Petroleum Science 18 (2021) 1011–1020

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

Factors controlling organic-rich shale development in the Liushagang Formation, Weixinan Sag, Beibu Gulf Basin: Implications of structural activity and the depositional environment

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A R T I C L E I N F O

Article history:
Received 17 August 2020
Accepted 8 December 2020
Available online 10 July 2021

Edited by Jie Hao

Keywords:
Organic-rich shale
Geochemical characteristics
Palynofacies
Structural activity
Depositional environment
Accumulation model
Beibu gulf basin

A B S T R A C T

The mechanisms of lacustrine organic-rich shale formation have attracted attention due to its association with global shale oil and shale gas exploration. Samples of general-quality and excellent-quality source rocks, and oil shale from the Beibu Gulf Basin were analyzed to investigate their organic geochemistry, palynofacies, and trace elements. Hydrocarbon potential was higher in the oil shale (29.79 mg/g) than in the general-quality source rock (3.82 mg/g), and its kerogen type was I-II_2. Hydrogen-rich liptinite (cutinite and sporinite) components derived from terrigenous higher plants provided most of the hydrocarbon potential of excellent-quality source rock and oil shale. Under the influence of depression-controlling fault activity, a deeper subsidence center promotes the deposition of excellent-quality source rock and oil shale in brackish-hypoxic bottom water. A shallower subsidence center, due to subsag-controlling fault activity, promotes the formation of excellent-quality source rock under fresh-brackish and weak oxidation-weak reducing conditions. The local uplift and shallow-slope led to the formation of general-quality source rock, under freshwater weak-oxidation conditions. A model was established for organic matter (OM) accumulation in organic-rich shales, accounting for fault activity, terrigenous hydrogen-rich OM, and the preservation conditions, to predict the development of excellent-quality source rock from areas with low levels of exploration.

1. Introduction

Organic-rich shales are the most important hydrocarbon source rocks in continental sedimentary basins, providing shale oil and shale gas globally (Potter et al., 2005; Lazar et al., 2015; Zou et al. 2016, 2019, 2019; Zhao et al. 2016, 2019). Organic matter enrichment is a complex physical and chemical process, which is influenced by several factors including the input, burial, and preservation of organic matter in sediments (Zonneveld et al., 2010; Zou et al., 2019). Lacustrine organic-rich shale formation is believed to be determined mostly by terrigenous nutrition input, algal blooms, sedimentary rates, saline stratification, and the formation of anoxic conditions (Lazar et al., 2015; Louchouarn et al., 1999; Jeppesen et al., 2007; Zhao et al., 2016; Liang et al., 2018). The models and mechanism for organic matter accumulation are focused mostly on bottom-water redox conditions and ocean surface primary productivity (Sageman et al., 2003; Rimmer, 2004; Tyson, 2005; Mort et al., 2007). Lacustrine organic-rich shale accumulation is sensitive to seasonal and paleogeomorphological variability, terrigenous organic matter input, and sediment filling rates, factors that enhance their heterogeneity (Louchouarn et al., 1999; Carroll and Bohacs, 1999; Bohacs et al., 2000; Liang et al., 2018; Wang et al., 2018). In addition to organic matter originating from the abundant phytoplankton in surface water, hydrogen-rich organic matter is also derived from higher plants forming, for instance, cutinite, resinite, sporinite, which is transported into sediments by flowing rivers (Boucsein and Stein, 2000; Li et al.,

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https://doi.org/10.1016/j.petsci.2020.08.001

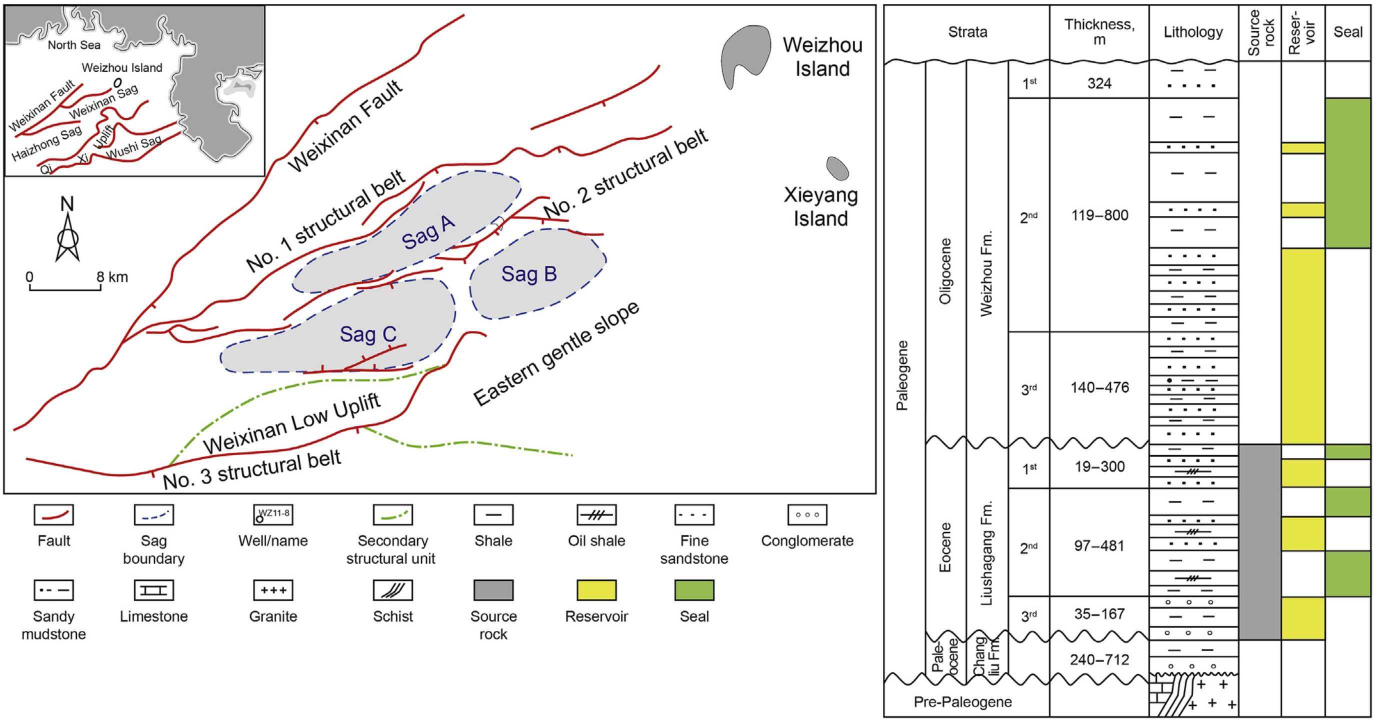

Fig. 1. Structure map and profile of the Weixinan depression, Beibu Gulf Basin.

