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Research paper

Burial evolution of evaporites with implications for sublacustrine fan reservoir quality: A case study from the Eocene Es4x interval, Dongying depression, Bohai Bay Basin, China

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A B S T R A C T

Eocene, sublacustrine-fan, sandstones that developed in a rift basin are important tight gas reservoirs in the Dongying Depression, Bohai Bay Basin, northeastern China. Two units of evaporites, developed at the top and bottom of the lower unit of the Es4 interval (Es4x), consist predominantly of anhydrite with subordinate gypsum. Evaporite and related diagenetic processes greatly influenced reservoir quality. $\delta^{13}C$ values for micritic dolomite cements in Es4x are depleted (−7.45 to −2.57‰) due to microbial sulfate reduction (MSR) under shallow burial conditions and this interpretation is supported by large $\delta^{34}S$ fractionation between anhydrite and framboidal pyrite. Precipitation temperatures for micritic dolomite are calculated as 57.5–72.8 °C. Anhydritization of gypsum probably occurred at 100.5–145.2 °C during progressive burial as evidenced by homogenization temperatures of aqueous inclusions within anhydrite cements. This process resulted in dehydration fractures within anhydrite cements that increased reservoir permeability by connecting isolated pores. Thermochemical sulfate reduction (TSR) probably resulted in dissolution of gypsum and anhydrite cements under relatively deep burial conditions. Ankerite cements are replaced by anhydrite cements and are enclosed by solid bitumen in Es4x. Ankerite cements likely were derived from TSR as reflected in negative $\delta^{13}C$ values (−7.12 to −3.70‰) and high calculated temperatures (121.3–185.1 °C). Dissolution by-products (e.g. saddle dolomite, ankerite, nodular pyrite) related to TSR precipitated in adjacent pores. A lack of significant $\delta^{34}S$ fractionation between parent sulfate and nodular pyrite indicates that TSR occurred in a relatively closed system. Therefore, dissolution of gypsum and anhydrite related to TSR contributed little to reservoir quality. Middle-fan lithofacies with better sorting, porosity and permeability than inner- and outer-fan lithofacies constitute high-quality reservoirs in Es4x.

1. Introduction

Evaporites have been studied broadly in different basins worldwide, mainly in relation to tectonic setting (e.g. Ortí et al., 2014; Schorn and Neubauer, 2014), depositional environments (e.g. Taberner et al., 2000; Trichet et al., 2001; Topper and Meijer, 2013), sequence stratigraphy (e.g. Tucker, 1991; Sarg, 2001) and mineralogy and geochemistry (e.g. Bahadori et al., 2011; Iribar and Ábalos, 2011; Tangestani and Validabadi, 2014). Evaporites typically develop in semi-arid or arid climatic settings where evaporation exceeds precipitation (Sarg, 2001; Trichet et al., 2001; Warren, 2006) and are closely associated with carbonate rocks (e.g. Major and Holtz, 1997; Tanguay and Friedman, 2001). Diagenesis of evaporites and related diagenetic processes (e.g. carbonate cementation) have been shown to exert a critical influence on reservoir quality (e.g. Machel and Buschkuehle, 2008; Rahimpour-Bonab et al., 2010).

Transformation of gypsum to anhydrite with progressive burial has been related to increases in temperature (95–200 °C) and pressure (0–100 MPa), and the geochemistry of pore fluids (saline

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to hypersaline brines) (e.g. Jowett et al., 1993; Ogawa et al., 2007; Amadi et al., 2012). Changes in pore fluid compositions with burial, in turn, influence later diagenesis (e.g. Nollet et al., 2005; Amadi et al., 2012). Moreover, gypsum and anhydrite are readily dissolved in the presence of hydrocarbons and acidic solutions (e.g. Baruah et al., 2000; Bildstein et al., 2001). Gypsum/anhydrite can react with hydrocarbons and result in dissolution associated with thermochemical sulfate reduction (TSR) at elevated temperatures (Worden et al., 2000; Machel, 2001; Hao et al., 2015). Dissolution of gypsum/anhydrite during TSR and its influence on reservoir quality are equivocal with ongoing debates focusing on whether dissolution by-products are removed from the system or precipitated *in-situ* (Machel, 2001; Hao et al., 2015).

The Eocene Es4 (Es4s and Es4x) interval in the Dongying Depression, Bohai Bay Basin in eastern China (Fig. 1) developed in a rift basin. Evaporites in the form of anhydrite and gypsum, and dark mudstones and deep-water sublacustrine fan facies are present at burial depths of 4000–5000 m in the lower unit (Es4x) (Fig. 2). Conversion of gypsum to anhydrite resulted in modification of the composition of pore fluids but this process is complicated at elevated temperatures and pressures, and is greatly influenced by the composition of deep burial brines (Jowett et al., 1993; Amadi et al., 2012). With a range of burial depths (4000–5000 m), formation temperatures (150–200 °C) and formation pressures (40–70 Mpa), the Es4x in Dongying Depression is ideally suited to investigate the burial evolution of evaporites and their influence on reservoir quality. Thus, the objectives of this study are to: (1) document the distribution of evaporitic minerals such as gypsum, anhydrite and halite using thin section petrography in combination with a range of analytical techniques; (2) understand diagenetic alterations of evaporites and associated minerals by utilizing fluid inclusion and stable isotope data; (3) illustrate that evaporite transformation resulted in dehydration fractures that influenced reservoir quality; and (4) evaluate the effects of evaporite transformation (gypsum to anhydrite) and dissolution on the diagenesis and, thereby, the reservoir quality of associated sandstones. Formation of dehydration fractures within anhydrite cements associated with anhydritization of gypsum has not been documented in previous research whereas the effects of gypsum and anhydrite dissolution (related to thermochemical sulfate reduction) on associated sandstone reservoirs has not been evaluated within the study area (e.g. Yuan and Wang, 2001; Chen et al., 2013). Sublacustrine fan deposits with associated evaporites are widely developed in eastern China (e.g. Guo et al., 2010; Jiang et al., 2013) and worldwide (e.g. Schenk et al., 1994; Warren, 2010) and, therefore, the results of this study have wide application to lacustrine reservoirs of similar tectono-sedimentary and diagenetic origin.

