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Research paper

Lacustrine massive mudrock in the Eocene Jiyang Depression, Bohai Bay Basin, China: Nature, origin and significance

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ABSTRACT

Massive mudrock refers to mudrock with internally homogeneous characteristics and an absence of laminae. Previous studies were primarily conducted in the marine environment, while notably few studies have investigated lacustrine massive mudrock. Based on core observation in the lacustrine environment of the Jiyang Depression, Bohai Bay Basin, China, massive mudrock is a common deep water fine-grained sedimentary rock. There are two types of massive mudrock. Both types are sharply delineated at the bottom and top contacts, abundant in angular terrigenous debris, and associated with oxygen-rich (higher than 2 ml O_2/L H_2O) but lower water salinities in comparison to adjacent black shales. In addition, type 1 is laterally isolated and contains abundant sand injections and contorted layers formed in the depositional process, but type 2 exactly distributes in the distal part of deep water gravity-driven sandstone units, and shows scoured bases, high-angle mineral crytsals, and fining-upward trend. It is suggested that type 1 is a muddy mass transport deposit (MMTD) formed by slide, slump, and/or debris flow, and type 2 is a turbiditic mudrock deposited by settling from dilute turbidity currents. A warm and humid climate and high subsidence rate are two main triggering events. Because of its mass movement nature, MMTD preserves the mineralogic composition and organic matter characteristics of the source sediment. By contrast, dilute turbidity currents are able to greatly entrain biochemically-formed micrite and planktonic organisms from the water column, and deposit them in the turbiditic mudrock. Because of their different ability to deposit organic matter, MMTD have poor or fair source rock potential, but the turbiditic mudrock is able to be a potentially effective source rock. The minerals in the massive mudrock are disorganized and chaotic, which cause fractures to develop in various directions, thereby, enhancing the vertical migration of oil and gas molecules to horizontal wellbore in shale reservoir exploitation.

1. Introduction

The deposition of fine-grained sediments (<62.5 μm; Schieber and Southard, 2009; Jiang et al., 2013) is important in sedimentologic research because of the economic importance as source rocks and shale reservoirs. Diverse types of mudrocks (mainly composed of fine-grained sediments) were recognized in previous studies (e.g., Loucks and Ruppel, 2007; Abouilresh and Slatt, 2012). Massive mudrock (also named as uniform mudrock by some geologists; e.g., Tripsanas et al., 2004) was originally discovered in the eastern Mediterranean (Stanley, 1977, 1981), and was also reported in the western equatorial Atlantic and the northwest Gulf of Mexico in subsequent studies (e.g., Behrens, 1985; Tripsanas et al., 2004). It refers to the mudrock with internally homogeneous characteristics (e.g., similar color and mineralogic composition) and an absence of sedimentary structures (i.e., non-laminated) (Behrens, 1985; Xian et al., 2013). Possible sedimentary characteristics of massive mudrock include the following: 1) a subtle textural fining-upward trend with the basal components being siltier (Damuth, 1977;

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Blanpied and Stanley, 1981; Cita et al., 1996), 2) a narrow range of time interval according to radiocarbon dating, which indicates rapid deposition (Stanley, 1981), 3) often occurring in trench basins with steep margins (Cita and Aloisi, 2000), and 4) disorganized and chaotic mineral assemblages (Bennett et al., 1991; Ochoa et al., 2013).

Several mechanisms have been proposed for the deposition of massive mudrock. Ryan (1977) indicated that massive mudrock was deposited by pelagic suspension-related processes in still water. More recent studies suggest that the massive structure is attributed to the development of a stratification interface generated by the continuous introduction of a turbulent cloud of the fine-grained nature formed by depositional segregation (Stow and Shanmugam, 1980; Tripsanas et al., 2004; Ochoa et al., 2013). In addition, McCave and Jones (1988) found that high-density non-turbulent turbidity currents can also be responsible for massive mudrock deposition when the current "froze" in some way. Note that later studies discovered that there are no high-density non-turbulent turbidity currents in nature, and the so-called high-density non-turbulent turbidity currents deposits are actually debrites (e.g., Shanmugam, 1996, 2002).

To date, massive mudrock has been exclusively discovered in marine environments. Lacustrine mudrock is equally as important as its marine counterpart (Katz and Lin, 2014). However, very few studies have investigated lacustrine massive mudrock, thus leaving its sedimentary characteristics and depositional origin poorly understood. In addition, the relationship between massive mudrock and hydrocarbon exploration and exploitation has received little attention in previous investigations.

Lacustrine mudrock is widely distributed in the half-graben of the Eocene Jiyang Depression, Bohai Bay Basin, China (e.g., Jiang et al., 2014; Zhang et al., 2016). Here massive mudrock is a common component of the fine-grained sedimentary rock succession of the Eocene Jiyang Depression. A systematic study of the massive mudrock is conducted in this paper, including:

1) A study of the sedimentary characteristics (e.g., petrology, depositional setting) of the massive mudrock;
2) An analysis of the origin (e.g., depositional mechanism, triggering events, and depositional process and model) of massive mudrock; and
3) An investigation of the relationship between massive mudrock and hydrocarbon exploration and exploitation.

