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Discussion

Depositional palaeoenvironment and models of the Eocene lacustrine source rocks in the northern South China Sea

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ABSTRACT

Element geochemical analysis of 94 ditch cutting samples of the shale source rock from the Wenchang Formation in the Zhuyi sub-basin and the Liushagang Formation in the Weixinan sub-basin was conducted to determine their palaeoenvironment and main controlling factors and to further establish development models. The results indicate that freshwater and a warm and humid climate were characteristics of the depositional palaeoenvironment between Wenchang and Liushagang formations. During the deposition of the Wenchang Formation, the parent rocks mainly consisted of felsic volcanic rocks, the water was characterized by a high palaeoproductivity, shallow-deep water depths, and weakly reducing conditions, whereas during the deposition of the Liushagang Formation, the parent rocks mainly consisted of mafic volcanic rocks, and the palaeoproductivity, palaeowater depth, and reducing conditions of the water were better than during the deposition of the Wenchang Formation. The formation of high-quality source rocks in the Liushagang Formation were mainly controlled by two factors: (1) The mafic igneous rock provenance and strong weathering provided macronutrients (e.g. P, Fe) for water. (2) A high palaeoproductivity provided a source of organic matter, which played a much important role than the preservation condition of organic matter. For the Wenchang Formation, the good preservation of organic matter which was due to the deep water reducing environment, was also necessary. Accordingly, two models were briefly summarized: a productivity and preservation model for the Wenchang Formation source rocks and a productivity model for the Liushagang Formation source rocks. Both of these models can develop high-quality source rocks, but the source rock quality of the former is lower than of the latter, this is mainly attributed to the difference in the nutrients and palaeoproductivity. This study provides valuable guidance for oil and gas exploration in the northern South China Sea and the study of lacustrine source rocks in other areas.

1. Introduction

High quality source rocks are the material basis for the formation of medium-large oil and gas fields (Qin, 2005; Wang, 2015), and lacustrine source rocks, which are an important category of source rocks, have self-evident research significance and value. The oil and gas production derived from lacustrine source rocks accounts for more than 20% of the total global production, and it has even exceeded 95% in the offshore areas of China (Kang and Yang, 2010). It has been confirmed that lacustrine source rocks are mainly distributed in the Early Cretaceous basins of both the eastern continental margin of Brazil and the passive continental margin of West Africa, the Triassic and Early-Middle Jurassic basins of the northwest continental shelf and the southern passive continental margin of Australia, the Palaeozoic basins of Western China, and the Meso-Cenozoic basins of eastern China and Southeast Asia (Li, 2015; Kang and Yang, 2010; Harris et al., 2004; Hou et al., 2015; Zhang et al., 2018; Wu et al., 2015; Cao et al., 2018).

Although lacustrine source rocks are widely distributed, they generally exhibit greater spatial and temporal variations in provenance, organic matter input, temperature, water depth, salinity, and redox conditions than marine source rocks (Gonçalves, 2002; Hao et al., 2011; Alalade, 2016). Therefore, there are numerous controversies as to their

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main controlling factors, which can be summed up in three models: the organic matter productivity model, the organic matter preservation model, and the synergism model of organic matter productivity and preservation conditions. The organic matter productivity model emphasizes the input of organic matter into the surface water of the lake (Meyers, 1997), which may be influenced by a warm and humid climate, nutrient input, terrigenous source, volcanic eruptions, seawater intrusion, and mineralisation of the sedimentary organic matter (Chen et al., 2017a,b; Meng et al., 2012; Yan et al., 2015; Wang et al., 2017a,b; Middelburg and Meysman, 2007; Algeo and Ingall, 2007). Furthermore, in this model, high-quality source rocks can form in high productivity conditions and the reducibility of the lake water is irrelevant (Meyers and Amaboldi, 2005; Li et al., 2017). The organic matter preservation model states that the reducing environment plays a crucial role in the organic matter enrichment. The reducing environment is generally caused by geographical isolation, a deep and stratified water column, and biological activity (Jones, 1973; Degens and Mopper, 1976). The synergism model of organic matter productivity and preservation states that the productivity and preservation of organic matter together control the development of the source rocks. Although there are various interpretations, there is no one model that can explain all of the mechanisms of source rock deposition given the heterogeneity of the productivity and preservation conditions. Therefore, it is necessary to study the main controlling factors and to develop models for the source rocks in a given area.

In recent years, the element geochemical method has been applied to palaeoenvironment reconstruction as the accuracy and efficiency of the geochemical testing technology have improved. The basic principle of this application is based on the behaviour of specific elements in the characteristic depositional environments; in other words, the types and contents of elements are closely related to the type of depositional environment (Kahle et al., 2002; Liu et al., 2012; Ghosh and Sarkar, 2010). Xiong and Xiao (2011) summarized the element geochemical indicators of depositional environment. Chen et al. (2019) determined the mechanism of the organic-matter enrichment in the Lower Longmaxi Formation shale using element geochemical methods. Therefore, element geochemistry not only provides an effective way of determining depositional conditions, but it also contributes to a better understanding of the organic-matter enrichment of source rocks. It should be noted that the element geochemical method has its limitations. For example, hydraulic sorting, weathering, and diagenesis can alter the geochemical compositions of basin sediments; and there is the problem of elements sources, that is, there are many element indexes that reflect the same type of environment. These factors make it difficult to select effective palaeoenvironment indicators (Abell and Nyamweru, 1988; Bauluz et al., 2000 Wei et al., 2011).

Three types of source rocks, that is, Eocene lacustrine, Oligocene sea-continental transitional, and Miocene Marine facies, are widely developed in the northern South China Sea. In particular, the Eocene lacustrine source rocks are the most prominent oil and gas generator (Yu et al., 2016; Li et al., 2011). Through the efforts of many geologists, the palaeoenvironment and its impacts on the development of lacustrine source rocks have been well explained in a given sub-basin, such as the Zhuyi sub-basin (Bao et al., 2017; Quan, 2015, 2017). However, the structural evolutions of the basins in the South China Sea are diverse, and the geographical landscape, sedimentary filling, and water conditions also vary horizontally (Yu et al., 2016; Li et al., 2011), which leads to a more complicated development model and distribution of the source rocks. The risk of oil and gas exploration increases if the source rock development model is not well understood. In addition, previous relevant studies have mainly used biomarker parameters (e.g., pristane/-phytane and gammacerane indexes) to reveal the palaeoenvironment information (Cao et al., 2005; Bao et al., 2017; Li and Zhang, 2018; Quan et al., 2015, 2017; Quan, 2018), which lacks the evidence provided by element geochemistry. Mainly based on element and organic geochemical data and previous relevant research results, in this study, we reconstructed the palaeoenvironment of the Eocene lacustrine source rocks in the northern South China Sea, investigated their main controlling factors, and established correlative models. These results not only provide information on the element geochemistry of the source rocks in the northern South China Sea, but they also serve as a reference for studying organic matter enrichment in other lacustrine sub-basins.

2. Geologic setting

The South China Sea is located on the western margin of the Pacific Ocean. The northern continental margin of the South China Sea, which is a typical passive continental margin, is situated at the intersection of the Eurasian, Indo-Australian, and Pacific plates (Gong and Li, 1997; Li and Zheng, 2007). Thus, it is easily affected by tectonic activities and has particularities in terms of sedimentary fillings (Hall, 2002; Hurchison, 2004). During the Cenozoic, the northern South China Sea mainly experienced three tectonic evolution stages of faulting, faulting-to-depression transition, and depression, which resulted in the formation of a number of rift basins, including continental margin rift basins (e.g., the Pearl River Mouth and Qiongdongnan basins), intra-continental rift basins (e.g., the Beibuwan basin), and strike-slip and pull-apart basins (e.g., the Yinggehai basin) (Yu et al., 2016) (Fig. 1A). Furthermore, the sedimentary filling can be divided into three facies: continental, marine-continental transitional, and marine facies (Xie et al., 2008, 2012). Due to the variations in their geotectonic locations and properties, the inter-basins exhibit several differences in terms of tectonic evolution and sedimentary filling (Yu et al., 2016). In this study, the Wenchang Formation in the Zhuyi sub-basin in the Pearl River Mouth Basin and the Liushagang Formation in the Weixinan sub-basin in the Beibuwan Basin were the main research areas and intervals. The main reasons these formations and locations were chosen are as follows. (1) The wells that penetrate the lacustrine source rocks in the northern South China Sea are mainly located in the Zhuyi and Weixinan sub-basins. (2) These two areas are rich in oil and gas resources and most of the oil and gas is derived from lacustrine source rocks. (3) The quality of the source rocks in these two areas is excellent. The total organic matter content (TOC) of Wenchang Formation ranges from 0.95 wt% to 11.43 wt%, with an average of 2.06 wt%, and the organic matter is mainly type II_1 oil-prone kerogen (Zhu et al., 2019). The TOC of Liushagang Formation ranges from 0.40 wt% to 10.35 wt%, with an average of 2.63 wt%, and the organic matter is predominantly type I-II_1 oil-prone kerogen (You et al., 2012; Ye et al., 2020).

The Zhuyi sub-basin is located in the northwest part of the Pearl River Mouth Basin, and it is bounded to the northwest by the Northern Uplift Belt, to the southwest by the Zhu 3 sub-basin, and to the southeast by the Dongsha and Panyu uplifts (Fig. 1C) (Hu, 2019). The Wenchang Formation deposited during the rifting stage in the Middle Eocene, and the main provenance was the Northern Uplift Belt, which had higher topography, while the Dongsha and Panyu uplifts in the south were secondary sediment sources. The sufficient amount of sediment was mainly transported along a gentle slope and deposited in the sub-basin. The thickness of lacustrine shales could reach 2000 m in the depocenter (Hu, 2019). The Enping Formation was deposited during the rifting stage in the Late Eocene and Early Oligocene, and the main provenance was the South China fold belt outside the basin (Wang et al., 2015). Shales interbedded with sandstones and coal were deposited in a few shallow lakes and swamps (Zhao et al., 2009; Huang, 1998). The Zhuhai and Zhujiang formations were deposited during the faulting-depression transition stage in the Late Oligocene and Early Miocene, and the sediments were predominantly composed of thicker littoral-shallow sea mudstones and sandstones (Zhao et al., 2009). After entering the Neogene and Quaternary depression stage, extensive open sea shelf deposits and local delta, bay, continental shelf, and carbonate rocks were deposited in the Hanjiang, Yuehai, and Wanshan formations in the Quaternary (Zhao et al., 2009).

The Weixinan sub-basin is located the north of Beibuwan Basin, and

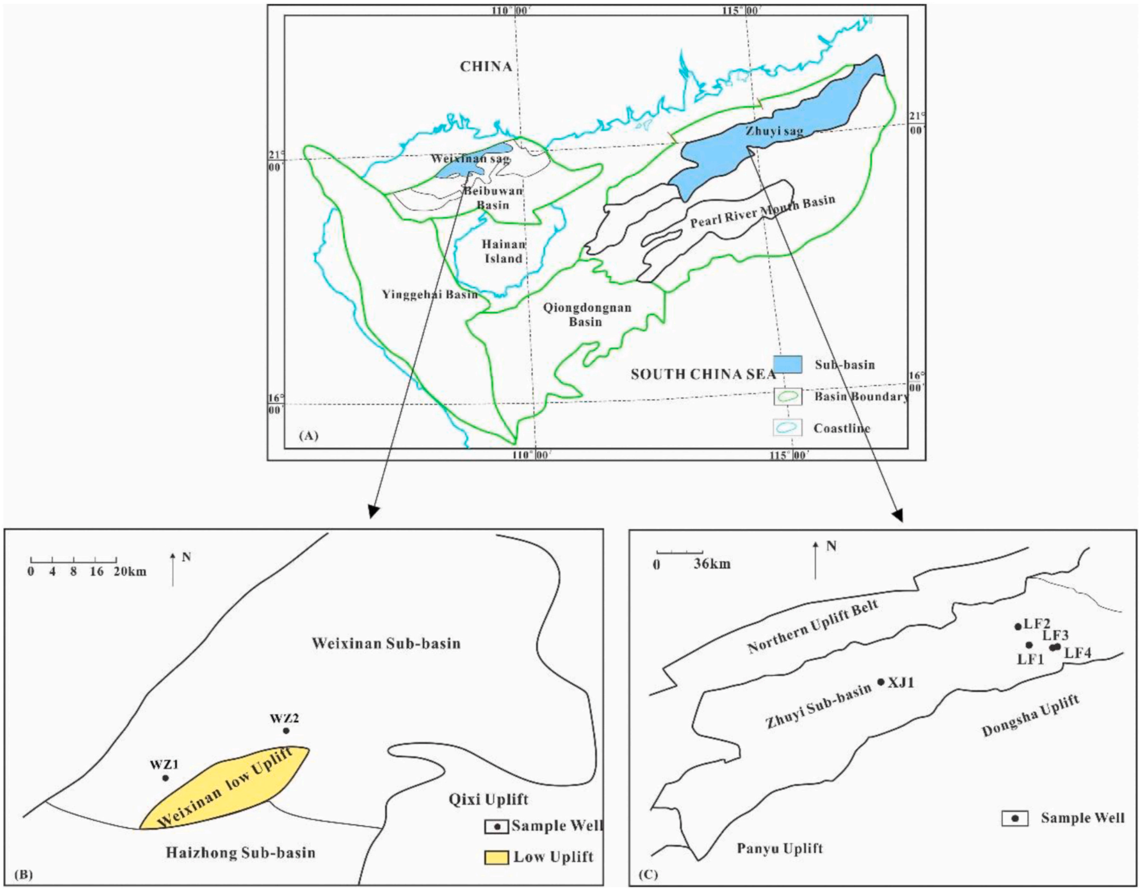

Fig. 1. Map showing (A) the distribution of the basins in the northern South China Sea, including the Pearl River Mouth, Qiongdongnan, Beibuwan, and Yinggehai basins, and the locations of the Zhuyi and Weixinan sub-basins, (B) the locations of the sampling wells in the Weixinan sub-basin, and (C) the locations of the sampling wells in the Zhuyi sub-basin.

