Geochemical characteristics and depositional environment of the Shahejie Formation in the Binnan Oilfield, China

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Abstract
Trace elements in sedimentary rocks are highly sensitive to palaeoaquatic environmental changes in a sedimentary environment, making them an effective means for studying the paleoclimate and paleoenvironment during the deposition of sediments. The trace elements and major elements of mudstone cores sampled in the Binnan Oilfield in China were tested by inductively coupled plasma mass spectrometry (ICP–MS). Strontium (Sr), barium (Ba), vanadium (V), nickel (Ni) and boron (B), which are all sensitive to the sedimentary environment, were selected as discriminant indicators, and the sedimentary environment of the Shahejie Formation in the Binnan Oilfield was studied by combining with sedimentary indicators. The results show that the equivalent B content and the Sr/Ba ratio discriminate the research area for salt water and freshwater sedimentary environments. The V/(V + Ni) ratio is between 0.65 and 0.81, meaning that this area has a highly reductive sedimentary stratum. The trend of the Rb/Sr curve indicates that the paleoclimate of the Shahejie Formation changed from dry to humid and then back to dry.

Keywords: Binnan Oilfield, geochemistry, sedimentary environment, paleosalinity, palaeoenvironment

1. Introduction
An important purpose of geochemical work is to evaluate geological processes quantitatively and determine the sedimentary environment (Gavrilov et al. 2017; Podkovyrov et al. 2017). Geologically, it is very important to use geochemical characteristics to identify the sedimentary environment. The physicochemical properties of different elements are affected by external sedimentary environments such as climate, biological activity, pH and regional sedimentary tectonic setting during weathering, handling and sedimentation (Gao et al. 2017; Ivanic et al. 2017; Qin et al. 2018). Regular migration, aggregation and deposition in different sedimentary environments occur to form new sediment. Therefore, the ratio of elements in the sediment is related closely to the evolution of the sedimentary environment and has been used widely to recover and discriminate the sedimentary environment (Yan et al. 2007; Chen et al. 2016). The use of elemental geochemical features to restore the paleosedimentary environment of the basin is very important for determining the tectonic setting, clastic rock size and offshore distance of sandstone formation (Tribovillard et al. 2006; Wirth et al. 2013; Adegoke et al. 2014). On one hand, the distribution of elements in the rock formation depends on the physicochemical properties of the elements themselves, and on the other hand it is influenced by the paleoclimate and paleoenvironment (Xu et al. 2018; Ji et al. 2019; Lopez et al. 2019). Aqueous conditions and paleoclimatic conditions in
different sedimentary environments can cause aggregation or dispersion of elements (Chen et al. 2013). By selecting those elements or combinations of elements that are sensitive to water conditions and paleoclimate, the paleosedimentary environment can be restored either qualitatively or semi-quantitatively, including paleosalt, paleooxygen and paleoclimate. There has been much previous research in this area. For example, Frederickson & Reynolds (1959) and Couch (1971) used boron to restore ancient salinity and paleowater depth either qualitatively or quantitatively. Jones & Manning (1994) and Tribovillard et al. (2006) used the ratio of V to V+Ni to judge the oxidation of aqueous media reduction conditions (Grimes et al. 2007). The results show that the dilution effect of quartz and calcite leads to the loss of some elements in sandstone transportation, whereas mudstone is relatively stable and preserves the source information to the maximum extent. Therefore, mudstone is more advantageous than sandstone in identifying provenances by using trace elements (Liu & Zhou 2007; Grimes et al. 2015).

The sedimentary organic matter in source rocks is the main material for forming oil and gas. The potential of source rocks to product oil and gas is determined by the abundance and maturity of the source rocks. Organic geochemical characteristics of source rocks are the premise and core content for evaluating oil and gas resources. The sedimentary environment is also an important part of studying high-quality source rocks and unconventional resources. By analysing the distribution of major elements and trace elements in the mudstone of the Binnan Oilfield, the water conditions of paleodeposits and paleoclimatic change of paleodeposition in this area are revealed and the sediment source areas are discussed. Sedimentary environment is also an important part of studying high-quality source rocks and unconventional resources. This is important theoretically for understanding comprehensively (i) the evolution of the paleosedimentary environment in the Binnan Oilfield, (ii) what constitutes perfect sedimentary paleogeographic conditions and (iii) the main factors controlling the reservoir. The kerogen type not only affects the hydrocarbon generating ability of the rock, but also decides whether the source rock is of oil source rock or gas source rock. Different types of kerogen formed in different sedimentary environments. In this paper, we use geochemical characteristics and single well facies analysis to study the sedimentary types. Sedimentation is an important factor affecting reservoir characteristics, and geochemical characteristics are ideally suited to analysing the sedimentary evolution characteristics of an area, thereby accelerating the exploration and development of various unconventional resources.

