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Research paper

Diagenesis and evolution of the lower Eocene red-bed sandstone reservoirs in the Dongying Depression, China

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ABSTRACT

The diagenetic evolution of the lower Eocene red-bed high-quality reservoirs in the Dongying Depression was systematically investigated through an integrated petrographic, petrophysical, fluid evolution and thermal history analysis. The reservoirs experienced several phases of diagenesis, including compaction, carbonate cementation, gypsum and ankerite cementation, feldspar and carbonate dissolution, quartz overgrowth cementation, and clay-mineral cementation and transformation. An early alkaline diagenetic environment caused significant cementation of calcite and gypsum in the reservoir sandstone units near the sandstone-mudstone contacts. Acidic formation fluids caused widespread dissolution of the feldspar and carbonate cements, leading to synchronous occurrences of primary intergranular pores and acidic dissolution pores. From the middle parts of the reservoir sandstone units to the sandstone-mudstone contacts, dissolution wanes gradually with ferro-carbonate progressively diminishing. Migration of exogenetic thermal fluid along faults may have contributed to the gradual decrease in dissolution and the gradual increase in cementation from the lower part to the upper part of fault blocks. The alternating alkaline and acidic diagenetic environments and the distribution of diagenetic products caused the development of the high-quality red-bed reservoirs in the middle part of the thick-layered sandstone units in the lower part of fault blocks. Because of the spatial and temporal relationships between the diagenetic stages and their products, lithological traps of a diagenetic origin were developed in the red-bed reservoirs.

1. Introduction

Red beds are unique detrital sedimentary rocks with a singular color of reddish–brown, caused by ferric oxide pigments on grains, filling pores, or dispersed in clay matrix (van Houten, 1973; Walker, 1974). Geological research on red beds dates back to the early 19th century, and focused primarily on aspects of their mineralogy and petrology, paleomagnetism, paleoclimate and paleontology. The geochemical effects of trace minerals in red beds, such as biotite and hematite, during the diagenetic process were also investigated to elucidate the causes of reddish color (Turner and Archer, 1977; Walker, 1967, 1976; 1981; Parcerisa et al., 2006). Paleomagnetism of red beds was used to reconstruct tectonic evolution by measuring residual magnetism in red beds (Kent and Opdyke, 1978; Yamashita et al., 2011). The occurrence of red beds had once been widely considered as direct indicators for arid palaeoclimatic settings related to desert or savanna, with assumptions that red soil might supply red alluvium, and that reddish–brown hydrated ferric oxides might not be converted to hematite at surface conditions (van Houten, 1973). However, numerous studies question these assumptions and therefore strongly oppose the view that red beds only indicate arid climate conditions (Turner, 1980; Sheldon, 2005). The occurrence of ferric oxides, mainly in the form of hematite in red beds, do not have climatic significance (van Houten, 1973; Turner, 1980; Sheldon, 2005). To date, generic continental red beds have been reported from environments and climatic settings of humid tropics (Walker, 1974; Besly and Turner, 1983), temperate monsoon (Dubiel and Smoot, 1994), (sub-)tropical monsoon (Retallack, 1991), as well as desert and savanna (Walker, 1976). Palaeo-environment changes were also deduced from the fossils in red beds (Marriott et al., 2009). In China, widely distributed red beds occur as outcrops and sedimentary strata in sedimentary basins, which are composed of continental clastic sediments formed in arid climatic conditions.

