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Thermal and maturation history of Jurassic source rocks in the Kuqa foreland depression of Tarim Basin, NW China

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ABSTRACT

Kuqa foreland depression of the Tarim Basin is one of the largest gas production provinces in China. Thermal history reconstruction using vitrinite reflectance data indicates that the palaeo-heat flow in Kuqa depression was relatively high (50–55 mW/m^2) during the Mesozoic, but gradually decreased during the Cenozoic to reach the present value of 40–50 mW/m^2. The cooling of the Kuqa depression is probably attributed to the crust thickening and the rapid sedimentary rate. The Jurassic source rocks entered conventional oil window at 100 Ma, and began to generate gas at approximately 75 Ma in the Kelasu area. Thermal maturation of the Jurassic source rocks accelerated significantly since 23.3 Ma, especially in the recent 5.2 Ma. In this foreland depression, source rock maturation, which is likely controlled mainly by burial history, also influenced by the presence of fault thrusting and salt-bearing formations.

1. Introduction

The Kuqa depression is a primary gas-producing area in the Tarim Basin. It consists of the North and South slopes, Baicheng and Yangxia sags, Yiqikelike, Kelasu and Qiulitage structural belts (Fig. 1). The potential hydrocarbon source rocks in the Kuqa foreland consist of the Upper Triassic lacustrine shales/mudstones and thin coal seams deposited in fluvial–deltaic and lacustrine environment, the Lower–Middle Jurassic coal beds of swamp–lacustrine origin. The Jurassic coal measures are composed of thick mudstones interbedded with sandstones and thick coal seams (Liu et al., 2003). Circumstantial evidences were presented earlier to show the importance of Jurassic coal measures as gas source rocks in the Kuqa depression (Dai et al., 2000; Liang et al., 2003; Ling et al., 2012; Sun et al., 2004). In the past decade, several giant gas fields, including the KL2 and DN2 (Ma et al., 2003; Liang et al., 2003; Xu et al., 2004; Zou et al., 2006) have been discovered. However, the overall exploration has not been very successful, mainly due to the lack of understanding of the tectonics and the petroleum systems.

The thermal history is one of the fundamental facets of petroleum systems as it controls the timing of hydrocarbon generation and expulsion (Carminati et al., 2010; Hudson and Hanson, 2010). Due to relatively limited well control, thermal history of the study area has not yet been reported so far. The Kuqa depression contains two salt layers: the Palaeocene–Eocene Kumugeliemu salt and the Miocene Jidike salt (Fig. 2). The salt layer in the Suweiyi formation is thin, whereas the evaporite layer in the Kumugeliemu group is thick (Chen et al., 2004; Wang et al., 2011). Salt layers are high efficiency decollement levels (Cotton and Koyi, 2000; Sans, 2003). They are extremely weak and mobile (Weijermars et al., 1993), so they may easily be displaced and deformed in response to any differential loading (Rowan and Vendeville, 2006; Duerto and Mcclay, 2009). Therefore, the salt-related structural styles including thrust faults, back-thrust faults, triangle zones imbricated thrusts and duplex structures are distributed widely in the Kuqa depression and have focused complex structural deformation (Chen et al., 2004; Tang et al., 2003). The previous researchers mainly focus on deformation geometry, structural styles, and deformation stages of the salt-related structures in the Kuqa foreland depression. So far, little attention has been paid to the relationship between the salt structures and the hydrocarbon accumulation (Tang et al., 2004), especially the thermal effect of the salt layers itself and salt-related structures on the source rock maturity.

The objectives of this paper are: (1) to reconstruct thermal histories of several exploration wells in the Kuqa foreland depression; (2) to evaluate the effects of salt occurrence and salt-related thrust-faulting on maturity of the Jurassic source rocks; and (3)

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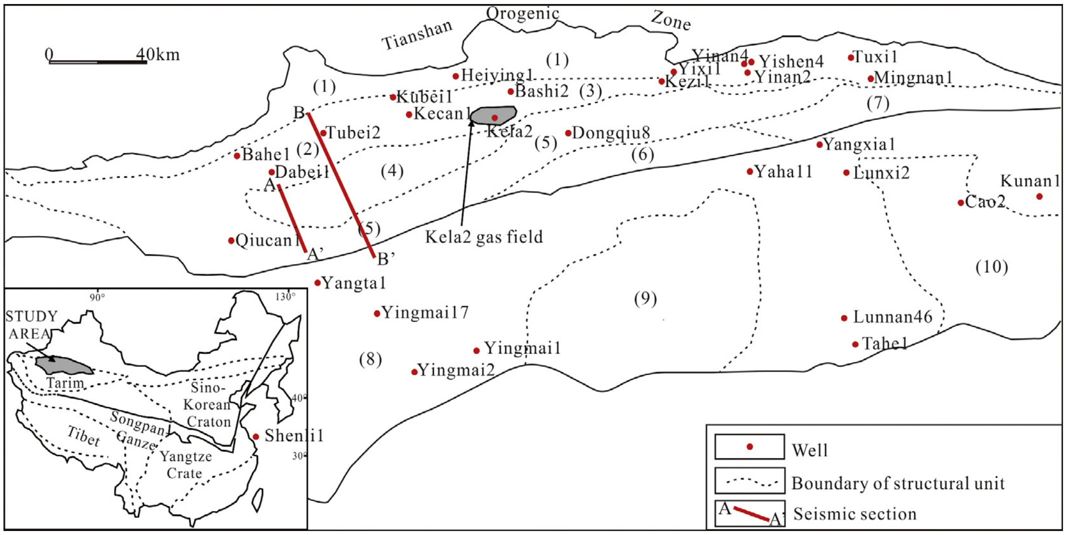