it is bounded by the Weixinan Fault to the north and by the Haizhong sub-basin and the Qixi uplift to the south (Fig. 1B) (Xie et al., 2014). Unlike the Zhuyi sub-basin, only one set of the Liushagang Formation was deposited during the entire Eocene (Fig. 2B), and the sufficient sediment supply was mainly from the Yuegui and Qixi uplifts, so the lake basin was also in a state of underfilling. A large area of deep lacustrine black shale was deposited, with a maximum thickness of 3000 m (Zhang et al., 2014). The Weizhou Formation was deposited during the faulting-depression transition stage in the Oligocene, and the sediments were mainly fluvial facies, but the marine-continental transitional facies is absent because of the location of the Weixinan sub-basin (close to the land, later affected by transgression). After entering the Neogene and Quaternary depression stage, marine deposits became an important part of the sedimentary filling of the Weixinan sub-basin.

3. Samples and methods

The present study includes the Wenchang Formation in the Zhuyi sub-basin in the Pearl River Mouth Basin and the Liushagang Formation in the Weixinan sub-basin in the Beibuwan Basin. For the Wenchang Formation, LF1, LF2, LF3, LF4, and XJ1 were selected as the sampling wells, providing a total of 65 blocks (Fig. 1). For the Liushagang Formation, WZ1, and WZ2 were selected as the sampling well sites, providing a total of 29 blocks (Fig. 1). The lithologies of the samples are mainly grey mudstone and grey-black mudstone and shale, and the sample type is debris.

The major and trace (including rare earth) element concentrations of the Wenchang and Liushagang formations were analysed by the State Key Laboratory of Marine Science of Tongji University and the State Key Laboratory of Geological Processes and Mineral Resources of the China University of Geosciences (Wuhan), respectively. The data obtained were used to investigate the palaeoenvironment of the study area. The instruments used for the major element analyses were a TU-1900 double-beam UV-spectrophotometer and a Hitachi ZA3000 Atomic Absorption Spectrophotometer. The analysis methods are shown in Table 1. For detailed processes refer to standard GBT/T14506-2010. The trace elements (including rare earth elements) were analysed by inductively coupled plasma mass spectrometry (ICP-MS) (Govindaraju, 1994; Liu et al., 2008).

4. Results

Nine major and 41 trace (including rare earth) element concentrations were analysed in this study. The major elements analysed include Al, Fe, K, Mg, Ca, Na, Ti, P, and Mn; and the trace elements analysed include Li, Be, B, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Cd, In, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb, Bi, Th, and U. In this study, only the elements useful for reconstructing the palaeoenvironment were statistically analysed. The selected element concentrations of the Wenchang and Liushagang formation samples and post-Archean Australian shale (PAAS) (Taylor and McLennan, 1985) are presented in Table 2. The selected element concentrations of the Wenchang and Liushagang formation samples after being normalized to post-Archean Australian shale (PAAS) are shown in Fig. 3. Compared with PAAS, the P, Mn, and Ba concentrations of the Wenchang and Liushagang formations samples vary significantly, Ba, Zn, Th, and U are enriched, and the concentrations of these elements are slightly higher in the Liushagang Formation samples than in the

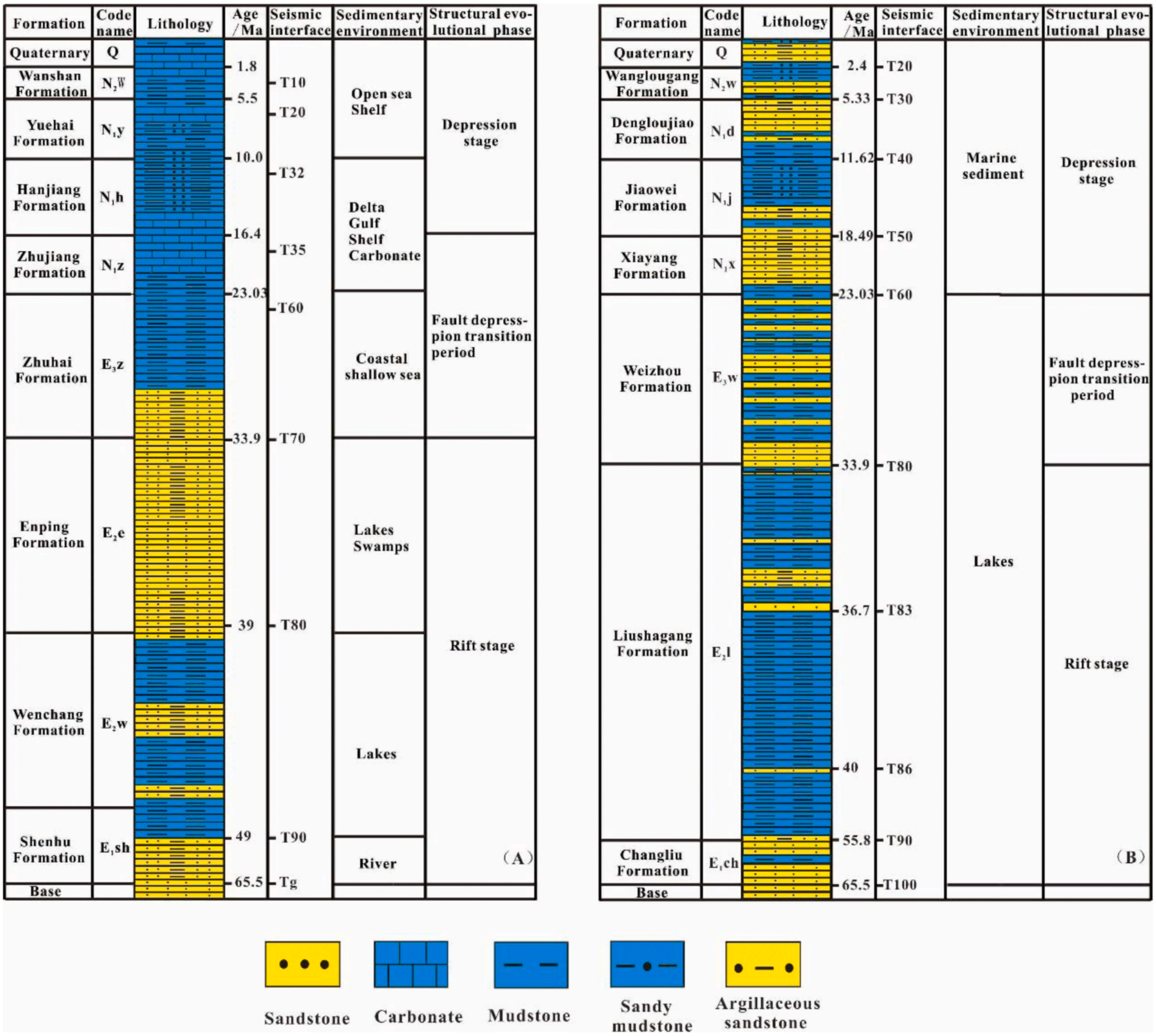

Fig. 2. Stratigraphic columns of (A) the Zhuyi sub-basin and (B) the Weixinan sub-basin.

Table 1
List of major element analysis methods.

Element	Analysis method	Element	Analysis method
Al	Fluoride replacement-EDTA volumetric method	Mn and low Mg and Ca contents	Atomic absorption spectrometry
Fe	sulfosalicylic acid spectrophotometry	High Mg and Ca contents	Precipitate and separate using the hexamethylenetetramine and sodium diethyldithiocarbamate-EDTA volumetric method
K and Na	Atomic emission spectrometry	Ti	Diantipyry methane spectrophotometry
P	P–Mo blue photometric method		

Wenchang Formation samples. Rb is depleted in the Wenchang Formation samples, whereas it is enriched in the Liushagang Formation samples. The other elements are depleted in the Wenchang and Liushagang formation samples. Furthermore, the Al, K, Mg, Ti, and Zr concentrations of the Wenchang Formation samples are slightly higher than those of the Liushagang Formation samples, whereas the Fe, P, Mn, Sr, V, Cr, Ni, and Cu are slightly lower.

5. Discussion

5.1. Implications for the palaeoenvironment

5.1.1. Origins of the major and trace elements

The major and trace elements in sediments mainly have hydrothermal, detrital, authigenic, biogenetic, and hydrogenous sources. However, only the major and trace elements originating from authigenic, hydrogenous, and biogenetic sources can reveal the depositional conditions of an aqueous system (e.g., palaeoproductivity, palaeoclimate, palaeowater depth, palaeoredox, and palaeosalinity), while the major and trace elements originating from the detrital provenance provide information about the provenance area. Therefore, it is necessary to determine the elements' origins before reconstructing the palaeoenvironment. Sediments of hydrothermal origin are characterized by high Mn–Fe fractions, but Mn and Fe are depleted in samples from the study area, so a hydrothermal origin can be ruled out. The gradient leaching experiment conducted by Murray and Leinen (1996) indicates the 95% of the Ti originated from the detrital minerals. In this study, we determined whether a given element mainly originated from an authigenic/hydrogenous/biogenetic or detrital source using plots of the element versus Ti. According to the correlation analysis, the major and trace elements can be divided into three groups (refer to Liang et al., 2018) (Fig. 4).

Table 2
Selected element concentrations of the Wenchang and Liushagang formations samples and PAAS related to the palaeoenvironment reconstruction.

Element	Concentration (%)		PAAS	Element	Concentration (ppm)		PAAS
	Wenchang Formation	Liushagang Formation			WenchangFormation	Liushagang Formation	
Al	11.184–23.975 17.785	12.040–21.600 17.668	18.90	Ba	209.768–13028.578 2478.118	344.329–9359.234 2904.697	650
Fe	3.032–10.426 5.080	4.720–9.310 6.392	7.18	Zr	72.721–224.671 142.132	46.745–290.594 115.306	210
K	1.963–4.719 3.292	1.510–3.340 2.294	3.68	Sr	51.788–242.601 106.496	51.647–325.533 119.980	200
Mg	0.828–2.277 1.266	0.800–1.580 1.215	2.19	Rb	89.645–239.986 145.309	109.661–230.632 169.197	160
Na	0.228–1.411 0.628	0.190–1.270 0.428	1.19	V	57.571–160.528 93.782	59.693–116.686 95.362	150
Ti	0.404–0.866 0.670	0.330–0.970 0.623	0.99	Cr	23.706–74.956 44.724	63.871–165.732 93.925	110
P	0.014–1.000 0.138	0.079–0.790 0.238	0.16	Zn	56.903–209.348 91.068	86.309–229.018 126.840	85
Mn	0.018–0.552 0.093	0.034–0.460 0.136	0.11	Ni	9.130–38.789 19.735	26.652–52.352 34.612	55
				Cu	17.647–42.642 28.352	24.440–43.774 32.635	50
				Th	10.288–27.417 17.347	16.993–31.805 23.493	14.6
				U	2.604–6.714 4.216	3.887–14.502 8.106	3.1

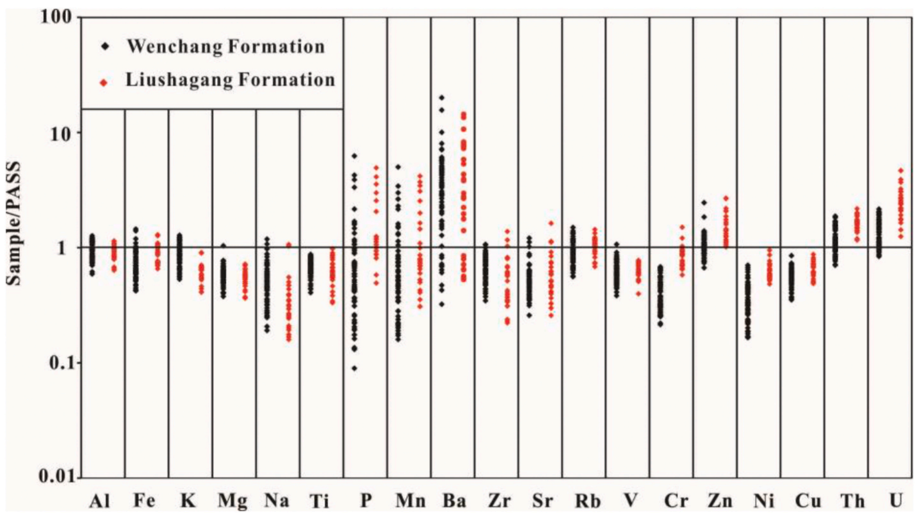

Fig. 3. Comparison of the selected element concentrations in the samples of the Wenchang and Liushagang formations samples after being normalized to post-Archean Australian shale (PAAS).

