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Geochemical characteristics, palaeoenvironment and formation model of Eocene organic-rich shales in the Beibuwan Basin, South China Sea

Baojia Huang [a,b,1], Hui Tian [a,*], R.W.T. Wilkins [c], Xianming Xiao [a], Li Li [b]

[a] State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] CNOOC China Limited, Zhanjiang Branch, Guangdong 524057, China
[c] CSIRO Earth Science and Resource Engineering, P.O. Box 136, North Ryde, NSW, Australia

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ABSTRACT

Lacustrine organic-rich shales in the Eocene are the most important source rock in the Beibuwan Basin. Palynological, petrographical and geochemical data were applied to define their palaeoenvironment, formation and petroleum potential. TOC values range from 2.84 to 14.77% and the kerogens of these dark gray or brown shales with numerous lamalginites can be classified as oil-prone type-I and type-II_1. Biomarkers are characterized by a high abundance of C_{30} 4-methylsteranes, a low content of oleanane and diterpanes, relatively abundant pentacyclic terpanes, which indicate that the organic matter in the shales is typically algal and microbial origin. Abundance of amorphous organic matter, the presence of low level gammacerane, small amounts of pyrite, Pr/Ph ratios of 1.38–2.42, and V/V + Ni ratios of 0.74–0.84 suggest that the organic-rich shales were formed in a less oxic to anoxic, stratified, fresh-brackish lake environment with a relatively low sedimentation rate. For this starved lake basin, the bloom and death of algae in nutrient-rich surface water supplied a large amount of organic matter to the lacustrine sediments. The oxygen-depleted bottom waters of the palaeo-lakes favored the accumulation and preservation of sedimentary organic matter, resulting in the formation of the organic-rich shale, a high-quality source rock. Future exploration or assessment of the petroleum potential of the basin could be assisted by considering the proposed formation model of the organic-rich shales, and their distribution relative to potential traps.

1. Introduction

The Beibuwan Basin, one of four petroliferous basins in the northern continental shelf area of the South China Sea (Fig. 1a), covers an area of nearly 40,000 km^2 (Fig. 1b). Thick sequences of lacustrine mudstones have been reported to underlie much of the basin. Previous studies have shown that an Eocene lacustrine sedimentary facies defines a transgressive–regressive cycle of approximately 2000 m gross thickness (Liu, 2004; Zhu, 2009) that includes dark gray mudstones, organic-rich shales and interbedded sandstones. The organic-rich shales which have total organic carbon contents up to 14% and Rock-Eval pyrolytic yields (S1 + S2) greater than 20 kg HC/t rock, are commonly considered to be one of the principle source rocks in the basin. Over the past 30 years, petroleum exploration has been continuously conducted in the basin and more than ten commercial oil fields and a few oil bearing structures have been discovered with oil resources estimated to be more than 3×10^8 tons. Several recent studies (Liu, 2004; Huang et al., 2011) have demonstrated that the oils were sourced from the lacustrine dark gray mudstones and organic-rich shales of the Eocene Liushagang Formation. However, data concerning the sedimentary facies and organic geochemistry of these organic-rich shales are extremely sparse in Chinese and western literatures. Additional detailed studies of these deposits are crucial for accurate estimation of the Beibuwan Basin hydrocarbon resource, for comparison with similar deposits elsewhere in the world, and for integration into more widely applicable models for the genesis of lacustrine petroleum source rocks. Our study describes the characteristics of these organic-rich shales in much greater detail than previously known, integrating depositional environment with bulk geochemical, hydrocarbon biomarker, trace element and palynological data. The primary goal of this paper is to provide new sedimentological, geochemical and petrological data on the organic-rich shales, and to present a hypothesis for their genesis in order to achieve a better understanding of the petroleum system,

* Corresponding author. Tel.: +86 20 85290309.
E-mail addresses: huangbj@cnooc.com.cn (B. Huang), tianhui@gig.ac.cn (H. Tian).
[1] Tel.: +86 759 3901782.

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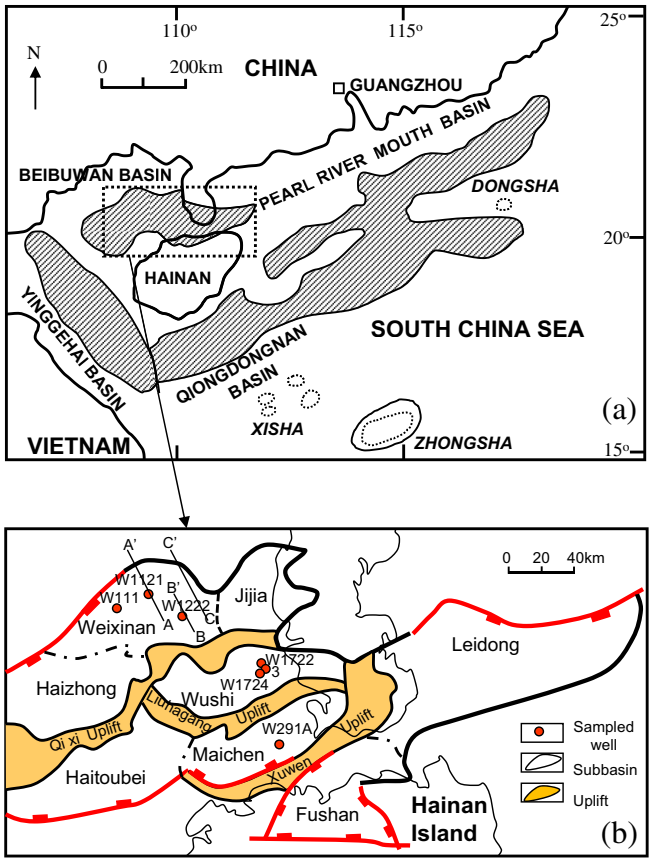

Figure 1. Maps showing the location (a) and structural divisions (b) of the Beibuwan Basin and sampled wells.

