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Modelling the petroleum generation and migration of the third member of the Shahejie Formation (Es3) in the Banqiao Depression of Bohai Bay Basin, Eastern China

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ABSTRACT

The mudstones in the third member of the Shahejie Formation (Es3) are the primary source rocks in the Banqiao Depression of Bohai Bay Basin. They are rich in organic matter with Total Organic Carbon (TOC) content up to 3.5%. The sandstones in the Es3 member are the deepest proven hydrocarbon reservoir rocks with measured porosity and permeability values ranging from 3.6% to 32.4% and from 0.01 md to 3283.7 md, respectively. One, two and three-dimensional basin modelling studies were performed to analyse the petroleum generation and migration history of the Es3 member in the Banqiao Depression based on the reconstruction of the burial, thermal and maturity history in order to evaluate the remaining potential of this petroleum province. The modelling results are calibrated with measured vitrinite reflectance (R_o), borehole temperatures and some drilling results of 63 wells in the study area. Calibration of the model with thermal maturity and borehole temperature data indicates that the present-day heat flow in the Banqiao Depression varies from 59.8 mW/m^2 to 61.7 mW/m^2 and the paleo-heat flow increased from 65 Ma to 50.4 Ma, reached a peak heat-flow values of approximately 75 mW/m^2 at 50.4 Ma and then decreased exponentially from 50.4 Ma to present-day. The source rocks of the Es3 member are presently in a stage of oil and condensate generation with maturity from 0.5% to 1.8% R_o and had maturity from 0.5% to 1.25% R_o at the end of the Dongying Formation (Ed) deposition (26 Ma). Oil generation (0.5% R_o) in the Es3 member began from about 37 Ma to 34 Ma and the peak hydrocarbon generation (1.0% R_o) occurred approximately from 30 Ma to 15 Ma. The modelled hydrocarbon expulsion evolution suggested that the timing of hydrocarbon expulsion from the Es3 member source rocks began from 31 Ma to 10 Ma with the peak hydrocarbon expulsion shortly after 26 Ma. Secondary petroleum migration pathways in the Es3 member of the Banqiao Depression are modelled based on the structure surfaces at 26 Ma and present-day, respectively. The migration history modelling results have accurately predicted the petroleum occurrences within the Es3 member of the Banqiao Depression based on the calibration with drilling results of 10 oil-producing wells, one well with oil shows and 52 dry holes. Six favorable zones of oil accumulations in the Es3 member of the Banqiao Depression are identified especially oil accumulation zones I and II due to their proximity to the generative kitchens, short oil migration distances and the presence of a powerful drive force.

1. Introduction

Basin modelling plays an important role in modern petroleum exploration in that it integrates the principles of petroleum generation, migration and accumulation in a quantitative manner, thereby helping the exploration geoscientist to understand the petroleum system and to verify different exploration scenarios (Wendebourg, 2003). In the past, basin modelling focused on risking petroleum generation (e.g., Vik and Hermanrud, 1993) through temperature modelling because the rate and timing of petroleum generation depended on thermal history of a basin. Modelling of maturity, hydrocarbon generation and migration in a sedimentary basin thus requires integration of burial and thermal histories. Temperature at any point and time in a given basin depends on heat flow and thermal conductivity, which is a function of lithologies (Abdalla et al., 1999). Heat-flow history of a basin is proposed

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by establishing an agreement between a calculated maturity parameter and the equivalent observed maturity parameter (such as vitrinite reflectance, or Rock–Eval T_{max}) (He and Middleton, 2002; Li et al., 2010). Models are calibrated with measured vitrinite reflectance (R_o) and borehole temperatures are then to model hydrocarbon generation. Basin modelling is focusing on risking migration pathways and integrity of cap rocks through fluid flow and pressure modelling (Burrus, 1998). The driving forces for secondary petroleum migration are buoyancy and groundwater flow, and the restraining force is capillary pressure, which increases with decreasing pore-throat size, increasing interfacial tension and wet ability (Hindle, 1997). The positions of petroleum migration pathways in sedimentary basins are controlled largely by structural morphology (Hao et al., 2007; Gussow, 1968; Momper, 1978; Momper and Williams, 1984; Pratsch, 1994; Hindle, 1997), and modelling of petroleum migration pathways can be a powerful tool to reduce exploration risk (Sylta, 1991; Hermans et al., 1992; Hindle, 1997, 1999).

