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Statistical analysis as a tool for assisting geochemical interpretation of the Upper Triassic Yanchang Formation, Ordos Basin, Central China

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ABSTRACT

The Yanchang Formation in the Ordos Basin is the most important petroleum play not only for conventional oil and gas accumulations, but also for newly emerging shale oil and tight gas resources. The molecular characterization of the basinwide source rocks predicts three groups of generative petroleum types: Paraffinic High Wax Oil, mixed base (Paraffinic-Naphthenic-Aromatic) Low Wax Oil, and Gas and Condensate. Supplementary to previous work, 68 samples including the crude oils, source bitumens and reservoir extracts from the Yanchang petroleum play are analyzed. The distribution of two terpane classes (eight tricyclic terpanes and eight pentacyclic terpanes) are determined with subsequent simultaneous RQ-mode factor analysis for a composite data set of these samples alongside 216 published crude oils worldwide with known facies descriptions. Thermal maturity has been evaluated as a consistent distribution at first using a combined method of a maturity-related biomarker [Ts / (Ts + Tm)] and aromatic parameters (Methyldibenzothiophene Ratios) to alleviate the maturity differences effect when discussing geochemical characterization. The R-mode factor analysis consists of the first two factors that are describing 45 present of the cumulative total variance in the data set, and presents a sample grouping pattern in Q-mode factor analysis which is determined by different contributions of terpane associations, i.e., the tricyclic C_{21} coupled with pentacyclic C_{26}, C_{27}, C_{28} and C_{30}, in the same factor space. Three terpane associations, the C_{26} and C_{28} terpanes, the C_{21} and C_{30} terpanes and the C_{27} pentacyclic terpenes, are respectively responsible for discriminating crude oil, reservoir extracts and source bitumens in RQ-mode factor analysis. Molecular compositions further address more detailed interrelationships among three sample groups that crude oils and reservoir extracts are sharing close genetic relationships both in depositional environment typing and C_{27}-C_{28}-C_{29} sterane distribution. Samples from source rocks vary much significantly. A mixing process which occurs after oils has been expelled from host source rocks into carrier units during accumulation. In addition, the migration-contamination of C_{29} sterols when oils are cross through the Chang 7–2 unit along migration pathways might also explain this lack of correlation between source rocks and oil-reservoir system.

1. Introduction

A source-oil correlation is defined as the discovery of a genetic relationship between a crude oil and its original source rock based on integrated geological and geochemical facts (Jones, 1987; Curiale, 1993). This relationship is of interest for scientific and economic reasons: it not only provides improved knowledge of the processes of petroleum generation, expulsion, migration and entrapment, but also improves the probability of commercial success based on a consideration of the petroleum fluids themselves rather than simply the reservoir, structure or trap in which the fluid is contained. Nevertheless, owing to the nature of "geological problems addressed with geochemical methods" (Curiale, 1993), the interdisciplinary character of source-oil correlation requires not merely detailed molecular and geochemical matching between oil and source rock, but also a consideration of what the circumstances were at the time the original source rock expelled a particular oil (Curiale, 1994).

The Mesozoic petroleum accumulations are a very important petroleum-bearing play in the Ordos Basin of Central China. Two Jurassic oil fields were firstly discovered during the 1970s followed soon thereafter by another seven (Qiu and Gong, 1999). In 1983, the Triassic Ansai oil

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field was discovered, and since then, more and more oil fields have been found in Triassic strata (Li and Lu, 2002). Over the past decades, the discovery of a series of oil accumulations in stratigraphic traps of the Yanchang Formation has made the Triassic the most important and prolific petroleum play in the Ordos Basin (Jia and Chi, 2004; Zou et al., 2009; Ji et al., 2016). Many scholars have selected Yanchang organic-rich lacustrine mudstones (Chang 7 Shale) as the effective source rocks for the Triassic petroleum play (Zhai, 1997; Hanson et al., 2007; Ji et al., 2007; Duan et al., 2008; Yu et al., 2010). Two sets of reservoir rocks are present in the Mesozoic petroleum play: the deltaic sandstones of the Upper Triassic Yanchang Formation (Chang 6) and the fluvial sandstones of the Lower Jurassic Fuxian and Yan'an Formation. Although the Triassic petroleum play was discovered almost three decades ago, it continues to attract more and more attention from academic and industrial communities, most recently due to the increasing development of unconventional oil accumulations in ultra-tight reservoirs (Li et al., 2015; Yang et al., 2015; Zou et al., 2015). Some researchers have proposed that crude oils from the Yanchang petroleum play are derived from mixed terrigenous and algal-bacterial organic matter which formed under a reducing and freshwater environment. These oils are predominated by long-chain *n*-alkanes, abundant C_{29} steranes related to C_{27} and C_{28} homologs, as well as tetracyclic and bicyclic terpanes (Hanson et al., 2007; Duan et al., 2008; Tao et al., 2015). The Chang 7 Shale has been assigned as a principal source rock for generating the Mesozoic oils in the Ordos Basin as it contains abundant bicyclic alkanes that are traced to the most significant biological precursor *B. braunii* (Ji et al., 2007, 2016). In order to better understand the sedimentation of the source rock, and the stack pattern of stratigraphic combination, Liu and Yang (2000) deciphered the sequence stratigraphy of the Upper Triassic - Jurassic sedimentary package based on three unconformity-bounded basin phases. According to Liu et al. (2008); Watson et al. (1987) and Zhao et al. (1996), the Ordos Basin can be subdivided into at least four obvious stages of tectonic deformations existing during the basin's evolution, and the main stages of generation, mineralization and positioning of the multiple energy resources have an obvious connection and relationships with the evolution and reformation of the basin during Mesozoic to Cenozoic period.