1.1. Geological background

The regional structure of the Binnan Oilfield is located in the west of the Binnan–Lijin fault zone in the northwestern margin of Dongying Sag in the Jiayang Depression of the Bohai Bay Basin (figure 1a). The whole regional structure is a monoclinic, anticline or nasal structure, the dominant fault directions are northeast (NE) and nearly east–west (EW), and some northward- and southward-inclined faults are combined into a ‘ridge of a roof’ or ‘anti-ridge’ trap. There are structural reservoirs, lithologic reservoirs, structural-lithologic reservoirs and stratigraphic overlap reservoirs, among others (Zhang et al. 2009). The area is a typical complex hydrocarbon accumulation area that is located geographically near Binzhou City, south of the Binxian Rise, north of Lijin Sag, east of the Lin Fanjia structure and west of the Lijin Oilfield; it is around 25 km wide from east to west, around 8 km wide from north to south and has an area of 200 km² (figure 1b). Because the oilfield is located in the southern part of Binzhou City, it is known as the Binnan Oilfield. It is divided into the Bin first-, Bin second- and Bin third-regions from east to west (figure 1c). Affected by tectonic action, this area has developed a series of near-east positive normal faults. The Bin second-region (including the Shanjia Temple) is characterised mainly by two groups of faults and boundary faults distributed in parallel, and the Binnan Oilfield is divided into three steps. The main faults along the boundary of the Bin first-region are NE-trending, and the nearly EW-trending caprock faults form a pinnate intersection with them. Because the fault system of the Binnan Oilfield is the result of the multi-screen tectonic in the middle and late Mesozoic to the early Tertiary (figure 1d), the area has the characteristics of a north-south fault block and an EW fault beam.

1.2. Sample collection and test method

In this study, many mudstone samples were collected in the Binnan Oilfield, mainly grey mudstone, light-grey mudstone, brown mudstone and taupe mudstone, among others. The main elements and trace elements of the samples were measured in the stratigraphic laboratories of the Shengli Oilfield Academy of Geology and Geological Research Institute. Related instruments such as an inductively coupled plasma emission spectrometer, an element analyser (Vario El III) and an AA-610S atomic absorption spectrophotometer were used.

The main method used for the present work was the inductively coupled plasma mass spectrometry (ICP–MS) method. The mass of each mudstone sample was 10 g, and each experimental sample was cleaned with an ultrasonic instrument and deionised water. The cleaned experimental sample was then crushed to 200 mesh for sample preparation, and the element content data were obtained for the mudstone samples of different depths provided for the present work.

In the study of the paleoenvironment in the Quaternary, the study of paleoclimatic indicators is relatively
Commonly used paleoclimatic indicators are spore pollen, carbonate content and carbon, oxygen isotope, magnetic susceptibility of lake clay deposits, particle size change of lake sediments, illite crystallinity index, kaolinite, illite, the proportion of montmorillonite and some geochemical indicators, such as Rb/Sr, Mg/Ca, Sr/Mg, Sr/Ca, Ca/Si+Al, Nb/Ta, the ratio of clastic sedimentary elements to chemical deposition elements, (Fe+Al+Mn+Cr+Co+Ni)/(K+Na+Ca+Mg+Sr) and the geochemical solubility coefficient, among others (Patocka & Storch 2004; Song 2005). Because the carbonates in the sediments of the study area obviously have recrystallisation phenomena of varying degrees, it is difficult to determine paleoclimate changes by using carbonates and carbon and oxygen isotopes. The palaeontological data in the study area are relatively poor, and the spore-pollen analysis is suitable only for long-period and large-scale stratigraphic analysis. The sensitivity of the fine research on the Shahejie Formation (SF) in the Binnan Oilfield is too low and difficult to apply. In this study, the widely used Rb/Sr ratio and equivalent boron content (EBC) were used to analyse the paleoclimate and paleosalinity characteristics of the SF in the Binnan Oilfield.

2. Paleosalinity change characteristics

Paleosalinity plays an important role in restoring sedimentary paleogeography and paleoclimate. Higher salinity is conducive to the preservation of organic matter. Because of the paleosalinity recorded in the sediment, it is not only
interfered by the external environment but also affected by the evolution of the environment and the product itself. In addition, the biological activity and the artificial sampling analysis process may also lead to deviations in the analysis results. Therefore, in this study, the EBC method and the trace-element ratio method are mainly used (Couch 1971; Nagarajan et al. 2015).

