Marine and Petroleum Geology 88 (2017) 696–711

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Present temperature field and Cenozoic thermal history in the Dongpu depression, Bohai Bay Basin, North China

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ARTICLE INFO

Article history:
Received 5 February 2017
Received in revised form
3 August 2017
Accepted 29 August 2017
Available online 8 September 2017

Keywords:
Dongpu depression
Bohai Bay Basin
Present temperature field
Heat flow
Thermal history
Source rock thermal evolution

ABSTRACT

The Dongpu depression is located in the southern Bohai Bay Basin, North China, and it has abundant oil and gas reserves. There has been no systematic documentation of this depression's temperature field and thermal history. In this article, the present geothermal gradient and heat flow were calculated for 68 wells on the basis of 892 formation-testing data from 523 wells. Moreover, the Cenozoic thermal history was reconstructed using 466 vitrinite reflectance data from 105 wells. The results show that the Dongpu depression is characterized by a medium-temperature field between stable and active tectonic areas, with an average geothermal gradient of 34.8 °C/km and an average heat flow of 66.8 mW/m^2. The temperature field in the Dongpu depression is significantly controlled by the Changyuan, Huanghe, and Lanliao basement faults and thin lithosphere thickness. The geothermal gradient twice experienced high peaks. One peak was during the Shahejie 3 Formation depositional period, ranging from 45 °C/km to 48 °C/km, and the second peak was in the middle and late of the Dongying Formation depositional period, ranging from 39 °C/km to 40 °C/km, revealing that the Dongpu depression experienced two strong tectonic rifts during the geothermal gradient high peak periods. The geothermal gradient began to decrease from the Neogene, and the geothermal gradient is 31–34 °C/km at the present day. In addition, these results reveal that source rock thermal evolution is controlled by the paleo temperature field of the Dongying Formation depositional period in the Dongpu depression. This study may provide a geothermal basis for deep oil and gas resource evaluation in the Dongpu depression.

1. Introduction

The present temperature field reflects the thermal state of the lithosphere. Different basins show varied temperature fields that exert distinct effects on source rocks. For a sedimentary basin with continuous deposition, the degree of source rock thermal evolution is directly controlled by the present temperature field. The present temperature field can thus provide constraints for the dynamic mechanisms and tectonic-thermal evolution and can also guide oil and gas evaluation (Hu et al., 2000; Irina, 2006; Mareschal and Jaupart, 2004; Zuo et al., 2011, 2013, 2015a, b; Peng et al., 2015). The thermal history of a sedimentary basin controls the source rock thermal evolution and hydrocarbon generation and expulsion histories, and therefore, oil and gas resource (Hu et al., 2001; He and Wang, 2004; Carminati et al., 2010; Himansu et al., 2013; Qiu et al., 2012a, 2010, 2015; Zuo et al., 2015a, b; 2016; Lu et al., 2016).

The Dongpu depression is located in the southern Bohai Bay Basin, North China (Fig. 1a). More than 12.37 × 10^8 tons (86.59 × 10^8 bbl) of oil reserves and 3.675 × 10^{11} m^3 of gas reserves have been found in this depression to date. These discoveries indicate that the Dongpu depression is a promising oil and gas exploration area. In recent years, however, major problems

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http://dx.doi.org/10.1016/j.marpetgeo.2017.08.037
0264-8172/

regrading oil and gas exploration have appeared in the Donpu depression. Oil and gas production is decreasing year by year in the shallow strata (buried depth less than 3500 m) and difficult oil and gas exploration is gradually increasing. It is crucial to locate deep oil and gas (main Shahejie 3 Formation; buried depth more than 3500 m) to solve the problem of the rapid decline in oil and gas production. Therefore, it is necessary to evaluate the oil and gas resource potential and its distribution in the deep strata. The present temperature field and thermal history studies are the important basic works. However, these works are still relatively few in the Dongpu depression to date. Limited temperature data and thermal gradient distribution problems are presented in previous studies, and the temperature field control factors have not been discussed in detail (Liu et al., 2007). Moreover, thermal history has not studied in the depression. In recent years, we collected 892 formation-testing data from 523 wells and 466 vitrinite reflectance data from 105 wells. All these provided the basis for the study of the present geothermal gradient and heat flow distribution and thermal history reconstruction.

Therefore, the heat flow and geothermal gradient distribution, Cenozoic thermal history of the Dongpu depression were studied in this paper. The present geothermal gradient and heat flow were calculated for 68 wells on the basis of 892 formation-testing data from 523 wells. The thermal history was modeled based on vitrinite reflectance (R_o) data using the BasinMod 1D software. This work can provide thermal information for oil and gas resource evaluation in the Dongpu depression.

2. Geologic setting

The Dongpu depression is located in the southern Bohai Bay Basin, North China, and it is the western depression of the Linqing subbasin. This depression is surrounded by the Luxi uplift to the east, the Neihuang uplift to the west, the Lankao uplift to the south and the eastern depression of the Linqing subbasin to the north (Fig. 1b). The depression extends NNE along its strike and covers an area of 5300 km^2 (2046 mi^2).