The Banqiao Depression was explored in 1960s, and the first discovery was the oil pool for Qianmiqiao buried hill structure of the Ordovician Formation in the south of this area in 1998 (Jiang, 2000). More than 500 exploration and development wells had been drilled in the Banqiao Depression by 2006, most of the significant recent discoveries are in the first and second member of Shahejie Formation with little in the Es3 member. Over 60 wells have been penetrated into the Es3 member, but only 10 oil wells and one well with oil show have been encountered. The mudstones of the Es3 member are the main source rock in the Banqiao Depression with the average TOC 1.08%. The porosity (3.6–32.35%) and permeability (0.01–3283.7 md) for sandstones in the Es3 member ranged are higher than the porosity (3.6–27.4%) and permeability (0.01–3283.7 md) for sandstones in the second member of Shahejie Formation. Therefore, it is very important to study the petroleum generation and migration of the Es3 member in Banqiao Depression. The aims of this paper are (1) to reconstruct the source rock thermal and maturity history in Banqiao Depression; (2) to determine the timing of petroleum generation and expulsion; (3) to investigate the pathway of petroleum migration is controlled by the structural morphology or permeability heterogeneity of the reservoir rocks in the Es3 member of the Banqiao Depression by basin modelling. Modelling was performed in three steps: (1) one-dimensional modelling of single well locations, by using version 7.61 of BasinMod 1-D; (2) two-dimensional modelling of a geological section was done using version 4.61 of BasinMod 2-D; and (3) a simple three-dimensional modelling, with version 7.61 of BasinView and version 2.61 of Basin flow.

2. Geological setting

Bohai Bay Basin, one of the most important hydrocarbon-producing basins in China, is located on the eastern coast of China and covers an area of approximately 200,000 km^2. It is a complex, rifted basin formed in late Jurassic and early Tertiary on the basement of the North China Platform (Hu et al., 1986). This basin tectonic evolution can be divided into two major stages: syn-rifting stage (65.0–24.6 Ma) and post-rifting stage (24.6 Ma to the present) (Hu et al., 2001). The syn-rifting stage can be further subdivided into an initial phase (the Kongdian Formation in the Palaeocene), an expansion phase (the fourth member of Shahejie Formation in the Eocene), an expansion and deep subsiding stage (from the Es3 member to the first member of Shahejie Formation in Oligocene) and a contraction phase (Dongying Formation in Oligocene) (Chang, 1991). The sediments in the syn-rifting stage were restricted to the grabens and half grabens and were deposited in lacustrine environments (Chen et al., 1998; Wu et al., 2006;) The post-rifting took place during deposition of the Guantao, Minghuazhen and Pingyuan Formations. The sediments were widespread and dominated by fluvial deposits (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 (Gong, 1997). The Banqiao Depression is located at the north of Huanghua sub-basin (Fig. 1A) and covers an area of 691 km^2, to the northwest by Chuangxian uplift, to the northeast by the Xingang buried hill structure and to the southeast by the Dagang buried hill structure. It can be further divided into four areas based on the structural position. These are the buried hill structure zone, the southern gentle slope zone, the northern steep slope zone and the central depression zone (Fig. 1B). The depression is filled with the Cenozoic sediments which are composed of the Oligocene the Shahehjie (Es) Formation and the Dongying (Ed) Formation, Miocene Guantao (Ng) Formation, Pliocene Minghuazhen (Nm) Formation and Pleistocene Pingyuan (Qp) Formation (Fig. 2). The Shahehjie Formation can be divided into the first, second and third member of Shahejie Formation. The Es3 member which is one of the major source units of the Banqiao Depression with the maximum sediment thickness of more than 2000 m is represented by lacustrine oil shales and dark-grey mudstone interbeded with fine- to coarse-grained sandstone. The second member of Shahejie (Es2) Formation deposited in restricted area and ranged in thickness from 300 m to 400 m. Four sedimentary systems such as fan delta system, braided-delta system, lacustrine system and gravity flow system are identified in this Formation. The sedimentary rocks are grey mudstone, white–grey fine sandstone, coarse-grained sandstone and red mudstone on the uplift. Widespread sediments of the first member of Shahejie (Es1) Formation with the thickness ranges from 100 m to 1000 m are further divided into the lower, the middle and the upper submembers. The lower submember is characterized by a sequence of interbedded sandstone and mudstone in the north of the Banqiao Depression and oil shale, calcareous shale and limestone in the southwest. The middle submember is represented by lacustrine mudstone and the upper submember is grey mudstone interbeded with sandstone interpreted to have been deposited in relatively deep water compared with the Es2 member. The Ed Formation is grey and greenish-grey mudstone with interbeds of light-coloured sandstone of fluvial and deltaic origin (Li et al., 2004; Chen and Zhang, 1991). The uplift and erosion occurred following Ed Formation and the boundary between the Ed Formation and Ng Formation is the main unconformity in the Banqiao Depression. Initial estimates of the amounts of eroded sediments are based on well correlations for penetrated strata seismic sections, and well-log data. The Miocene sediments of Ng Formation are mainly white–grey fine sandstone, coarse-grained sandstone interbeded with greenish-grey and red mudstone. The Pliocene sediments of Nm Formation, which are widespread and large in thickness, are dominated by purple–red, brownish-red, grey–green mudstone and grey sandstone with interbeds of brownish and greenish-grey mudstone representing a fluvial origin.

3. Modelling methodology and parameters

Present-day structure surfaces at the top of different formations, a representative seismic section AB from southwest to northeast and four wells (well Z1, B35, Bs47 and B28) located on section AB in the Banqiao Depression are selected to simulate the petroleum generation and migration. The location of the section AB and wells are shown in Fig. 1A. Thermal history of this study area has been investigated by means of one-dimensional modelling of single wells Zeng1, B35, Bs47 and B28. The representative single