In the analysis, the paleosalinity recorded in the sediment is not only interfered with by the external environment but also affected by the environment and the evolution of the product itself. In addition, the biological activity and the artificial sampling analysis process may also lead to deviations in the analysis results. Therefore, various methods are used for comprehensive study, their respective advantages are used to avoid large deviations and one should also consider the comprehensive analysis of the background factors of the paleoclimate.

2.1. The equivalent boron method

Boron (B) is present mainly in the form of boric acid (H₃BO₃) and its dissociation products (H₃O⁺ and H(OH)−). In sedimentary water, B is adsorbed on the edges of flakes of clay minerals, is then fixed at those edges by electrostatic action and finally enters the clay mineral crystal lattice because of the growth of new substances and the diffusion of B. As early as 1932, Goldschmidt and Peter proposed the use of B as an indicator of paleosalinity for argillaceous sediments (Jones & Manning 1994), and Landergren affirmed this view in 1945 (Deng et al. 2017). Frederickson & Reynolds (1959) proved that B and salinity dissolved in modern seawater are related, and Degens pointed out that marine shale contains higher B than freshwater shale (Ji et al. 2006). The mass fraction of B in clay minerals is proportional to that in the sedimentary water, and the B content in the water is also proportional to the salinity of the water. Therefore, the mass fraction of boron (B, μg g⁻¹) measured in clay minerals is also proportional to the salinity of the water. Walker’s ‘adjusted boron’ is used to refer to the boron content in the ideal illite with a K₂O content of 8.5%, while the illite B content is related to the K content. To compare under the same conditions, the B content equivalent to 5% of K₂O is known as the EBC. The correct boron content distribution is shown in figure 2. Essentially, the B and illite contents of the samples are known, based on which the B content corresponding to the 100% content of illite is determined. According to previous research experience, an EBC of 300–400 ppm indicates a salt water environment, 200–300 ppm indicates brackish water deposition and less than 200 ppm indicates freshwater deposition.

The specific steps for calculating the EBC are as follows:

\[
\text{Adjusted boron} = B \times \frac{8.5}{K_2O\%},
\]

\[
\text{Equivalent boron} = 11.8 \times \frac{\text{boron}}{1.7 \times 11.8 - K_2O\%},
\]

The two commonly used paleosalinity calculation formulas are as follows.

(1) The Adams formula is

\[
S = 0.0977X - 7.043,
\]

where \( S \) is the paleosalinity (‰) and \( X \) is Walker’s EBC (10⁻⁶).

(2) The Couch formula is

\[
S = 10^{(\log B^* - 0.11)/1.28},
\]

where \( B^* \) is the Couch adjusted B content and again \( S \) is the paleosalinity.

Using the Couch formula, the B content of the mudstone sample must be corrected to calculate the paleosalinity using equation (6). The Couch correction formula is

\[
B^* = \frac{B_{\text{sample}}}{4x_i + 2x_m + x_k},
\]

\[
\log S = (\log B^* - 0.11)/1.28,
\]

where \( x_i, x_m \) and \( x_k \) are the B contents of illite, montmorillonite and kaolinite, respectively, measured in the sample, and
### Table 1. Changes in boron content and paleosalinity of mudstone in the Binnan Oilfield.

