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Research paper

Thermal anomaly profiles inferred from fluid inclusions near extensional and strike-slip faults of the Liaodong Bay Subbasin, Bohai Bay Basin, China: Implications for fluid flow and the petroleum system

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ABSTRACT

Different types of faulting may greatly impact the flow of hot fluids and related thermal anomalies, which may substantially affect the migration and accumulation of petroleum. However, little is known about the effects of fault types. In this study, 64 core samples were collected from localities controlled by extensional and strike-slip faults in the Liaodong Bay Subbasin, Bohai Bay Basin, and fluid inclusions in these samples were used as thermal indicators of paleo-fluids. The results show strong thermal anomalies near the extensional and strike-slip faults due to the flow of hot fluids. The highest anomalies were recorded at localities proximal to the faults: 134.4 °C at a distance of 375 m from an extensional fault and 145.5 °C at a distance of 262.5 m from the strike-slip fault. However, these anomalies are all local and decrease with increasing distance from the faults, up to a maximum distance of approximately 3000 m. Compared with those near the strike-slip fault, the anomalies near the extensional faults decrease more slowly and typically exhibit higher anomalies at similar distances, which indicates that the extensional faults are better pathways for the flow of hot fluids. The thermal effects of hot fluids have enhanced the maturation of organic matter and shifted the threshold depth for petroleum generation upward by approximately 300 m. Such effects on source rock maturation decrease with increasing distance from the faults, up to a maximum distance of approximately 3000 m. Most Ro values near the extensional faults are clearly higher than those near the strike-slip fault. Thus, the extensional faults play a more efficient role in the enhancement of source rock maturation and are interpreted as preferential pathways for the migration of generated hydrocarbons in the Liaodong Bay Subbasin.

1. Introduction

Hot fluid flow and its related thermal anomalies play a significant role in petroleum migration and accumulation, as well as ore emplacement (Cathles and Adams, 2005; Chu and Chi, 2016; Xie et al., 2001). Such anomalies are often found in the vicinity of faults (Fernandez and Banda, 1990; Magri et al., 2010; Meier et al., 1979; Poort and Klerkx, 2004), as faults are widely considered to be one of the most important permeable pathways for fluid migration. Various studies have examined the role that faults played in hot fluid flow and their subsequent thermal anomalies. For example, a comparison of the values of fault density and heat flow revealed that higher thermal anomalies due to hot fluids were found in areas with a higher density of faults (Lysak and Sherman, 2002). The variations in heat flow across faults further demonstrated that heat flow increases closer to the fault (Poort and Klerkx, 2004; Vanneste et al., 2002). A study of fluid inclusions in the Tim Mersoï Basin indicated that, because of the flow of hot fluids along the fault, the temperatures in all of its formations are much higher (by approximately 60–80 °C) than its background temperature (Mamadou et al., 2016). Within the last decade, several numerical studies have been performed to better understand coupled fault and thermal anomalies in hot fluid environments. Some authors have reported that thermal anomalies due to hot fluids are local phenomena with a maximum extension of only 1–2 km from the vertical fault (Poort and Klerkx, 2004; Vanneste et al., 2002). Several observations have suggested that faults can affect the location and size of thermal convection

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(Li et al., 2016; Wüstefeld et al., 2017), which is a potential mechanism that may explain the mass and heat transport of hot fluids (Garven et al., 2001; Raffensperger and Garven, 1995). Simms and Garven (2004) suggested that faults can induce thermal convection in neighbouring strata even if they are not generally favourable to convective flow.

However, many studies have recognized that different types of faulting (i.e., extensional, reverse, strike-slip) and their ambient stress regimes may exert different impacts on fluid migration (Sibson, 1994; Wood, 1994). In an extensional tectonic regime, extensional faults demonstrated favourable pathways for fluid migration, and they can transport vertical fluids flow across thick basin sediments (Simms and Garven, 2004). In a compressional regime, the prevalent reverse faults, which exhibited low permeability, may not represent good pathways for fluid flow (Rühaak et al., 2010); however, the upward and lateral migration of fluids along thrust faults to adjacent foreland basins has been reported (Bethke and Marshak, 1990; Chu and Chi, 2016; Guo et al., 2016). Strike-slip faults often controlled cross-formational fluid flow and can intersect different flow regimes (Pérez-Flores et al., 2016; Muchez and Sintubin, 1998). Therefore, different fluid migration modes, which are controlled by different types of faulting, may result in different thermal anomaly profiles, which can have significant impacts on the maturity of organic matter. However, there is currently a lack of systematic semi-quantitative or quantitative analyses of the role that fault types play in these processes.

The West Pacific Continent-Ocean Connection Zone (WPCOCZ) is located at the junction of the Eurasian, Pacific and Indian plates (Fig. 1) (Jiang et al., 2017). A series of extensional or transtensional basins have developed in this region, most of which produce large amounts of oil and gas (Ren et al., 2002). Within these basins, episodic periods of hydrothermal fluid activity along the faults have occurred due to the subduction of the Pacific Plate since the beginning of the Cenozoic (Ren et al., 2002; Xu et al., 2014), leading to a significant overprint of organic matter as indicated by increased Ro values in these basins (Hao et al., 1998, 2000; Nie et al., 2005; Xie et al., 1999, 2001; Yu et al., 2012). The Liaodong Bay Subbasin (LDBS) is located in the northeast of the Bohai Bay Basin in the WPCOCZ (Fig. 1 and Fig. 2), contains 12×10^8 tons of potential oil reserves and $500 \times 10^8\,m^3$ of gas reserves (Ma et al., 2011), and has drawn much attention from geologists in recent years. Seismic data have revealed that two types of faulting occurred in this basin during the Cenozoic, namely extensional faulting and strike-slip faulting (Sun et al., 2016); these faults were suggested to have acted as major migration pathways for hot fluids and hydrocarbons. The data indicated that this basin is a prime candidate for investigating how different fault types have influenced the migration of hot fluids and the related thermal anomalies as well as their different effects on the maturity of organic matter.