Although some scholars have pointed to two Mesozoic intervals as source rocks for the Yanchang petroleum play from nine potential source rock candidates within Proterozoic to Lower Paleozoic marine carbonate, Carboniferous and Permian coal deposits, and Mesozoic lacustrine strata, several important issues regarding aspects of the Triassic petroleum play still need to be further scrutinized based on extensive data and materials. As an expansion of the work presented by Pan et al. (2016), the current study was established to apply depositional environment typing based on geochemical characterization. Here we present a geochemical characterization using a set of samples from the Upper Triassic Yanchang Formation as a case study, in order to take advantage of traditional geochemical methods and the statistical analysis. The simultaneous R- and Q-mode factor analysis as a multivariate statistical approach has been proved effective and useful in grouping samples and discriminating different depositional facies based on tricyclic and pentacyclic terpane compositions (Klovan, 1975; Zhou et al., 1983; Zumberge, 1987; Walden et al., 1992). It allows the variables and samples to be displayed on the same set of diagrams, which greatly facilitates the interpretation of the factors. Alongside the steranes, which contain much useful information on the origin of crude oils (Mackenzie, 1984; Moldowan et al., 1985), terpane biomarkers were chosen as the main statistic variables in the study because of their ubiquitous occurrence, and ease of quantification. Notably, the terpanes tend to be more stable (especially the tricyclics) than steranes when they are subjected to thermal alteration (Seifert and Michael Moldowan, 1978, 1979; Mackenzie, 1984). The detailed summary of the origins of tricyclic and pentacyclic terpanes are outlined by Zumberge (1987). RQ-mode factor analysis is able to separate the investigated samples into different categories according to their different terpane associations. Small maturity fluctuation can influence how the sample behaves, yet the trends do not obscure the interpretation of the genetic sample populations.

2. Geological framework and thermal history

The Ordos Basin is an important non-marine petroliferous basin, and contains oil and natural gas resources that amount to nearly one third of the national annual gross output (Yang and Deng, 2013). As an intraplate depression on the North China Craton during the Mesozoic to Cenozoic, the basin is bounded by a series of synchronous, polyphase orogens, and can be subdivided into six regional structural units (Fig. 1). The stratigraphic combination of the Yanchang Formation consists of ten members named Chang 10 to Chang 1 based on marker beds, sedimentary cycles and lithological association, and is unconformably overlying and overlain by the Middle Triassic Zhifang Formation and the Lower Jurassic Fuxian Formation, respectively (Fig. 2).

A detailed analysis of the geological framework and petroleum play of the area under study has recently been published (Pan et al., 2016), building upon earlier works (Sun et al., 1989; Zhao et al., 1996; Liu and Yang, 2000; Yang et al., 2005; Ren et al., 2007; Yang and Deng, 2013; Zou et al., 2013). Tectonic events and thermal history are responsible for the formation of many resources (e.g., petroleum, coal and uranium mine) in the Ordos Basin (Jiao et al., 2005; Chen et al., 2007; Hanson et al., 2007; Ren et al., 2007; Yang et al., 2016). Generally, basin formation since the Paleozoic can be split into three stages

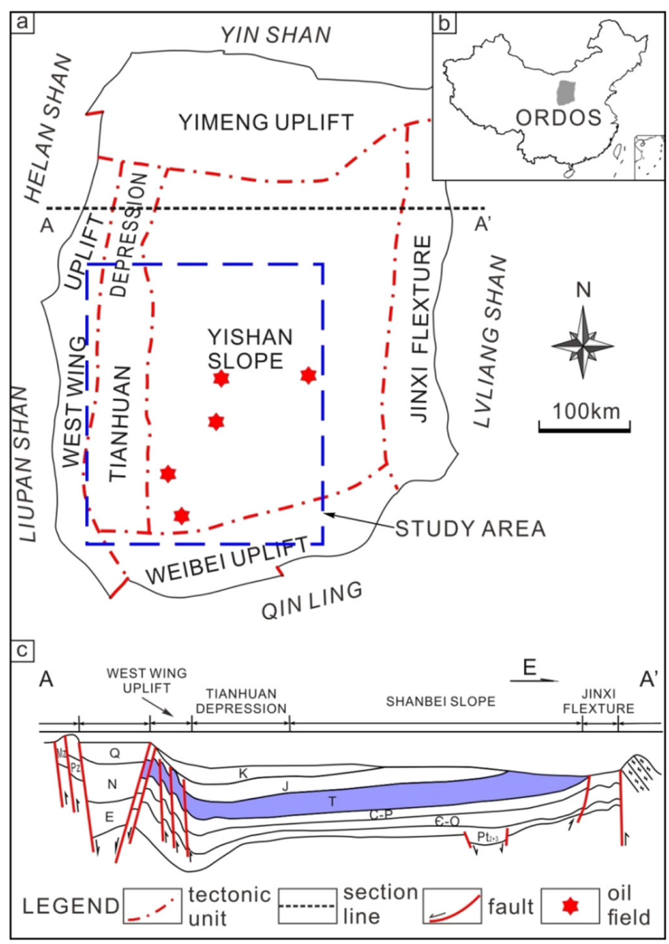

Fig. 1. Sketch map showing tectonic units of Ordos Basin, study area and oil fields locations (a). Inserted map showing the location of Ordos Basin (b). Cross-section across the Ordos Basin illustrating relatively uniform distribution of Triassic stratigraphic packages (c). “Shan” and “Ling” in Chinese both mean mountains.