Fig. 1. Structural division of the Kuqa depression, location of studied well and seismic section. (1) Northern slope zone; (2) Yiqikelike structural zone; (3) Kelasu structural zone; (4) Baicheng sag; (5) Qiulitage structural zone; (6) Southern slope zone; (7) Yangxia sag; (8) Tabei uplift; (9) Halahatang sag; and (10) Caohu sag.

to obtain an overall spatial and temporal maturity evolution picture of the Jurassic source rocks.

2. Geological setting

The Kuqa depression, located on south of the Tianshan orogenic belt, is a Mesozoic foreland basin in the northern part of the Tarim Basin. It has experienced three evolution stages: a foreland basin stage (Late Permian to Triassic), a continental depression stage (Jurassic to Paleogene) and a rejuvenated foreland basin stage (since Neogene) (Graham et al., 1993; Jia et al., 2000). At the Late Permian, the South Tianshan fold turned into a mountain system and formed the Kuche foreland basin under structural loads of southward thrusting. The foreland basin further developed into a continental depression from the foreland basin at the Early Jurassic (Liu et al., 2000). By the end of Oligocene, the compression stress in response to the collision between the Indian and Qinghai–Tibet plates caused rapid uplift of the northern Tarim Basin, resulting in the rejuvenation of the Kuqa foreland (Wang et al., 2011). Kuqa depression has undergone several tectonic movements from the Mesozoic to present, among which the Himalaya movements are of the greatest significance. Mass nappe structures such as overthrust fault and thrust fault, have been developed under far-field compression (Guo et al., 1992) caused by the Himalayan collision (Graham et al., 1993; Hendrix et al., 1992).

Mesozoic and Cenozoic strata are fully developed in the Kuqa basin (Fig. 2). From the Triassic to the Quaternary, the basin was filled by alternating terrestrial clastic rocks, coal layers and salt layers. Coal layers were deposited in the Upper Triassic Taliqike formation, Lower Jurassic Yangxia formation and early Middle Jurassic Kezileinuer formation. During the Cenozoic time, the Kuqa basin transitioned into a lacustrine and swamp evaporative system. This transition in the depositional environment was translated by the deposition of salt, gypsum, anhydrite and dolomite interbedded with thin mudstone and shale in the Palaeocene–Eocene Kumugeliemu group and early Miocene Jidike formation (Li et al., 2012; Li and Qi, 2012; Wang et al., 2011). The source rocks in the Kuqa foreland basin are Triassic–Jurassic coal measures and lacustrine mudstones. They are overlain by salt and gypsum layers developed in the Kumugeliemo and Jidike formations.

3. Present-day organic maturity and thermal regime

Vitrinite reflectance is an important parameter widely used in assessing the thermal maturation of organic material. A profile of vitrinite reflectance vs. time can be obtained for a given stratigraphic level if the time–temperature history for that level has been estimated (Price, 1983; Sweeney and Burnham, 1990). Table. 1 lists vitrinite reflectance data measured from the Mesozoic source rock samples in the Kuqa depression. The maturity of the Jurassic rocks ranges from 0.55 to 1.88%Ro (Fig. 3a). Due to slightly deeper bury, the Triassic source rocks have reached higher maturity levels (ranging from 0.66 to 2.59%Ro). Fig. 3b indicates that the measured vitrinite reflectance values generally increase with depth. To be mentioned, samples collected from wells in the overthrusted zone (e.g. Heiying1) show much higher maturity levels than those from the unthrusted zone (e.g. Yangxia1) at similar depth.

There are two kinds of temperature data from the exploration well in the study area, that is the measured bottom hole temperature (BHT) and the continuous borehole logging temperature (CBT) in quasi steady-state condition. BHT data were corrected using the method of Horner-plot (Horner, 1951). In general, the temperatures increase linearly with increasing depth (Fig. 4). However, abnormal temperatures due to high thermal conductivity of the salt sequence have also been observed in a few boreholes. At the Lunxi 2 well location, for example, the temperature gradients in the 4000–4800 m depth interval are much lower than those in other intervals (see Fig. 4). Overall, the temperatures at the depth of 2000, 4000 and 6000 m are 40–60, 60–90 and 100–150 °C, respectively. According to Wang et al. (1995, 2003), the present-day geothermal gradients in the study area is 18–28 °C/km and the present-day heat flow values vary between 40 and 50 mW/m^2.

4. Methodologies and parameters

4.1. Thermal history reconstruction

Based on the present-day heat flow, the thermal history of the basin can be estimated using thermal indicators such as vitrinite reflectance, apatite fission track, and clay mineral compositions (Waples, 1980; Lerche et al., 1984; Wood, 1988; Royden and Keen, 1980; Lutz and Omar, 1991; Bray et al., 1992; Gallagher,