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Research paper

Source rock deposition controlled by tectonic subsidence and climate in the western Pearl River Mouth Basin, China: Evidence from organic and inorganic geochemistry

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A B S T R A C T

Interest in factors controlling lacustrine source rock deposition has increased over the last few decades because this type of deposits contain significant petroleum resources. Generally, tectonic subsidence and climate are the two root causes as they control the accommodation potential, water column properties and sources of organic matter. In this study, coupling organic geochemical and elemental geochemical data, two potential source rocks, i.e., the Eocene Wenchang Formation (E_2w) and Oligocene Enping Formation (E_3e) were investigated. Two models were finally raised to explain deposition of the two set of source rocks according to their paleoclimatic and tectonic properties. The source rock potential shows a strong heterogeneity. The second member of the Eocene Wenchang Formation (E_2w_2) is characterized by high organic matter content and oil-prone kerogen type. In contrast, the first member of the Eocene Wenchang Formation (E_2w_1) and the Oligocene Enping formation (E_3e) are characterized by low organic matter content and gas-prone kerogen type. The primary productivity and depositional environment exhibit notable differences between the two potential source rocks horizons and show an obvious variation from the depocenter to the slope and can be best explained by the coevolution of tectonic subsidence and climate. During the E_2w depositional stage, low sediment supply led to mudstone deposited in deep lacustrine environment and resulted in underfilled lake basin. The low water inflow provided little terrigenous organic matter (low bicadinane, perylene and floranthene contents) and oxygen. Besides, the low area/depth ratio impeded the water circulation, thus resulted in shallow thermocline and anoxic-suboxic bottom environment (abundant dibenzothiophene and high C_{35}/C_{31}22S hopane ratios). Therefore abundant algae, which contributed to the high amorphous organic matter (AOM) content, can be preserved. The warm and wet climate (high Mn/Mg ratios) gave birth to autochthonous organism, such as dinoflagellates and *Pavlova gyrans* (abundant 4-methyl sterane). During the E_3e depositional stage, the sufficient sedimentary supply resulted in expanding, shallow lacustrine and swamp environment. The higher area/depth ratio and high sediment supply made environment unstable and can be strongly influenced by external environment (broader range of Mn/Mg ratios). Enough terrigenous organic matter (TOM) was transported to the slope but little to the depocenter. The slightly hot and dry climate (low Mn/Mg ratios) led to decreasing autochthonous organism and evaporation environment. The shallow water depth and relative dry climate resulted in saline, suboxic-dysoxic acid bottom environment. The co-variation of organic and inorganic indexes indicates the combination is a valid method in reconstructing source rock depositional models.

1. Introduction

Lake deposits, which contain significant petroleum resources, are important to understand and predict (Carroll and Bohacs, 1999;

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Katz, 1990, 1995). The deposition of lacustrine source rocks displays strong heterogeneity, which is caused in part by the relatively small water reservoir size and sensitivity to changes in external environment (Garcés et al., 1995; Kelts, 1988). The strong heterogeneity can be evidenced by wide ranges of salinity, pH, Eh and marked variation in biota (Carroll and Bohacs, 1999; Demaison and Moore, 1980; Hao et al., 2011) and can be traced by various geochemical parameters (Hao et al., 2011; Peters et al., 2005). A lot of researchers have noted and attempted to interpret these phenomena. For example, Eugster and Kelts (1983) emphasized the control of lake type (open and closed) on source rock properties; Glenn and Kelts (1991) focused on cyclic records of climatic forcing; Carroll and Bohacs (1999) suggested that it was the relative balance of potential accommodation (tectonism) with sediment and water supply (climate) that controls the source rock properties. Since then, influence of external factors, such as climate and tectonics, on lacustrine deposition has been a much-talked-about topic (Alonso-Zarza, 2003; Alonso-Zarza and Calvo, 2000; Bouaziz et al., 2015; Dunagan and Turner, 2004; Pietras et al., 2003; Valero Garcés et al., 1997). The reason why tectonism and climate are emphasized is because they are the two root causes which control sediment accumulation potential, water column properties and sources of organic matter. But even so, there is still a lot of work need be done.

Organic geochemical parameters, such as molecular biomarkers, are regarded as effective methods in characterizing organic matter sources, depositional environment and water column properties (Ding et al., 2016; Hackley and SanFilipo, 2016; Hu et al., 2015a; Murray et al., 1994; Peters et al., 2005; Sfidari et al., 2016). Similarly, the elemental geochemistry can also provide information about climate, primary productivity and water properties (Akinlua et al., 2010; Li et al., 2015; Meinhold et al., 2013; Nijenhuis et al., 1999; Tripathy et al., 2014). Therefore, the integration of organic and inorganic geochemical data is more reliable in tracing source rock depositional paleoenvironment and organic matter sources. Connecting source rock depositional conditions (as interpreted from various parameters) with tectonic and climatic properties can help us better understand the process of source rock deposition.

