks. In the case of source rocks interbedded with thin salt rocks, it is commonly believed that salt minerals can affect and modify the charge distribution on the surface of kerogen molecules through solvent effect and electron induction effect, thus reducing the C-C bond energy (Li et al., 2002), This alteration can impact the hydrocarbon generation of the source rock. Through the hydrocarbon generation simulation experiments and computer molecular simulations, Ban (2018) obtained the variation of dissociation energy with salinity and generated a chart illustrating thehydrocarbon production rate of source rocks in a saline lacustrine basin (Figure 10). The chart shows that higher-quality organic matter and higher salinity contribute to higher hydrocarbon content. Changes in salinity have a more pronounced effect on the hydrocarbon generation of type III kerogen than compared to type I kerogen (Figure 10).

In sulfate-type lake basin, the activation energy of the S-C/S-S bonds, which are abundant in high sulfur kerogen, is lower than that of C-C and C-O bonds, making them easier to break at low temperatures. This characteristic promotes the early generation of hydrocarbons. Ma et al. (2013) conducted hydrocarbon generation and expulsion simulation experiments on saline and non-saline shale samples from the Dongpu Sag, Bohai Bay Basin. The results showed that the oil expulsion rate from saline samples was much higher than that from non-saline samples. This is primarily due to the existence of salt minerals, which reduces the internal adsorption capacity of the source rock and facilitates expulsion of hydrocarbons (Figure 11). Therefore, the gypsum salt rocks formed in the saline lacustrine basins not only promote the hydrocarbon generation of organic matter but also facilitate the expulsion of hydrocarbon expulsion of source rock.

7 CONCLUSIONS

The source rocks in saline lacustrine basins in China are diverse and span a wide geological time range, making them important for shale oil exploration. Saline lacustrine basins undergo different stages of development and sedimentation, resulting in the formation of various salt minerals. These include Ca-Mg carbonates in the early salinization stage, sulfate minerals like gypsum and calcium glauberite in the late salinization stage, and alkaline minerals such as reedmergnerite and nahcolite when HCO^{3-} ions dominates over Ca^{2+} and Mg^{2+} ions.

Saline lacustrine basins host a wide variety of biological organisms and exhibit extensive biological activities. Algae, microorganisms, halophilic bacteria, and halophilic archaea are abundant in these basins, with their proliferation supported by the saline environment and mechanisms like internal salt accumulation. This biological activity contributes to the enrichment of sedimentary organic matter in the basins. The enrichment process involves biological bloom and primary productivity, as well as water stratification and organic matter preservation. Fluctuations in salinity due to climate and environmental changes can lead to episodes of rapid organism flourishing and subsequent death, creating favorable conditions for organic matter enrichment. The water stratification in saline lacustrine basins promotes the preservation of sedimentary organic matter through bottom water anoxia.

Furthermore, salt minerals play a significant role in hydrocarbon generation and expulsion within saline lacustrine basins. Thick gypsum salt beds have high thermal conductivity, facilitating the thermal evolution and hydrocarbon generation of overlying source rocks. In source rocks interbedded with thin salt rocks, salt minerals impact the charge distribution on kerogen molecules, reducing C-C bond energy and promoting hydrocarbon generation. Salt minerals also reduce the internal adsorption capacity of source rocks, facilitating the expulsion of hydrocarbons. Overall, saline lacustrine basins provide favorable conditions for the generation and expulsion of hydrocarbons from organic-rich shales.

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Figure captions

FIGURE 1 Worldwide distribution of evaporite-related source rocks named with respect to hosting basins (from Warren, 2016)

FIGURE 2 Spatial and temporal distribution of source rocks in continental lacustrine basins of China. Abbreviations: P, Permian; T, Triassic; J, Jurassic; K, Cretaceous; E, Eocene, N, Neogene

FIGURE 3 Hydrologic classification and brine evolution pathways of concentrating non-marine waters and a listing of major evaporite minerals associated with the different brine types (from Warren, 2016)

FIGURE 4 (A) Lithologic histogram of different types of saline lacustrine basins; (B1-B4) sulphate core and its microscopic characteristics; (C1-C4) Na carbonate cores and microscopic features (Figure C1-C4 from Wang et al., 2018; Cao et al., 2015)