2. Geologic setting

The formation of the Bohai Bay Basin was co-controlled by extensional and transtensional tectonics (e.g., Allen et al., 1997, 1998; Qi and Yang, 2010). The Jiyang Depression located in the southeast of the Bohai Bay Basin (Fig. 1A) is a sub-basin filled with lacustrine successions. The depression or sub-basin occupies an area of 26,000 square kilometers, which is bounded by the Luxi Uplift in the southeast, the Kendong-Qingtuozi Uplift in the east, and the Chengning Uplift in the northwest (Fig. 1B). The Dongying Sag is located in the southern part of the Jiyang Depression with an area of 5,700 square kilometers, and the Zhanhua Sag is located in the northeastern part of the Jiyang Depression with an area of 2,800 square kilometers (Fig. 1B).

The Cenozoic Jiyang Depression includes Paleogene, Neogene, and Quaternary strata (e.g., Jiang et al., 2011) (Figs. 1C and 2). The Paleogene strata are sub-divided into the Kongdian (Ek), Shahejie (Es), and Dongying (Ed) Formations, and the Es strata are sub-divided into four members (Es_4 to Es_1 from bottom to top) (Fig. 2). The strata targeted in this study are the upper Es_4 and lower Es_3. The subsidence rate was about 260 m/My, 520 m/My in the upper Es_4 and lower Es_3 strata, respectively (Fig. 2). The climate changed from arid to humid from the Es_4 to Es_3 strata (Li et al., 2004) (Fig. 2). A series of fan-deltas and braid-deltas developed along the lake margin during this time, and the center of the lake was filled with deep water mudrock that reaches 1,000 m in thickness in the Es_4 and Es_3 strata. The thick mudrock layers are the primary source rocks for the petroliferous depression.

The Paleozoic carbonate of the North China Craton was one of main provenance rocks for these Cenozoic strata in the Jiyang Depression (e.g., Wang et al., 2013). It makes the mudrock rich in carbonate minerals (4–92 wt%, avg. 43.06 wt%) (Fig. 3). In addition, quartz and feldspar content ranges from 6 to 82 wt% (avg. 31.59 wt %), and clay content ranges from 2 to 65 wt% (avg. 25.35 wt%) in the mudrock (Fig. 3).

3. Samples and methods

Cores and cut samples of the deep water lacustrine mudrock from the upper member of Es_4 (Es_4^U) and the lower member of Es_3 (Es_3^L) were collected from five continual core sections (wells N1, L69, F1, L1, and L75; Fig. 1B), with a total thickness of 1,093 m. The core lengths are 203 m, 223 m, 414 m, 218 m, and 35 m in the above five wells, respectively. The basic analysis includes thin section and spore and pollen samples from 508 samples, whole rock X-ray diffraction (XRD) from 163 samples, major and trace element geochemistry from 670 samples, total organic carbon (TOC) from 78 samples, Rock-Eval from 78 samples, high-resolution field emission scanning electron microscopy (FESEM) from 45 samples, and kerogen separation from 45 samples. In addition, sedimentary cross-sections from the lake margin to lake center are established using the wire-line logging data.

In regards to XRD analysis, pretreatment of the samples are necessary, in which the particles were dried at 40 °C for 2 days and dispersed by an agate mortar. D8 DISCOVER equipment was used for analysis of the minerals at a voltage of 40 kV and a current of 25 mA. Major elements were measured from the fusion discs, and trace elements from the pressed powder pellets, using the Philips PW 1400 XRF spectrometer. TOC was determined by a LECO CS-200 carbon analyzer, in which the measurement technique was based on the combustion of the samples in an oxygen atmosphere to convert the organic carbon to CO_2. The TOC value was determined with the aid of a combustion calculation. Rock-Eval analysis was carried out on a Vinci Rock-Eval-6 instrument, and about 100 mg for each sample was pyrolized using helium as the carrier gas. The samples were heated to 300 °C to release its residual hydrocarbons (S_1), and then pyrolized to 600 °C to obtain hydrocarbons (S_2) cracked from kerogen. The FESEM analysis was conducted on a HITACHI S-4800 with a working current set at 10 kV and working distance of 8 mm. The sample for kerogen separation should be no less than 100 g. First, the sample was dipped in fresh water for three days to make the mudrock loosen. Second, it was dipped in 36% HCl for 24 h to remove the alkaline minerals (i.e., carbonate). Third, it was washed to pH = 7 and then dipped in 60% HF for 48 h to remove the acidic materials (i.e., siliceous minerals). Fourth, it was once again washed to pH = 7 and dipped in 36% HCl to further remove the alkaline minerals. Framboidal pyrites were then removed by a solution of $NaBH_4$. The remaining material was dominantly kerogen.

4. Sedimentary characteristics of massive mudrock

The 1,093 m of core sections for this study are composed of 998 m of black shale and 95 m of massive mudrock. Massive mudrock accounts for 8.69% in thickness. It includes two types