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Research paper

Diagenesis of the palaeo-oil-water transition zone in a Lower Pennsylvanian carbonate reservoir: Constraints from cathodoluminescence microscopy, microthermometry, and isotope geochemistry

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A B S T R A C T

Oil-water transition zones in carbonate reservoirs represent important but rarely studied diagenetic environments that are now increasingly re-evaluated because of their potentially large effects on reservoir economics. Here, data from cathodoluminescence and fluorescence microscopy, isotope geochemistry, microthermometry, and X-ray tomography are combined to decipher the diagenetic history of a 5-m-long core interval comprising the oil-water transition zone in a Lower Pennsylvanian carbonate reservoir. The aim is to document the cementation dynamics prior, during, and after oil emplacement in its context of changing fluid parameters. Intergrain porosity mean values of 7% are present in the upper two sub-zones of the oil-water transitions zone but values sharply increase to a mean of 14% in the lower sub-zone grading into the water-saturated portions of the reservoir and a very similar pattern is observed for permeability values. In the top of the water-filled zone, cavernous porosity with mean values of about 24% is found. Carbonate cements formed from the earliest marine to the late burial stage. Five calcite (Ca-1 through 5) and one dolomite (Dol) phase are recognized with phase Ca-4b recording the onset of hydrocarbon migration. Carbon and oxygen cross-plots clearly delineate different paragenetic phases with Ca-4 representing the most depleted $\delta^{13}C$ ratios with mean values of about −21‰. During the main phase of oil emplacement, arguably triggered by far-field Alpine tectonics, carbonate cementation was slowed down and eventually ceased in the presence of hydrocarbons and corrosive fluids with temperatures of 110–140 °C and a micro-hiatal surface formed in the paragenetic sequence. These observations support the “oil-inhibits-diagenesis” model. The presence an earlier corrosion surface between phase Ca-3 and 4 is best assigned to initial pulses of ascending corrosive fluids in advance of hydrocarbons. The short-lived nature of the oil migration event found here is rather uncommon when compared to other carbonate reservoirs. The study is relevant as it clearly documents the strengths of a combined petrographic and geochemical study in order to document the timing of oil migration in carbonate reservoirs and its related cementation dynamics.

1. Introduction

Reservoir oil-water transition zones (Christiansen et al., 2000; Heasley et al., 2000; Byrnes and Bhattacharya, 2006; Carnegie, 2006) are generally described as the intervals from which both oil and water are produced. Following the definition of Fanchi et al. (2002), the top of this interval is the elevation at which water-free oil is produced. The lower limit, although often gradual, is the shallowest depth at which oil-free water is present. In some reservoirs, the entire column is in a transition zone. In the past, oil-water transition zones, ranging in thickness from less than 1 to several 100 m, were considered non-economic and often not cored (Christiansen et al., 2000). More recently, however, oil-water transition zones in reservoir rocks worldwide have been

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increasingly re-evaluated and are now considered significant because of their potentially large effects (>30% of the estimated original oil in place) on reservoir economics (Fanchi et al., 2002).

Burial diagenetic processes and products within the interstices of reservoir rocks (shelf carbonates, chalk, clastics etc.) are clearly non-trivial with regard to the processes involved as these take place in the presence of two immiscible fluids, here oil and water (Worden et al., 1998, 1999; Jesenius and Burruss, 1990; Helgeson et al., 1993; Heggheim et al., 2005; Risnes et al., 2003, 2005; Sathar et al., 2012). This holds particularly true in the case of often mixed-wet carbonate reservoirs. This is because hydrocarbons contain abundant polar organic compounds that interact with the carbonate minerals (Ingalls et al., 2004; Hao et al., 2015). As a consequence, work dealing with experimental approaches, field studies and modeling with focus on the relationship between water-saturation, pH, wettability and relative permeability abounds (Christiansen et al., 2000; Morrow and Mason, 2001; Zhang et al., 2007; Sathar et al., 2012; Al-Dhahli et al., 2014).

Considering the potential significance of the oil-water transition zone, however, the number of published case studies dealing specifically with the carbonate diagenetic pathways of rocks in this crucial interval is still remarkably limited (Sellwood et al., 1993; Neilson et al., 1998; Heasley et al., 2000). The comparable scarcity of detailed studies represents an important information gap given the fact that the in-depth analysis of the paragenetic succession at water-oil contacts allows for the assessment of the timing of petroleum migration relative to diagenetic and tectonic events both for carbonate and clastic reservoirs (Burruss et al., 1983; Sellwood et al., 1993; Helgeson et al., 1993; Worden et al., 1998; Cox et al., 2010). Moreover, the comprehensive study of Worden et al. (1998) discusses, albeit from the perspective of clastic reservoirs, two conflicting schools of mind one termed as “oil-inhibits-diagenesis-model”, the other as “oil-does-not-inhibits-diagenesis-model”. The “oil-inhibits-diagenesis” model predicts that early emplacement of oil will inhibit (quartz, clay mineral, or carbonate) cementation and related pressure solution and consequently, reservoir quality is preserved. Conversely, the “oil-does-not-inhibits-diagenesis” model suggests that oil migration and emplacement is no major control of diagenetic pathways and attributes excess porosity to other factors.