FIGURE 5 Characteristics of organic matter in shale of saline lacustrine basin. (A) Coccolithophores; (B) Coccolithophores; (C) Coccolithophores (cross-extinction); (D) algophytes; (E) algophytes; (F) apatite

FIGURE 6 (A) Biological development of seawater with different salinities; (B) Mechanisms of biogenesis with salinity; (C) Relationship between species and biomass as salinity changes (Figure A modified from Barbe et al., 1990; Figure B and C modified from Warren, 2016)

FIGURE 7 (A) Organic matter enrichment mechanism in stratified water; (B) Source rock laminar structure of saline lacustrine basin

FIGURE 8 (A) Comprehensive histogram of the seventh Member of Dameigou

Formation; (B) Core photos of the seventh member of Dameigou Formation; (C) Pyrite

FIGURE 9 Relationship between deposition rate and organic carbon content (modified from Ding et al., 2015)

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Table captions

Table 1 Sedimentary rate of tertiary partially saline lacustrine basin (data from Jiang et al., 2004)

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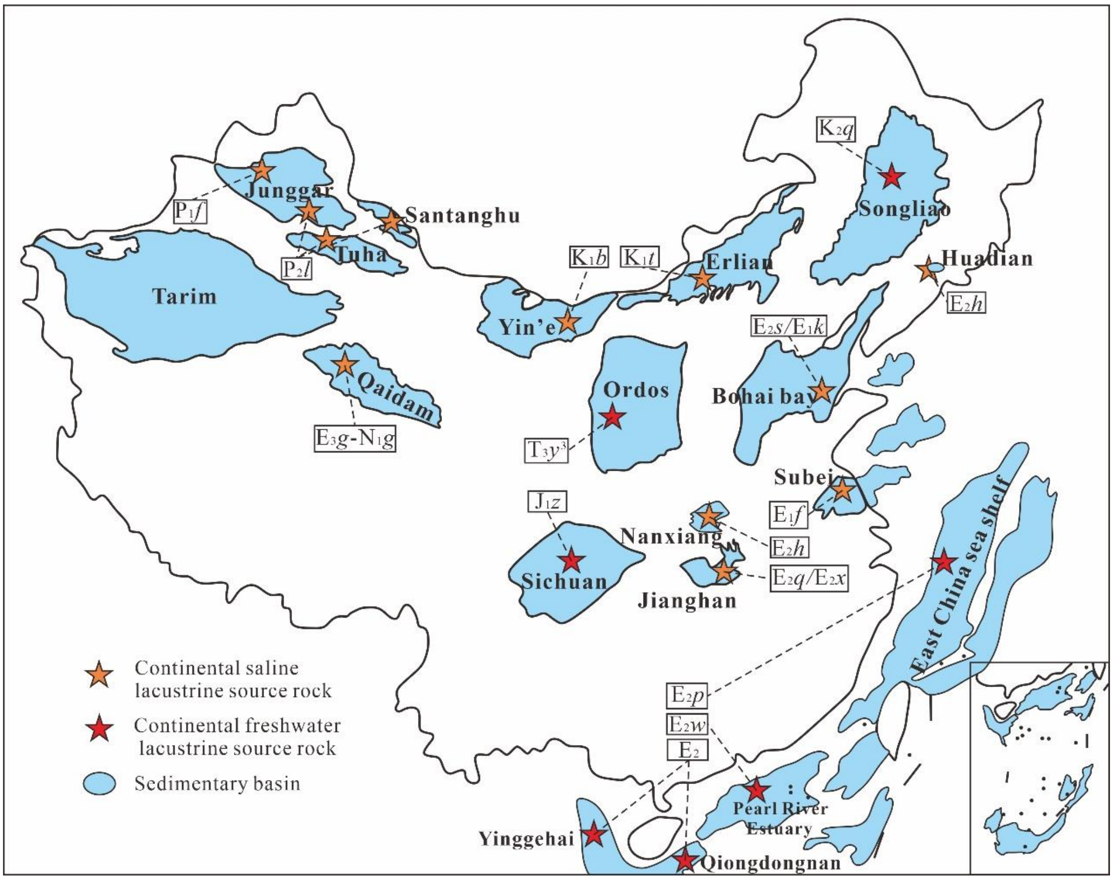