(1) The authigenic/hydrogenous/biogenetic group (Mn, P): these elements are characterized by negative correlations with Ti and are governed by authigenic, hydrogenous, or biogenetic sources.
(2) The detrital group (Mg, Zr, Rb, K, Th, Al): the elements in this group are affected by the detrital provenance and exhibit excellent positive correlations with Ti.
(3) The uncertain group (Fe, Na, Ba, Sr, Zn, V, Cr, Cu, Ni): these elements exhibit weak negative correlations with Ti (Fe, Ba, Zn, Sr, and Na) or weak positive correlations with Ti (Ni, V, Cr, Cu). They may indicate a mixed source with authigenic/hydrogenous/biogenetic and detrital provenance sources.

As was previously discussed, the authigenic/hydrogenous/biogenetic group elements (e.g., Mn and P) can be used to reconstruct the palaeoenvironment of the study area and the detrital group elements (e.g., K, Rb, Al, and Zr) provide information about the provenance area, but the uncertain and detrital group elements may still have some ability to reveal the depositional conditions in an aqueous system, for example, the successful application of Cr/Zr, Ba, palaeoclimate index C, and Sr/Ba, Sr/Ca, Sr/Cu, Mn/Fe, Cu/Zn, Th/U, Sr, and K/Na. The reason for this is that detrital group and uncertain group elements are affected by the authigenic/hydrogenous/biogenetic source (no element is completely correlated with Ti) during sedimentation, which also reflects the superiority of the element geochemical method.

5.1.2. Provenance

In common igneous rocks, Cr predominantly resides in mafic minerals, but Zr is mainly accommodated by feldspars (Sampa and Soumen, 2010). A Cr/Zr ratio of <0.5 indicates felsic igneous parent rocks, whereas a Cr/Zr ratio of >1 indicates mafic igneous parent rocks (Huntsman-Mapila et al., 2005). According to the statistical analysis (Table 3), the Cr/Zr ratios of the Wenchang Formation samples are 0.174–0.549 (average 0.318), and most of the samples plot in areas suggesting felsic igneous rocks. While the Cr/Zr ratios of the Liushagang Formation samples (0.250–2.422, average 1.012) are higher than those of the Wenchang Formation samples, and most of the samples plot in or close to areas suggesting mafic igneous rocks, and some of the samples plot in or close to areas suggesting felsic igneous rocks. This indicates that the Wenchang Formation sediments mainly originated from felsic igneous rocks with minor mafic igneous rocks, whereas the Liushagang Formation sediments were derived from mafic igneous rocks with minor felsic igneous rocks (Fig. 5A). This is consistent with the statement above that the contents of the Al elements (the main elements in felsic volcanic rocks) (Lézin et al., 2013) of the Wenchang Formation samples are generally higher than those of the Liushagang Formation samples, while the Fe contents (the main element in mafic volcanic rocks) (Lézin et al., 2013) in the Liushagang Formation samples are generally higher than those of the Wenchang Formation samples. In addition, previous studies have revealed that the Wenchang Formation sediments were predominantly derived from Mesozoic granite and pyroclastic rocks, which came from the low bulges and uplift zones within the Zhuyi sub-basin (Wang et al., 2015), while the sources of the Liushagang Formation sediments were more complex and included the Mesozoic granite and clastic rocks and the Upper Palaeozoic limestone from the low bulges and uplifts

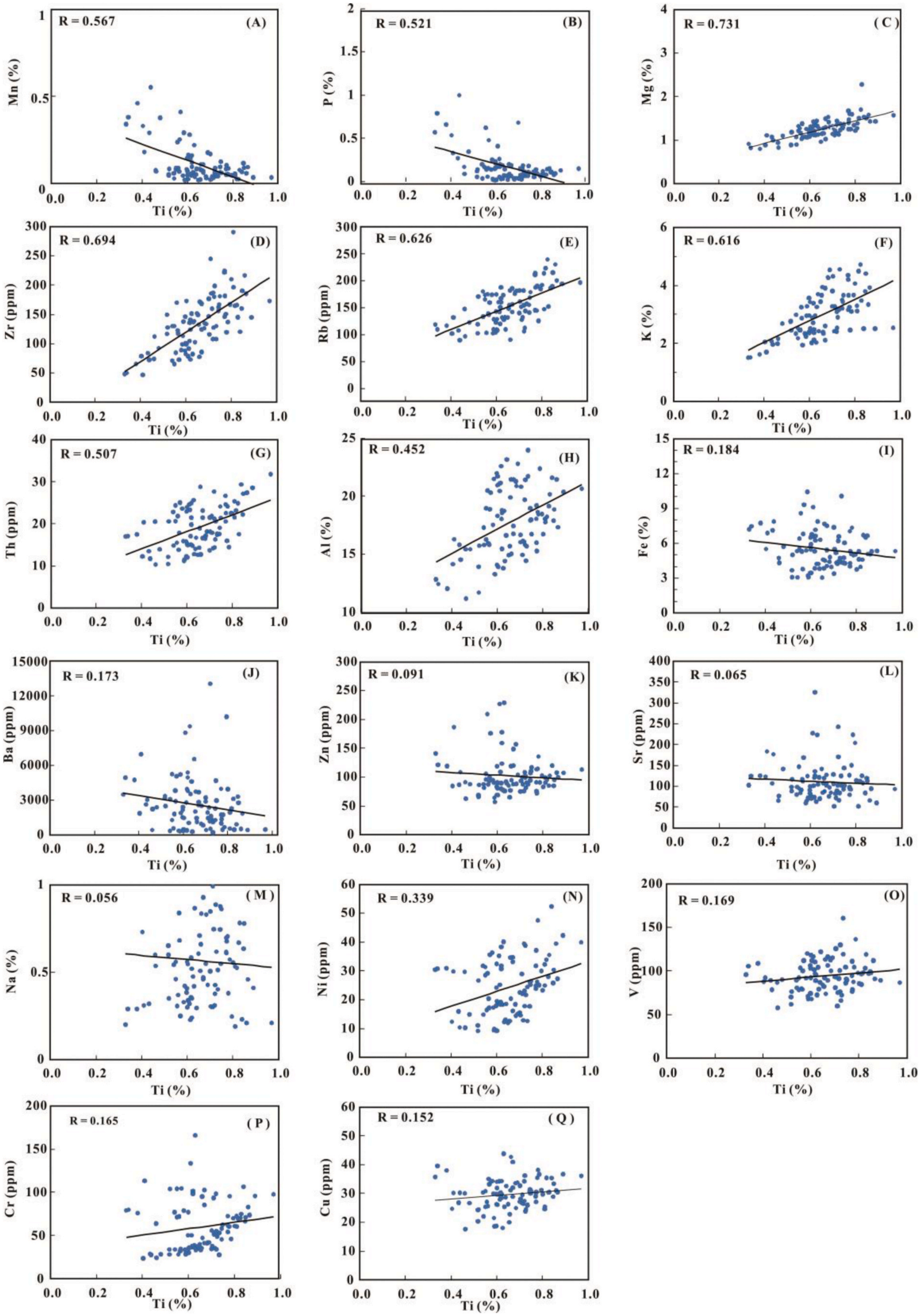

Fig. 4. Plots of Ti vs. (A) Mn, (B) P, (C) Mg, (D) Zr, (E) Rb, (F) K, (G) Th, (H) Al, (I) Fe, (J) Ba, (K) Zn, (L) Sr, (M) Na, (N) Ni, (O) V, (P) Cr, and (Q) Cu for the samples from the northern South China Sea.

Table 3
Indexes of provenance (Cr/Zr and Rb/K), palaeoproductivity (Baxs and P/Al), palaeoclimate (C, Sr/Ba, Sr/Ca and Sr/Cu), palaeowater depth (Mn and Mn/Fe), redox (Cu/Zn and Th/U), and palaeosalinity (K/Na and Sr) for the samples from Wenchang and Liushagang formations in the northern South China Sea.

Formation	Provenance		Palaeoproductivity		Palaeoclimate		
	Cr/Zr	K/Rb	Baxs	P/Al (%)	C	Sr/Ba	Sr/Ca
WenchangFormation	0.174–0.549 0.318	192.732–~289.963 228.992	48–12485 2358	0.102–6.882 0.795	0.525–2.500 0.918	0.019–0.484 0.081	0.004–0.124 0.045
Liushagang Formation	0.250–2.422 1.012	116.955–159.408 135.515	173–8715 3253	0.368–6.345 1.485	0.568–2.297 1.343	0.024–0.227 0.079	0.004–0.039 0.020
Formation	Palaeoclimate	Palaeowater depth		Redox conditions		Palaeosalinity	
	Sr/Cu	Mn (ppm)	Mn/Fe	Cu/Zn	Th/U	K/Na	Sr (ppm)
Wenchang Formation	1.840–8.846 3.812	0.018–0.552 0.093	0.004–0.070 0.017	0.129–0.451 0.391	2.853–5.514 4.164	1.391–14.870 6.056	51.788–242.601 106.496
Liushagang Formation	1.629–9.488 3.693	0.034–0.460 0.136	0.006–0.060 0.020	0.151–0.375 0.272	1.177–7.170, 3.255	1.843–17.368 6.767	51.6–325.5120

within the Weixinan sub-basin and Cenozoic basalt and diabase (Li et al., 2006; Fan et al., 2006).

According to Huntsman-Mapila et al. (2005), high K/Rb ratios indicate a low degree of weathering and vice versa. Rb and K are positively correlated with Ti, suggesting a detrital provenance, so the K/Rb ratio is an effective indicator of the degree of weathering of the parent rocks of the study area. The K/Rb ratios of the Wenchang and Liushagang formation samples are 192.732–289.963 and 116.955–159.408, with averages of 228.992 and 135.515, respectively (Table 3, Fig. 5A), suggesting that there was a higher degree of weathering in the provenance area of the Liushagang Formation. In general, tectonic uplift and the resulting higher slope gradient lead to an increase in the degree of weathering (Riebe et al., 2001; Jacobson and Blum, 2003; Moradi et al., 2016; Tawfik et al., 2017). During the Eocene, the slope gradient of the Weixinan sub-basin increased due to the tectonic uplift of the Weixinan low and Qixi uplifts (Li et al., 2018), while the Zhuyi sub-basin had a shallow lake with a large area (Jia et al., 2017). Thus, the slope gradient of the Zhuyi sub-basin was lower than that of the Weixinan sub-basin, which may be the major reason for the different weathering degrees of the provenance areas of the Wenchang and Liushagang formations source rocks.

In summary, the Cr/Zr and K/Rb ratios indicate a significant difference in the parent rock compositions and the weathering degrees of the provenance areas of the Wenchang and Liushagang formations. The parent rock of the Wenchang Formation was mainly felsic igneous rocks, whereas that of the Liushagang Formation mostly consisted of mafic igneous rock with minor felsic igneous rocks. The degree of weathering of the provenance area of the Liushagang Formation was higher than that of the Wenchang Formation.

