PS Secondary Migration of Petroleum Along Syncline Axis: A Case Study of the Southern Kuqa Foreland Basin and Their Significance in Petroleum Geology*

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Abstract

Tracing petroleum migration pathways is one of the major challenges for exploring of petroleum in a sedimentary basin. The paleo-uplifts are generally considered to be primary migration directions of petroleum. However, here we propose a model that petroleum migrates along the axis of synclines between paleo-uplifts based on geological analysis of integrated seismic, geochemical, and production output data. Detailed seismic data interpretation shows that due to lack of Mesozoic reservoirs or relative low position or disruption of faults, the paleo-uplifts can hardly be petroleum migration directions. Geochemical parameters, including the ratios of alkyl dibenzothiophenes and wetness parameter, which reflect that maturity of petroleum gradually decreases along axes of synclines between paleo-uplifts from northeastern to southwestern. In addition, petroleum production output and GOR also show a deceasing trend from northeastern to southwestern. All of those evidences suggest that petroleum from the sources in the central and northern Kuqa Foreland Basin, is more likely to migrate along the axes of the synclines between the paleo-uplifts from northeastern to southwestern. This understanding can not only enrich the scientific research on secondary migration, but also be potentially be used to guide petroleum exploration in the southern Kuqa Foreland Basin.

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Secondary migration of petroleum along syncline axes: a case study of the southern Kuqa Foreland Basin and their Significance in Petroleum Geology

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Abstract

Abstract: Tracing petroleum migration pathways for petroleum exploration in a sedimentary basin is challenging. Paleo-uplifts are generally considered to represent the primary migration directions of petroleum. Here we propose a model for the Kuqa Foreland Basin, in which petroleum migrates along the axes of synclines between paleo-uplifts, based on an integrated analysis of seismic, geochemical, and production data. Interpretation of detailed seismic data indicates that petroleum is unlikely to migrate to the paleo-uplifts because of their relatively low positions, fault disruptions, or a lack of Mesozoic reservoirs. Geochemical parameters, including the ratios of alkyl dibenzothiophenes and the gas wetness parameter, show that petroleum maturity gradually decreases along the axes of synclines between paleo-uplifts from northeast to southwest. Petroleum production data and gas/oil ratios also show decreasing trends from northeast to southwest. This evidence suggests that petroleum is likely to migrate along the axes of the synclines between the paleo-uplifts from northeast to southwest. This study not only enhances the scientific understanding of secondary migration, but also may be useful to guide petroleum exploration in the southern Kuqa Foreland Basin.

Introduction

Buoyancy is a major force driving secondary petroleum migration (Schowalter 1979). Hindle (1997) suggested, based on three-dimensional computer modelling, that petroleum migration in sedimentary basins is mainly controlled by structural morphology. Hubbert (1953) proposed the concept of fluid potential and suggested that fluid within a reservoir, controlled by fluid potential, always migrates from areas of high potential toward areas with low potential. This hypothesis has been verified by other studies (Tissot and Welte 1984; Pratsch 1986; Welte et al. 2000; Karlsen and Skeie 2006; Hao et al. 2010; Lerch et al. 2016; Peng et al. 2016).

Therefore, paleo-uplifts where topography is characterized by persistent paleo-highs are generally considered to be the primary migration destinations of petroleum. However, because failed wells have been drilled in paleo-uplifts in the southern Kuqa Foreland Basin, one of the most petroleum-rich areas of China, petroleum exploration has been redirected to synclines between the paleo-uplifts. Improved understanding of petroleum migration pathways from generative kitchens to adjacent reservoirs would aid in de-risking exploration. The purpose of this study was to trace petroleum migration directions from generative kitchens to the reservoirs.

Method

A considerable amount of seismic data has been collected over the last decade in the Kuqa Foreland Basin. These data enable detailed tectonic study of paleo-uplifts in the basin. During the interpretation phase, structural models from published literature and unpublished internal reports were reviewed. Key selected wells provide biostratigraphic and chemostratigraphic age controls on seismic stratigraphy. In addition, the models described herein were established by combining geologic mapping data with field observations.

Fluid properties and production output data were provided by the PetroChina Tarim Oilfield Company, and 16 oil samples were selected for alkyl dibenzothiophenes (DBTs) analysis.