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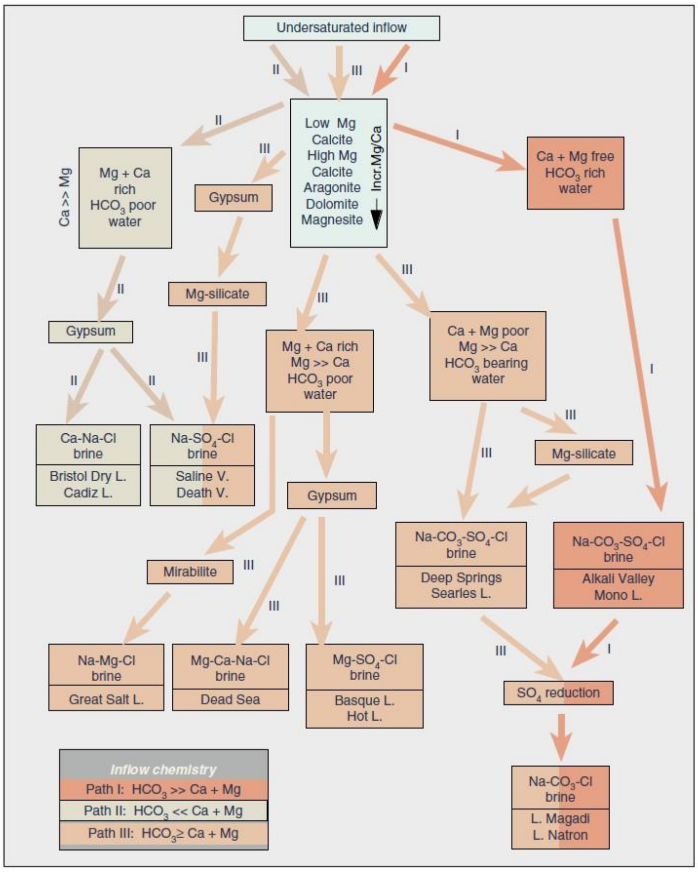
Brine type	Saline mineral	
Ca-Mg-Na-(K)-Cl	Antarcticite	$CaCl_2·6H_2O$
	Bischofite	$MgCl_2·6H_2O$
	Carnallite	$MgCl_2·KCl·6H_2O$
	Halite	NaCl
	Sylvite	KCl
Na-(Ca)-SO_4-Cl	Tachyhydrite	$CaCl_2·2MgCl_2·12H_2O$
	Glauberite	$CaSO_4·Na_2SO_4$
	Gypsum	$CaSO_4·2H_2O$
	Halite	NaCl
	Mirabilite	$Na_2SO_4·10H_2O$
	Thenardite	Na_2SO_4
Mg-Na-(Ca)-SO_4-Cl	Bischofite	$MgCl_2·6H_2O$
	Bloedite	$Na_2SO_4·MgSO_4·4H_2O$
	Epsomite	$MgSO_4·7H_2O$
	Glauberite	$CaSO_4·Na_2SO_4$
	Gypsum	$CaSO_4·2H_2O$
	Halite	NaCl
	Hexahydrite	$MgSO_4·6H_2O$
	Kieserite	$MgSO_4·H_2O$
	Mirabilite	$Na_2SO_4·10H_2O$
	Thernadite	Na_2SO_4
Na-CO_3-Cl	Halite	NaCl
	Nahcolite	$NaHCO_3$
	Natron	$Na_2CO_3·10H_2O$
	Thermonatrite	$NaCO_3·H_2O$
	Trona	$NaHCO_3·Na_2CO_3$
Na-CO_3-SO_4-Cl	Burkeite	$Na_2CO_3·2Na_2SO_4$
	Halite	NaCl
	Mirabilite	$Na_2SO_4·10H_2O$
	Nahcolite	$NaHCO_3$
	Natron	$Na_2CO_3·10H_2O$
	Thernadite	Na_2SO_4
	Thermonatrite	$NaCO_3·H_2O$