| Well  | Sample serial number | Horizon | K (%) | B ($\times 10^{-6}$) | Adjusted boron (ppm) | Equivalent boron (ppm) | Paleosalinity (%) |
|-------|----------------------|---------|-------|----------------------|----------------------|------------------------|-------------------|
| D5    | 1.00                 | Es1     | 8.50  | 50.88                | 50.88                | 107.02                 | 3.41              |
| D5    | 2.00                 | Es1     | 5.00  | 74.20                | 126.14               | 128.76                 | 2.36              |
| J9    | 1.00                 | Es1     | 1.70  | 28.00                | 140.00               | 95.47                  | 2.28              |
| J9    | 10.00                | Es1     | 1.50  | 25.00                | 141.67               | 92.78                  | 2.02              |
| J9    | 12.00                | Es1     | 1.70  | 35.00                | 175.00               | 120.27                 | 4.71              |
| J9    | 13.00                | Es1     | 1.50  | 25.00                | 141.67               | 95.47                  | 2.28              |
| J9    | 2.00                 | Es1     | 1.90  | 46.00                | 217.22               | 150.78                 | 7.69              |
| J9    | 3.00                 | Es1     | 1.80  | 49.00                | 208.25               | 147.50                 | 7.37              |
| J9    | 4.00                 | Es1     | 2.00  | 49.00                | 259.47               | 181.92                 | 10.73             |
| J9    | 8.00                 | Es1     | 1.90  | 58.00                | 146.39               | 101.61                 | 2.88              |
| J9    | 9.00                 | Es1     | 1.80  | 60.00                | 146.39               | 101.61                 | 2.88              |
| C412  | 18.00                | Es2     | 0.36  | 45.24                | 1068.17              | 648.11                 | 56.28             |
| C412  | 20.00                | Es2     | 0.48  | 43.78                | 775.27               | 475.38                 | 39.40             |
| D5    | 3.00                 | Es3     | 5.00  | 44.52                | 75.68                | 77.26                  | 0.50              |
| D5    | 4.00                 | Es3     | 5.50  | 53.00                | 81.91                | 90.25                  | 1.77              |
| D6    | 1.00                 | Es3     | 1.13  | 30.92                | 232.58               | 151.30                 | 7.74              |
| Z25   | 1.00                 | Es3     | 2.48  | 44.52                | 152.59               | 113.64                 | 4.06              |
| Z25   | 2.00                 | Es3     | 1.65  | 36.04                | 185.66               | 126.97                 | 5.36              |
| Z25   | 3.00                 | Es3     | 0.95  | 50.88                | 455.24               | 291.24                 | 21.41             |
| Z306  | 1.00                 | Es3     | 1.50  | 38.16                | 216.24               | 145.72                 | 7.19              |
| D6    | 4.00                 | Es4     | 2.89  | 103.50               | 304.41               | 237.15                 | 16.13             |
| D6    | 5.00                 | Es4     | 1.13  | 53.00                | 398.67               | 259.35                 | 18.30             |

again $S$ is the paleosalinity. The coefficient represents the absorption intensity of B of various clay minerals. The larger the coefficient, the stronger the absorption.

The Adams and Couch formulas apply to the calculation of paleosalinity for both marine and non-marine strata. The Adams formula is applicable mainly to mudstone samples composed mainly of illite. The advantage of the Couch formula is that it considers the existence of various clay minerals and the difference in their adsorption capacity, which is more in line with the facts of nature and is more suitable for terrestrial formations. Because all the samples from the Binnan Oilfield are mudstone samples, the Adams formula can be used to analyse the paleosalinity of the Binnan Oilfield more accurately. According to the elemental analysis results of the samples, the paleosalt values calculated according to this method are given in Table 1.

The element B is used widely in environmental analysis. The B content in water is linear with salinity. The B content in seawater is between $20 \times 10^{-6}$ and $980 \times 10^{-6}$, and that in fresh water is between $0.15 \times 10^{-6}$ and $1 \times 10^{-6}$. In general, the B content in marine sediments exceeds $100 \times 10^{-6}$, while that in continental freshwater sediments is less than $100 \times 10^{-6}$. In only one sample from the Binnan Oilfield does the B content exceed $100 \times 10^{-6}$. The B content of the other samples varies between $25.00 \times 10^{-6}$ and $74.20 \times 10^{-6}$, with an average of $45.66 \times 10^{-6}$. This reflects the fact that the lake-basin waterbody experienced alternating salinisation and desalination during the sedimentary period of the SF. According to the traditional classification standard of paleosalinity, the data for the SF (Table 1) are classified as follows: the average Es4 paleosalinity is 14.83, which belongs to the range of medium salt water in brackish water according to the traditional classification standard; the average Es3 paleosalinity is 8.02, which belongs to the range of little salt water in brackish water; the average Es2 paleosalinity is 47.84, which belongs to the range of super-saline water in salt water and the average Es1 paleosalinity is 4.58, which belongs to the range of less saline water in salt water. It can be seen from this that during the Es2 period, the climate was arid, the flow of water into the lake decreased, evaporation increased the salinity of the lake-basin water and salt minerals increased. In the other strata, because of the humid climate, the flow of water carrying fine sand into the lake increased, the salinity of the lake-basin water decreased and the content of salt minerals decreased. It can be seen that the change of paleoclimate plays an important role in controlling the change of paleosalinity. When the lake waterbody has a certain salinity, the salinised waterbody not only facilitates the preservation and...
enrichment of organic matter in the sediment but also causes the density stratification of the waterbody and promotes the upward migration of the redox interface, thus being the oil-bearing rock series. Development provides alkaline reduction conditions and larger accumulation space, which is conducive to the formation and development of oil-bearing rock series. The semi-salty lake environment of the Binnan Oilfield is conducive to the formation of a huge source of rock formation. The salinity stratification of the waterbody creates favourable conditions for the preservation of organic matter.