2006; Huang et al., 2013; Hakimi and Ahmed, 2016). The quantities of nutritional elements associated with algal blooms and with the reducing conditions of deep waters are significantly influenced by seasonal climate changes (Jeppesen et al., 2007; Hallegraeff, 2010; Liang et al., 2018). The weak water circulation activity in lacustrine basins inhibits the overturn of deep waters, causing water-column stratification, which favors the formation of anoxic bottom-water conditions (Picard, 1971). Water-column stratification can be induced by a thermocline in freshwater lake basins, under a wet climate regime, and by a halocline in saline and brackish lake basins, under a continental dry regime. Salinity-driven stratification induced by seawater intrusion and strong evaporation is more stable, and favors the preservation of organic matter (Surdam and Staley, 1979; Song et al., 2012, 2016; Xu et al., 2019). Moreover, the distribution of organic-rich shales within lacustrine basins is affected by lake water-level variability, tectonics, sediment provenance, and basin morphology (Lemons and Chan, 1999; Carroll and Bohacs, 1999; Bohacs et al., 2000). Accordingly, organic-rich shales differ substantially between sedimentary basins in terms of their depositional mechanisms, distribution patterns, organic matter composition, and kerogen types.

Following the formation of an important hydrocarbon-rich sag developed in Beibu Gulf Basin, several studies have examined the formation of source rock in the Weixinan Sag. Most previous studies have focused on the organic geochemical characterization of source rocks of the Liushagang Formation (Song et al., 2012; Huang et al., 2017; Zhou et al., 2019). However, few studies have focused on the accumulation of organic matter or the development of excellent-quality source rocks in the Liushagang Formation (Huang et al. 2012, 2013, 2013; Nytoft et al., 2020). Although high-quality source rock is believed to form under the anoxic-reducing conditions of bottom water and under higher primary productivity, it is hard to predict the development and distribution of organic-rich shale in other poorly explored sags, such as the Haizhong and western Wushi Sags, for which there are few boreholes and core samples (Huang et al. 2012, 2013, 2017). Further, regional structural activity and the sedimentary system is known to affect the hydrocarbon potential and distribution of lacustrine source rocks in the Beibu Gulf Basin (Xie et al., 2011; Xu et al., 2013; Liu et al., 2014). Therefore, it is necessary to clarify the influence of structural activity, sedimentary sands, and the depositional environment on the distribution and development of source rock in the Weixinan Sag. This will make it possible to accurately predict petroleum resources in the Haizhong and western Wushi Sags.

This study examined differences in hydrocarbon generation potential, organic matter provenance, and source rock components in the Weixinan Sag. It investigated the depositional environment of the source rock, the rate of structural activity, and sand distribution, to determine the hydrocarbon potentials of the source rocks, and to understand how high-quality source rock was formed. A model was established to describe the formation of high-quality source rock, to assist in predicting petroleum resources in poorly explored sags with similar geological settings.

2. Geological setting

The Beibu Gulf Basin is one of the most petroliferous basins in the northern continental shelf area of the South China Sea, covering an area of 3.9 × 10^4 km^2; it was formed by Paleogene syn-rift activity (65-23 Ma) and subsequent Neogene post-rift tectonic activity, from 23 Ma to the present (Fig. 1) (Zhang et al., 2014; Liu et al., 2014). The Weixinan Sag, controlled by the Weixinan fault, is in the northeastern part of the Beibu Gulf Basin, and is separated from the Haizhong and Wushi sags by the Weixinan low uplift and Qixi uplift (Fig. 1). The sag is divided into three subsags (A, B, and C), which formed during three extensional episodes: the onset of Paleocene, Eocene, and Middle-Late Oligocene, respectively. The subsags were the main regions of source-rock deposition and were formed by the growth of the No. 1 fault (F1) and No. 2 fault (F2), both normal faults. The subsag-controlling faults extended over

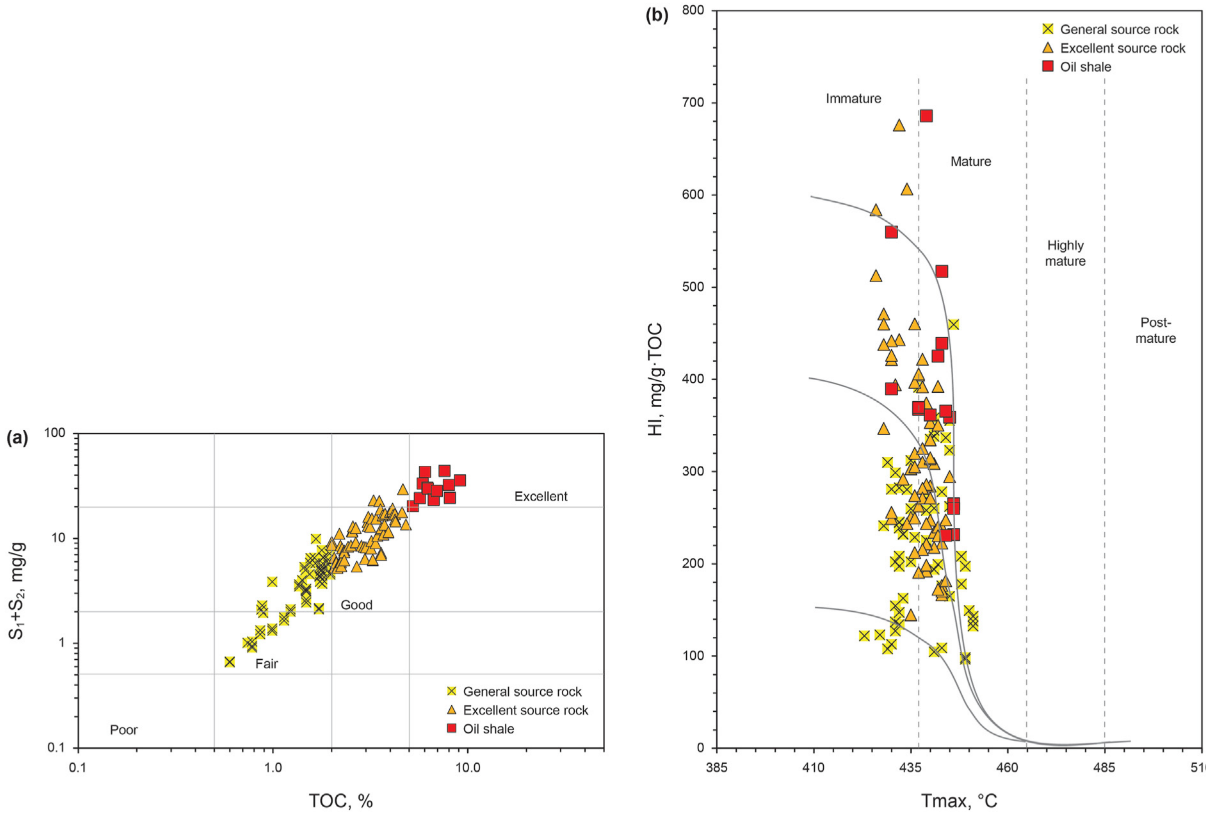

Fig. 2. The organic matter abundance, type, and maturity of source rocks with different hydrocarbon potentials.