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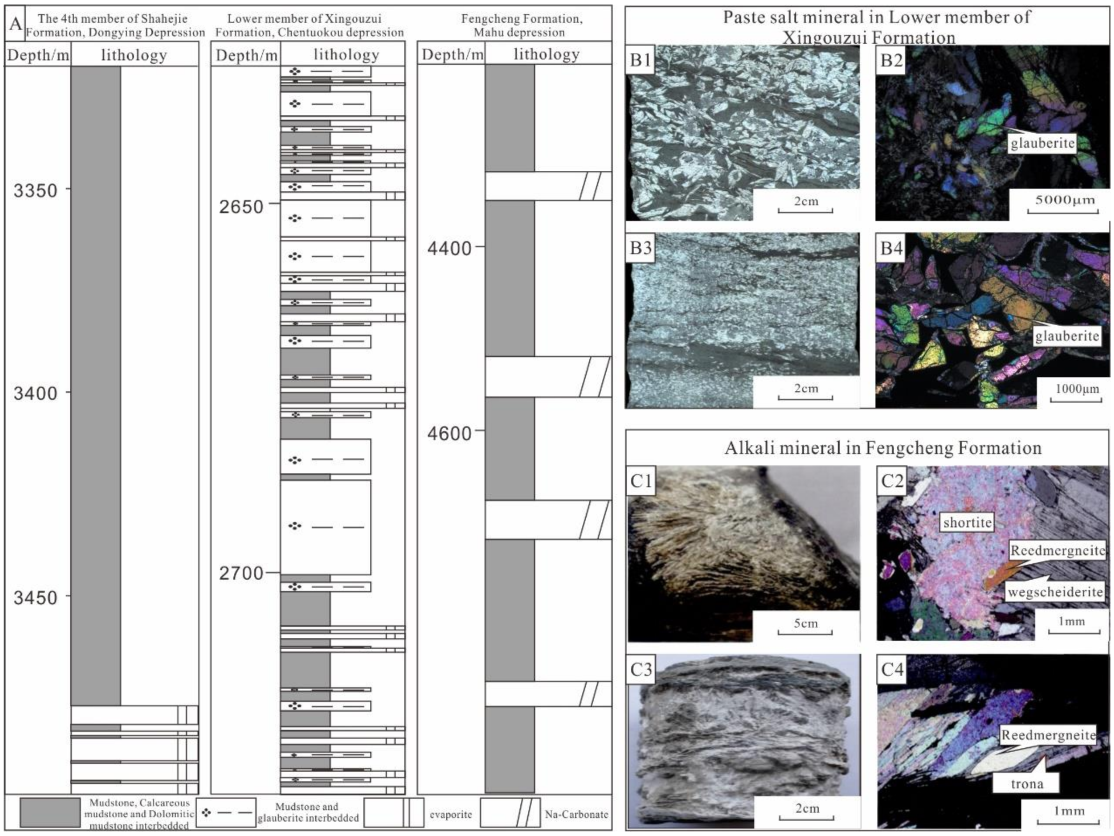

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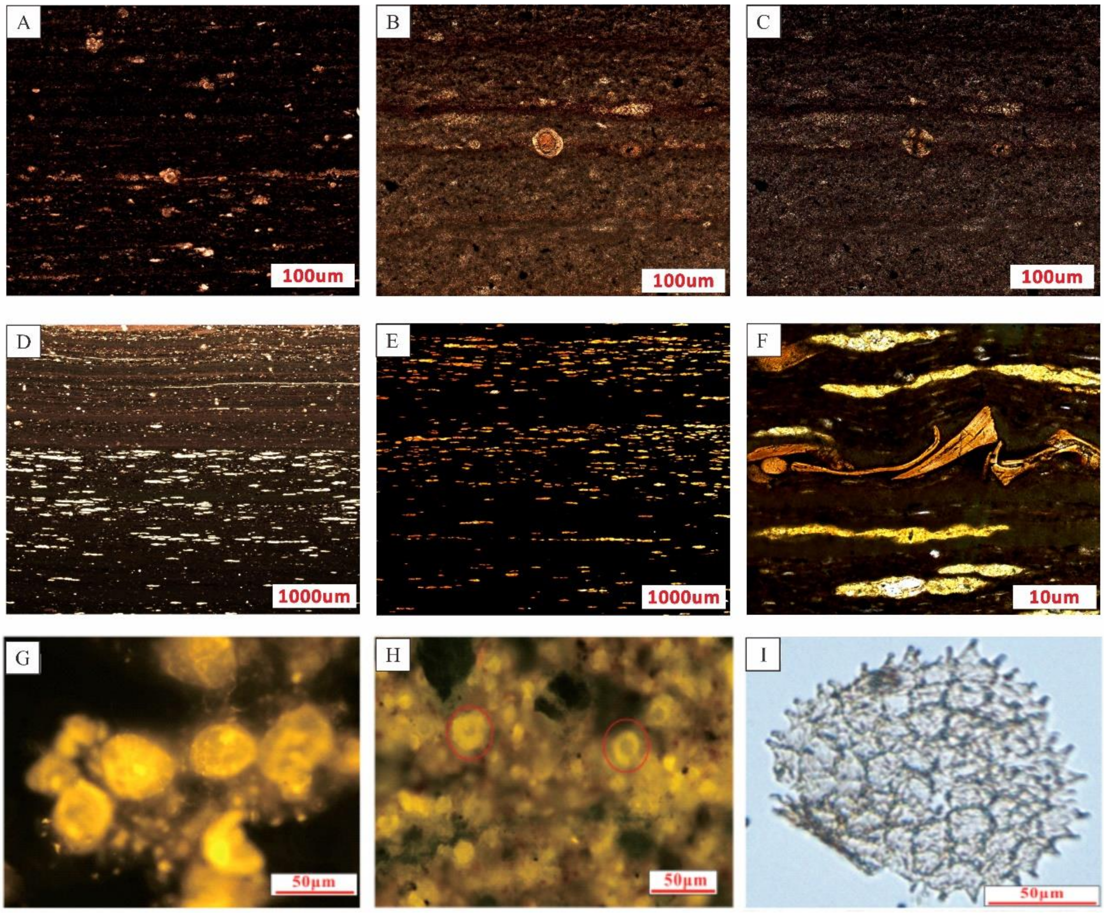