### 2.2. Trace-element comparison method

Many scholars consider the elemental Sr/Ba ratio to be a sensitive indicator of paleosalinity. In nature, Sr migrates in aqueous solution more than does Ba, and the solubility product of its sulfate compounds is larger than that of Ba. It is precisely because of the special geochemical properties of Sr and Ba that they occupy an important position in geochemical research. The occurrence of Sr and Ba is usually bicarbonate. In the process of increasing salinity in a waterbody, the initial precipitation of Ba (in the form of BaSO₄) results in a higher content of Sr than Ba. According to the geochemical properties of Sr and Ba, many scholars believe that their ratio increases gradually from freshwater to marine sediments.

Through much research, the Sr/Ba value in shale is an effective salinity index: less than 0.6 is generally considered as marine sediment, brackish water or a freshwater environment in continental facies, and brackish water environment is excessive between 0.6 and 1 (Yuan et al. 2006). In the present study, 22 wells were selected for comparison, and the specific data are given in Table 2.

In this study, the Sr/Ba values of Es1 to Es4 in the Binnan Oilfield were selected, and the value of Sr/Ba in Es2 was lower than that of Es3. For Es1, the Sr/Ba ratio averaged 1.38; for Es2, the Sr/Ba ratio averaged 0.46; for Es3, the Sr/Ba ratio averaged 0.97 and for Es4, the Sr/Ba ratio averaged 1.34. In general, the overall trend of the Sr/Ba ratio in the SF area of the Binnan Oilfield is high to low and then low to high, which reflects not only the trend of a decreasing amount of terrestrial materials but also the change of salinity of the water medium the decrease becomes elevated (figure 3). According to the study of the ratio of Sr and Ba mass fractions in the continental basins in China, Sr/Ba is often used as a marker to distinguish between marine and terrestrial deposits. The general cases are Sr/Ba > 0.5, which is marine facies, and Sr/Ba < 1, which is continental facies. On the Sr and Ba discriminant maps, the samples are distributed in the continental, and transitional phases, indicating that the carbonate sedimentary waters in the Es1 to Es4 sedimentary period experienced salinisation and desalination and then salinisation the alternation process or the process of event transgression (figure 4).

Ba can also be sensitive enough to reflect the sedimentary environment. The Ba content in the marine environment generally does not exceed 200 × 10⁻⁶ (Wen et al. 2008; Zhao et al. 2016). However, the Ba content in the SF of the Binnan Oilfield...
Figure 3. Characteristics of trace elements in different layers of the Binnan Oilfield.

Figure 4. Diagram of relationship between Sr and Ba in the Shahejie Formation (SF) of the Binnan Oilfield.

Oilfield exceeded $200 \times 10^{-6}$, with an average of $756 \times 10^{-6}$, of which the Es2 Ba content averaged $454 \times 10^{-6}$ and the average Ba content in the other layers exceeded $800 \times 10^{-6}$. It can be seen that Es1, Es3 and Es4 were affected by seawater or evaporation during the deposition period.

3. Paleoclimatic change characteristics

In humid climates, the content of Fe, Mn, V, Cr, Co, Ni and other elements in sedimentary rocks is relatively high. Under dry climatic conditions, atmospheric precipitation is reduced, the alkalinity of the aqueous medium is enhanced by evaporation of water and Mg, Ca, K, Sr, Ba etc. present in the aqueous medium are precipitated in large amounts to form various salts and are deposited on the bottom of the water, resulting in their relative increase in content. Therefore, these two types of element can be used to determine the paleoclimate; that is, the smaller the value of the element, the more humid the climate, and as the value increases, the climate gradually transitions to dryness.

The paleoclimatic conditions of the Binnan Oilfield directly affect various geological processes. Paleoclimate is an important condition for sedimentary facies and paleogeographic analysis. Therefore, in the paleoclimatic indicators of the Binnan Oilfield, the content of Mn in sedimentary rocks and the content of Sr in aqueous media were selected for analysis.
3.1. Sr element analysis