Results & Discussion

(1) Evidence from seismic data

In the past, the paleo-uplifts in the Kuqa Foreland Basin were of little interest to researchers because of the limited data available. Based on seismic data and data from drilled wells, the geometry and certain dynamics of four ENE-trending en-echelon paleo-uplifts were studied, namely, the Wensu paleo-uplift (WSPU), Xiqiu paleo-uplift (XPU), Xinhe paleo-uplift (XHPU), and the Yaha paleo-uplift (YHPU, Fig. 1). These paleo-uplifts share a number of characteristic features. Each paleo-uplift from west to east is briefly described below to emphasize their roles in petroleum migration within the southern Kuqa Foreland Basin.

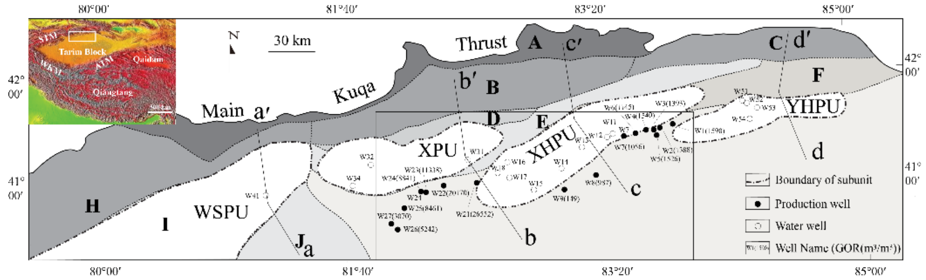

Figure 1. Map showing the location of the Kuqa Foreland Basin (modified after Zeng, 2010). A: Northern monocline tectonic zone; B: Kelasu tectonic zone; C: Yiqikelike tectonic zone; D: Baichen sag; E: Qiulitag tectonic zone; F: Yangxia sag; G: Front uplift belt; H: Wushi sag; I: Wensu salient. STM: South Tianshan Mountains; WKM: Western Kunlun Mountains; ATM: Altum Mountains; WSPU: Wensu paleo-uplift; XPU: Xiqiu paleo-uplift; XHPU: Xinhe paleo-uplift; YHPU: Yaha paleo-uplift. The locations of seismic lines are indicated by a–a′, b–b′, c–c′, and d–d′.

Previous research has shown that petroleum in the southern Kuqa Foreland Basin was generated from Triassic and Jurassic source rocks in the central and northern Kuqa Foreland Basin (Li et al. 2004). According to Liang et al. (2003), peak oil generation occurred during the early Miocene (23–12 Ma), whereas peak gas generation took place more recently, during the last 5 Ma. After oil and gas generation to the north of the paleo-uplifts, oil and gas may have migrated to the Mesozoic traps within the southern Kuqa Foreland Basin. Although the paleo-uplifts where topography is characterized by persistent paleo-highs are generally considered primary migration destinations, the paleo-uplifts in the southern Kuqa Foreland Basin are unlikely to be petroleum migration destinations for the following reasons:

A) Detailed seismic interpretation shows that some of these paleo-uplifts, such as the WSPU (Fig. 2) and the XPU (Fig. 3), lack Mesozoic reservoirs, and have Cenozoic successions that conformably overlie Paleozoic carbonate rocks.

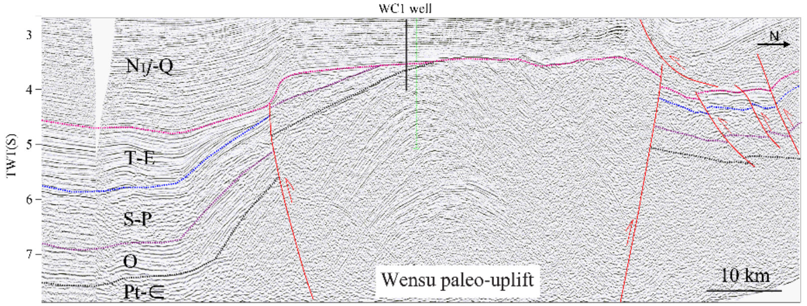

Figure 2. Interpreted seismic section through the Wensu paleo-uplift showing its structural features including onlap of the Triassic strata. See a–a' in Figure 1 for the line location. Pt–Є: Cambrian and Precambrian strata; O: Ordovician strata; S–P: Silurian to P-ermian strata; T–E: Triassic to early Tertiary strata; N1j–Q: late Tertiary to Quaternary strata; TWT = two-way traveltime.

