Journal of Petroleum Science and Engineering 152 (2017) 136–155

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Diagenetic evolution of deep sandstones and multiple-stage oil entrapment: A case study from the Lower Jurassic Sangonghe Formation in the Fukang Sag, central Junggar Basin (NW China)

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A R T I C L E I N F O

Keywords:
Diagenesis
Oil charge
Heterogeneity
Sandstone reservoirs
Deep petroleum

A B S T R A C T

The deposition and preservation of high-quality rocks in a heterogeneous petroleum reservoir and associated mechanisms for hydrocarbon emplacement and migration are one of the most critical issues in deep exploration. Applying an integrated approach of petrography, SEM, stable carbon and oxygen isotopes, and fluid inclusion analyses, this study was designed to examine the relationship between diagenetic evolution and oil emplacement in the Lower Jurassic Sangonghe Formation in the Fukang Sag, central Junggar Basin (NW China). The sandstones consist mainly of feldspathic litharenite, and litharenite. Primary sandstone texture and compositions (grain size, ductile lithic sand grains) determine reservoir diagenetic heterogeneity. Grain size controls the overall abundances of cement and porosity, and reservoir properties through its effect on ductile lithic grains and hence on mechanical compaction. Ductile lithic-rich, very fine- to fine-grained sandstones had a limited diagenetic process in which compaction of easily deformed, clay-rich lithic grains predominated, resulting in a very rapid loss of porosity during burial. They achieved a high capillary entry pressure before the first oil arrival and were not charged later. In contrast, diagenetic events in the relatively coarser-grained sandstones with less abundant ductile lithic grains included dissolution and cementation as well as ductile compaction. Diagenesis progressed alternately with oil emplacement and in some cases, they occurred synchronously. Late diagenetic Fe-calcite, ankerite, and barite may be good mineralogical signatures of oil charge and migration. The nonreservoir, ductile lithic-rich, tightly compacted sandstones can constitute impermeable barrier interbeds embedded in permeable reservoir rocks, probably resulting in heterogeneous flow.

1. Introduction

Propelled by continued advances in seismic imaging, drilling and completion technologies and associated declining finding costs, major discoveries have been obtained in the deeper parts of China's sedimentary basins over the last decade. In particular, the polycyclic superimposed basins in western China, due to a unique tectonic regime during the Cenozoic, host most petroleum accumulations at burial depths greater than 15,000 ft (about 4572 m) (Zhu and Zhang, 2009; Pang, 2010). Such siliciclastic reservoirs exist at three current deep areas in China: Kuqa depression of Tarim Basin, Sichuan Basin, and central Junggar Basin (Sun et al., 2013).

Compared to intermediate-shallow burials, deep sandstone reservoirs have commonly experienced a multiple-stage tectonic history and fluid evolution. They are generally characterized by poor petrophysics, high-grade diagenesis and strong heterogeneity (Bloch et al., 2002; Ehrenberg and Nadeau, 2005; Taylor et al., 2010). The deposition and preservation of high-quality rocks in a heterogeneous petroleum reservoir and associated mechanisms for oil emplacement and migration are one of the most critical issues in deep exploration. Diagenesis may progress alternately with hydrocarbon charge in a reservoir, resulting in an extremely complex reservoir-quality evolution (Nedkvitne et al., 1993; Wilkinson et al., 2006; Zhang et al., 2009). Therefore, understanding the relationship between diagenetic evolution and hydrocarbon emplacement is of great importance for deciphering the temporal and spatial characteristics of fluid (hydrocarbon

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http://dx.doi.org/10.1016/j.petrol.2017.02.019
Received 14 July 2016; Received in revised form 17 January 2017; Accepted 28 February 2017
Available online 06 March 2017
0920-4105/