more than 40 km and were active from the beginning of the basin formation to the Upper Cretaceous-Late Oligocene. The thick dark shale and structural belt of the Weixinan Sag were controlled by the F1 and F2 faults (Zhang et al., 2014; Zhou et al., 2019). The strata were deposited in a shore-shallow lake delta, fan delta, and shallow, semi-deep, and deep lacustrine environments during the Paleogene (Yang et al., 2012; Li et al., 2013). The first and third members of the Liushagang Formation (LSG-1 and LSG-3) were dominated by the shore-shallow delta and shallow lacustrine environments. However, the LSG-2 mainly includes gray and dark gray shales and oil shale, which were deposited in semi-deep and deep lacustrine environments (Fig. 1). Oil shale layers mainly formed at the bottom and top of LSG-2 and occur locally at the bottom of the LSG-1 and top of LSG-3. The hydrocarbon-rich dark shale has been identified as the major source rock, providing abundant petroleum and gas (Li et al., 2008; Huang et al. 2013, 2017, 2017; Zhou et al., 2019; Nytoft et al., 2020).

3. Data and methods

3.1. Data

A total of 143 samples were collected from the LSG-1 to LSG-3 members of wells WZ10-8-1, WZ11-2-1, WZ11-4N-3, WZ5-7-1, WAN4, and WZ10-7-1 in the Weixinan Sag. The samples consisted of normal dark shale and oil shale. Fifteen samples were used to analyze the trace element contents, 33 were used for palynofacies analysis, and 27 were used for biomarker analysis. Pyrolysis was carried out on all samples and the total organic carbon (TOC) contents were determined.

3.2. Methods

3.2.1. TOC and pyrolysis

The samples were crushed into a 200-mesh powder for TOC analysis. In total, 200 mg of the powdered samples were added to HCl at 60 °C, and washed with distilled water in a crucible. After the carbonate contents were removed, the washed subsamples were dried for 24 h at 50 °C. The TOC contents were measured using a LECO CS-230 analyzer. Pyrolysis was carried out using an OGE-II instrument, using 60–100 g of each crushed sample. The crushed samples were placed in a helium atmosphere for heating. The heating rate was set to 50 °C/min and the temperature was increased from 300 to 600 °C. TOC content and pyrolysis measurements were performed at the China University of Petroleum (East China).

3.2.2. Palynofacies analysis

The shale samples were crushed and ground to 20 μm to 2 mm and embedded in epoxy. The samples were polished and microscopically analyzed under reflected light and fluorescence conditions. The samples for the palynological analysis were treated with HCl, HF, and $ZnBr_2$ (Tyson, 1993). Quantitative palynological analysis of the overall kerogen composition was carried out on sieved unoxidized material. One slide per sample was analyzed under a microscope and the kerogen was counted using a series of three or more traverses across the slide until 500 macerals were counted for each sample. The data generated by the kerogen counting procedure are expressed as relative percentage of the particle abundances (% PAs).