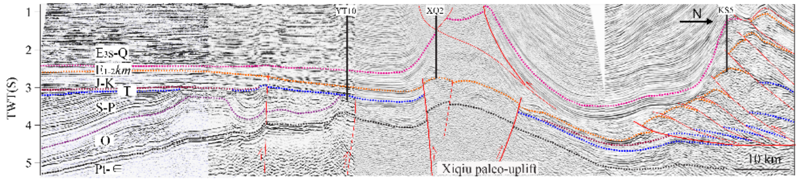

Figure 3. Interpreted seismic section through the Xiqiu and Xinhe paleo-uplifts showing their structural features. See b–b' in Figure 1 for the line location. T: Triassic strata; J–K: Jurassic to Cretaceous strata; E1-2 km: Kmugelimu Formation; E3s–Q: Sushanhe Formation and late Tertiary to the Quaternary strata; TWT = two-way traveltime. Other strata codes are the same as in Figure 2.

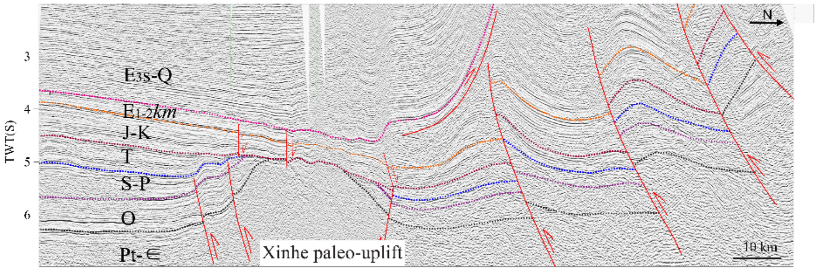

Figure 4. Interpreted seismic sections through the Xinhe Paleo-uplift showing its structural features. See c–c' in Figure 1 for the line location. TWT = two-way traveltime. Strata codes are the same as in Figure 2 and Figure 3.

B) Although some paleo-uplifts are overlain by relatively thin Mesozoic successions, the Mesozoic reservoirs at the cores of these paleo-uplifts either occur at lower positions relative to the nearby synclines (such as in the case of the XHPU, Fig. 4), or have been destroyed by normal faults (such as in the YHPU, Fig. 5). This geological evidence demonstrates that little petroleum can migrate through these paleo-uplifts and accumulate in the southern traps. The synclines, generally found at relatively low positions, were formed by deposits of thick Miocene sandstones, and may act as carrier beds for oil migration. Therefore, petroleum from the northern part of the basin may migrate laterally along the axes of the synclines between the paleo-uplifts from northeast to southwest.

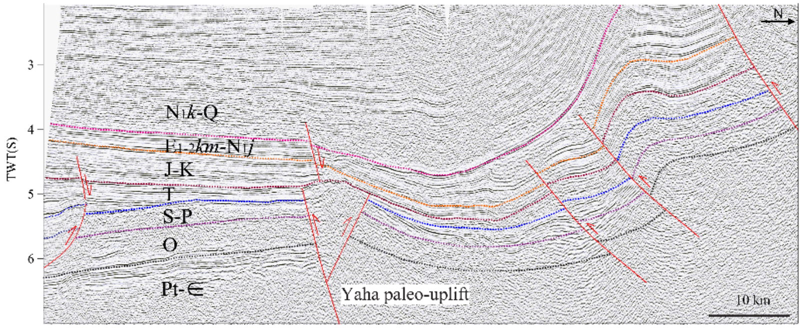

Figure 5. Interpreted seismic sections through the Yaha Paleo-uplift showing its structural features. See d–d' in Figure 1 for the line location. TWT = two-way traveltime. Strata codes are the same as in Figure 2 and Figure 3.

(2) Evidence from seismic data

A) Oil–oil correlation

The results show that the previously discovered oils in Mesozoic reservoirs of the basin are primarily light crudes, with densities of 0.57–0.85 g/cm3 . Oil densities range from 0.65–0.85 g/cm3 in the syncline between the YHPU and the XHPU, and between 0.57–0.69 g/cm3 in the syncline between the XHPU and the XPU. The diagrams in Fig. 6 illustrate the relative molecular compositions of acyclic alkane ratios (pristane/n-C17 n-alkane and phytane/n-C 18 n-alkane) and C27–C29 steranes (Fig. 7) for the oil samples. Apart from the above parameters, the 22S/(22S + 20 R) ratios of the C29 steranes are 0.34–0.44.