The Zhu III sub-basin, one of the four sub-basins in the Pearl River Mouth Basin (PRMB), is an important oil-producing region (Guo et al., 2015; Jiang et al., 2009). It is a narrow sub-basin trending from southwest to northeast (Fig. 1). The Zhu III sub-basin is about 200 km long, 80 km wide and its total area is about 16,000 km^2 (Li et al., 2014). Five tectonic movements led to different tectonic subsidence rates and various climate conditions during the evolution of the Zhu III sub-basin (Li and Rao, 1994; Ru and Pigott, 1986; Xie et al., 2006). Therefore, the Zhu III sub-basin is an excellent natural laboratory for investigating the source rock deposition models controlled by the tectonic subsidence and climate. In recent years, great attention has been paid to this area because of its huge exploration potential. Since the first well was drilled in 1980s, a series of oil fields have been found (Quan et al., 2015). However, these oil fields are medium and small size in the PRMB and no large oil field is found. The hydrocarbon found in Wenchang A depression is mainly gas condensate, whereas in Wenchang B depression is mainly oil. This distinct property of output is attributed to different qualities of their main source rocks, i.e., the Oligocene Enping Formation (E_3e) and Eocene Wenchang Formation (E_2w) (Cheng et al., 2013; Huang et al., 2003; Quan et al., 2015; Zhu et al., 1999). Utilizing molecular biomarkers, organic petrography and palynology, previous studies indicated fresh water, reducing and middle-deep lacustrine facies environment during the E_2w deposition stage; saline, oxidic and swamp facies environment during the E_3e deposition stage (Cheng et al., 2013; Huang, 1998; Huang et al., 1996; Xia and Wu, 1996; Xie et al., 2012). However, the reason why the two source rocks exhibit such distinct properties is rarely reported. Hence, coupling organic geochemical and elemental geochemical data of the E_2w and E_3e source rocks, (1) the source rock quality and depositional conditions were interpreted; (2) the paleoclimatic and tectonic properties of Zhu-III sub-basin during the two stages were analyzed; (3) and two models were finally raised to explain the depositional history of the source rocks.

2. Geological setting

The geological setting for the PRMB has been intensively described (e.g. Li and Rao, 1994; Song et al., 2011; Xie et al., 2014) and will be briefly described here.

The PRMB is located on the northern shelf of South China Sea (SCS) and has an area of about 175,000 km^2 (67, 568 mi^2, Fig. 1A). The basin can be divided into five tectonic zones from the north to south: the north terrace, the northern depression zone, the central uplift zone, the southern depression zone and the southern uplift zone. The PRMB experienced the interaction of the Eurasin, Pacific and Indian Ocean plates (Li, 1994; Zhao et al., 2010; Zhong, 1994) and therefore has unique tectonic frame work and complex development history (Li and Rao, 1994). The evolution of PRMB can be divided into two stages, i.e., the syn-rifting stage from 65.5 to 30 Ma and the post-rifting stage from 30 to the present (Fig. 2), thus forming the so-called typical Double Structural Layer (Chen and Pei, 1993; Hu et al., 2015b; Huang et al., 2003; Zuo et al., 2015). During the syn-rifting stage, a series of half grabens, with faulting in the north and overlap in the south, were generated along major NNE and NE trending owing to the extensional forces. And after that these half grabens gradually coalesced to form one large basin.

The study area is the Zhu III sub-basin which lies in the west of the northern depression zone (Fig. 1A). The Zhu III sub-basin is made up of five depressions and two uplifts, of which Wenchang A and B depressions are considered as generative kitchens (Fig. 1B). The formation and evolution of Zhu III sub-basin were largely controlled by the South Boundary Fault (SBF) (Chen, 2002; Li et al., 2007; Zhang et al., 2013). The SBF consists of three segments, i.e., SBF-1, SBF-2 and SBF-3 (Fig. 1B). SBF-2 is the boundary of Wenchang B and C depressions and SBF-3 is the boundary of Wenchang C depression and Shenhu Uplift. The SBF-3 has a short life, which kept active from the Paleocene to the late Eocene. During the Paleocene and Eocene, the fault active rate of SBF-3 was about 170 m/Ma at the depocenter of Wenchang C depression. SBF-2 was much more complex because the fault activity intensity and the initial activity time shown strong heterogeneity within this fault. SBF-2 was initially composed of some small separate segments. With the increasing activity intensity at the late Eocene, these segments connected with each other and form one large fault. The fault active rate was about 210 m/Ma. SBF-1 separates Wenchang A depression from Shenhu Uplift and its fault activity rate (about 160 m/Ma) was weaker than SBF-2 and SBF-3. During the early Oligocene, the SBF-3 stopped active anymore but the activity intensity of SBF-2 and SBF-1 increased. The fault active rate of SBF-2 (about 400 m/Ma) was weaker than SBF-1 (up to 750 m/Ma) and the depocenter, therefore, migrated from Wenchang B to Wenchang A depression (Li et al., 2007; Lv et al., 2008). Although the active rate of SBF during the E_3e depositional stage was greater than the E_2w depositional stage, the sufficient sediments supply led to balanced fill or overfilled lake basin (Carroll and Bohacs, 1999; Zhu et al., 1997) and therefore resulted in shallow lacustrine depositional environment (Fig. 2). The shallow water depth and gentle slope can hinder the terrigenous organic matter to be transported to the lake center. In contrast, the insufficient sediments supply generated underfilled lake basin and probably had a stratified water column.