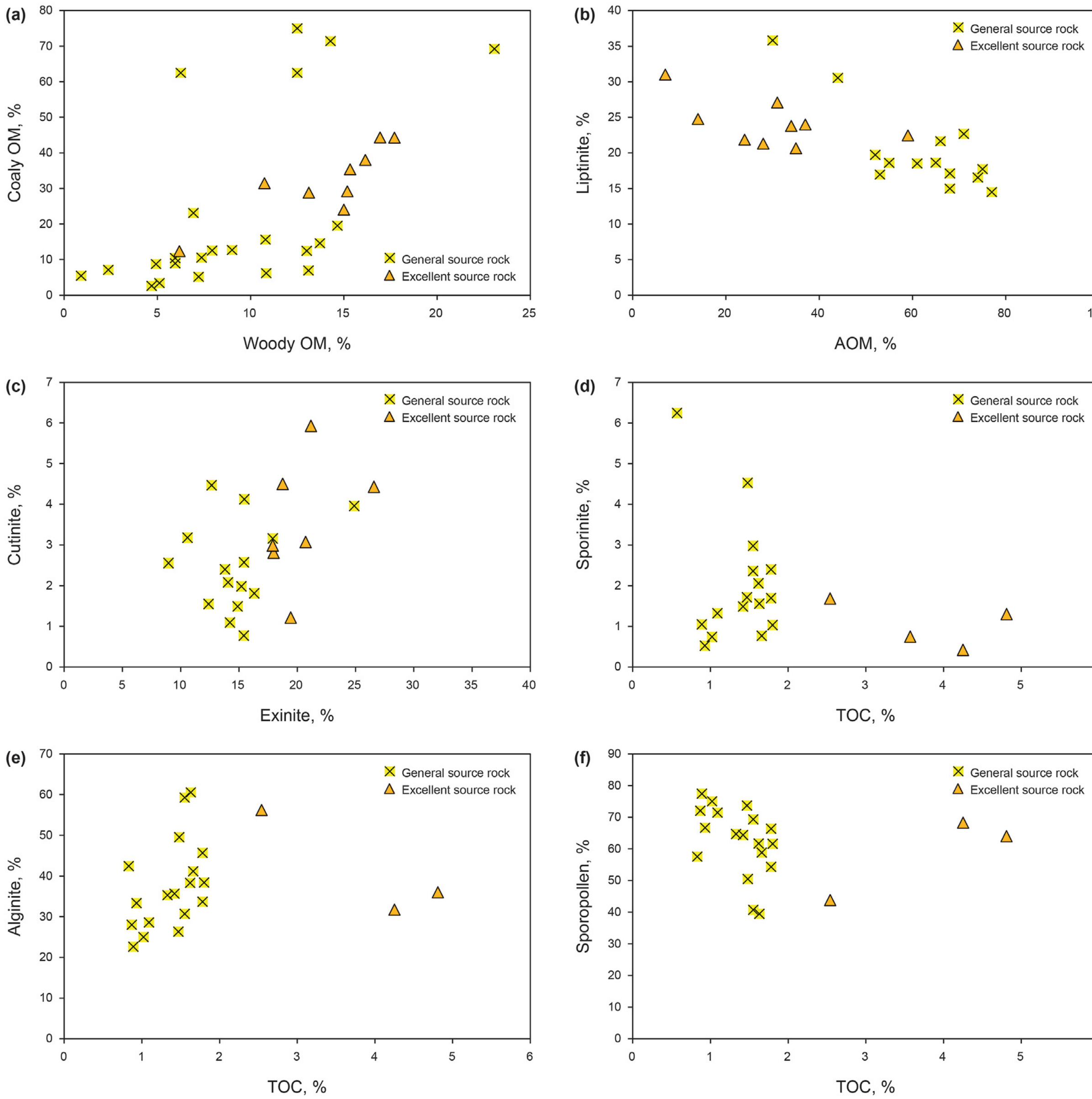

Fig. 3. Differences between palynofacies accumulated in general-quality and excellent-quality source rocks: (a and c) Positive associations between coaly and woody organic matter in all types of source rocks. (b) Negative associations between liptinite and amorphous organic matter content in all types of source rocks. (d) With an increase in the TOC content, the sporinite content decreases from general-quality to excellent-quality source rocks. (e and f) General-quality and excellent-quality source rocks displaying similar alginite and sporopollen contents.

3.2.3. Trace element measurements using inductively coupled plasma mass spectrometry (ICP-MS)

The shale samples were crushed into 200-mesh powders in a clean environment for the trace element analysis. ICP-MS was used to analyze the trace elements, using a NexION 300D plasma mass spectrometer. The ambient laboratory temperature was 20 °C and the relative humidity was maintained at 27%. The relative error of trace element concentrations ranging from <6 ppm was <10%; at trace element concentrations of >6 ppm, the relative error was <5%. The test methods and procedures follow the Chinese National Standard GB/T 14506.30–2010. The trace element concentrations of the shale were measured at the Analytical Laboratory of the Beijing Research Institute of Uranium Geology.

3.2.4. Gas chromatography-mass spectrometry (GC-MS) analysis

For the GC-MS analysis, Soxhlet extraction was used to treat the powdered samples for 72 h with dichloromethane. Asphaltenes dissolved in a mixture of hexane-dichloromethane (80:1) were removed by centrifugation. The hydrocarbons, and nitrogen, sulfur, and oxygen compounds, were separated using column chromatography (in columns filled with silica gel and Al_2O_3). The saturates were eluted with hexane and the aromatics were extracted with dichloromethane-hexane solution (2:1). The saturated and aromatic hydrocarbons were measured using a gas chromatograph coupled to an Agilent 7890 GC-MS device. The fused silica column in the GC-MS analyzer was a 30 m DB-5MS (inner diameter 0.25 mm; 0.25 μm film thickness). The oven was heated from 70 to 300 °C at a rate of 3 °C/min; subsequently, the temperature was maintained for 30 min. The scan range of the mass-to-charge ratio

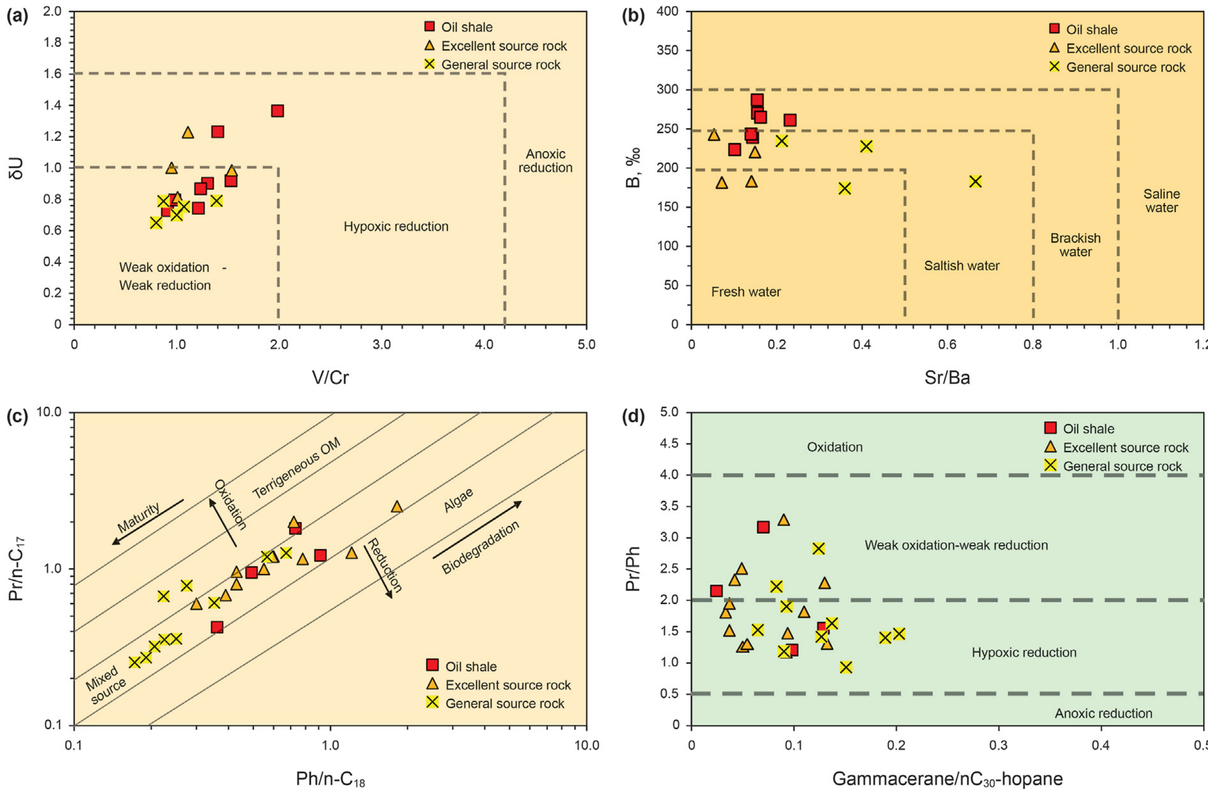

Fig. 4. Paleowater column and redox conditions of different sedimentary environments forming source rocks. (a) The parameters δU [$\delta U = 2U/(U + Th/3)$ (Elderfield and Greaves, 1982)] and V/Gr indicate the depositional environments of different source rocks, ranging from weak oxidation-weak reduction to hypoxic reduction. (b) The high boron content (Walker, 1963) and Sr/Ba ratio indicate that all source rocks were deposited in fresh to brackish bottom waters. (c) The Pr/nC_{17} and Ph/nC_{18} ratios reflect an increase in the reducing conditions from general-quality source rock to oil shale. (d) The higher Pr/Ph and Ga/C_{30} hopane ratios indicate the weak-strong reduction of the bottom water.