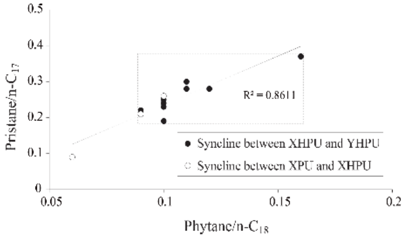

Figure 6. Cross-plots of phytane/n-C18 versus pristane/n-C17 (modified after Shanmugam, 1985).

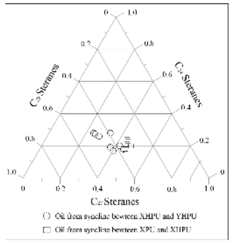

Figure 6. Ternary diagram of C27–C29 steranes.

A) Variations of geochemical parameters during migration

In recent years, some researchers (Wang et al. 2004; Li et al. 2014) have reported that for several reasons, the molecular parameters of DBTs may be used as tracers of oil migration or reservoir filling. When maturity increases, alky1-DBT molecular parameters, such as the ratios of 4-/1-MDBT and 2,4-/1,4-DMDBT, should increase because of increased concentrations of thermostable isomers, such as 4-MDBT, and 2,4-DMDBT (Chakhmakhchev et al. 1997; Santamaría-Orozco et al. 1998; Wang et al. 2-004). Therefore, alkyl DBT molecular parameters may be used as tracers of reservoir migration. For oils in the synclines of the southern Kuqa Foreland Basin, the relative ratios of 4-/1-MDBT and 2,4-/1,4-DMDBT decrease along the axes of the synclines from northeast to southwest (Fig. 8 and Fig. 9).

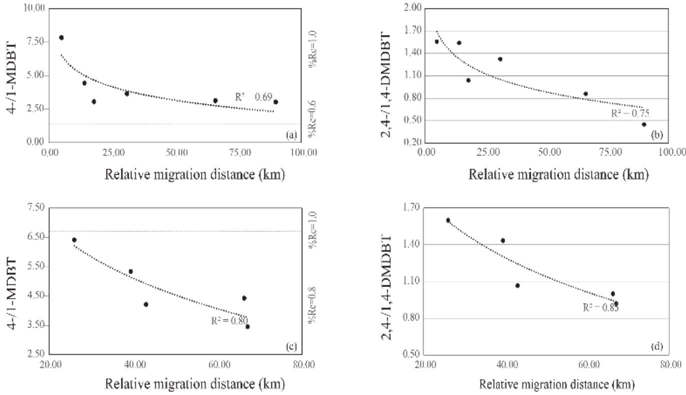

Figure 8. SThe MDBT and DMDBT ratios for oils from the syncline between the YHPU and the XHPU (a and b) and from the syncline between the XPU and the XHPU (c and d), plotted against estimated distances relative to a reference oil (W-1 or W21 well). The reference oil is assigned an arbitrary migration distance of 5 km. %Rc: calculated vitrinite reflectance; %Rc = 0.51 + 0.073*(4-/1-MDBT) (Radke 1988).

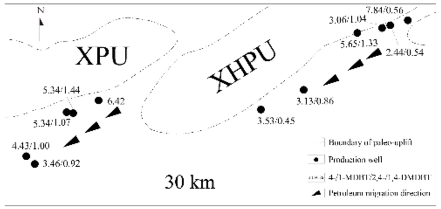

Figure 9. Map showing change in MDBT and DMDBT ratios for oils in the syncline between the YHPU and the XHPU. See box in Fig. 1 for the location.

The natural gas within the synclines was generated in later periods and likely migrated along the oil migration pathways (Thompson 1991). Therefore, this gas may have originated from the central and northern Kuqa Foreland Basin, and followed the pathways of previous oil migration, which are indicated by changes in the %C2+. Because gas migration through carrier layers will result in the loss of methane due to its solubility in water (Karlsen and Sheie 2006), gas close to the source rock will be enriched in methane (Prinzhofer and Pernaton 1997). Based on the petroleum filling model (England et al. 1987) and this loss of methane, we infer that the %C2+ may be strongly affected by migration. Consequently, the distance of migration will be positively correlated with %C2+, which is consistent with the results described above (Fig. 10).