5.1.3. *Palaeoproductivity*

Biology is one of the important factors influencing organic matter enrichment. Numerous studies have confirmed that Ba enrichment is closely related to biological processes. Plankton and algae have the ability to enrich Ba in water (Mou et al., 1999); however, the surface water has a high SO_4^{2-} concentration due to biological decomposition, which can be combined with the Ba^{2-} in the water to form barite ($BaSO_4$), which is then precipitated (Goldberg and Arrhenius, 1958; Dehairs et al., 1980; Schmitz, 1987; Dymond, 1992; Francois et al., 1995; Zhao et al., 2001; Shen et al., 2011; Algeo and Ingall, 2007). Ba has a weak negative correlation with Ti, which also indicates that the Ba content was influenced by terrigenous sources. Therefore, the Ba content can be used as an indicator to measure palaeoproductivity after the Ba originating from the terrigenous sediments has been eliminated (Eagle et al., 2003). As the Ba originating from the terrigenous sediments cannot form independent minerals during magmatism, it enters the aluminosilicate lattice with K during magma differentiation. Based on this principle, we can assume that the continental Ba and Al are completely derived from aluminosilicates, and the Al does not have a chemical and biological genesis; and thus, Ba_{xs} can represent the palaeoproductivity when calculated as follows:

$$Ba_{xs} = Ba_{sam} - Ba_{sam} \times Al_{sam}/Al_{PAAS}, \quad (1)$$

where Ba_{sam} and Al_{sam} represent the Ba and Al concentrations of the samples, respectively; and Al_{PAAS} is the average concentration of Al in the post-Archean Australian shale (PAAS) from Taylor and Mclennan (1985). Yi et al., (2007) reported that Ba_{xs} values of >1000 ppm, 200–1000 ppm, and <200 ppm indicate high, medium, and low palaeoproductivities, respectively. The Ba_{xs} values of the Wenchang Formation samples are 48–12485 ppm, with an average of 2358 ppm, while those of the Liushagang Formation samples range from 173 ppm to 8715 ppm, with an average of 3253 ppm (Table 3, Fig. 5B), indicating that the Wenchang and Liushagang formations source rocks were predominantly formed under high palaeoproductivity conditions, and the palaeoproductivity of the Liushagang Formation was higher than that of the Wenchang Formation.

Moreover, previous studies have revealed that the organic matter of the Wenchang and Liushagang formations source rocks was mainly derived from lacustrine organisms, especially plankton (Li et al., 2015). P is negatively correlated with Ti, indicating a biogenic origin. Therefore, P can also be used as an alternative indicator of palaeoproductivity (Rimmer, 2004; Sannigrahi et al., 2006; Wang et al., 2019a,b). Generally, the P/Al ratio is used to characterize the nutritional level of lakes in order to eliminate the effect of P originating from terrigenous material. As is shown in Fig. 5B and Table 3, the P/Al ratios of the Wenchang and Liushagang formations source rocks are 0.102%–6.882% and 0.368%–6.345%, with averages of 0.795% and 1.485%, respectively, indicating the palaeoproductivity of the Liushagang Formation was higher than that of the Wenchang Formation.

In summary, the Ba and P concentrations of the samples indicate that the palaeoproductivities of both the Wenchang and Liushagang formations source rocks were high, but that of the Liushagang Formation was relatively higher.

5.1.4. *Palaeoclimate*

The palaeoclimate index (C), which is defined as (Fe + Mn + Cr + Ni + Co)/(K + Mg + Ca + Na + Sr + Ba), is a measure for the abundance of hygroscopic metal elements (Fe, Mn, Cr, Ni, and Co) compared with the abundance of dry metal elements (K, Mg, Ca, Na, Sr, and Ba) (Song, 2005; Li et al., 2015; Li and Zhou, 2007). The calculated results show that the palaeoclimate index (C) of the Wenchang and Liushagang formations source rocks fluctuated from 0.525 to 2.500 (average 0.918) and from 0.568 to 2.297 (average 1.343), respectively (Fig. 5C, Table 3), indicating that the wettability during the deposition of the Liushagang Formation was higher than that during the deposition of the Wenchang Formation.

Sr/Ba and Sr/Ca are good palaeoclimate proxies, and the drier the climate, the higher the Sr/Ba and Sr/Ca ratios (Song, 2005; Xiong and Xiao, 2011; Adegoke et al., 2014; Wang et al., 2018). As is shown in Table 3 and Fig. 5D and E, the Sr/Ba and Sr/Ca ratios of the Wenchang

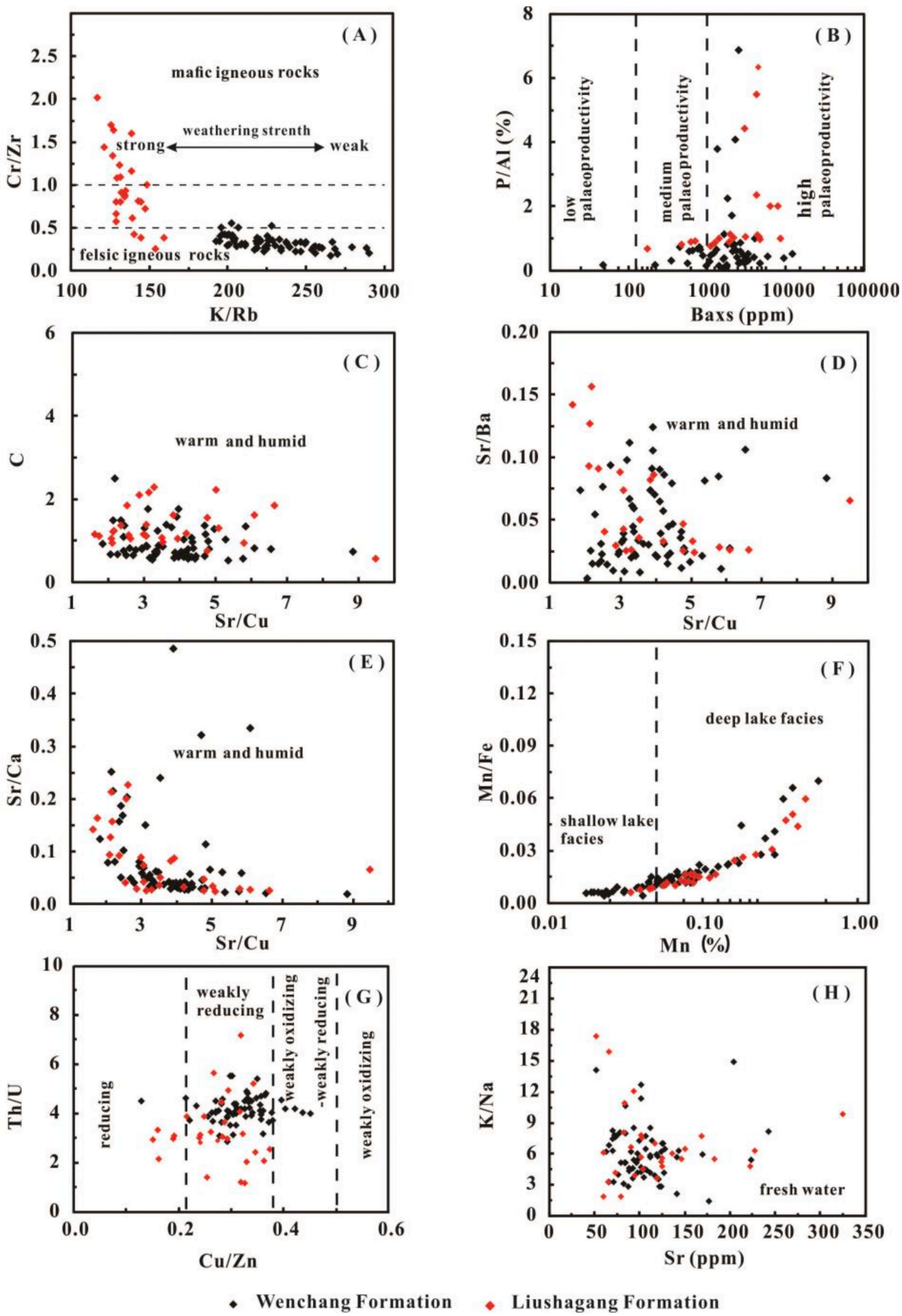

Fig. 5. Plots of (A) K/Rb vs. Cr/Zr, (B) Baxs (ppm) vs. P/Al (%), (C) Sr/Cu vs. C, (D) Sr/Cu vs. Sr/Ba, (E) Sr/Cu vs. Sr/Ca, (F) Mn (ppm) vs. Mn/Fe, (G) Cu/Zn vs. Th/U, and (G) Sr (ppm) vs. K/Na for Wenchang and Liushagang formations in the northern South China Sea.

Formation samples range from 0.019 to 0.484 (average 0.081) and 0.004 to 0.124 (average 0.045), respectively, while those of the Liushagang Formation samples range from 0.024 to 0.227 (average 0.079) and 0.004 to 0.039 (average 0.020), respectively, which also suggests that the climate was wetter during the deposition of the Liushagang Formation than during the deposition of the Wenchang Formation.

In addition, the Sr/Cu ratio can also be used to geochemically investigate palaeoclimate. Fu et al. (2016) and Zeng et al. (2019) reported that Sr/Cu ratios of 1–10 indicate a warm and humid climate and values of >10 indicate a dry and hot climate. Fig. 5C and E and Table 3 show that the Sr/Cu ratios of the Wenchang and Liushagang formations samples are 1.840–8.846 and 1.629–9.488, with averages of 3.812 and

3.693, respectively, indicating a warm and humid palaeoclimate during the deposition of both the Wenchang and Liushagang formations.

In summary, the above inorganic palaeoclimate proxies reveal that the Wenchang and Liushagang formations source rocks were deposited in a warm and humid palaeoclimate. This is consistent with the humid tropical-subtropical climate indicated by the sporopollen flora, in which the tropical-subtropical moist evergreen broad-leaved forest accounted for the largest proportion (Wang et al., 2005; Li, 2015). This suggests that these four inorganic proxies, that is, the palaeoclimate index and the Sr/Ba, Sr/Ca, and Sr/Cu ratios, are suited for the investigation of the palaeoclimate in the study area, which also supports the idea presented in Section 5.1.1.

5.1.5. *Palaeowater depth*

Studies of modern sedimentary geochemistry have shown that Mn tends to accumulate in deeper water areas, and Mn contents changes of 0.00094 ppm–0.0015 ppm to 0.051 ppm indicate a transition in lake water depth from shore-shallow to shallow to deep (Xiong and Xiao, 2011; Li et al., 2017). Mn is negatively correlated with Ti, so it is an effective indicator of the palaeowater depth of the lake in the study area. The Mn contents of the Wenchang Formation samples are 0.018–0.552 ppm (average 0.093 ppm) (Table 3), and the samples plot in the shallow and deep lake facies areas (Fig. 4F), whereas those of the Liushagang Formation samples vary from 0.034 ppm to 0.460 ppm, with an average of 0.1362 ppm (Table 3), and most of the samples plot in the deep lake facies area (Fig. 5F).

Contrary to Mn, Fe is often distributed in shallow water, so the Mn/Fe ratio increases with increasing water depth (Xiong and Xiao, 2011; Li et al., 2017). The Mn/Fe ratios of the Wenchang Formation samples are 0.004–0.070, with an average of 0.017, which is lower than those of the Liushagang Formation samples (0.006–0.060, average of 0.020) (Fig. 5F, Table 3). This indicates the palaeowater depth was deeper during the deposition of the Liushagang Formation, which is consistent with the conclusion drawn from the Mn values. This suggests that even if Fe has a mixed source, the Mn/Fe ratio is an effective indicator of palaeowater depth.

In conclusion, the depth of the lake water was shallower during the deposition of the Wenchang Formation, and it is estimated to have been >7 m according to the relationship between the sedimentary model and the palaeowater depth (Wang et al., 2006; Zhang et al., 2011), whereas during the deposition of the Liushagang Formation, the lake was deeper and may have been more than 20 m deep.

5.1.6. *Redox conditions*

Although both Cu and Zn are sulfophile elements, Zn has a stronger sulfophile affinity because its outermost electrons are more easily lost, while Cu can form sulfides only in strongly reducing environments due to its stability (Mou, 1999). Therefore, the Cu/Zn ratio is an effective indicator of redox conditions. Generally, Cu/Zn values of <0.21, 0.21–0.35, 0.35–0.5, 0.5–0.63, and >0.63 correspond to reducing, weakly reducing, weakly oxidizing to weakly reducing, weakly oxidizing, and oxidizing environments, respectively (Abedini and Calagari, 2017). The statistical results of the Cu/Zn ratios are presented in Table 3 and are shown in Fig. 5G. The Cu/Zn ratios of the Wenchang Formation samples are 0.129–0.451, with an average of 0.391, which are lower than those of the Liushagang Formation samples (0.151–0.375, average of 0.272), indicating that the Wenchang Formation was dominantly deposited under weakly reducing conditions, while the Liushagang Formation was deposited under weakly reducing to reducing conditions.