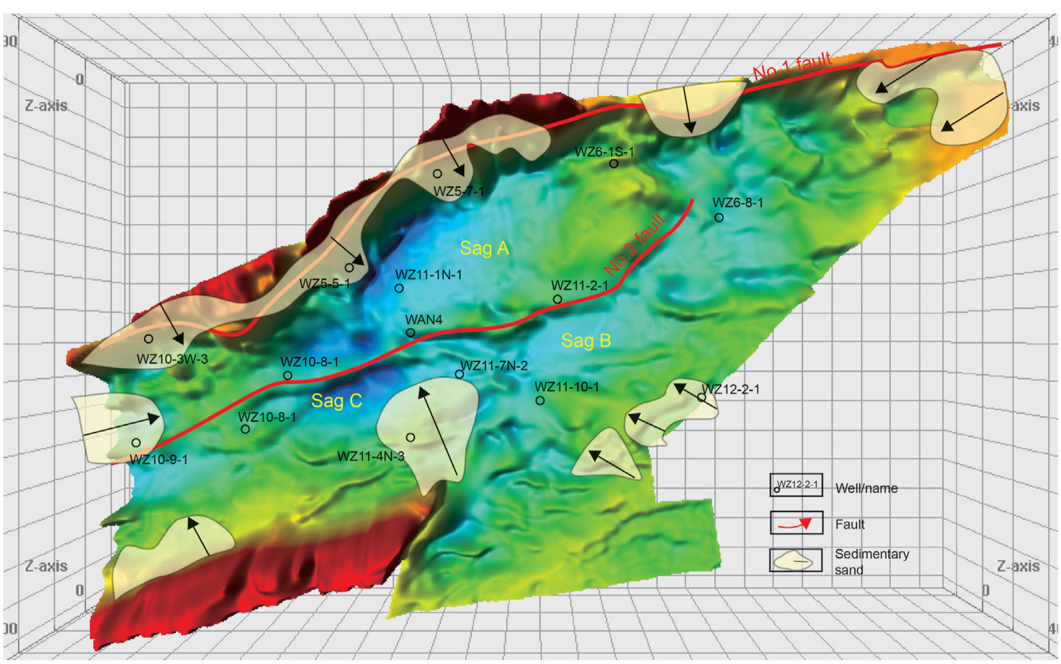

Fig. 5. Map of the distribution of basin-controlling faults and sand in the Beibu Gulf Basin.

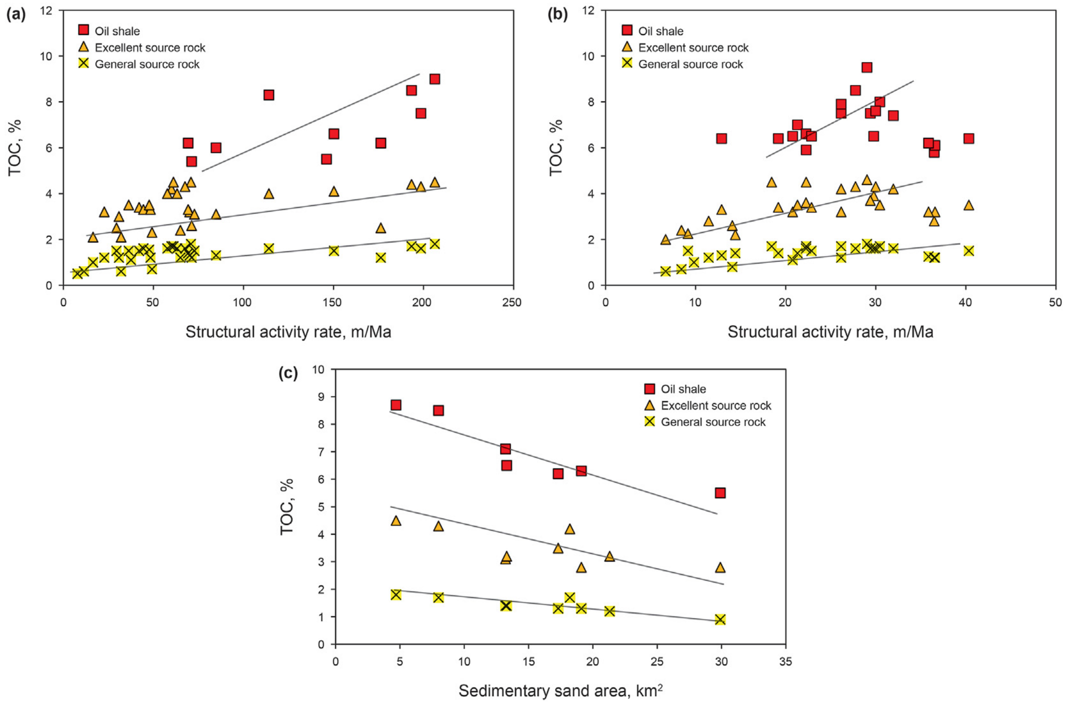

Fig. 6. Structural activity rate and sand area controlling the hydrocarbon potential of source rocks. (a) The higher, and positive, structural activity rate of the No. 1 fault (206.3 m/Ma) is associated with the TOC content of all source rocks. (b) The activity rate of the No. 2 fault (up to 40.3 m/Ma) is positively associated with the source-rock TOC content. (c) Distribution of the area of sedimentary sand, showing its negative influence on source-rock TOC content.

was set to 50–650 with a scan time of 0.7 s. Every compound was analyzed using the NIST library and published mass spectra.