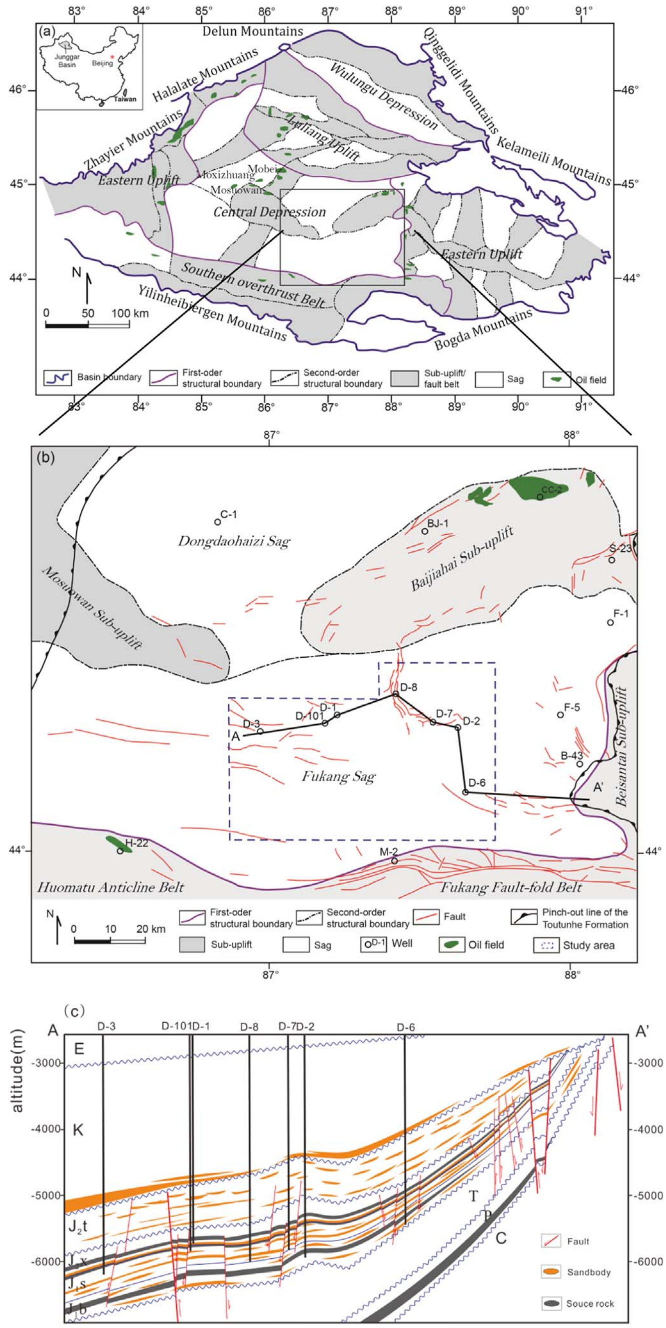

Fig. 1. (a) Regional geological map showing structural features of the Junggar Basin and location of the study area (modified from Li et al. (2010)). (b) Location of the studied wells. (c) Schematic structural section crossing the studied wells.

fluids included)-rock interactions in a reservoir during burial, and clarifying the formation of high-quality rocks and associated hydrocarbon charge histories.

In recent years, the Jurassic lithologic and stratigraphic traps have been a major focus of current deep exploration in the central Junggar Basin. Some oil fields such as Mobei, Mosuowan and Moxizhuang oil fields have been discovered in the Jurassic sandstones (Fig. 1a), reflecting promising deep exploration prospects. No significant discoveries have been obtained in the Fukang sag. By the end of 2014, the Shengli Oilfield Company, Sinopic has completed seven wells in this area (Fig. 1b) and has obtained substantial findings in the Lower-Middle Jurassic sandstones. The recoverable oil original reserves were estimated to be approximately 2109.35×10^4 t (155 million bbl). The focus of this study is the Lower Jurassic Sangonghe Formation (Fig. 2). The sandstones in this formation are buried at depths of approximately 4900–6600 m. The sandstones are characterized by poor, but heterogeneous petrophysics with porosities of 1.6–10.1% and permeabilities of 0.03–1.5 mD. The inhomogeneity of oil shows has been noted from core description, well logging and well tests. The study was designed to examine the relationship between diagenetic evolution and oil emplacement. Understanding effect of diagenesis on reservoir quality, and then oil charge, will help reservoir evaluation and provide improved future exploration strategies.