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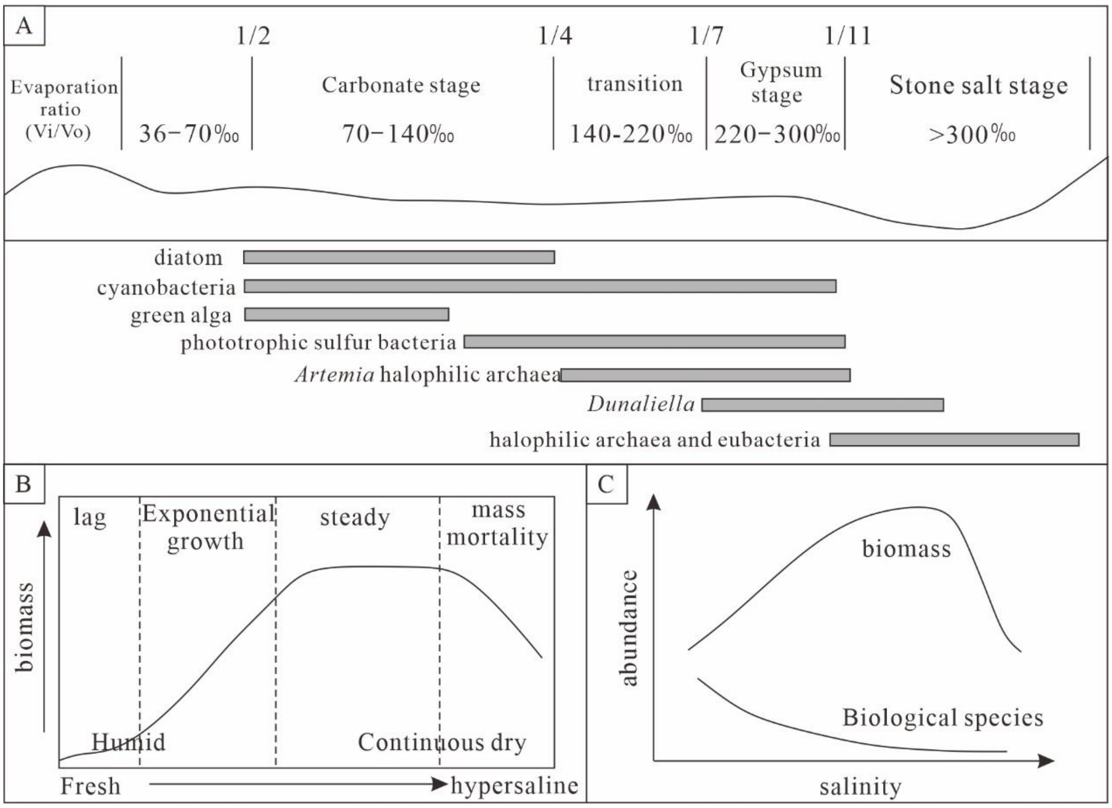

