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Petroleum generation and charge history of the northern Dongying Depression, Bohai Bay Basin, China: Insight from integrated fluid inclusion analysis and basin modelling

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A B S T R A C T

The petroleum generation and charge history of the northern Dongying Depression, Bohai Bay Basin was investigated using an integrated fluid inclusion analysis workflow and geohistory modelling. One and two-dimensional basin modelling was performed to unravel the oil generation history of the Eocene Shahejie Formation (Es3 and Es4) source rocks based on the reconstruction of the burial, thermal and maturity history. Calibration of the model with thermal maturity and borehole temperature data using a rift basin heat flow model indicates that the upper interval of the Es4 source rocks began to generate oil at around 35 Ma, reached a maturity level of 0.7% R_o at 31–30 Ma and a peak hydrocarbon generation at 24–23 Ma. The lower interval of the Es3 source rocks began to generate oil at around 33–32 Ma and reached a maturity of 0.7% R_o at about 27–26 Ma. Oil generation from the lower Es3 and upper Es4 source rocks occurred in three phases with the first phase from approximately 30–20 Ma; the second phase from approximately 20–5 Ma; and the third phase from 5 Ma to the present day. The first and third phases were the two predominant phases of intense oil generation.

Samples from the Es3 and Es4 reservoir intervals in 12 wells at depth intervals between 2677.7 m and 4323.0 m were investigated using an integrated fluid inclusion workflow including petrography, fluorescence spectroscopy and microthermometry to determine the petroleum charge history in the northern Dongying Depression. Abundant oil inclusions with a range of fluorescence colours from near yellow to near blue were observed and were interpreted to represent two episodes of hydrocarbon charge based on the fluid inclusion petrography, fluorescence spectroscopy and microthermometry data. Two episodes of oil charge were determined at 24–20 Ma and 4–3 Ma, respectively with the second episode being the predominant period for the oil accumulation in the northern Dongying Depression. The oil charge occurred during or immediately after the modelled intense oil generation and coincided with a regional uplift and a rapid subsidence, suggesting that the hydrocarbon migration from the already overpressured source rocks may have been triggered by the regional uplift and rapid subsidence. The expelled oil was then charged to the already established traps in the northern Dongying Depression. The proximal locations of the reservoirs to the generative kitchens and the short oil migration distance facilitate the intimate relationship between oil generation, migration and accumulation.

1. Introduction

Accurate reconstruction of hydrocarbon charge history is crucial for any successful petroleum exploration. The timing of petroleum charge may be determined by using fluid inclusion entrapment temperatures combined with burial (thermal) history plots, predictions of oil generation and migration from heat flow and subsidence models, or using the age of minerals precipitated before or after the oil charge (Parnell, 2010). During and after fluid migration in subsurface, including oil migration and entrapment in reservoirs, tiny fluids may be encapsulated as inclusions during mineral precipitation and/or microfracture annealing (Parnell et al., 2001). Fluid inclusions therefore provide valuable information on

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the pressure and temperature of mineral growth at the time of the fluid migration and entrapment as well as on the compositions of the fluids involved in diagenesis and may provide important insight on the mineral diagenesis and fluid dynamics within sedimentary basins (Burruss, 1987). Despite the problems of dealing with typically tiny and rare inclusions, and with the uncertainties involving extrapolation of the results from small fluid samples to a basin scale, fluid inclusions are particularly useful in determining (1) the temperature and pressure history (Burruss, 1989; Swarbrick, 1994; Aplin et al., 2000); (2) the timing of petroleum migration/entrapment relative to the paragenesis (Mclimans, 1987; Rezaee and Tingate, 1997) and the history of petroleum charge (Oxtoby et al., 1995; Lisk et al., 1998; Parnell, 2010), including migration pathways, petroleum types, and sources (Karlsen et al., 1993); and (3) the evolution in pore-water compositions, which may be critical for evaluating the possible influence of fluid flow upon mineral cementation (Burley et al., 1989; Wilkinson et al., 1998; Hartmann et al., 2000). Petroleum and aqueous inclusions can sometimes be trapped simultaneously in suitable mineral hosts during the heterogeneous migration of petroleum in water saturated reservoir rocks. These inclusions should have the same trapping temperature and pressure. The history of petroleum charge may therefore be determined by using fluid inclusion analyses because they record the thermal history. The fluid trapping temperature can normally be approximated by using the aqueous fluid inclusion homogenization temperature data, provided the fluid (brine) is saturated with CH_4 (Hanor, 1980). When integrated with burial and thermal history modelling the timing of oil migration/entrapment through carrier beds or into reservoirs can be determined (e.g. Nedkvitne et al., 1993; Xiao et al., 2006).