4. Results

4.1. Bulk organic geochemical characteristics

Previous studies suggest that source rocks with TOC content >0.5 wt% are conducive to the formation of commercial oil-gas reservoirs (Fuloria, 1967; Katz, 1990; Peters and Cassa, 1994). Many significant oil deposits are related to excellent-quality source rock (TOC > 2.0 wt%) based on the analysis of the hydrocarbon potential and on the oil-source rock correlation (Peters and Cassa, 1994; Gao et al., 2020). Organic-rich shale (TOC content > 5.0 wt %) is similar to oil shale, as reflected by the high oil yield that occurs at TOC > 3.5 wt% (Tao et al., 2010; Sun et al., 2013; Liu et al., 2017). Therefore, according to their potential commercial value and TOC content, we divided the lacustrine organic-rich shales into general-quality source rock (0.5 wt% < TOC < 2.0 wt%), excellent-quality source rock (2.0 wt% < TOC < 5.0 wt%) and oil shale (TOC > 5.0 wt%). Most of the samples of general-quality source rock from the study area had a high hydrocarbon generation potential ($S_1 + S_2$ of 0.66–9.90 mg/g). The excellent-quality source rock was characterized by higher $S_1 + S_2$ values (5.23–29.44 mg/g), and the oil shale had the highest hydrocarbon potential (20.40–44.11 mg/g) (Fig. 2a). The hydrogen indexes display an increasing trend from general-quality source rock, to high-quality source rock, to oil shale (Fig. 2b). The hydrogen index of general-quality source rock was 96.67–459.64 mg HC/g TOC and its maximum pyrolysis temperature (T_{max}) was 423–456 °C, indicating mainly type II_2 kerogen. In our samples, excellent-quality source rock is reflected by the presence of type II_2-II_1 kerogen, with a hydrogen index of 140.99–675.91 mg HC/g TOC and Tmax values of 426–445 °C. In contrast to the general- and excellent-quality source rock samples, the oil shale contained more hydrogen-rich type II_1–I kerogen. For all samples, Tmax values was <460 °C, indicating an immature to mature stage (Tao et al., 2010).

4.2. Palynofacies analysis

The excellent-quality source rock contained more coaly and woody organic matter, although several samples of general-quality source rock had a high proportion of coaly organic matter (>62.5%; Fig. 3a). Excellent-quality and general-quality source rocks had the same negative relationships between liptinite and amorphous organic matter content. Excellent-quality source rock contained more liptinite (20.7–31.0%) than most of the general-quality source rocks (14.3–22.7%; Fig. 3b). The relative contents of cutinite and exinite in excellent-quality source rock were consistent with the liptinite content (Fig. 3c). Although we measured the TOC content and palynofacies of three to four samples of excellent-quality source rock, we were unable to determine the association between organic matter abundance and palynofacies in either general-quality or excellent-quality source rock. With the increase in TOC content, sporinite content increased in general-quality source rocks, and it tended to be lower in excellent-quality source rock samples (Fig. 3d). The relative alginite and sporopollen contents of all samples were ca. 20.0–60.0% and 40.0–80.0%, respectively (Fig. 3e and f).

4.3. Paleosalinity and redox conditions

A combination of trace elements and biomarkers can be used to identify the salinity and redox conditions of depositional environments (Filby, 1994; Huang et al., 2013; Goldberg and Humayun, 2016; Wood and Hazra, 2017). In our study, oil shale samples had higher δU ratios (0.73–1.37; mean 0.94), V/Cr ratios (0.91–1.98; mean 1.32), and boron contents (B wt.%) (123.44–287.06; mean

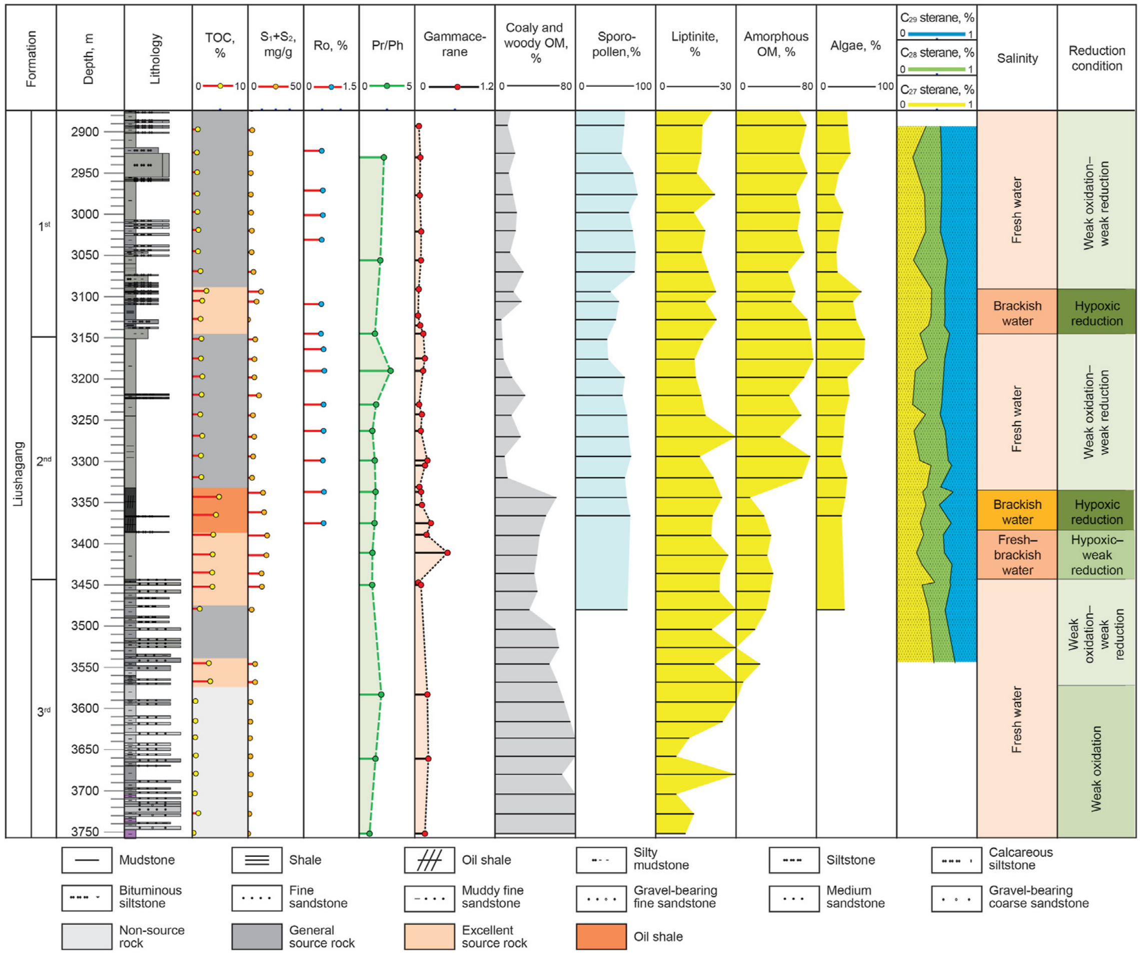

Fig. 7. Evolution of organic matter abundance, source, and depositional environments based on Liushagang Formation samples from well WZ11-2-1.