In this study, we collected 64 core samples from localities controlled by the extensional fault and strike-slip fault based on the seismic data from the LDBS and used 758 fluid inclusions from these samples as thermal indicators of the paleo-fluids in the basin. These results were used to compare the thermal anomaly profiles controlled by extensional and strike-slip faults and to infer the fluid flow patterns that may explain these observed thermal anomaly profiles. We also discussed the thermal effects of the hot fluids along the faults on the enhancement of organic-matter maturation and the different roles that the extensional and strike-slip faults played in this thermal process.

2. Geologic setting and characteristics of extensional and strike-slip faults

2.1. Tectonic setting

The Bohai Bay Basin, a petroliferous Cenozoic basin with a rhombus-shape and a total area of $2 \times 10^5\,km^2$, is located in the northern region of the WPCOCZ (Fig. 1 and Fig. 2). The basin is surrounded by the Yanshan massif to the north, the Jiaoliao massif to the east, the Luxi massif to the south, and the Taihang massif to the west. The LDBS is a secondary tectonic unit of the Bohai Bay Basin (Fig. 2 and Fig. 3), occupying an area of $1.4 \times 10^4\,km^2$ (Teng et al., 2016). The well-known Tan-Lu strike-slip fault (TLF) zone runs in a roughly NNE-trending direction through the eastern edge of the basin (Fig. 3). In general, the structural units of the LDBS can be divided into three depressions and two uplifts; from west to east, these include the Liaoxi Depression, Liaoxi Uplift, Liaozhong Depression, Liaodong Uplift and Liaodong Depression (Fig. 3). Although the evolution of this basin remains controversial, it was generally interpreted to represent a typical rift basin that was modified by synchronous strike-slip deformation (Hsiao et al., 2004; Qi and Yang, 2010).

During the Paleogene (65 Ma to 23.3 Ma) (Fig. 4), rifting processes occurred episodically with intensive volcanic activity and can be divided into two sub-rifting events (Allen et al., 1997). The earlier, Palaeocene-Middle Eocene phase (65-43 Ma) was controlled by a sinistral transtensional stress field due to the NNW movement of the Pacific Plate (Huang et al., 2012), which resulted in the deposition of the Kongdian Formation (Ek) and the 4th member of the Shahejie Formation (Es4). These formations comprise mudstone, carbonate interbeds and layered sandstone and mudstone that are representative of a lacustrine, fluvial and deltaic origin (Fig. 4). The second phase began ca. 43 Ma and continued until the end of the Oligocene (Allen et al., 1997). The TLF's slip reversed from left lateral to right lateral (Hsiao et al., 2004; Huang et al., 2012) due to a change in the plate boundary conditions that occurred at approximately 43 Ma (Allen et al., 1997), which resulted in a dextral transtensional stress field during this period. This megasequence consists of the 3rd-1st members of the Shahejie Formation and the Dongying Formation (Ed), which are dominated by layered sand-mudstone and mudstone that formed in lacustrine, deltaic and fluvial environments (Hsiao et al., 2004). Among these formations, the 3rd member of the Shahejie Formation (Es3), the 2nd member of the Shahejie Formation (Es2) and the 3rd member of the Dongying Formation (Ed3) are the three main source rocks in the LDBS (Fig. 4). During the Neogene and Quaternary post-rift phase (23.3 Ma to the present), nearly N-S-trending extension and dextral strike-slip were prevalent throughout most of the basin (Zhang et al., 2003), which resulted in the reactivation of faults and widespread basaltic magmatism. This period was characterized by relatively uniform and continuous deposition of flat layers. The three sequences of this post-rift stage are represented by the Guantao (Ng) and Minghuazhen (Nm) Formations and the Quaternary Pingyuan (Qp) Formation (Fig. 4), which were predominately deposited in fluvial and shallow water delta environments (Gong et al., 2010).

2.2. Features of extensional and strike-slip faults

The major faults that cut into the basement of the LDBS are distributed towards the NNE and exhibit good continuity. Based on their geodynamic characteristics, these faults can be grouped into two types: extensional faults and strike-slip faults (Sun et al., 2016). The major extensional faults are mainly distributed in the Liaoxi Depression and include the LX1, LX2 and LX3 faults (Fig. 3), whereas the major strike-slip faults are predominantly developed across the Liaozhong and Liaodong Depressions and include the LZ1, LD1 and LD2 faults (Fig. 3). These branched strike-slip faults are the main parts of the Tan-Lu Fault Zone (Fig. 3) and have been studied by many researchers (Hsiao et al., 2004; Teng et al., 2016). In this paper, we used high-quality seismic data to investigate two extensional faults, the LX2 and LX3 faults, as well as one strike-slip fault, the LZ1 fault (Fig. 3).

The LX2 and LX3 faults are large-scale extensional faults that formed at the end of the Mesozoic. Seismic profiles have revealed that these faults have typical listric natures with gentle slopes that dip to the NW. They were characterized by episodic extensional activities that controlled the deposition and evolution of the Liaoxi Depression (Sun