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Middle Eocene paleohydrology of the Dongying Depression in eastern China from sedimentological and geochemical signatures of lacustrine mudstone

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A B S T R A C T

Previous understanding that stratigraphic variability in lacustrine sequences is primarily caused by depositional processes governed by regional tectonics and climatic change remains to be tested on microscopic scale. Here we study the upper fourth Member (Es4U) of the Eocene Shahejie Formation, the major source rock of the Dongying Depression, eastern China, in order to understand stratigraphic heterogeneity and tectonic and climate controls on depositional processes in lacustrine mudstone. Our study integrates core descriptions, microscopic observations, and studies of mineralogy, TOC and chemical weathering proxies of CIA* and Ln(Al_2O_3/Na_2O) from two full-bore cores and correlation of gamma ray logs from six wells across the depression. We identified four major lithofacies, including the interbedded evaporite and mudstone deposited in a shallow salt lake; the silt-bearing clay-rich mudstone deposited in a pro delta environment within a shallow open lake; the laminated calcareous mudstone deposited in a deep, stratified meromictic lake with frequent earthquake activities; and the massive calcareous mudstone deposited in a shallow and oxygenated lake. The Es4U Member changed from the interbedded evaporite and mudstone-dominated lithofacies association to silt-bearing clay-rich mudstone-dominated lithofacies association, and then laminated calcareous mudstone-dominated lithofacies association, suggesting basin-wide changes in depositional processes, lake level, lake water chemistry, and paleohydrology. We suggest that these changes reflect balance between sediment and water supply and potential accommodation of the lake basin, which were governed by paleoclimate in the lake drainage and extensional tectonics. We infer that during the deposition of the Es4U Member, the lake basin evolved from an underfilled lake basin with salty lake water under arid climate to a shallow balanced-fill lake basin when climate became humid, then to a deep balanced-fill basin with stratified bottom lake water when climate became more humid and the basin was deepened by tectonic activity. This study demonstrates that climate and tectonics both control paleolimnological changes and depositional processes of lacustrine mudstone.

1. Introduction

Organic-rich mudstones of lacustrine origin are not only source rocks in petroleum systems and account for about 20% of the conventional global oil endowment, but also became increasingly important unconventional reservoirs (e.g., Bohacs et al., 2000; Katz and Lin, 2014; Xie et al., 2016). Such examples include the Eocene Shahejie Formation in eastern China (Zhang et al., 2009; Xie et al., 2016; Ma et al., 2016a), the Eocene-Oligocene Brown Shale in southeastern Asia (Rodriguez and Philp, 2015), the Eocene Green River Formation in the western U.S.A. (Burton et al., 2014), and the Aptian-Albian lacustrine sequences in Brazil (Neumann et al., 2003). Compared to their marine counterparts, lacustrine mudstones typically have limited geographical distributions, great stratigraphic heterogeneity, mixed kerogen types, and wide ranges of TOC (e.g., Katz and Lin, 2014), which make systematic characterization of lacustrine mudstones necessary for understanding variations in reservoir characteristics and guiding hydrocarbon exploration and production.

Depositional processes primarily control stratigraphic variability in lacustrine sequences because lake basins are highly sensitive to local

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tectonics and climatic changes (e.g., Garcés et al., 1995; Carroll and Bohacs, 1999; Bohacs et al., 2000; Carroll and Bohacs, 2001; Gonçalves, 2002; Jia et al., 2013; Katz and Lin, 2014). Previous studies on lacustrine basins have concluded that the depositional processes in lake basins reflect balance between water and sediment supply and potential accommodation (Carroll and Bohacs, 1999; Bohacs et al., 2000; Carroll and Bohacs, 2001). Climate variations result in rapid changes in water salinity and pH, biota, lake level, and tectonic subsidence causes changes in basin morphology and potential accommodation (Carroll and Bohacs, 1999; Bohacs et al., 2000; Carroll and Bohacs, 2001). Such understandings are largely based on lithofacies variations on macroscopic scale, and the application to lacustrine mudstones with subtle stratigraphic heterogeneity in microscopic scale remains to be tested.

Recent studies integrating sedimentologic observations of cores in both macroscopic and microscopic scales and whole-rock geochemical analysis to marine mudstone have demonstrated that such integrated approach is powerful in characterizing mudstone heterogeneity and providing understanding on depositional processes, organic matter accumulation and preservation, and paleowater chemistry (e.g., Hickey and Henk, 2007; Loucks and Ruppel, 2007; Hammes and Frébourg, 2012; Wang and Carr, 2012; Könitzer et al., 2014; Bruner et al., 2015; Harazim and McIlroy, 2015; Ma et al., 2016b). Application of such integrated studies to lacustrine mudstone is relatively rare, but is proven powerful in identifying subtle stratigraphic heterogeneity (Ma et al., 2016a). In this study, we integrate lithofacies and whole-rock geochemical analysis and well-log correlation to understand basin-scale depositional controls on stratigraphic variability in lacustrine mudstone. Using the upper fourth Member (Es4U) of the Eocene Shahejie Formation in the Dongying Depression in eastern China as an example, we demonstrate that the depositional processes of lacustrine mudstone are ultimately controlled by both paleoclimate and tectonics.

2. Geological setting and stratigraphy

As one of the most petroliferous petroleum basins in China, the Bohai Bay Basin is a Cenozoic rift basin located in the eastern coast of China with an area of approximately 200,000 km^2 (Fig. 1A) (Ye et al., 1985; Hsiao et al., 2004; Liu and Wang, 2013). The basin initiated as a back-arc basin during the Late Jurassic when the Pacific Plate subducted beneath eastern China, and evolved into an intracratonic rift basin during the Cenozoic (Allen et al., 1997; Hu et al., 2001). A series of grabens and half grabens developed along major northwest-southeast and northeast-southwest trending normal faults during the Paleogene (Allen et al., 1997; Huang and Pearson, 1999). These grabens and half grabens coalesced to form the large Bohai Bay Basin, and the basin experienced thermal subsidence during the Neogene (Allen et al., 1997; Hu et al., 2001).