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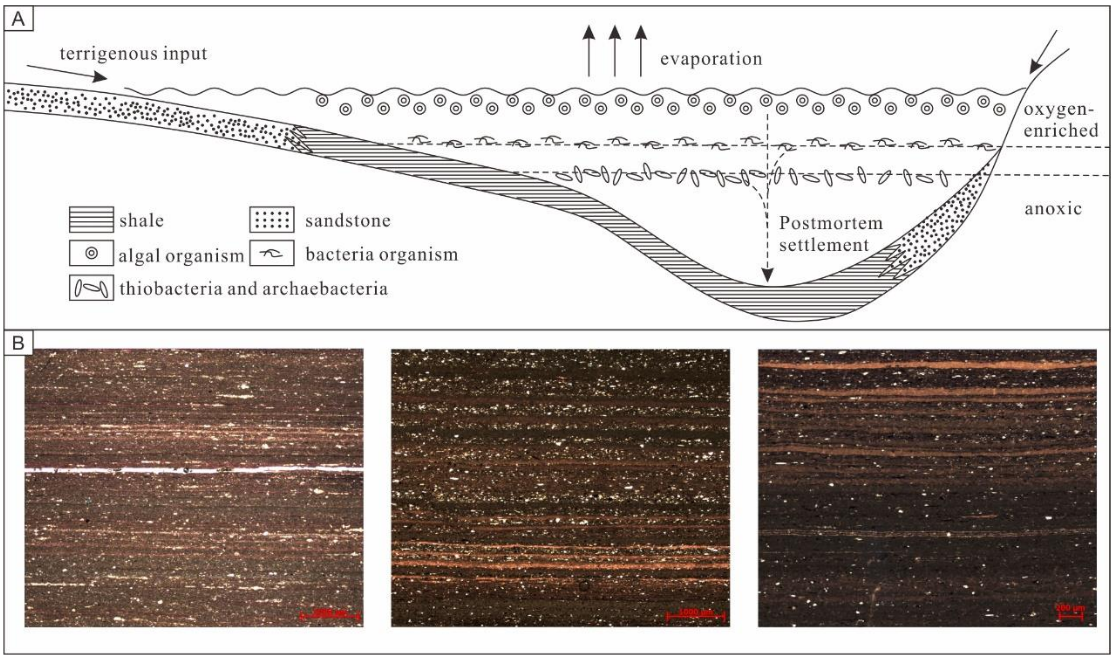