Similarly, both Th and U are lithophile elements with strong affinities for oxygen, and UO_2^{2+} is highly soluble under oxidizing environments and precipitates under reducing environment (Anderson et al., 1989; Arthur and Sageman, 1994). Thus, the Th/U ratio can reflect redox conditions, and the lower the value is, the stronger the reducibility is. As is shown in Table 3 and Fig. 5G, the Th/U ratios of the Wenchang and Liushagang formation samples are 2.853–5.514 and 1.177–7.170, with averages of 4.164 and 3.255, respectively, suggesting the reducibility of the water body was stronger during the deposition of the Liushagang Formation than during that the deposition of the Wenchang Formation.

The above analysis demonstrates that the Wenchang Formation was deposited in a weakly reducing environment, and the Liushagang Formation was deposited in a weakly reducing and reducing environment. Next, we must analyse the rationality of this conclusion from the perspective of the formation of a reducing environment due to factors such as the water depth and water stratification. In terms of water depth, compared with the Wenchang Formation, the palaeowater depth was deeper during the deposition of the Liushagang Formation, and there was a negative correlation between the palaeowater depth index (Mn) and the palaeo-oxygen facies indexes (Cu/Zn and Th/U) (Fig. 6A and B), indicating that the deep-water environment was closely related to the formation of a reducing environment. As far as water stratification is concerned, compared with the Wenchang Formation, temperature and salinity stratification of the water during the deposition of the Liushagang and Wenchang formations may have been weak in a freshwater environment in a subtropical humid climate (as was mentioned in Section 5.1.6 on palaeosalinity). Thus, Cu, Zn, Th, and U can be used to classify the redox conditions based on the consistency of the conclusions drawn from the Cu/Zn and Th/U ratios and the reasonable explanations discussed in this study area.

5.1.7. *Palaeosalinity*

K and Na are two elements with different adsorption capacities on clays and Illite lattices in water with various salinities. Jiao et al., (2004) reported that higher K/Na ratios reflect higher salinity. The K/Na ratios of the Liushagang and Wenchang formations samples are 1.391–14.870 and 1.843–17.368, with averages of 6.056 and 6.767, respectively (Fig. 5H, Table 3), indicating that the palaeosalinity of the water was slightly higher during the deposition of the Liushagang Formation than during the deposition of the Wenchang Formation.

Sr is widely considered to be a sensitive palaeosalinity indicator. Generally, Sr concentrations of <300 ppm, 300–500 ppm, and >500 ppm suggest fresh water, brackish water, and salt water, respectively (Zheng and Liu, 1999; Li and Chen, 2003). The Sr contents of the Wenchang Formation samples range from 51.788 ppm to 242.601 ppm, with an average of 106.496 ppm, while those of the Liushagang Formation samples range from 51.6 ppm to 325.5 ppm, with an average of 120 ppm (Fig. 5H, Table 3), suggesting that both the Liushagang and Wenchang formations source rocks were deposited in a predominantly freshwater environment.

In summary, the palaeosalinity of the water body was slightly higher during the deposition of the Liushagang Formation than during the deposition of the Wenchang Formation, but they were both deposited in a freshwater environment. The possible reason for this is that the water was not affected by the transgression during the Eocene deposition, but the steep slopes provided more minerals during the deposition of the Liushagang Formation, as was previously mentioned. Therefore, like the palaeo-oxygen facies index, K/Na and Sr are effective indicators of palaeosalinity.

5.2. *Main factors controlling the development of the source rocks*

The development of source rock is generally related to the palaeoproductivity and preservation conditions of the organic matter. Statistical correlation analysis is one of the commonly used and most effective methods of determining the factors controlling the development of source rocks (Canfield, 1994; Wang et al., 2019a,b). The regular geology and the relationships between the TOC and the geochemical palaeoenvironment indicators were analysed comprehensively in this study to reveal the main controlling factors in the study area (Fig. 7).

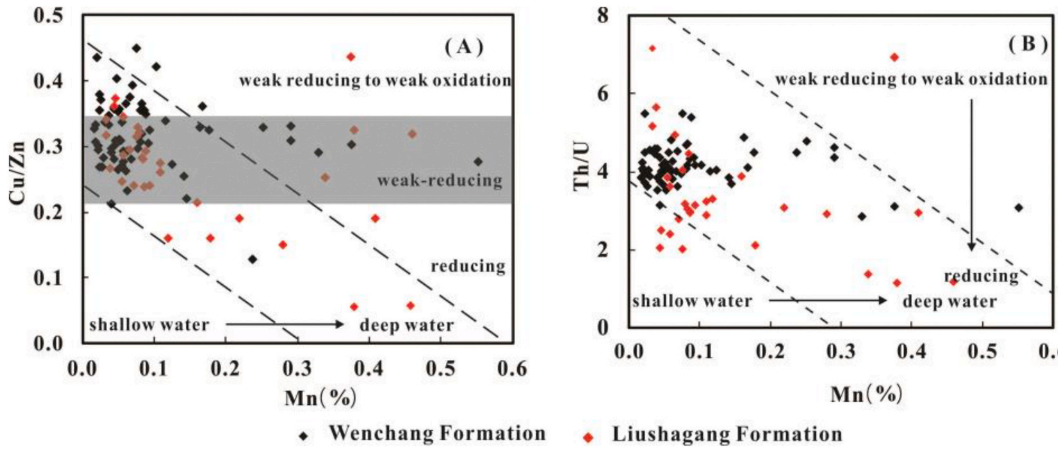

Fig. 6. Plots of Mn versus (A) Cu/Zn, and (B) Th/U for Wenchang and Liushagang formations in the northern South China Sea.

(1) Provenance

Mou (1999) reported that P is one of the essential elements for the normal growth of phytoplankton, and the P content can reach up to over 1.8%. Hutchins et al. (1999), Johnson et al. (1999), Bod et al. (2000), Hurtado et al. (2004), and Mcgillicuddy et al. (2007) demonstrated that Fe can promote the absorption of nutrients by planktonic algae when phosphate and other nutrients are sufficient through the study of the relationship between volcanic activity or Fe and algal blooms. However, P and Fe must be derived from the dissolution of minerals in the surrounding terrane and parent rocks. After bioabsorption, they are deposited at the bottom with the death of organisms. Consequently, the lithology of the parent rocks and the degree of weathering in the provenance area are a significant factor controlling their availability. Compared with the felsic igneous rock provenance of the Wenchang Formation, the mafic igneous rock provenance of the Liushagang Formation contained more nutrient elements, such as Fe, and the parents rocks were subjected to strong weathering and could provide more nutrients (e.g., P) for the growth of the organisms in the lake basin. This may have been the reason the palaeoproductivity of the Liushagang Formation was higher than that of the Wenchang Formation. The concrete reasons for the differences in the lithology of the parent rocks and the degrees of weathering have been discussed in Section 5.1.2). In addition, the relationships between TOC and the provenance parameters (Cr/Zr and K/Rb) have medium-high positive correlations for all of the Wenchang and Liushagang formations source rock samples with correlation coefficients (R) of 0.677 and 0.453 (Fig. 7A and B), respectively, indicating that the lithology of the parent rocks and the degree of weathering significantly influenced the organic matter enrichment of the Wenchang and Liushagang formations.

(2) Palaeoproductivity

The palaeoproductivity of a water body provides a material basis for the formation of organic-rich sediments. The palaeoproductivities of both the Wenchang and Liushagang formations source rocks were high, but that of Liushagang Formation was higher(The concrete reasons for the differences in their palaeoproductivities are discussed in the provenance and palaeoclimate subsections of this section). This is consistent with the distribution of the TOC, suggesting that palaeoproductivity had an effect on the development of the Wenchang and Liushagang formations source rocks. The relationship between TOC and palaeoproductivity is also supported by Fig. 7D. There is no correlation between TOC and the palaeoproductivity indices (Baxs), with an R value of only 0.084 (Fig. 7C). This is ascribed to the fact that Baxs will be dissolved in a reducing environment.

(3) Palaeoclimate

Climate is regarded as a major controlling factor of organic matter input. A warm-humid climate is beneficial to the mineral nutrient supply and phytoplankton growth (Talbot, 1988; Makeen et al., 2015). Both the Wenchang and Liushagang formations source rocks were deposited in a warm and humid palaeoclimate, which may also be one of the reasons that the palaeoproductivities of both the Wenchang and Liushagang formations source rocks were high. The palaeoclimate proxies (C and the Sr/Ba and Sr/Ca ratios) have a weak-intermediate correlation with TOC (Fig. 7E–G), which also indicated that the warm and humid environment played a positive role in the development of the source rocks.

(4) Palaeowater depth

As was discussed in Section 5.1.4, the palaeowater depth affected the development of the source rock by influencing the redox conditions, and the deeper water of Liushagang Formation was more favourable for the preservation of organic matter than the Wenchang Formation. However, a positive relationship only exists between TOC and the palaeowater depth indicators (Mn and Mn/Fe ratio) for the Wenchang Formation samples (Fig. 7I and J), indicating that the palaeowater depth significantly affected the development of the Wenchang Formation source rocks but was not one of the main factors controlling the development of the Liushagang Formation source rocks.

(5) Redox conditions

After the production and deposition of organic matter, there are still the burial and preservation processes to consider. In other words, the quantity of the original organic matter does not always lead to a high abundance of sedimentary organic matter, which is often preserved and enriched or destroyed and diluted due to various factors during the deposition process. Harevy (1995) reported that the turnover period of various organic components in water is less than 45 days under oxidizing conditions, while it is 1.4–10.4 times greater under reducing conditions based on an experiment on the changes in the different biochemical components of diatoms, cyanobacteria, and lumbar flagellates in water. Therefore, the redox conditions are an important factor affecting the preservation of organic matter. As was discussed in the previous section, the Liushagang Formation samples were deposited under weakly reducing and reducing conditions, which are more favourable for the preservation of organic matter than the weakly reducing Wenchang Formation's deposition environment. The Th/U redox proxy is only weakly correlated with TOC for the Wenchang and Liushagang formation samples (Fig. 7L), indicating that the redox conditions affected the development of the source rocks, but the effect was

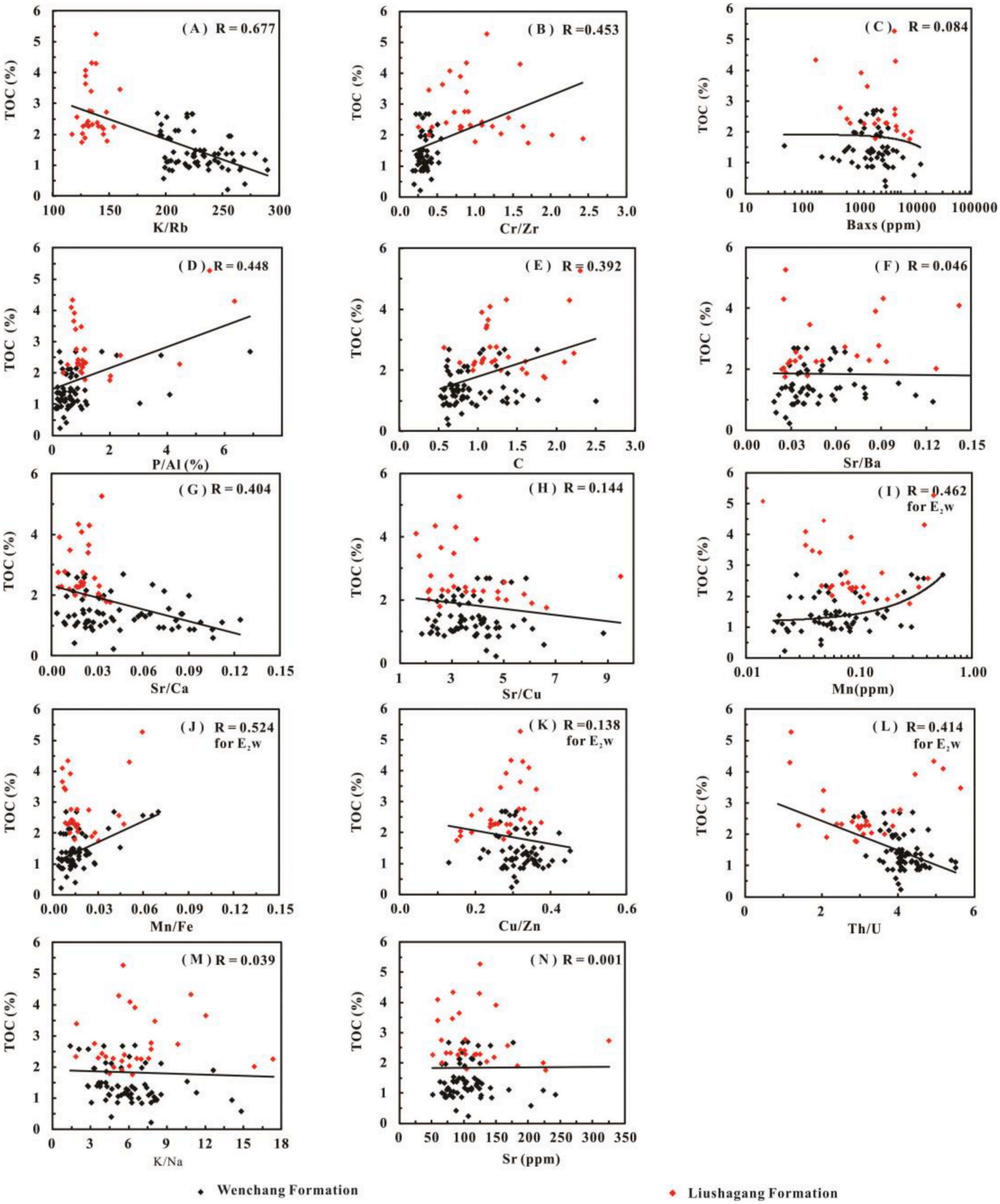

Fig. 7. Plots of TOC (%) vs. (A) K/Rb, (B) Cr/Zr, (C) Baxs (ppm), (D) P/Al (%), (E) C, (F) Sr/Ba, (G) Sr/Ca, (H) Sr/Cu, (I) Mn (ppm), (J) Mn/Fe, (K) Cu/Zn, (L) Th/U, (M) Sr (ppm), and (N) K/Na for Wenchang and Liushagang formations in the northern South China Sea.