The Dongying Depression in the Bohai Bay Basin, northeastern China is a prolific oil-producing province in China. The grey to black mudstones, calcareous mudstones and oil shales in the lower Es3 (the third member) and upper Es4 (the fourth member) intervals of the Eocene Shahejie Formation are considered as the main source rocks, which are dominated by Type I kerogens with TOC contents up to 18.6% (Zhang et al., 2009). The oil generation from the source rocks within the Es3 and Es4 intervals caused an overpressure generation with micro-fractures being widely developed, forming major pathways for oil migration and pore-fluid pressure releases (Guo et al., 2010). Overpressured fluids (e.g. oil and water) expelled from the source rocks charged into the reservoir rocks to cause widespread overpressure in the oil saturated or oil-bearing reservoirs (Bao et al., 2008; Guo et al., 2010). Therefore, petroleum migration and charge are intimately related to the oil generation history of the source rocks in the Dongying Depression because the oil pools are proximal to the generative kitchens.

Basin modelling plays an important role in modern petroleum exploration in that it integrates the elements and processes of petroleum generation, migration and accumulation in a quantitative manner, thereby helping the exploration geoscientists to understand the petroleum system and to verify different exploration scenarios (Wendebourg, 2003). Basin modelling primarily focused on risking petroleum generation (Vik and Hermanrud, 1993) through thermal history modelling because the rate and timing of petroleum generation depended upon the thermal history of a basin. Modelling hydrocarbon generation in a sedimentary basin thus requires the integration of burial, thermal and maturity history. The objectives of this paper are to: (1) to reconstruct the petroleum generation history of the Es3 and Es4 source rocks in the northern Dongying Depression by basin modelling based on the reconstruction of the burial, thermal and maturity history; (2) investigate the petroleum charge history by using an integrated fluid inclusion investigation; and (3) determine the relationship between the petroleum generation and charge in this study area.

2. Geological background

The Bohai Bay Basin, an important hydrocarbon-producing province in China, is located on the eastern coast of China and covers an area of approximately 200,000 km^2 (Fig. 1). It is a rift basin developed in the late Jurassic through to the early Cenozoic on the basement of the North China Platform (Hu et al., 1986). The tectonic evolution of the basin can be divided into two major stages: a syn-rifting stage (65.0–24.6 Ma) and a post-rifting stage (24.6 Ma to the present) (Fig. 2; Hu et al., 2001). The syn-rifting stage can be further subdivided into an initial phase, an expansion phase, an expansion and rapid subsiding stage, and a contraction phase (Chang, 1991). The sediments deposited at the syn-rifting stage were only restricted to the grabens or half grabens and were deposited primarily under lacustrine setting (Chen et al., 1998; Wu et al., 2006). The facies deposited during the post-rifting stage as represented by the deposition of the Guantao, Minghuazhen and Pingyuan formations, were predominantly of fluvial origin (Xiao and Chen, 2003; Gong, 2004).

The Bohai Bay Basin consists of several sub-basins, namely the Liaohe, Liaodong Bay, Bozhong, Jiyang, Huanghua, Jizhong and Linqing sub-basins (Fig. 1A; Gong, 1997). The Dongying Depression, developed during the Cenozoic rifting, is located at the southern part of the Jiyang sub-basin and covers an area of 5700 km^2. It is 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. The distribution of the sedimentary systems was controlled by a series of small-scale normal faults which developed in an en echelon pattern as a result of a dextral movement along the Tanlu Fault. The Dongying Depression is subdivided into four sags (the Minfeng Sag, the Lijin Sag, the Niuzhuang Sag and the Boxin Sag) by several normal faults and one uplift (the Central Anticlinal Belt) (Fig. 1B). The depression can be further subdivided into five secondary tectonic zones from the north to south, namely the Northern Steep Slope zone, Northern Sag zone, Central Anticline zone, Southern Sag zone and the Southern Gentle Slope zone (Fig. 1C). The northern Dongying Depression includes the Northern Steep Slope zone, the Northern Sag zone (Lijing Sag and Minfeng Sag), and the Central Anticline zone.

The depression is filled with a thick Cenozoic sediment sequence, which comprises the Paleogene Kongdian (Ek), Shahejie (Es) and Dongying (Ed) formations, the Neogene Guantao (Ng) and Minghuazhen (Nm) formations, and the Quaternary Pingyuan (Qp) Formation (Fig. 2). The Shahejie Formation contains the main source rocks and sandstone reservoir rocks and is divided into four intervals, Es1, Es2, Es3 and Es4 (from top to base). Es4 consists of grey and dark-grey mudstones, siltstones and fine sandstones with gypsum and halite interbeds in the lower part; and intercalated with brown-grey, grey to black shale, calcareous shale, calcareous mudstones, mudstone, dolomite as well as marlstone in the upper part. The lower Es3 interval is dominated by lacustrine oil shales, dark-grey mudstones and calcareous mudstones and is an important source rock within the depression. The main lithology of the middle Es3 interval includes grey to dark-grey mudstones and calcareous mudstones. The upper Es3 interval is a thick grey and dark-grey mudstone with interbeds of siltstones, sandstones and coarse-grained sandstones. Es2 consists of purple and grey-green mudstones interbeded with grey sandstones and calcareous sandstones deposited in a fluvial-swamp setting. Es1 was deposited in shallow lacustrine environments and is composed of dark-grey mudstones, oil shales, calcareous sandstones and dolomites. The sediments of the Ed comprise sandstones interbedded with mudstones developed in fan delta, delta and shallow lacustrine environments. The subsequent uplift and erosion following the