In the continental facies basin, chemical weathering is strong under humid conditions and Rb is precipitated and adsorbed by clay. However, these clays do not remain in place but instead are mainly denuded and transported into lake sediments. At the same time, the dissolved Sr\(^{2+}\) entering the lake basin is generally deposited with the carbonates in the dry period, thus causing an increase in the Rb/Sr ratio in a humid environment (Scheffler et al. 2006; Chen et al. 2018). Therefore, in the continental facies basin, the meaning of the Rb/Sr ratio is actually opposite to that under the marine facies conditions; that is, a high Rb/Sr ratio represents a humid climate and a low Rb/Sr ratio represents arid climatic conditions. Most of the mud shale has quartz and feldspar fine silty sand, and coarse debris enters the lake basin mainly through the lake water flow. In the small-scale sedimentary cycle, when the fine silt content in the shale is increased significantly, it indicates that the water flow into the lake is enhanced, the circulation of the lake is better, and the sedimentary background is a humid climate. From the Rb/Sr ratio relationship diagram (figure 5), it can be seen that the Rb/Sr curve rises gradually, indicating that the paleoclimate was a humid climate at that time. The Rb/Sr ratio reaches its maximum value when the deposition proceeds to Es2, after which it decreases gradually. This reflects the fact that the paleoclimate was relatively dry. The water flow into the lake is reduced, aquatic organisms and nutrients are scarce and the lake water level is lowered. The analysis of paleoclimate further indicates that the rise and fall of the paleosalinity in the region is related to the paleoclimate, which affects the paleosalinity by affecting the evaporation of the lake.

3.2. Elemental analysis of Fe and Mn

The ratio of the content of paired elements in sedimentary rocks is often constrained by the formation conditions. Therefore, the ratio of the content of the paired elements is commonly used as a characteristic of the climate change during the sedimentary diagenesis. The chemical properties of the elements iron and manganese are quite different. During the deposition process, the two elements are affected by the Eh and pH values of the aqueous medium. Iron oxide has the highest solubility at pH < 3, and after entering the lake basin, the pH value is significantly increased, its solubility is greatly reduced and precipitation occurs, so Fe\(^{3+}\) is often enriched in the estuary or coastal zone (Meng et al. 2017; Zhou et al. 2019). The oxides and sulfides of manganese are more stable than iron, and the divalent manganese Mn\(^{2+}\) is more stable in the reducing environment; that is to say, in long-distance migration in the basin, manganese is deposited in the centre of the deep lake basin (Chen et al. 2006; Meng et al. 2017). Therefore, the change of Fe/Mn ratio can be used as a sign of the depth change of the waterbody from the offshore to the deep lake.

Mn is often stabilised by Mn\(^{2+}\) in lake water. Only when the lake water is strongly evaporated is the concentration of Mn\(^{2+}\) supersaturated, and a large amount of precipitation occurs, which shows high Mn content in the rock and indicates a hot and dry climate. A steady change in Mn content can indicate a relatively continuous wet or semi-arid climate. It can be concluded from Table 5 that the average value of Mn content of Es1 is 553.67%; the average value of Mn content of Es2 is 635%; the average value of Mn content of Es3 is 328.04% and the average value of Mn content of Es4 is 371.66%. From the Mn curve (figure 3), it can be seen that the overall change is stable and Es2 has a slight peak, from which it can be judged that the climate at that time was relatively dry. Comparing the Fe\(^{3+}\) and Mn\(^{2+}\) element curves (figure 6), the Fe\(^{3+}\) content in this region is less and the Mn\(^{2+}\) content is relatively high and stable. It can be judged that the region was a deep-water lake area.

In summary, according to the analysis of Mn in the sedimentary rock of the sampled well and Sr in the water body, the sedimentary rock is mainly carried in the lake basin during the relatively humid climate by lake water and the salinity of the lake-basin body is reduced significantly. Also, salt minerals are reduced; while salt minerals are deposited when the climate shifts to drought, the flow of water into the lake decreases and the water level of the lake decreases. The sedimentary environment indirectly affects kerogen by affecting the composition of sedimentary organic matter. The study area’s climate in the Es3 period is humid, and the land vegetation is very prosperous. Mixed organic matter formed because of the terrestrial material in the lake input, kerogen is relatively abundant. In contrast, the Es2 period, the climate is dry, the terrestrial matter in the lake is relatively few, so kerogen is relatively barren.

4. Ancient redox variation characteristics

The trace elements sensitive to redox are more soluble in the oxidising environment than in the reducing environment,
and they are enriched in authigenic minerals in the anoxic deposition environment. This characteristic makes U, V, Mo, Cr and other elements become indicators to judge the redox property of water body. In addition, some elements sensitive to redox conditions (such as Ni, Cu, Zn and Cd) are adsorbed by organic matter and enter the sediment, and they are symbiotic with pyrite after the organic matter rots, which can be used to indicate a reducing environment (Sial et al. 2015; Yang et al. 2018).