small. The reason for this may be that the role of organic matter productivity is more important than the reducibility during the development of source rocks. To verify this hypothesis, the samples were divided into high productivity and medium productivity groups; the results show that reducibility plays an important role in the development of source rocks, with an importance similar to that of palaeoproductivity (Fig. 8A and B). Therefore, palaeoproductivity played a more important role than the redox conditions. It should be noted that there is a medium correlation ($R = 0.414$) between TOC and Th/U for the Wenchang Formation samples (Fig. 7L), indicating that the redox conditions had an effect on the TOC. In addition, the TOC is not correlated with the Cu/Zn ratio (Fig. 7K), which may be because the Cu/Zn ratio cannot reflect the subtle variations in the oxygen content.

(6) Palaeosalinity

As was discussed in the previous section, the samples analysed in this study were deposited in a freshwater environment, which was not

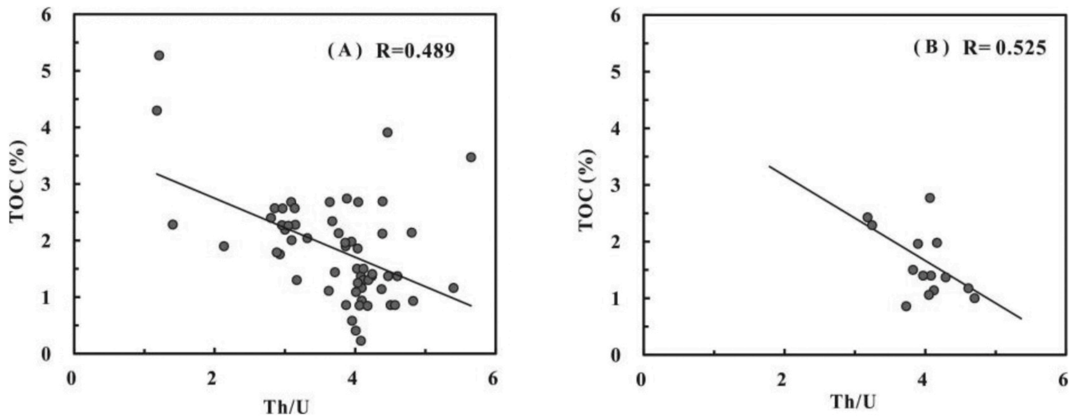

Fig. 8. Plots of TOC vs. Th/U for (A) high palaeoproductivity and (B) middle palaeoproductivity in the northern South China Sea.

favourable to the formation of a reducing environment. No correlations were observed between the palaeosalinity indexes (K/Na ratio and Sr) and TOC (Fig. 7M, N) for the Wenchang and Liushagang formation samples, which also suggests that palaeosalinity may had very little influence.

Generally, during the deposition of the Eocene lacustrine source

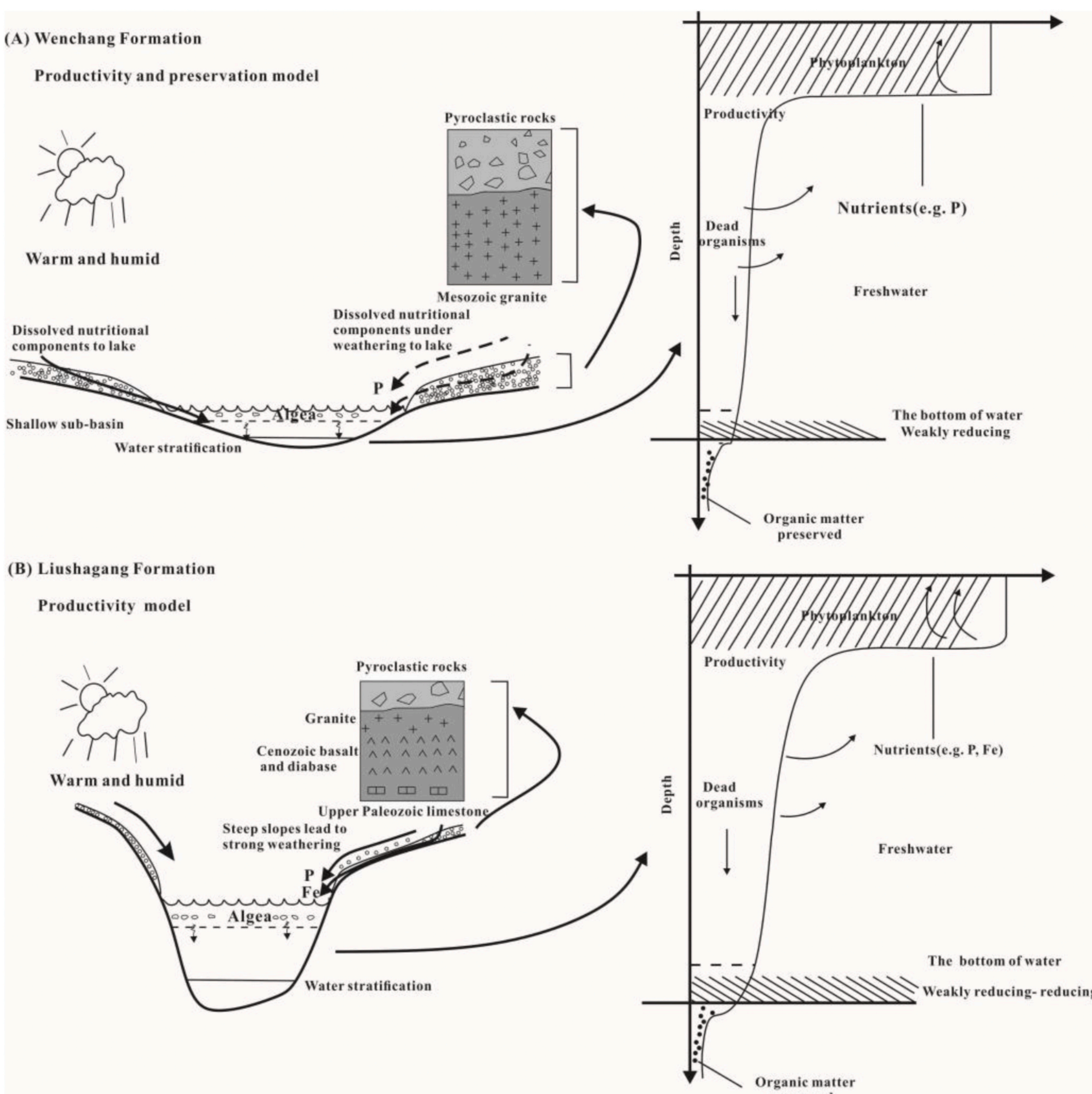

Fig. 9. Developmental models for the two source rock intervals, (A) Wenchang Formation deposition stage and (B) Liushagang Formation deposition stage, showing the palaeoenvironments and the factors controlling the formation of the source rocks in the northern South China Sea.

rocks, the mafic igneous rock provenance provides macronutrients (e.g. P, Fe) to form nutrient rich water under a strong degree of weathering, which was the material basis for the growth of phytoplankton. The high palaeoproductivity was the source of organic matter, and the palaeoclimate played an indirect role in the high palaeoproductivity. The deep water reducing environment resulted in good organic matter preservation conditions, but the palaeosalinity had little effect. High-quality source rocks can be formed in the nutrient rich water under the conditions formed by the strong weathering of a mafic igneous rock provenance, and the high palaeoproductivity in the Liushagang Formation. However, the nutrient content and palaeoproductivity of the Wenchang Formation were lower than those of the Liushagang Formation, and good preservation conditions in deep and reducing water were also needed, which was also the main reason why the quality of the Wenchang Formation source rocks is lower than that of the Liushagang Formation source rocks.

5.3. Developmental models for the lacustrine source rocks

To summarize the above analysis, combined with the theory of organic matter deposition (Rullkotter, 1999), two developmental models for the Eocene lacustrine source rocks in the northern South China Sea were created, that is, the productivity and preservation model for the Wenchang Formation source rocks and the productivity model for the Liushagang Formation source rocks. Both of these models can develop high-quality source rocks. However, due to the differences in the nutrients and palaeoproductivity, the overall quality of the source rocks developed by the former were lower than those of the latter.

During the deposition of the Wenchang Formation (Fig. 9A), the Zhuyi sag was located in a shallow basin with a large lake; the sediment supplies were dominated of the Mesozoic granite and pyroclastic rocks from the low bulges and uplift zones in the Zhuyi sub-basin; and the weathered felsic volcanic rocks provided the nutritional components for algae growth. In addition, the warm and humid climate provided a good environment for the algae to grow in the surface water, resulting in a high palaeoproductivity in the surface of water. However, the organic matter content decreases sharply with increasing depth due to the consumption (e.g. microbial decomposition) of organisms in the weakly reducing water until the organic matter is buried by sediments at the bottom of the water column, and the redox conditions are influenced by the palaeowater depth during this process. In this model, high-quality source rocks are formed due to high palaeoproductivity and good preservation of organic matter.

During the deposition of the Liushagang Formation (Fig. 9B), the sediment supplies mainly came from the low bulges and uplift zones in the Weixinan sub-basin; and the parent rocks were composed of granite, clastic rocks, and Upper Palaeozoic limestone. However, with the basalt eruptions and the shallow diabase intrusion at about 45 Ma, the contents of the nutrient elements, such as Fe, in the parent rocks were significantly improved. In addition, the slope gradient of the lake basin gradually became steeper due to the uplift of the Weixinan low and the Qixi uplifts, resulting in a strong degree of weathering of the parent rocks, so more of the nutrient elements in the parent rocks were transported into the lake water. The warm and humid climate also provided a good environment for algae growth in the surface water, which facilitated the bloom of algae and a high palaeoproductivity. The residual process is similar to that of the organic matter deposition in the Wenchang Formation. The difference is that the loss of organic matter may have been less than that of the Wenchang Formation duo to the weakly reducing-to-reducing conditions during the deposition of the bottom of the Liushagang Formation. However, the palaeoproductivity of this area was very high, and the output of the sedimentary organic matter was maintained at a high level under weakly reducing conditions. In other words, the development of the high-quality source rocks was due to the high palaeoproductivity. The quality of the source rocks developed in this model was higher than that of those developed in the productivity and preservation model.

6. Conclusions

There were two developmental models for the Eocene lacustrine source rocks in the northern South China Sea, that is, the productivity and preservation model for the Wenchang Formation source rocks and the productivity model for the Liushagang Formation source rocks. Both of these models can develop high-quality source rocks, but the quality of source rock developed in the productivity model was higher than that developed in the productivity and preservation model. This was mainly attributed to the differences in the amount of nutrients and the palaeoproductivity. During the deposition of the Liushagang Formation, the parent rocks were composed of mafic igneous rocks with minor felsic igneous rocks and had a strong degree of weathering; the palaeoclimate was warm and humid; and the water was characterized by a high palaeoproductivity, deep water, weakly reducing-reducing and freshwater. In addition, the formation of high-quality source rocks was mainly controlled by two factors. (1) The mafic igneous rock provenance under strong weathering provided macronutrients (e.g. P, Fe) for the water, which was the material basis for the growth of phytoplankton. (2) The high palaeoproductivity provided a source of organic matter, which played a more important role than the preservation conditions of the organic matter. In this model, the development of the high-quality source rocks was due to the high palaeoproductivity. During the deposition of the Wenchang Formation, the parent rocks were mainly felsic igneous rocks, and the degree of weathering of the parent rocks was lower than that for theLiushagang Formation; the palaeoclimate was warm and humid; and the water was characterized by a high palaeoproductivity, shallow-deep water, and weakly reducing and freshwater. In this model, the good organic matter preservation conditions of the deep and reducing water were also needed, expect for the high productivity, so the high-quality source rocks were formed due to the high palaeoproductivity and good preservation of the organic matter.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2021.105015.