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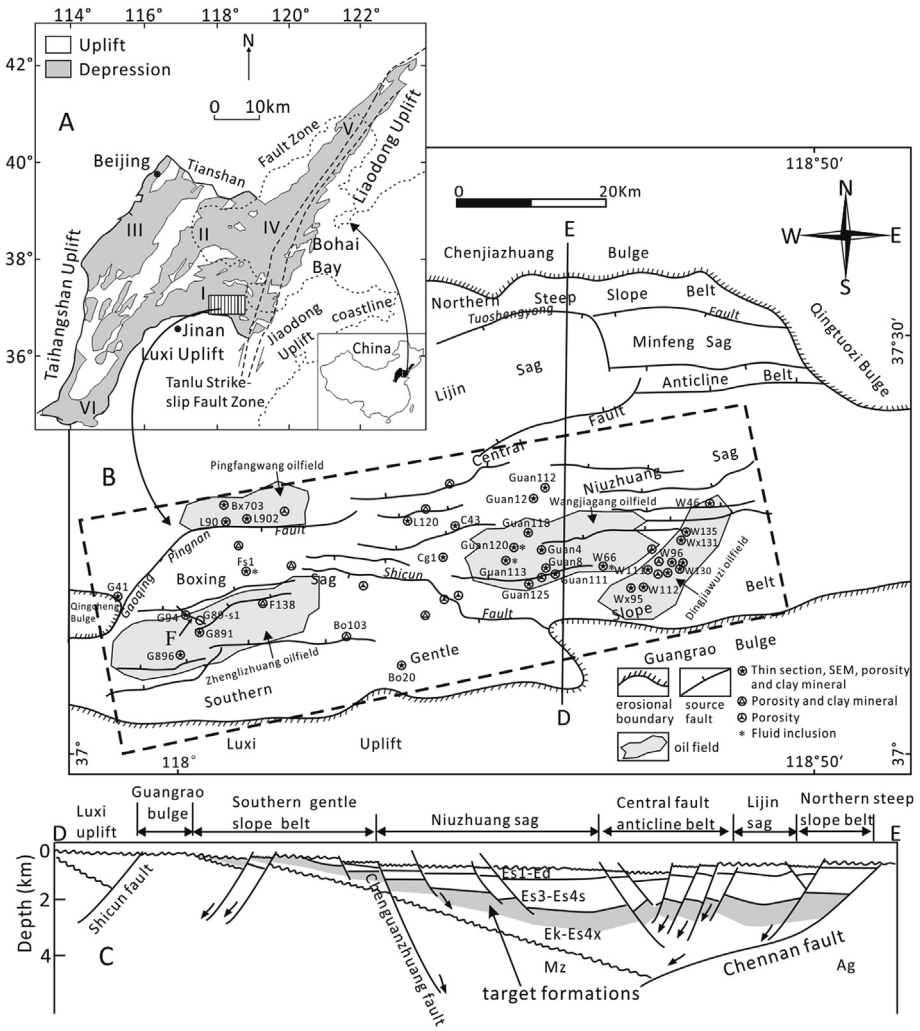

Fig. 1. (A) Tectonic setting of the Dongying Depression in the southern Jiyang subbasin (I) of the Bohai Bay basin. Other subbasins in Bohai Bay basin are Huanghua subbasin (II), Jizhong subbasin (III), Linqing subbasin (IV), Bozhong subbasin (V) and Liaohe subbasin (VI). (B) Structural map of the Dongying depression with well locations, main faults and oil fields of the *Ek1-Es4x*. (C) Section structural characteristics and target formations of the Dongying depression. (F) Location for cross section of Fig. 18.

Influenced by seasonal inflowing water, red beds in basins of East China usually occur as alternated sandstone and mudstone intervals (Wang et al., 2015). Under an arid climatic setting, the palaeo-salinity levels in lake waters were relatively high, often causing evaporites being deposited in the sag belts of basins (Wang et al., 2015; Liu et al., 2017).

Red-bed sandstone reservoirs have recently become an important exploration target in the Bohai Bay Basin (Wei and Yuan, 2008; Wang et al., 2015, Fig. 1A). The early exploration results indicate that the red beds of the first member of the Kongdian Formation (*Ek1*) and lower fourth member of the Shahejie Formation (*Es4x*) are important exploration target reservoir intervals in the Dongying Depression (Fig. 2). Since 2006, four oil fields have been discovered in the two red-bed reservoir intervals, including the Zhenglizhuang (2950–4150 m), Pingfangwang (1800–3250 m), Wangjiagang (2000–3650 m), and Dingjiawuzi (1300–3500 m) oil fields (Fig. 1B). Such discoveries show an enormous exploration potential of the red-bed sandstone reservoirs in the Dongying Depression. The dark mudstone of the top part of the upper fourth member of the Shahejie Formation*(Es4s)*immediately above *Es4x* not only provided considerable hydrocarbons to red-bed sandstones by lateral connection through faults but also act as a good top seal for the red-bed reservoirs (Jiang et al., 2011). Because of the favorable combinations of the hydrocarbon source, reservoir and seal, the red-bed sandstones are considered to be the favored exploration targets in the Dongying Depression.

Sedimentation controls the initial porosity and influences the diagenesis of the reservoirs to a certain degree (Aagaard and Jahren, 2010; Hammer et al., 2010). Diagenesis is the dominant factor in the evolution of the porosity of clastic reservoirs during the burial process (Schmid et al., 2004; Al Gahtani, 2013; Nguyen et al., 2013; Wilson et al., 2013; Henares et al., 2014). A series of ordered stacking diagenetic events occurred during the evolution of diagenetic environments; these events controlled the diagenetic transformation process, formed the present diagenetic appearance and reservoir features (Li et al., 2006). Compared with the study of depositional characteristics of the sandstones, the study of diagenesis and its influence on reservoirs is rather limited in scope (Dill et al., 2005; Schoner and Gaupp, 2005; Parcerisa et al., 2006). In this study, we investigated the characteristics of diagenesis, diagenetic environments and diagenetic evolution and the causes for the development of high-quality reservoirs of red-bed reservoirs in the Dongying Depression using an integrated petrographic, petrophysical, fluid evolution and burial history analysis.

2. Geological background

The Bohai Bay Basin is an important hydrocarbon producing basin that is located on the eastern coast of China and covers an area of