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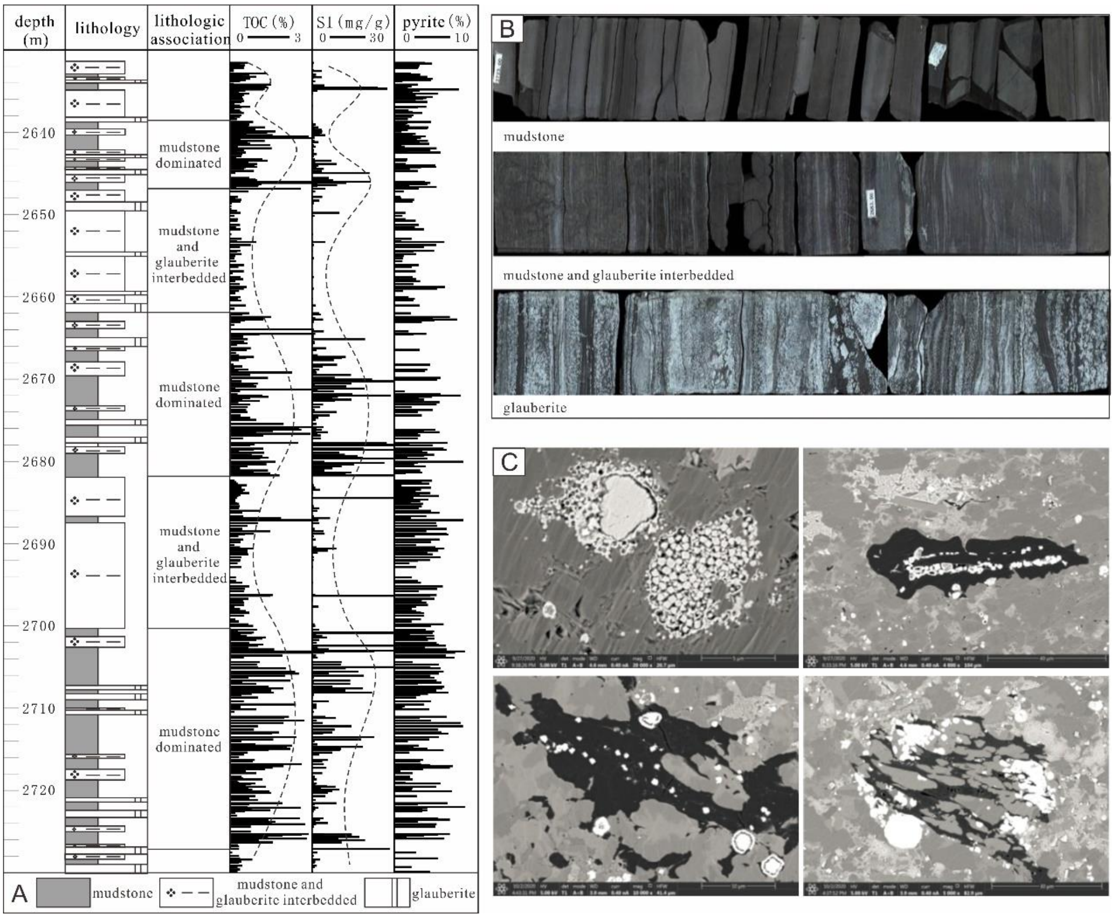

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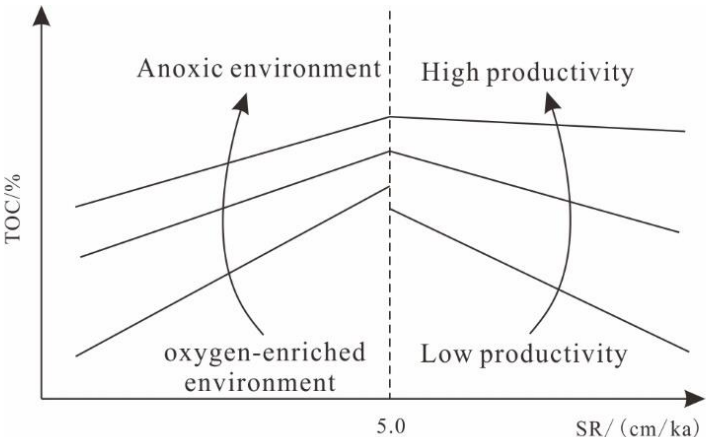
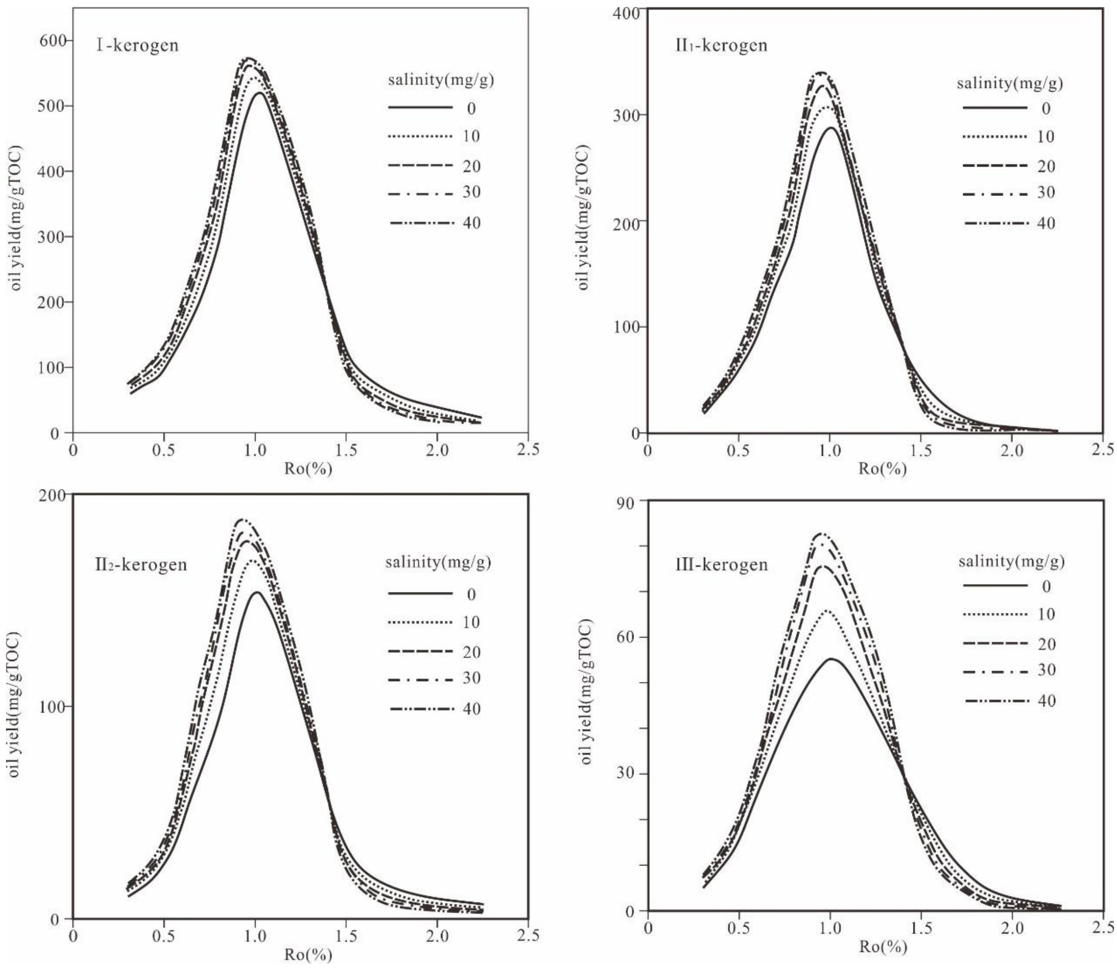