References

Abedini, A., Calagari, A.A., 2017. Geochemistry of claystones of the Ruteh Formation, NW Iran: implications for provenance, source-area weathering, and paleo-redox conditions. Neues Jahrbuch fur Mineralogie, Abhandlungen 194, 107–123.

Abell, P.I., Nyamweru, C.K., 1988. Paleoenvironments in the chalbi basin of Kenya. Chem. Geol. 72, 283–291.

Adegoke, A.K., Andreu, B., Abdullah, W.H., Hakimi, M.H., Yandoka, B.M.S., 2014. Geochemical characterisation of Fika Formation in the Chad (Bornu)Basin, northeastern Nigeria: implications for depositional environment and tectonic setting. Appl. Geochem. 43, 1–12.

Alalade, B., 2016. Depositional environments of late cretaceous gongila and fika formations, Chad (bornu) basin, northeast Nigeria. Mar. Petrol. Geol. 75, 100–116.

Algeo, T.J., Ingall, E., 2007. Sedimentary C_{org}: P ratios, paleocean ventilation, and phanerozoic atmospheric pO_2. Palaeogeogr. Palaeoclimatol. Palaeoecol. 256, 130–155.
Anderson, R.F., Fleisher, M.Q., Lehuray, A.P., 1989. Concentration, oxidation state, and particulate flux of uranium inthe Black Sea. Geochem. Cosmochim. Acta 53, 2215–2224.
Arthur, M.A., Sageman, B.B., 1994. Marine black shales: depositional mechanisms and environments of ancient deposits. Annu. Rev. Earth Planet Sci. 22, 499–551.
Bao, X.H., Ji, Y.B., Hu, Y., 2017. Geochemical characteristics, origins, and model of lacustrine source rocks in the Zhu 1 depression, eastern Pearl River Mouth Basin, South China Sea. AAPG (Am. Assoc. Pet. Geol.) Bull. 101, 1543–1564.
Bauluz, B., Mayayo, M.J., Nieto, C.F., Lopez, J.M.G., 2000. Geochemistry of Precambrian and Paleozoic siliciclastic rocks from the Iberian Range (NE Spain): implication for source-area weathering, sorting, provenance, and tectonic setting. Chem. Geol. 168, 135–150.
Boyd, P.W., Watson, A.J., Law, C.S., 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. Nature 407, 695–702.
Canfield, D.E., 1994. Factors influencing organic carbon preservation in marine sediments. Chem. Geol. 114, 315–329.
Cao, J., Zhang, Y.J., Hu, W.X., Yao, S.P., Wang, X.L., Zhang, Y.Q., Tang, T., 2005. The Permian hybrid petroleum system in the northwest margin of the Junggar Basin, northwest China. Mar. Petrol. Geol. 22, 331–349.
Cao, J., Yang, R.F., Hu, G., Hu, W.X., Xie, Y.G., Gao, Y.G., Gao, J., 2018. Hydrocarbon potential of the Lower Cretaceous mudstones in coastal southeastern China. AAPG (Am. Assoc. Pet. Geol.) Bull. 102 (2), 333–366.
Chen, Z.P., Cui, J.P., Ren, Z.L., Jiang, S., Liang, X., Wang, G.C., Zou, C., 2019. Geochemistry, paleoenvironment and mechanism of organic-matter enrichment in the Lower Silurian Longmaxi Formation shale in the Sichuan Basin, China. Acta Geologica Sinica (English Edition) 93, 505–519.
Chen, Z., Ding, Z., Tang, Z., Yang, S., Wang, X., Cui, L., 2017a. Paleoweathering and paleoenvironmental change recorded in lacustrine sediments of the early to middle Eocene in Fushun Basin, Northeast China. G-cubed 18, 41–51.
Chen, Z.P., Cui, J.P., Ren, Z.L., Jiang, S., Liang, X., Wang, G.C., Zou, C., 2017b. Paleoenvironment and mechanism of organic-matter enrichment in the lower silurian Longmaxi Formation shale in the sichuan basin, China. Acta Geol. Sin. 93, 505–519.
Degens, E.T., Mopper, K., 1976. Factors controlling the distribution and early diagenesis of organic material in marine sediments. In: Riley, J.P., Chester, R. (Eds.), Chemical Oceanography. Academic Press, London.
Dehairs, F., Chesselet, R., Jedwab, J., 1980. Discrete suspended particles of barite and the barium cycle in the open ocean. Earth Planet Sci. Lett. 49, 528–550.
Dymond, J., Suess, E., Lyle, M., 1992. Barium in deep-sea sediment: a geochemical proxy for paleoproductivity. Paleoceanography 7, 163–181.
Eagle, M., Paytan, A., Arrigo, K.R., Dijken, G. Van, Murray, R.W., 2003. A comparison between excess barium and barite as indicators of carbon export. Paleoceanography 18, 1–13.
Fan, Q.C., Sun, Q., Long, A.M., Yin, K.J., Sui, J.L., Li, N., 2006. Geology and eruption history of volcanoes in weizhou island and xieyang island, northern bay. Acta Petrol. Sin. 22, 1529–1537.
Francois, R., Honjo, S., Manganini, S.J., 1995. Biogenic barium fluxes to the deep sea: implications for paleoproductivity reconstruction. Global Biogeochem. Cycles 9, 289–303.
Fu, X.G., Wang, J., Chen, W.B., Feng, X.L., Wang, D., Song, C.Y., Zeng, S.Q., 2016. Elemental geochemistry of the early Jurassic black shales in the Qiangtang Basin, eastern Tethys: constraints for palaeoenvironment conditions. Geology 51, 443–454.
Ghosh, S., Sarkar, S., 2010. Geochemistry of permo-triassic mudstone of the satpura gondwana basin, central India: clues for provenance. Chem. Geol. 277, 78–100.
Goldberg, E.D., Arrhenius, G.O.S., 1958. Chemistry of Pacific pelagic sediments. Geochem. Cosmochim. Acta 13, 153–212.
Gong, Z.S., Li, S.T., 1997. Continental Margin Basin Analysis and Hydrocarbon Accumulation in the Northern Part of the South China Sea. Science Press, Beijing, pp. 44–122.
Gonçalves, F.T.T., 2002. Organic and isotope geochemistry of the Early Cretaceous rift sequence in the Camamu Basin, Brazil: paleolimnological inferences and source rock models. Org. Geochem. 33, 67–80.
Govindaraju, G., 1994. Compilation of working values and sample description for 383 geostandards. Geostand. Newsl. 18, 1–158.
Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SE Pacific: computer-based reconstructions, model and animations. J. Asian Earth Sci. 20, 353–413.
Hao, F., Zhou, X., Zhu, Y., Yang, Y., 2011. Lacustrine source rock deposition in response to co-evolution of environments and organisms controlled by tectonic subsidence and climate, Bohai Bay Basin, China. Org. Geochem. 42, 323–339.
Harris, N.B., Freeman, K.H., Pancost, R.D., White, T.S., Mitchell, G.D., 2004. The character and origin of lacustrine source rocks in the Lower Cretaceous synrift section, Congo Basin, west Africa. AAPG (Am. Assoc. Pet. Geol.) Bull. 88, 1163–1184.
Harvey, H.R., Tuttle, J.U., Bell, J.T., 1995. Kinetics of phytoplankton decay during simulated sedimentation : Changes in biochemical composition and microbial activity under oxic and anoxic condition. Geochem. Cosmochim. Acta 59, 3367–3377.
Hou, Y.G., He, S., Yang, X.H., Duan, W., Zhu, G.H., Xu, X.M., Dong, T., 2015. Geochemical characteristics and development model of transitional source rocks during the continental margin rifting stage, Bonaparte Basin, Australia. Petroleum Geology & Experiment 37, 375–382.
Hu, Y., 2019. Basin structure and genetic evolution of the Zhu 1 depression during the cenozoic, Pearl River Mouth Basin, south China. Geol. J. China Univ. 25, 81–92.
Huang, Z., 1998. Nonmarine source rock and petroleum formation of Pearl River Mouth basin. China Offshore Oil Gas 12, 255–261.
Huntsman-Mapila, P., Kampunzu, A.B., Vin, B., Ringrose, S., 2005. Cryptic indicators of provenance from the geochemistry of the Okavango Delta sediments, Botswana. Sediment. Geol. 174, 123–148.
Hurchison, C., 2004. Marginal basin evolution: the southern south China sea. Marine and petroleum geology, 21, 1129–1148.
Hurtado, L.A., Lutz, R.A., Vrijenhoek, R.C., 2004. Distinct patterns of genetic differentiation among annelids of eastern Pacific hydrothermal vents. Mol. Ecol. 13, 2603–2615.
Hutchins, D.A., Witter, A.E., Butler, A., 1999. Competition among marine phytoplankton for different chelated iron species. Nature 400, 858–861.
Jacobson, A.D., Blum, J.D., 2003. Relationship between mechanical erosion and atmospheric CO_2 consumption in the New Zealand Southern Alps. Geology 31, 865–868.
Jia, L.B., Ji, Y.L., Zhong, D.K., Yan, R.T., Liu, J.L., Mi, L.J., Yi, Z., Yu, J.S., Zhang, P.C., 2017. Depositional filling model of the Eocene Wenchang Formation in rift stage of L sag , Pearl River Mouth Basin. Journal of Palaeogeography 19, 525–540.
Jiao, Y.Q., Lu, X.B., Wang, Z.H., Wang, M.F., 2004. Two distinct geological environments from sedimentary to diagenesis stages: examples from sandstone-type uranium deposits, Turpan-Hami Basin. Earth Sci. 29, 615–620.
Johnson, K.S., Chavez, F.P., Friederich, G.E., 1999. Continental-shelf sediment as a primary source of iron for coastal phytoplankton. Nature 398, 697–700.
Jones, G.E., 1973. An ecological survey of open ocean and estuarine microbial populations. 1. The importance of trace metal ions to microorganisms in the sea. In: Stevenson, L.H., Colwell (Eds.), Estuarine Microbial Ecology. University of South Carolina Press, Columbia.
Kahle, M., Kleber, M., Jahn, R., 2002. Review of XRD-based quantitative analyses of clay minerals in soils: the suit ability of mineral intensity factors. Geoderma 109, 191–205.
Kang, A., Yang, L., 2010. Lacustrine source rock occurrence and its petroleum reservoir distribution of Paleogene fault basins in Offshore China and Southeast Asia. Petroleum Xinjiang Petroleum Geology 31, 337–340.
Lézin, C., Andreu, B., Pellenard, P., Bouchez, J.L., Emmanuel, L., Fauré, P., Landrein, P., 2013. Geochemical disturbance and paleoenvironmental changes during the early toarcian in NW europe. Chem. Geol. 341, 1–15.
Li, Y.C., 2015. Main controlling factors for the development of high quality lacustrine hydrocarbon source rocks in offshore China. China Offshore Oil Gas 27, 1–8.
Li, J.L., Chen, D.J., 2003. Summary of quantified research method on paleosalinity. Petroleum Geology and Recover Efficiency 10, 1–3.
Li, W.H., Zhang, Z.H., 2018. Paleoenvironment and its control of the formation of Oligocene marine source rocks in the deep-water area of the northern South China Sea. Energy Fuels 31, 10598–10611.
Li, J.Y., Zheng, L.H., 2007. Study on petroleum geology in south China sea basins. Special Oil Gas Reservoirs 14, 22–28.
Li, M.L., Lu, H., Wang, T.G., Wu, W.Q., Liu, J., Gao, L.H., 2006. Relationship between magma activity and CO_2 gas accumulation in Fushan depression, Beibuwan basin. Natural Gas Geoscience 17, 55–59.
Li, Y.C., Mi, L.J., Z, G.H., 2011. The formation and distribution of source rocks for deep water area in the northern of South China Sea. Acta Sedimentol. Sin. 29, 970–979.
Li, H., Lu, J.L., Li, R.L., 2017. Generation paleoenviroment and its controlling factors of lower cretaceous lacustrine hydrocarbon source rocks in changling depression, south songliao basin. Earth Sci. 42, 1774–1786.
Li, C., Yang, X.B., Fan, C.W., Hu, L., Dai, L., Zhao, S.L., 2018. On the evolution process of the Beibu Gulf Basin and forming mechanism of local structures. Acta Geol. Sin. 92, 2028–2039.
Liang, L.R., Xu, G.S., Xu, F.H., L, J.J., W, D.Y., 2018. Paleoenvironmental evolution and organic matter accumulation in an oxygen-enriched lacustrine basin: a case study from the Laizhou Bay Sag, southern Bohai Sea (China). Int. J. Coal Geol. 19.
Liu, Y.S., Zong, K.Q., Kelemen, P.B., Gao, S., 2008. Geochemistry and magmatic history of eclogites and ultramafic rocks from the Chinese continental scientific drill hole: subduction and ultrahigh-pressure metamorphism of lower crustal cumulates. Chem. Geol. 247, 133–153.
Liu, S.L., Wang, Q.F., Gong, C.J., et al., 2012. Paleogene microfossil assemblages from the Bohai area and their importance for the oil and gas exploration. Journal of Stratigaraphy 36, 700–709.
Makeen, Y.M., Mohammed, H.H., Wan, G.A., 2015. The origin, type and preservation of organic matter of the Barremian-Aptian organic-rich shales in the Muglad Basin, Southern Sudan, and their relation to paleoenvironmental and paleoclimate conditions. Mar. Petrol. Geol. 65, 187–197.
Mcgillicuddy, D.J., Anderson, L.A., Bates, N.R., 2007. Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms. Science 316, 1021–1026.
Meng, Q., Liu, Z., Bruch, A.A., et al., 2012. Palaeoclimatic evolution during Eocene and its influence on oil shale mineralisation, Fushun basin, China. J. Asian Earth Sci. 45, 95–105.
Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Org. Geochem. 27, 213–250.
Meyers, P.A., Arnaboldi, M., 2005. Trans-Mediterranean comparision of geochemical paleoproductivity proxies in a Mid-Pleistocene interrupted sapropel. Palaeogeograghy, Palaeochimatology, Palaeoecology 222, 313–328.
Middelburg, J.J., Meysman, F.J.R., 2007. Burialat sea. Science 316, 1294–1295.
Moradi, A.V., Sari, A., Akkaya, P., 2016. Geochemistry of the Miocene oil shale (Hançili Formation) in the Çankırı-Çorum Basin, Central Turkey: implications for