This study provides a detailed description and interpretation of carbonate paragenetic phases from core material of a selected Bashkirian (Lower Pennsylvanian, *ca* 323–315 Ma) limestone reservoir in the Volga-Ural region of Russia. The focus is on a 5-m-long core interval representing the palaeo-oil-water transition zone. Paragenetic phases are brought into a temporal, burial, and mechanistic context. Making use of the detailed cement stratigraphy across the oil-water-transition zone documented here, we address the following four main questions:

1. What is the relation between carbonate diagenesis and oil migration? Specifically, does oil emplacement inhibits carbonate cementation or not?
2. Is oil migration assigned to a single paragenetic phase or expanded over a significant portion of the diagenetic pathway of the reservoir rock studied?
3. Are diagenetic fluids during oil emplacement discernible – in terms of their temperature and chemistry – from ambient pore fluids prior to and after oil migration?

The data shown here are significant for the wider understanding of palaeo-oil-water transition zones in carbonate reservoirs in general and highlight the potential of petrographic, microthermometric, and geochemical tools applied studied to these critical reservoir intervals.

2. Geological setting and economic significance

The focus of this study is on Lower Bashkirian limestones from an oil field of the Nurlatsky district in the Republic of Tatarstan (Russian Federation; Fig. 1). The units cored are situated in the Melekesskaya depression located in the south-central part of the vast Precambrian Russian craton (Fig. 1; Hachatryan, 1979). Devonian, Carboniferous, and Lower Permian clastic and shallow water carbonate units, overlaying a weathered Proterozoic basement surface, form the predominant sedimentary succession (Fig. 1; Alekseev et al., 1996; Buggisch et al., 2011). The thickness of the Paleozoic cover reaches about 1900 m. Exposures in this region are only present along major river valleys and are restricted to Neogene and Quaternary rocks.

In terms of its geological setting, the core interval studied is from an oil field located in the eastern part of the East-European carbonate platform, forming portions of the Volga-Ural anticline (Fig. 2; Hachatryan, 1979; Voytovich and Gatiyatullin, 2003). Following Permian sedimentation, the Volga-Ural region experienced a phase of tectonically stability with only minor vertical tectonic movements and very limited sedimentation. From the Neogene onwards, a steady tectonic uplift lead to erosion and the formation of major alluvial depositional systems (thickness up 100–150 m). The main structures of the Volga-Ural anticline were formed as a result of this vertical basement uplift (Hachatryan, 1979; Mkrtchyan, 1980).

Economically significant carbonates reservoir units are concentrated in the Lower Mississippian and the Lower Pennsylvanian, with the Bashkirian units being one of the main carbonate target intervals in the Volga-Ural region (Fig. 3). From a production point of view, significant portions of the Devonian clastic reservoirs rocks are in a late production stage and consequently, the main focus of oil exploration in this region is now on the Carboniferous reservoir rocks. The source rocks of the oil fields in Volga-Ural region (Gordadze and Tikhomirov, 2005; Galimov and Kamaleeva, 2015) are Upper Devonian (Frasnian–Famennian) black shales (Aizenshtat et al., 1998). These units comprise thinly bedded calcareous-siliceous successions with abundant organic matter (Yudina et al., 2002; Gordadze and Tikhomirov, 2005).

3. Depositional environment, stratigraphy, and sedimentology

Accessible data in the international literature with focus on the Carboniferous of the Russian platform are scarce to absent. Here, we provide a brief overview of the facies types found and place our findings in the ramp model of Proust et al. (1998). During the Pennsylvanian and Early Permian, the Russian Platform was characterized in its eastern domains by a large, wave-dominated carbonate ramp and the subsiding foredeep of the Ural Mountains (Proust et al., 1998, Fig. 2). Within this ramp setting, the carbonates studied here were deposited. Based on palaeomagnetic and palaeoenvironmental data, the climate zone assigned to the Melekesskaya depression during Pennsylvanian times was semi-arid and (sub-)tropical (Proust et al., 1998). As recognized in Lower Pennsylvanian sections worldwide (Heckel, 1986; Soreghan and Giles, 1999), the relative sea level fluctuated repeatedly forming hiatal and karstified units on a regional scale. In the short core interval studied here, however, evidence for significant subaerial diagenesis is lacking.

With reference to the middle Carboniferous ramp of the Russian platform, Proust et al. (1998) subdivide inner, mid- and outer ramp facies. The definition used is such that the inner ramp environment is placed permanently above the effective fair-weather wave base, the middle ramp environment is situated between the effective