The Bohai Bay Basin consists of seven sub-basins, including the Linqing, Jizhong, Huanghua, Jiyang, Bozhong, Liaodong Bay, and Liaohe sub-basins (Fig. 1A; Allen et al., 1997; Feng et al., 2016). The Jiyang sub-basin contains a cluster of half-grabens, including the Dongying, Zhanhua, Chenzhen, and Huimin depressions. Located in the southern part of the Jiyang sub-basin (Fig. 1A), the Dongying Depression is one of the most hydrocarbon-rich depressions in China. Up to today, a total of 32 oil fields and two gas fields have been discovered (Zhang et al., 2009; Wei et al., 2012). The depression is asymmetric and bounded by the Chenjiazhuang Uplift to the north, the Qingtuozi and Guangrao uplifts to the east, the Luxi Uplift to the south, and the Qingcheng-Linjia-Binxian uplifts to the west (Fig. 1B). Within the Dongying Depression, a series of syndepositional normal faults further divide the depression into secondary tectonic zones (Fig. 1C) (Zhang et al., 2009; Guo et al., 2012). These normal faults were induced by intense extension during the Paleogene, which may have influenced depositional processes and petroleum migration and accumulation in the Dongying Depression (Guo et al., 2012; Feng et al., 2013).

The thick Cenozoic basin fills in the Dongying Depression are divided into the Paleogene synrift sequence and Neogene post-rift sequence (Fig. 2) (e.g., Hu et al., 2001; Hao et al., 2009, 2011). The synrift sequence unconformably overlies the Mesozoic strata, and contains the Paleogene Kongdian, Shahejie and Dongying formations that were deposited primarily in lacustrine environments. The postrift sequence includes the Neogene Guantao, Minhuazhen and Pinyuan formations that were deposited primarily in fluvial environments (Fig. 2).

The Eocene Shahejie Formation spans the early Eocene-early Oligocene, and consists of interlayered sandstone, siltstone, oil shale, mudstone and evaporite (Fig. 2; Guo et al., 2012; Feng et al., 2013; Feng et al., 2016). This formation is divided into the Es1, Es2, Es3 and Es4 members. The Es1, Es2, and Es4 members are further divided into upper and lower intervals, and the Es3 Member is divided into the upper, middle, and lower intervals (Guo et al., 2012). Our study target is the upper Es4 (Es4U) Member in the Dongying Depression, which is the major source rock of the Shahejie Formation and has a high oil-generating potential (Li et al., 2003; Wei et al., 2012). The Es4U Member is dominated by evaporite, siltstone, and calcareous mudstone that were mainly deposited in a lacustrine environment (Fig. 2; Li et al., 2003; Feng et al., 2013), and the organic matter is mostly of type I kerogen (Zhang et al., 2009). The Es4U Member is conformably overlain by the lower Es4 (Es4L) Member, which consists of predominantly interlayered sandstone, mudstone and evaporite deposited in fluvial-lacustrine environment (Fig. 2; Feng et al., 2013).

3. Materials and methods

Our investigation to the drilling data of the Dongying Depression documents that only two wells (N1 and F1) recovered the entire Es4U Member. The two wells are about 35 km apart, and both are located in areas with negligible influence of faulting (Fig. 1B). The two cores have moderate burial depth and thicknesses of the targeted interval. The slabbed cores of the two wells are extremely well preserved. The N1 core is 166.29 m long and the F1 core is 190.08 m long. Gamma ray logs of six wells, including N1, F1, W73, G6, L1 and L79 (Fig. 1B), were included in this study for basin-scale correlation. These logs were provided by the Shengli Oilfield Company of the SINOPEC. Core-to-log comparison from N1 and F1 wells was used to guide basin-scale log correlation. We collected both sedimentological and geochemical data from the N1 and F1 cores. From the N1 core, we studied 55 standard thin sections, and collected 81 mineralogy, 128 total organic carbon content (TOC wt%), and 75 major element composition data. From the F1 core, we studied 35 standard thin sections, and collected 50 mineralogy, 49 TOC wt%, and 78 major element composition data. Samples used for these analyses were cut from the core after removing weathered surface.

We made observations from the standard thin sections using an Axio Imager A2m polarizing microscope. Our sedimentological observations follow the guidelines in Lazar et al. (2015). Our descriptions include fresh rock color, lithology, grain size, sedimentary structures, presence and types of biogenic features, degree of bioturbation, mineralogy of cements, types and distribution of lenses, presence and relative abundance of fractures. The classification of mudstone lithofacies is primarily based on lithology, and the names of lithofacies are modified by sedimentary structures and chemical compositions (Lazar et al., 2015). Condensed version of the descriptions is shown in Fig. 3.

Mineralogical analyses were carried out at the Petroleum Geology Research Center of the Shengli Oil Field (SINOPEC). Powdered samples were oven-dried at 40 °C for two days. Samples were then placed in copper holders and scanned using a D8 DISCOVER X-ray diffractometer. The generator settings of the diffractometer were 40 kV and 25 mA. Samples were scanned from 3° to 70° at 2° min^{-1} with a step width of 0.02° and using Cu-Kα radiation and a secondary graphite monochromator for whole-rock composition. Minerals were identified by computer analysis