239.14) than excellent- and general-quality source rock. The δU ratio (0.81–1.23) and V/Gr ratio (0.95–1.54) of excellent-quality source rocks exceeded those of general-quality source rock (0.65–0.79 and 0.80–1.39, respectively) (Fig. 4a). The source-rock types had similar B contents, representative of fresh-saltish water (Fig. 4b). The ratio of isoprenoids to normal alkane hydrocarbons (the Pr/n-C_{17} and Ph/n-C_{18} ratios) was similar in excellent-quality source rock (0.43–2.52) and oil shale (0.30–1.82) (Fig. 4c). General-quality source rock was characterized by a lower Pr/n-C_{17} to Ph/n-C_{18} ratio (0.17–1.26). The organic-rich shales showed little variability in the association between the Pr/Ph and Gammacerane/C30-hopane ratios, reflecting weak oxidation (Fig. 4d).

4.4. Rate of structural activity and distribution of sand

We analyzed the association between organic matter abundance and the structural activity rates and distributions of sedimentary sand, referring to previous findings (Liu et al. 2013, 2018; Yan et al., 2020). The spatial distribution of the sand, and the direction of its long axis, are shown in Fig. 5. The activity rate of the No. 1 and No. 2 faults presents a notable positive association with TOC content in all types of source rocks (Fig. 6a and b). The activity rate of the No. 1 fault (maximum rate of 206.23 m/Ma) was significantly higher than that of the No. 2 fault (maximum rate of 40.30 m/Ma). For the oil shales, the two faults showed similar associations between TOC contents and structural activity rate (Fig. 6a and b). The highest TOC value of oil shale was obtained near fault No. 2, at an activity rate of 29.00 m/Ma, which is lower than that of fault No. 1 (200.00 m/Ma). Sedimentary sand area and organic matter abundance were negatively associated (Fig. 6c). The oil-shale content decreased rapidly with increasing sand area.

5. Discussion

5.1. Effects of the paleosalinity and redox conditions on organic matter preservation

High salinity enhances halocline formation and promotes an anoxic environment in bottom water (Baird et al., 1988; Fleet et al., 1987; Daffonchio et al., 2006). The salinity and redox conditions of bottom water are positively associated with the organic matter abundance in bottom sediments (Heckel, 1991; Wignall and Hallam, 1991; Ding et al., 2016; Zhao et al., 2017). This viewpoint is supported by our finding that the oil shale deposition occurred in the bottom water, in brackish and hypoxic environments (Fig. 4a and b, Fig. 7). However, we found that excellent-quality source rocks formed under the lower salinity of fresh-to brackish water, in a weak oxidation-weak reduction environment (Fig. 7), and that the salinity and redox conditions did not significantly affect organic-matter accumulation in excellent-quality source rock. Our findings indicate that, as the reduction conditions changed from hypoxic to weak oxidation-weak reduction, the source rock changed from oil shale to general-quality source rock (Fig. 7), revealing the effect of the depositional environment.

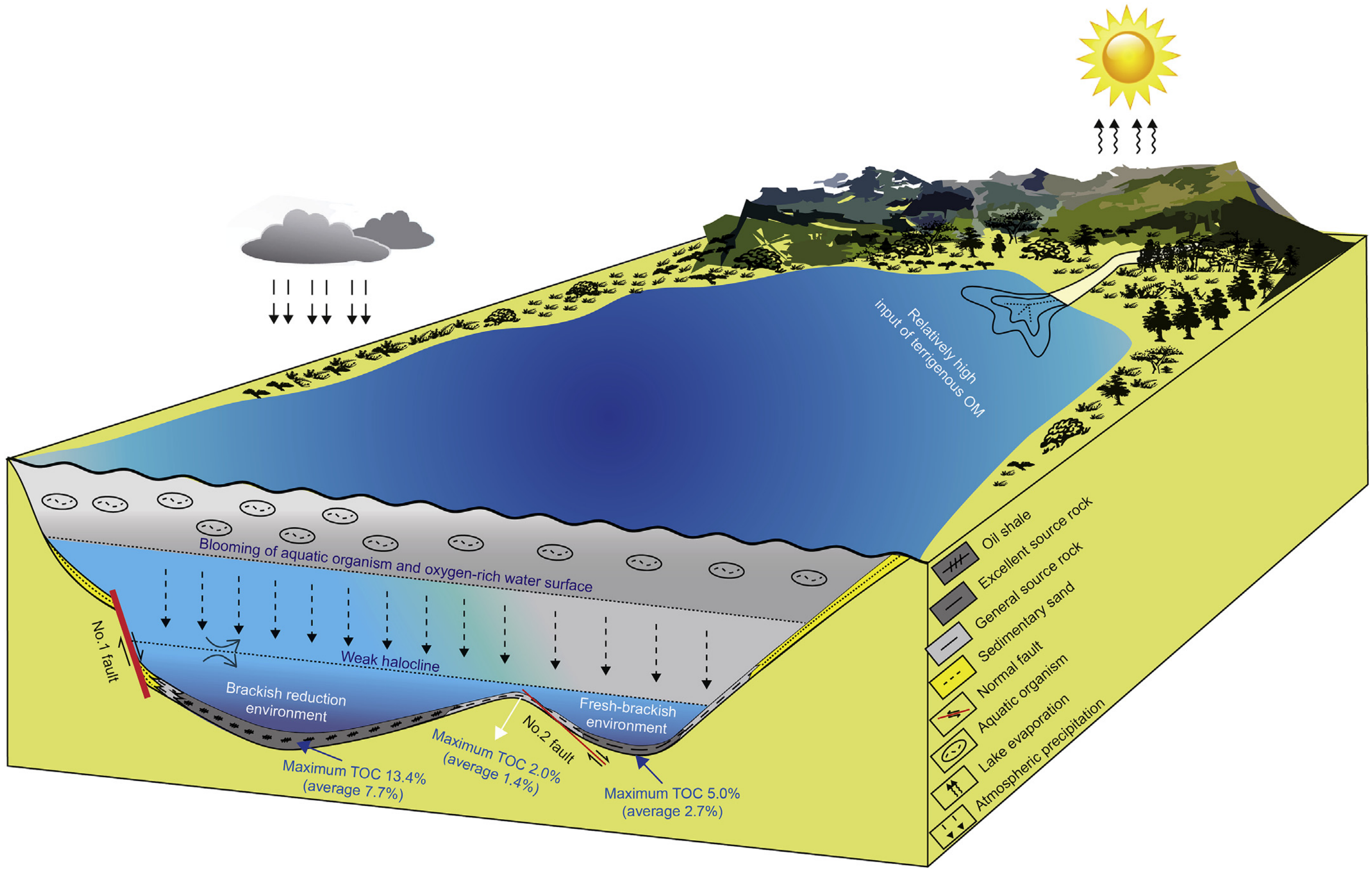

Fig. 8. Model of the accumulation of organic-rich source rocks in the Liushagang Formation, Beibu Gulf Basin.