V is present in vanadate under oxidising conditions and is often adsorbed by oxides or kaolinites of Mn and Fe. Under depleted oxygen conditions, especially in the case of a large amount of humus, V is easily reduced to oxides; in an anoxic environment, V is further reduced and precipitates to form an enrichment. Ni is present mainly in the form of soluble nickelate in oxygen-enriched seawater, and it is reduced to various hydrated ions under anoxic conditions and is taken up by sediments of humic acid or Mn and Fe hydroxide to be enriched. Although both are soluble in water in an oxidising environment and are easily enriched in sediments in a reducing environment, the reduction of Ni occurs in the upper part of the boundary and the reduction of V occurs in the lower part of the boundary (Li et al. 2008), so V/(V + Ni) can be used as a parameter for determining the redox parameters of the paleoocean, which is very effective for mudstone.

The ratio of redox-sensitive elements in fine sediments has been used widely in the restoration of paleosedimentary environments. It has the characteristics of anti-interference and stability to judge paleoredox conditions by the element ratio method. The comparison method and judgement conditions are as follows: V/(V + Ni) < 0.5 indicates an oxidising environment and V/(V + Ni) > 0.5 indicates a reducing environment (Cai et al. 2009). According to the data of figure 7, the average value of V/(V + Ni) can be obtained as 0.64, thus it can be judged that the Binnan Oilfield is a reducing environment. Whether carbonate or clastic rock, its V/(V + Ni) ratio varies from 0.39 to 0.81 and 87% of the samples have V/(V + Ni) > 0.5, which shows the characteristics of a strong reduction environment.

5. Depositional environment characteristic

The colour of mudstone is a good reflection of the sedimentary environment (Wang et al. 2012). The reduction colours such as grey and dark grey generally reflect a semi-deep or deep lake sedimentary environment under humid climate conditions, while the oxidation colours such as magenta, red, brown-red and variegated colour generally reflect the sedimentary environment such as onshore and lakeside under climatic drought conditions. The transitional colours such as grey-green and green generally reflect the sedimentary environment such as lakeside or shallow lake under a relatively dry climate (Caracciolo et al. 2011; Wu et al. 2016). The colour of the sediments in the SF of the Binnan Oilfield shows that the colour of mudstone is mainly grey, brown, greyish white, taupe and other reducing colours, and there is very little oxidised colour such as purple, red and brown. It is shown that the sedimentary period of the SF in the Binnan Oilfield was humid, and the water in the lake basin was relatively open. The salinity of the lake basin was up to 26 g l⁻¹, which is the typical salt-lake sedimentary environment in a humid climate.

Based on the analysis of paleoclimate and paleosalinity index, the mudstone cores sampled from the Binnan Oilfield
are analysed. The lithology of this area is mainly grey mudstone, shale, lime mudstone, dolomitic mudstone, brown mudstone and grey-brown mudstone. Vertically, the increase of the Rb/Sr ratio reflects the relative humidity of the climate, the flow of water into the lake increases, the relative lake level rises, the salinity of the water body decreases, the content of carbonate and sulfate decreases significantly and the content of fine silt increases, mainly in the sedimentary grey mudstone and shale deposits. The decrease of the Rb/Sr ratio reflects the relative drought of the climate, and the flow of water into the lake decreases obviously. Because of strong evaporation, the occurrence is intense, the salinity of the water body increases, the content of carbonate and sulfate increases obviously and the content of fine silt decreases. The main deposits are grey limestone mudstone, dolomitic mudstone, brown mudstone and grey-brown mudstone. The SF in this area can be used to identify the cycle of dry–wet climate change by observation.

According to the aforementioned mudstone colour distribution characteristics and paleoclimate and paleosalinity change characteristics, the paleoclimate of the SF in the Bin nan Oilfield is mainly arid, showing alternate wet and dry changes. During the relatively humid period, the inflow of water carrying a large amount of debris material increases, the relative lake level rises and the salinity of the lake water decreases significantly. However, in the relatively arid period, the flow of water in the lake is obviously reduced, evaporation is strong, the lake level drops rapidly and the salinity of the lake waterbody increases. Therefore, during the sedimentary period of the SF in the Bin nan Oilfield, the range of lake