2. Geological setting

The Dongying Depression is located in the southern part of the Jiyang Subbasin of the Bohai Bay Basin (Yuan and Wang, 2001; Guo et al., 2010) and covers an area of 5700 km^2 (Fig. 1A, B). Tectonic evolution of the depression is characterized by a syn-rift stage between 65.0 and 24.6 Ma and a post-rift stage from 24.6 Ma to the present (Hu et al., 2001; Guo et al., 2010; Dong et al., 2011). The Dongying Depression consists of five secondary tectonic units from north to south: the northern steep slope, the northern sag (Minfeng Sag), the central anticline, the southern sag (Niuzhang Sag), and the southern gentle slope (Fig. 1C). The Minfeng Sag is located in the northeastern part of the Dongying Depression and the northern margin of the sag is defined by the Chennan Boundary Fault (Fig. 1C; Jiang et al., 2013).

Stratigraphic successions in the Dongying Depression consist of the Paleocene Kongdian (Ek), Shahejie (Es), and Dongying (Ed) formations, the Neogene Guantao (Ng) and Minghuazhen (Nm) formations, and the Quaternary Pingyuan (Qp) Formation (Fig. 3). The Eocene Es4x interval is an important tight gas reservoir in the Dongying Depression and is the subject of this study (Fig. 2; Wan et al., 2010; Wang et al., 2014). Es4x consists of dark lacustrine source rocks, evaporites interbedded with multi-stage, sublacustrine fan sandy conglomerates, pebbly sandstones and sandstones close to the boundary fault (Fig. 2). Evaporites in cumulative thicknesses of more than 1600 m are located at the bottom and the top of Es4x (Fig. 2).

During the initial deposition of Es4x, lake water had relatively high salinity associated with arid climatic conditions that resulted in the precipitation of gypsum and subordinate halite (Song et al., 2009; Wang et al., 2014). For most of the time of Es4x deposition, seasonal floods carried abundant siliciclastic sediments into the lake and large, sublacustrine fans developed adjacent to the footwall of the Chennan Boundary Fault and interfingered with more distal mudstones (Fig. 2). A return to arid conditions late in the history of Es4x deposition resulted in a second stage of evaporite precipitation. Multi-stage sublacustrine fan deposits are overall retrogradational and onlap the boundary fault (Fig. 2); this pattern is attributed to a long-term rise in lake level (Song et al., 2012).

Sublacustrine-fan deposits can be subdivided into inner-fan, middle-fan and outer-fan facies based on analysis of lithologies and sedimentary structures (Fig. 4; Sui et al., 2010; Cao et al., 2014; Wang et al., 2014). Matrix- or framework-supported conglomerates (Fig. 5A) are interpreted as inner-fan deposits that developed on steep slopes adjacent to the boundary fault (Fig. 4). Coarse-grained pebbly sandstones (Fig. 5B) and medium- or coarse-grained sandstones developed in braided channel in the middle-fan on relatively gentle slopes (Fig. 4). Graded, thin-bedded siltstone or fine-grained sandstones (Fig. 5C) were deposited in interdistributary areas in the middle-fan and on outer-fan (Fig. 4) and grade basinwards into deep lacustrine mudstones (Fig. 5D). Evaporites in Es4x (Fig. 5E) are interbedded with dark mudstones (Fig. 5F). Locally, evaporites (mainly anhydrite) are impregnated with oil (Fig. 5E) and fill fractures in mudstones (Fig. 5F).

3. Samples and methods

Core samples were collected from eight boreholes in the Eocene Es4x at depths ranging from 4000 to 5000 m (Fig. 4). Fifty three (53) thin sections, impregnated with pink epoxy under vacuum and stained with alizarin red-S and potassium ferricyanide (Dickson, 1965), were prepared for determining rock compositions, diagenetic constituents and percentages and types of porosity. Percentages of framework grains, authigenic cements and porosity were determined by 400 point counts per thin section.

Twelve (12) gold-coated sample chips were prepared for determining the compositions of authigenic minerals and spatial relationships, using a JSM-5500LV scanning electron microscope (SEM) equipped with a QUANTAX 400 energy dispersive X-ray spectra (EDX) under an acceleration voltage of 20 kV using a beam current of 1.0–1.5 nA. Highly magnified backscatter (BSE) and secondary electron (SE) techniques were used to determine the compositions of zoned carbonate cements. X-ray spectrometry was used to generate element distribution maps and for quantitative point analyses to further characterise the compositions of carbonate and evaporite cements. X-ray diffraction (XRD) analysis using an Ultima IV X-ray diffractometer at the Exploration and Development Research Institute of the Sinopec Zhongyuan Oilfield Company was carried out on <10 μm, air-dried powders to determine the compositions of whole rocks.

Eleven (11) samples from six boreholes were prepared for