2.1. Geologic setting of the Bohai Bay Basin

The Bohai Bay Basin is the largest petroliferous basin in China, including the Shengli, Liaohe, Zhongyuan, Jidong, Jizhong, Bohai, and Dagong oilfields, with an annual oil and gas equivalent of more than 7000 $\times$ 10^4 tons (4.9 $\times$ 10^8 bbl). The Bohai Bay Basin is a Meso–Cenozoic continental rift basin of approximately 200, 000 km^2 (77,220 mi^2) that developed on the Archean–Paleoproterozoic crystallized basement. This basin is bounded by the Jiaodong uplift to the east, the Taihangshan fault zone to the west, the Yanshanian orogenic belt to the north, and the Luxi uplift to the south. This basin consists of the Liaohe, Bozhong, Jiyang, Huanghua, Jizhong, and Linqing subbasins, as well as the Cangxian, Chengning, and Neihuang uplifts (Fig. 1b). The Linqing subbasin includes a western subbasin, the Dongpu depression, and an eastern subbasin. The strata are the Paleozoic, Mesozoic, and Cenozoic. The Cenozoic includes the Shahejie, Dongying, Guantao, Minghuazhen, and Pingyuan Formations (Fig. 2).

The Bohai Bay Basin has experienced four tectonic evolution phases since the Middle Proterozoic (Hou et al., 2001; Tian et al., 2000): (1) the stable sedimentary phase from the Middle to Late Proterozoic to the end of the Paleozoic, (2) the folding phase in the Mesozoic, (3) the synrift phase in the Paleogene, and (4) the regional depression phase from the Neogene to the Quaternary.

2.2. Temperature field and thermal history of the Bohai Bay Basin

A plethora of temperature data and documents on the present temperature field of the Bohai Bay Basin have been recorded (Hu et al., 2000; Gong et al., 2003a, b, c; Gong, 2003; Qiu et al., 2009; Zuo et al., 2011, 2014; Chang et al., 2016). The present geothermal gradient generally ranges from 24 °C/km to 55 °C/km, with an average value of 35 °C/km, and the heat flow generally ranges from 40 mW/m^2 to 90 mW/m^2, with an average value of 64 mW/m^2 in the Bohai Bay Basin (Gong, 2003).

As oil and gas exploration primarily focuses on the strata above the Shahejie Formation, studies on the Cenozoic thermal history principally involve the thermal history since the Shahejie Formation depositional period, focusing on the areas with high levels of petroleum exploration, namely, the Jiyang, Bozhong, Huanghua, and Liaohe subbasins (Qiu et al., 2003, 2004, 2007, 2010; Hu et al., 1999, 2001; Su et al., 2006). Due to the rapid development of oil and gas exploration since the 2000s, additional thermal indicators, such as the apatite fission track (AFT) and vitrinite reflectance (R_o), have been measured for the Mesozoic of all structural units in the Bohai Bay Basin. Therefore, the Meso-Cenozoic thermal history has been systematically reconstructed using AFT and R_o data from the Bohai Bay Basin (Zuo et al., 2011, 2013, 2015b; Qiu et al., 2014, 2015). Overall, the Bohai Bay Basin experienced the Early Cretaceous, with maximum surface heat flows from 81 mW/m^2 to 87 mW/m^2, and Paleogene heat flow peaks, with maximum surface heat flows from 81 mW/m^2 to 88 mW/m^2 (Zuo et al., 2011, 2013, 2015b; Qiu et al., 2014, 2015).

2.3. Geologic setting of the Dongpu depression

The Dongpu depression is one of the most important oil and gas units in the Bohai Bay Basin (Fig. 1a). The Moho beneath the Dongpu depression is 28–33 km (91,863.5–108,267.7 ft) deep, and its lithosphere is 80–90 km (262,467.2–295,275.6 ft) thick according to thermochronology (Qiu et al., 2015). The depression experienced a crystal basement formation stage from the Archean to the Paleoproterozoic, a platform cover deposition stage from the Mesoproterozoic to the Triassic and a continental rift stage from the Mesozoic to the Cenozoic (Su et al., 2006; Hou et al., 2001). In the Paleogene, faulted structures were well-developed due to the subduction of the Pacific plate under the Indonesian plate, and the Shahejie Formation (E*s*) and Dongying Formation (E*d*) have been deposited. From the Neogene to the present day, the depression has been in the thermal subsidence stage, and the Neogene Guantao Formation (N*g*), the Minghuazhen Formation (N*m*) and the Quaternary Pingyuan Formation (Q*p*) have been deposited (Fig. 2). The third and fourth parts of the Shahejie 3 Formation are the important source rocks, and they are dominated by interbedded deep grey mudstone, pale gray siltstone and sandstone developed in semi-deep and deep lacustrine, fan delta and turbidite facies. The Shahejie 3 and 2 Formations are the important reservoir. The Shahejie 2 Formation was developed in the fan delta, fluvial, flood plain facies. It consists of red mudstone, sandstone and conglomerate. Affected by the Lanliao, Huanghe and Changyuan basement faults, the depression can be divided into the Lanliao fault zone (the eastern steep slope belt), the eastern sub-depression, the central uplift belt, the western sub-depression and the western gentle slope belt from east to west (Fig. 1b). These structural units are further divided into 9 s level structural units (Fig. 1b, Table 1).