5.2. Effects of higher-plant-derived hydrogen-rich components on organic matter abundance

Palynofacies analysis can be used to determine the provenance, types, and abundance of organic matter (Tyson, 1987, 1993, 1993; Cirilli et al., 2015; Huang et al., 2017). The palynofacies analysis in this study indicates the mixed input of terrigenous and lacustrine organic matter. Our evidence suggests that higher-plant-derived organic matter has a larger influence than other sources of organic matter on the hydrocarbon generation potential of excellent-quality source rock and oil shale; this effect was notable in LSG-2. Coaly and woody organic matter contributed >30% and >15%, respectively, of the organic matter of excellent-quality source rock (Fig. 3a). Excellent-quality source rock contained more liptinite and less amorphous organic matter, indicating that it is hydrocarbon-rich (Figs. 3b and 7). The concentrations of hydrogen-rich cutinite and exinite, derived from chitin of higher plants, are higher in excellent-quality than general-quality source rock (Fig. 3c). The higher-plant-derived hydrogen-rich components significantly enhanced the hydrocarbon generation potential of excellent-quality source rock and oil shale of from LSG-2 significantly. However, in the excellent-quality source rock of LSG-1, which was characterized by less coaly and woody organic matter, the hydrocarbon generation potential was provided by liptinite (containing some cutinite and sporinite) and mostly by algae. This indicates that hydrogen-rich liptinite (cutinite and exinite) derived from higher plants dominated the hydrocarbon generation potential of excellent-quality source rock and oil shale. Although more coaly and woody organic matter and some algae were supplied during general-quality source rock deposition, weak preservation conditions may explain the lower TOC contents and low $S_1 + S_2$ values of these rocks (Fig. 7).

5.3. Effects of the structural activity and sand on the organic matter abundance

Together with the settlement of the entire paleolake basement caused by the No. 1 fault, differential subsidence induced by the No. 2 fault developed in Weixinan Sag, forming subsags A, B, and C (Fig. 5; Xie et al., 2011; Yang et al., 2012; Liu et al., 2014). The subsag settlement amplitude influences the amount of accommodation space available for organic-rich sediment deposition, and affects bottom-water redox conditions, altering organic-rich sediment preservation (Carroll and Bohacs, 1999, 2001, 2001; Bohacs et al., 2000). The interaction between the No. 1 and No. 2 faults in the southern part of the Weixinan Sag (Subsag A) provided sufficient accommodation space for a thick organic-rich sediment deposit (Figs. 5 and 6a). Under the background influence of the No. 1 fault, and the stronger No. 2 fault activity, subsag B formed more available accommodation space and a deeper water environment than subsag C, which was controlled mostly by the weak southern part of the No. 2 fault (Figs. 5 and 6c). The distribution of sedimentary sand was closely associated with the structural activity and paleogeomorphology. There were many long and narrow sedimentary sand deposits on the gentle slopes of subsags B and C (Fig. 5). The sand significantly affected the distribution of organic-rich fine sediments. Several short and wide sedimentary sand deposits occurred on the downthrown side of the No. 1 fault, which has less influence on the development of organic-rich shales. The presence of the lacustrine basin delta, accompanied by terrigenous sediment and nutrient input, and the higher-plant-derived hydrogen-rich organic matter, favored the development of organic-rich shales. This evidence indicates that the high fault-activity rates and the presence of short deltas (occurring in subsags A and B) were the primary factors influencing the development of the thick and wide deposits of excellent-quality source rock and oil shale, which were abundant in hydrogen-rich components (Martínek et al., 2006; Ntamak-Nida et al., 2008; Xu et al., 2013, Fig. 5).

5.4. Model of organic matter accumulation controlled by fault activity and organic matter input

This comprehensive analysis indicates that structural activity, sedimentary sand distribution, the depositional environment, and organic matter input play important roles in organic-rich shale formation. Furthermore, it suggests that, in the Weixinan Sag, high fault-activity rates, large algal input from the inner lake, and higher-plant-derived hydrogen-rich components are the primary factors leading to the development of excellent-quality source rock and oil shale, with deltaic-sand distribution and the brackish-hypoxic conditions of the bottom water being secondary factors. Notably, the favorable area for oil shale and excellent-quality source rock formation was a settlement area (i.e., subsags A and B), characterized by the fresh-brackish and weakly reducing conditions of the bottom water, the abundance of hydrogen-rich components (i.e., alginite, cutinite, exinite, and sporinite), and steep slope sands (Fig. 8). The uplift and shallow-slope areas were conducive to the deposition of general-quality source rock under the freshwater and weakly oxidative conditions, and under the influence of paleoslope sands (Fig. 8).

6. Conclusions

To estimate source rock and oil shale resources in the Weixinan depression of the Beibu Gulf Basin, and to reveal the mechanisms of source rock formation, this study integrated structural activity, organic matter provenance and type, and preservation conditions. The findings lead to the following conclusions. Oil shale and excellent-quality source rock have notably higher hydrocarbon generation potentials and hydrogen indexes than general-quality source rock. Terrigenous coaly and woody organic matter are the primary components of excellent-quality source rock and oil shale. The higher-plant-derived liptinite content (in the form of cutinite and exinite) governs the hydrocarbon generation potential of the excellent-quality source rock and oil shale. Oil shale deposited in a hypoxic environment with brackish bottom water provides a better hydrocarbon resource than excellent-quality source rock that forms in fresh-brackish and weak oxidation-weak reduction bottom water environments. A reduction in salinity and reducing conditions causes the deposition of general-quality source rock. Depression-controlling faults control the location and abundance of excellent-quality source rock and oil shale deposits. The subsag-controlling local uplift of the palaeogeomorphology and shallow-slope led to the formation of general-quality to excellent-quality source rocks. Structural activity influenced the quality and location of the source rock deposits. The formation model, which accounts for these controlling factors, can be used to evaluate regional source rock resources, when there are insufficient drilling cores or when only seismic and well-logging data are available.

Acknowledgements

The work presented in this paper was supported by the Certificate of National Science and Technology Major Project of the Ministry of Science and Technology of China (2016ZX05006-007-004), National Natural Science Foundation of China (41702139, 41772138, 41602142, 42072130) and the Fundamental Research Funds for the Central Universities (18CX02008A).

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