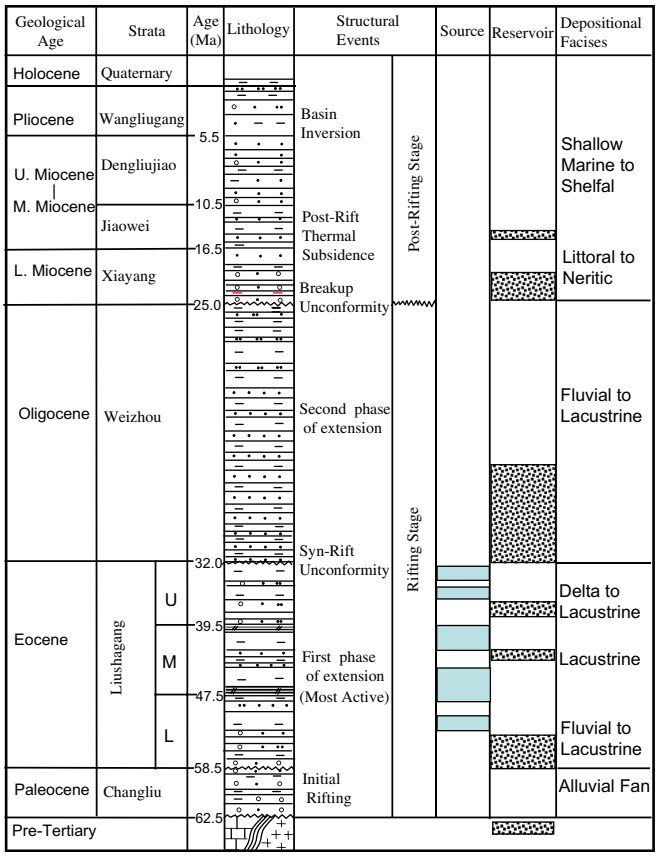

Figure 2. Schematic stratigraphic column of the Beibuwan Basin.

and its potential value for additional oil discoveries with reduced exploration risk in this area.

2. Geological setting

The Beibuwan (BBW) Basin, located in the northern continental shelf of the South China Sea (Zhu, 2009) (Fig. 1a), is a Mesozoic–Cenozoic extensional basin. It contains eight sags and three structurally positive units (Fig. 1b). The structural evolution of the basin can be largely divided into two stages: an early rifting and a later subsiding stage, which resulted in forming two distinctive structural layers (Figs. 2 and 3). During the rifting stage (from Paleocene to Oligocene), a series of half-grabens were formed as the result of fault extension and rifting. The extension is thought to have been caused by a combination of southward slab pulling related to the subduction of the proto South China Sea oceanic crust with extension related to the extrusion and clockwise rotation of Indo-china along the Red River fault (Gong and Li, 1997; Zhu, 2009). The post-rift stage (from Miocene to present time) is characterized by a set of relatively unstructured conformable strata. In response to the above structural evolution, the dominant environments for sedimentary deposition in the Beibuwan Basin evolved from the continental non-marine fluvial and lacustrine deposition in the early rifting stage to marine deposition in the late subsidding stage (Liu, 2004; Huang et al., 2011).

Figure 2 shows the reconstructed stratigraphy for the BBW basin. The basement of the basin is mainly composed of granite-gneiss and Mesozoic carbonate rocks. The Paleocene Changliu Formation is about 50–500 m thick, and dominated by coarse grained, often mud-rich, matrix-supported conglomerate without any hydrocarbon source potential. The Eocene Liushagang formation is 1000–2500 m thick, and consists mainly of black shales, siltstone and sandstones. Based on the lithology and fossil assemblages, the Liushagang Formation is subdivided into upper, middle and lower sections: Liushagang-1 (LS-1), Liushagang-2 (LS-2) and Liushagang-3 (LS-3), respectively (Liu, 2004). The organic-rich shales occur widely in the Liushagang-2 section developed during the peak stage of lake expansion. They are major petroleum source rocks in the basin (Liu, 2004; Huang et al., 2011). The low to moderate energy fluvial and shallow lake facies sandstones within the Liushagang-1 and Liushagang-3 are potential reservoirs. The Weizhou Formation is composed of shallow lake and high-energy fluvial facies sandstones interbedded with black shales, with a total thickness of 900–1800 m. These sandstones formed the most important reservoir rocks in the BBW basin, as well as the carrier beds for hydrocarbons and the shales in this Formation act as a significant seal. The top of the Weizhou Formation is marked by a significant regional unconformity surface, which is dated at about 25 Ma (Liu, 2004; Li et al., 2011) based on the paleontologic, seismic and sequence stratigraphic data, defines the boundary between the syn-rift and post-rift (passive) sediments and is probably related to the onset of sea-floor spreading in the South China Sea and the formation of oceanic crust (Li et al., 2011). The overlying post-rift marine sediments (from Miocene to Pleistocene) consist mainly of interbedded sandstones and mudstones with a total thickness of about 1500–3000 m. The middle Miocene Jiaowei Formation mudstones act as an excellent regional seal for hydrocarbon fluids.

3. Samples and analytic methods

About 140 mudstone samples of Eocene age were collected from the cores and cuttings of six wells, and a total of five crude oil