| Well name | Depth (m) | Horizon | Ni (%) | V (%) | V/(V+Ni) (%) |
|-----------|----------|---------|--------|-------|-------------|
| CG330     | 2000     | Es1     | 0      | 50    | 0           |
| CG330     | 2000     | Es1     | 0      | 50    | 0           |
| CQ16      | 2300     | Es2     | 0      | 100   | 0           |
| CQ16      | 2300     | Es2     | 0      | 100   | 0           |
| C15       | 2600     | Es3     | 0      | 100   | 0           |
| D677      | 2600     | Es3     | 0      | 100   | 0           |
| DX363     | 2600     | Es3     | 0      | 100   | 0           |
| B423      | 2600     | Es3     | 0      | 100   | 0           |
| DX363     | 2600     | Es3     | 0      | 100   | 0           |
| D656      | 2600     | Es3     | 0      | 100   | 0           |
| F111      | 2600     | Es3     | 0      | 100   | 0           |
| CG207     | 2600     | Es3     | 0      | 100   | 0           |
| C63       | 2600     | Es3     | 0      | 100   | 0           |
| CQ16      | 2600     | Es3     | 0      | 100   | 0           |
| C15       | 2600     | Es3     | 0      | 100   | 0           |
| F120      | 2600     | Es3     | 0      | 100   | 0           |
| F124-2    | 2600     | Es3     | 0      | 100   | 0           |
| F137      | 3100     | Es4     | 0      | 100   | 0           |
| C11       | 3100     | Es4     | 0      | 100   | 0           |
| F138      | 3100     | Es4     | 0      | 100   | 0           |
| F411      | 3100     | Es4     | 0      | 100   | 0           |
| FS1       | 3100     | Es4     | 0      | 100   | 0           |

Figure 7. V/(V + Ni) element ratio characteristic curve.
waterbody changed very frequently. During the wet period, the range of lake waterbody increased and the range of lake waterbody decreased rapidly during the dry period. Controlled by the alternating dry and wet climatic conditions, the lakes of the SF have obvious characteristics of high-frequency oscillation during the sedimentary period. In the wet climatic period, sedimentary sand bodies are dominant, while in the dry climatic period, sedimentary carbonate rocks are dominant.

6. Sand-body deposition type and distribution characteristics

During the sedimentary period of the SF in the Binnan Oilfield, the climate alternates frequently between wet and dry, and the lake basin shows the characteristics of high-frequency oscillation. The fluctuation of lake level is controlled mainly by the intermittent inflow controlled by climate, which leads to the complex and diverse types of sedimentation. During the sedimentary period, the gentle slope zone developed both aquatic sedimentation and underwater sedimentation, gravity flow sedimentation and traction flow sedimentation. Therefore, during the sedimentary period of the SF, the genesis types of sand body in gentle slope zone vary. Alluvial fan deposits, shallow water delta deposits and shore bar deposits are mainly developed, and offshore underwater fan deposits of a certain scale are developed in the steep slope zone near the fault (figure 8).

The water-fed fan delta deposits are developed mainly at the edge of the steep slope zone in the Es4 sedimentary period, and the lithology is generally coarse, mainly grey gravel, glutenite, pebbly sandstone, coarse sandstone and sandstone. In the alluvial fan deposits, both debris flows and flood channel sediments reflecting the gravity flow properties are developed, and braided channel deposits with traction flow properties are developed.

During the sedimentary period of Es3, the water body reaches its deepest point and the lake level is characterised by high-frequency oscillation. The subaqueous fan system is developed in the steep slope zone, and the centre of the lake basin has developed a slump turbidite system.

River-delta deposits are developed mainly in the Es1 sedimentary period. They are obviously affected by rivers. They develop box-shaped and finger-shaped channel sandstones. At the same time, funnel-shaped estuarine dam sandstones and spike-shaped sands are developed. The mudstone colour is greyish green and grey.

7. Conclusion

The paleoclimate of the SF in the Binnan Oilfield was relatively arid in the sedimentary period. The analysis of paleoclimate and paleosalinity indices shows that the
paleoclimate underwent frequent alternation of dry and wet. The lake level rose and the salinity decreased in the wet period, and the lake level decreased and the salinity rose in the dry period. The lake showed obvious high-frequency oscillation characteristics. The Sr/Ba ratio generally decreased from high to low, then from low to high, which reflects the increasing and decreasing of land-derived materials and is closely related to the reduction of salinity in the water medium. During the Es2 sedimentary period, carbonate sedimentary water in this area experienced alternating salinization and desalination or episodic transgression, and the V/(V + Ni) ratio ranged from 0.39 to 0.81. Around 87% of the samples exceeded 0.5, showing a strong reduction environment.

Based on the study of paleoclimate and sediment distribution, the sedimentary model of the SF in the Binnan Oilfield was studied. In the humid climate period, the relative lake level rose, the lake water salinity decreased, alluvial fan, shallow delta and beach bar were the main deposits in the gentle slope zone of the lake basin, offshore underwater fan was deposited locally in the steep slope zone and mudstone and lime mudstone were the main deposits in be sunken. The relative lake level decreased in the dry climate period, the salinity of the lake water increased and sedimentation mainly occurs in be sunken. Limestone and argillaceous gypsum developed from the lake margin to the lake centre.

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