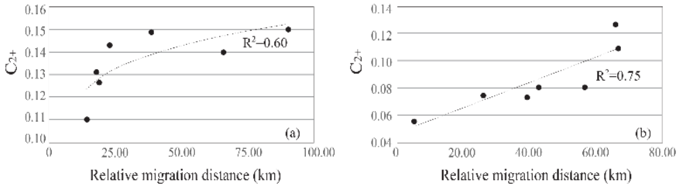

Figure 10. The wetness parameter (C2+) for oils in the syncline between the YHPU and the XHPU (a) and the syncline between the XHPU and the XPU (b) plotted against estimated distances relative to a reference oil.

(3) Evidence from production data

Demaison (1984) studied the distribution features of 12 generative basins in different parts of the world and concluded that exploration risk increased with increasing distance from the effective source. Pang (2003) investigated the relationships between 73 large- and medium-sized oil–gas fields and their respective distances of petroleum migration and concluded that the number of oil–gas fields diminished as the distance of petroleum migration increased. Hu (2005) affirmed these conclusions based on examination of more than 200 sedimentary basins around the world, and further concluded that the probability of discovering large- and medium-sized oil–gas fields was higher in areas more proximal to the petroleum source. Therefore, distance from mature source rocks is inferred to determine the size, distribution, and resource potential of petroleum reservoirs. With increasing distance from the reference wells, petroleum production decreased considerably, and failed wells were typically drilled in the paleo-uplifts, both of which reflect petroleum generated to the north migrating along the axes of the synclines from northeast to southwest.

Based on the well production data from around the southern Kuqa Foreland Basin, water wells are distributed within the domain of the paleo-uplifts, such as the W11, W31, W41, and W51 wells, whereas commercial production wells are generally distributed in the synclines between these paleo-uplifts (Fig. 11). Furthermore, daily production is notably high in the northeastern parts of the synclines between the uplifts, and tends to diminish with increasing distance from the reference wells (W1 and W21, Fig. 11).

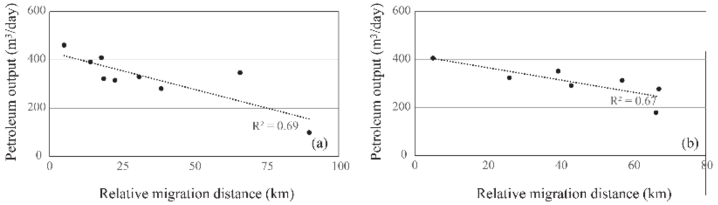

Figure 11. Petroleum output for oils in the syncline between the YHPU and the XHPU (a) and the syncline between the XHPU and the XPU (b) plotted against estimated distances relative to a reference oil.

In addition, closer to the petroleum kitchen, there is higher charge of gas into reservoirs that formerly contained oil, which is consistent with a higher GOR. The GOR is abnormally high at the northeastern parts of the synclines and gradually decreases along the axes of the synclines from northeast to southwest, which indicates that the gas migrates along the oil migration pathway.

The gas/oil ratio (GOR) values decrease with increasing distance from the northeast of the synclines. For example, the GOR decreases from 1,590 m^3/m^3 in the W1 well to 159 m^3/m^3 in the W9 well along the axis of the syncline between the YHPU and the XHPU, and the GOR decreases from 26,552 m^3/m^3 in the W21 well to 3,070 m^3/m^3 in the W27 well along the axis of the syncline between the XHPU and the XPU (Fig. 12).

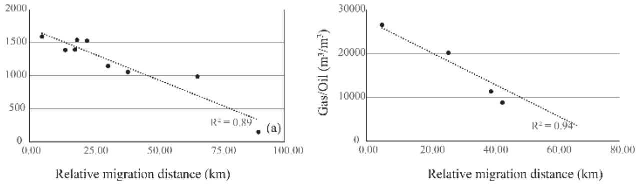

Figure 12. Diagram of interpretative origin of natural gas (modified after Bernard et al. 1978; Whiticar. 1999) based on the molecular and isotope compositional information, showing the gas samples from the study area are thermogenic gas.

Although no drilling has yet been performed in the traps of the syncline between the WSPU and the XQPU, petroleum accumulation may be inferred from structural patterns similar to those of the other two synclines. Therefore, the petroleum migration patterns described above may serve as an effective analog for understanding the migration characteristics of petroleum within this syncline as well. The results of this study may therefore provide an important foundation for future petroleum exploration in the southern Kuqa Foreland Basin.