Paleoclimate conditions, source–area weathering, provenance and tectonic setting. Sediment. Geol. 341, 289–303.
Mou, B.L., 1999. Element Geochemistry. Peking University Press, Beijing, pp. 1–225.
Murray, R.W., Leinen, M., 1996. Scavenged excess aluminum and its relationship to bulk titanium in biogenic sediment from the central equatorial Pacific Ocean. Geochimica et Cosmochimca Acta 60, 3869–3878.
Qin, J.Z., 2005. Hydrocarbon Source Rocks of China. Science Press, Beijing.
Quan, Y.B., 2018. Lacustrine Source Rock Development Mechanism and its Contribution to Hydrocarbon Accumulation in Zhu III Sub-basin, Pearl River Mouth Basin. China University of Geosciences.
Quan, Y.B., Liu, J., Zhao, D., Hao, F., Wang, Z., Tian, J., 2015. The origin and distribution of crude oil in Zhu III sub-basin, Pearl River Mouth Basin, China. Mar. Petrol. Geol. 66, 732–747.
Quan, Y.B., Hao, F., Liu, J., Zhao, D., Tian, J., Wang, Z., 2017. Source rock deposition controlled by tectonic subsidence and climate in the western Pearl River Mouth Basin, China: evidence from organic and inorganic geochemistry. Mar. Petrol. Geol. 79, 1–17.
Riebe, C.S., Kirchner, J.W., Granger, D.E., Finkel, R.C., 2001. Strong tectonic and weak climatic control of long-term chemical weathering rates. Geology 29, 511–514.
Rimmer, S.M., 2004. Geochemical paleoredox indicators in devonian–mississippian black shales, central appalachian basin (USA). Chem. Geol. 206, 373–391.
Rullkotter, J.Z., 1999. Organic Matter:The driving force for early digenesis. In: Marine Geochemistry. Springer Verlag, Berlin Heidelberg, pp. 129–172.
Sampa, G., Soumen, S., 2010. Geochemistry of Permo-Triassic Mudstone of the Satpura Gondwana Basin, Central India: Clues for Provenance, vol. 277, pp. 78–100.
Sannigrahi, P., Ingall, E.D., Benner, R., 2006. Nature and dynamics of phosphorus containing components of marine dissolved and particulate organic matter. Geochem. Cosmochim. Acta 70, 5868–5882.
Schmitz, B., 1987. Barium, equatorial high productivity and the northward wandering of the Indian continent. Paleoceanography 2, 63–77.
Shen, J., Shi Z, Y., Feng, Q.L., 2011. Review on geochemical proxies in paleo-productivity studies. Geol. Sci. Technol. Inf. 30, 69–77.
Song, M.S., 2005. Sedimentary environment geochemistry in the Shasi section of southern ramp, Dongying depression. Mineral. Petrol. 2, 67–73.
Talbot, M.R., 1988. The Origins of Lacustrine Oil Source Rocks: Evidence from the Lakes of Tropical Africa. Geological Society, London, Special Publications40, pp. 29–43.
Tawfik, H.A., Ghandour, I.M., Maejima, W., Armstrong-Altrin, J.S., Abdel-Hameed, A.-M. T., 2017. Petrography and geochemistry of the siliciclastic Araba Formation (Cambrian), east Sinai, Egypt: implications for provenance, tectonic setting and source weathering. Geology Magazine 154, 1–23.
Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: its Composition and Evolution. Blackwell Scientific Publication, Carlton, p. 312.
Wang, Q., Fu, X.W., Xu, Z.M., 2005. Development and application of stable carbon iostopes in natural gas and oil geochemistry. Natural Gas Geoscience 16, 233–237.
Wang, M.F., Huang, C.Y., Xu, Z.C., Chen, J.X., Yang, S., 2006. Review on paleosalinity recovery in sedimentary environment. Xinjiang Oil & Gas 2, 9–12.
Wang, J., Wang, Q., Zhong, X.M., Dong, X.Y., Ma, X.F., Sui, L.M., 2015. Characteristics of high-quality hydrocarbon source rocks and their contributions to reservoirs in the Erlian Basin. Petroleum Geology & Experiment 37, 642–647.
Wang, C., Wang, Q., Chen, G., He, L., Xu, Y., Chen, L., Chen, D., 2017a. Petrographic and geochemical characteristics of the lacustrine black shales from the Upper Triassic Yanchang Formation of the Ordos Basin, China: implications for the organic matter accumulation. Mar. Petrol. Geol. 86, 52–65.
Wang, Z.W., Fu, X.G., Feng, X.L., Song, C.Y., Wang, D., Chen, W.B., Zeng, S.Q., 2017b. Geochemical features of the black shales from the Wuyu Basin, southern Tibet: implications for palaeoenvironment and palaeoclimate. Geology Journal 52, 282–297.
Wang, Z.W., Wang, J., Fu, X.G., Z, W.Z., Armstrong-Altrin, J.S., Yu, F., Feng, X.L., Song, C.Y., Zeng, S.Q., 2018. Geochemistry of the upper triassic black mudstones in the qiangtang basin, tibet: implications for paleoenvironment, provenance, and tectonic setting. J. Asian Earth Sci. 160, 118–135.
Wang, N., Li, M.J., Tian, X.W., Hong, H.T., Liu, P., Chen, G., Wang, M.L., 2019a. Main factors controlling the organic matter enrichment in the Lower Cambrian sediments of the Sichuan Basin, SW China. Geol. J. 55, 1–14.
Wang, Y.X., Shang, X., Hao, F., Lu, Y.B., Shu, Z.G., Yan, D.T., Lu, Y.C., 2019b. Geochemistry, Geochemical and petrographic characteristics of Wufeng-Longmaxi shales, Jiaoshiba area, southwest China: implications for organic matter differential accumulation. Mar. Petrol. Geol. 102, 138–154.
Wei, X.Z., Zheng, T.S., Hu, C.Z., Qiong, Z.M., Feng, Q.C., Guo, L.L., Guang, J.C., Ming, D., 2011. Elemental geochemistry and paleoenvironment evolution of shell bar section at Qarhan in the Qaidam basin, China. IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2221–2224.
Wu, K.Q., Jiang, X., Sun, H.F., 2015. Model of lacustrine source rocks in offshore oil kitchen sags: a case study of peleogene in huanghekou sag. Geol. Sci. Technol. Inf. 34, 63–70.
Xie, W.Y., Zhang, Y.W., Sun, Z., Jiang, J.Q., 2008. The mechanism research of the formation of the Qiongdongnan basin during the Cenozoic through modeling experiments. Earth Sci. Front. 15, 232–241.
Xie, J.Y., Zhu, Y.H., Li, X.S., Mai, W., Zhao, P.X., 2012. The cenozoic sea-lev-el changes in Yinggehai-Qiongdongnan basin, northern South China sea. Marine Origin Petroleum Geology 14, 49–58.
Xie, R.Y., Huang, B.J., Li, X.H., You, J.J., 2014. Hydrocarbon generation potential evaluation of source rocks in Liushagang Formation in Weixinan sag of Beibuwan Basin. J. Geol. 38, 670–675.
Xiong, X.H., Xiao, J.F., 2011. Geochemical indicators of sedimentary environments—a summary. Earth Environ. 39, 405–414.
Yan, D., Wang, H., Fu, Q., Chen, Z., He, J., Gao, Z., 2015. Organic matter accumulation of Late Ordovician sediments in North Guizhou Province, China: sulfur isotope and trace element evidences. Mar. Petrol. Geol. 59, 348–358.
Ye, J.R., Zhao, N.B., Yang, B.L., Xu, J.Y., 2020. Productivity and development model of source rocks of Liushagang formation in weinan sag. Bulletin of Geological Science and Technology 39, 105–113.
Yi, L., Bin, X., Ge, L., Xue, J.C., Xiao, Q.H., Pin, Y., Fa, Q.Z., 2007. Geochemistry of the sedimentary rocks from the Nanxiong Basin, South China and implications for provenance, paleoenvironment and paleoclimate at the K/T boundary. Sediment. Geol. 197, 127–140.
You, J.J., Xu, D.L., Li, L., Xie, Y.R., Li, X.H., Yang, G.L., 2012. Organic facies of source rocks of the second member of Liushagang Formation in the Weixinan sag. China Mining Magazine 21, 87–90.
Yu, X.H., Li, S.L., Q, Y.R., 2016. The Cenozoic changes of seas and lands and sedimentary filling responses of different basins in northern South China Sea. J. Palaeogeogr. 18, 349–366.
Zeng, S.Q., Wang, J., Chen, W.B., Fu, X.G., Feng, X.L., Song, C.Y., Wang, D., Sun, W., 2019. Geochemical characteristics of Early Cretaceous marine oil shale from the Changshe Mountain area in the northern Qiangtang Basin, Tibet: implications for palaeoweathering, provenance, tectonic setting, and organic matter accumulation. Geol. J. 55, 329-324.
Zhang, C.L., Gao, A.L., Liu, Z., Huang, J., Yang, Y.J., Zhang, Y., 2011. Study of character on sedimentary water and palaeoclimate for Chang7 oil layer in ordos basin. Natural Gas Geoscience 22, 582–587.
Zhang, B.T., T, J.Y., Wang, W.J., Yi, C.L., 2014. Characteristics of technic sedimitary evolution in northern depression of Beibuwan basin. Offshore Oil 34, 7–12.
Zhang, B., He, Y.Y., Chen, Y., Meng, Q.Y., Huang, J.X., 2018. Formation mechanism of excellent saline lacustrine source rocks in western Qaidam Basin. Petroleum. Acta Pet. Sin. 39, 674–685.
Zhao, Z.Z., Li, Y.T., Ye, H.F., Zhang, Y.W., 2001. Tectonic Characteristics and Basin Evolution of the Tibet Plateau. Science Press, Beijing, pp. 23–25.
Zhao, Z., Zhou, D., Liao, J., 2009. Tertiary paleogeography and depositional evolution in the Pearl River Mouth Basin of the northern South China sea (in Chinese). Journal of Tropical Oceanography 28, 52–60.
Zheng, R.C., Liu, M.Q., 1999. Study on paleosalinity of Chang-6 oil reservoir set in Ordos basin. Oil Gas 20, 20–25.
Zhu, M., Zhang, X.T., Huang, Y.P., Zhu, J.Z., Long, Z.L., Shi, Y.L., Shi, C., Zhang, X.L., 2019. Source rock characteristics and resource potential in peral River Mouth basin. Atca Petrolei Sinica 40, 53–68.