Figure 9 Relationship between deposition rate and organic carbon content (modified from Ding et al., 2015)



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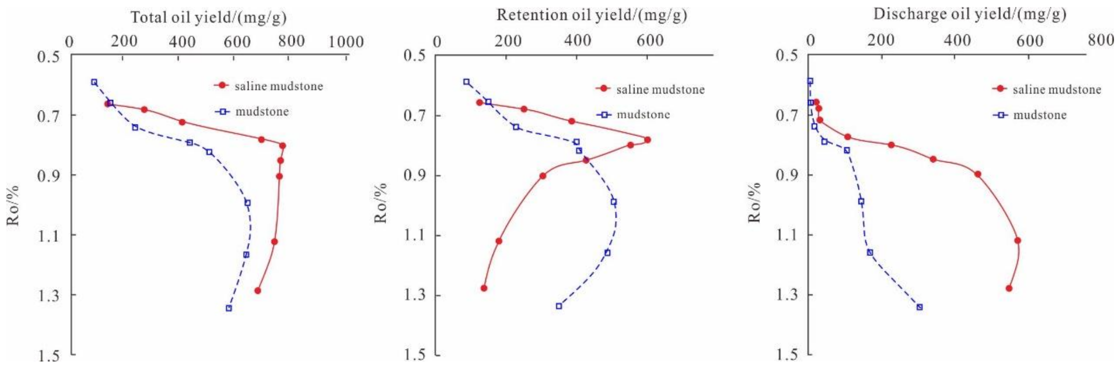

Figure 11 Simulation of hydrocarbon generation and expulsion from saline and non-saline shale samples (modified from Ma et al., 2013)

Table.1 Sedimentary rate of tertiary partially saline lacustrine basin (data from Jiang et al., 2004)

Basin	Qianjiang Depression Jianghan Basin	Wuyang Depression Zhoukou Basin	Dongpu Depression Bohai Basin	Jinxian Depression Bohai bay Basin	Mangya Depression Qaidam Basin
stratigraphic	Eq	Eh	Es	E_{S4}-E_k	N_1-E_3
Maximum deposition thickness/m	4200	3800	>4000	>2000	4200
source rock thickness/m	2000	1400	2500	700	2500
deposition rate/ (cm/ka)	32	29	29	22	15