2. Geological background

The Junggar Basin is located in the northern part of Xinjiang Uygur Autonomous Region, northwest China, with an area of approximately 136,000 km^2 (52,509 mi^2) (Fig. 1a). The basin lies at a three-block junction between Kazakhstan, Siberia and Tarim and is a part of the Kazakhstan block (Ren et al., 1980). The Junggar Basin is an Upper Paleozoic, Mesozoic and Cenozoic superimposed basin which is underlain by Precambrian crystalline basement and part of Hercynian folded basement (Zhao, 1992a). The basin can be tectonically divided into three evolutionary stages: the Middle-Late Permian rift basin, Triassic to Paleogene depression basin and Neogene to Quaternary foreland basin (Wu, 1986; Zhao, 1992b) (Fig. 2). The Junngar Basin contains six structural units: Wulungu depression, Luliang uplift, Western uplift, Central depression, Southern overthrust Belt, and Eastern uplift (Li et al., 2010) (Fig. 1a). The Fukang sag lies in the Central depression (Fig. 1b). The sag is characterized by a northeast-southwest trending monocline (Fig. 1c), which formed as a result of the uplift of the Bogda Mountains near the southern edge of the basin since the Paleogene (Li et al., 2010).

The central basin contains Carboniferous to Quaternary sediment fills up to 10 km thick (Fig. 2). Rather than attempting a detailed coverage of all the sediments, here, we only summarize general depositional evolution of the Jurassic sequence. During the Early-early Middle Jurassic period, the central basin was an intracontinental shallow lacustrine basin under the low-amplitude oscillating tectonic regime. The deposits are typical of a coal-bearing succession (Fig. 2). Due to the Early Yashanian orogeny, the lacustrine area began to shrink rapidly during the late Middle-Late Jurassic period (Tang et al., 1997; Zhang et al., 2000). A major unconformity occurs at the Toutunhe-Xishanyao Formation boundary (Fig. 2). The Toutunhe Formation has local erosions, and the Upper Jurassic succession is entirely absent.

Four sets of potential source rocks (i.e., Carboniferous, Permian, Triassic and Jurassic) occur in the Fukang sag (Fig. 2). Among these source rocks, oils produced from the Jurassic sandstones have been most closely associated with the Permian and Jurassic source facies (Wang et al., 2003; Chen et al., 2004; Kuang, 2009) (Fig. 1c). Previous published organic geochemistry studies that are pertinent to the two sets of source rocks have been almost entirely restricted to the northern and eastern slope of the sag (Chen et al., 2003; Kuang, 2009). This is because that they are deeply buried and have been not easily penetrated by the drill. The source rocks in the Lower Permian Pingdiquan Formation are composed of deep lacustrine black mudstones, oil shales and dolomitic mudstones with a total thickness of 50–650 m (Chen et al., 2003). The mudrocks have total organic carbon (TOC) contents ranging from 0.46% to 10.2%. The organic matter is of type I–II kerogen with vitrinite reflectance (Ro) values of 1.2–2.0% (Kuang, 2009). It can be inferred that the source rocks are mature to over mature towards the sag center (Chen et al., 2003). The Lower-lower Middle Jurassic contains lacustrine-swamp deep gray mudstones, and carbargilites interbedded with thin coalbeds. The mudstones have a total thickness of up to 500 m (Chen et al., 2003). The TOC contents range from 0.30% to 3.7%. The organic matter is of type II–III kerogen with Ro values of 0.6–1.0% (Kuang, 2009). The Badaowan Formation source rocks are of better quality than the