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Research paper

Bicyclic alkanes in source rocks of the Triassic Yanchang Formation in the Ordos Basin and their inconsistency in oil-source correlation

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ABSTRACT

The Triassic Yanchang Formation is the main source rocks for Mesozoic oil in Ordos Basin. The formation includes 10 oil-bearing beds (Ch 1–Ch 10), that each can be further divided into two to three intervals. Abundant C_{12}–C_{14} and C_{15}–C_{16} bicyclic alkanes have been detected in the formation in the Xifeng oilfield, Ordos Basin. The C_{12}–C_{14} group is dominated by C_{12} and C_{13}, and the C_{15}–C_{16} group contains abundant C_{15}. The groups show three distribution patterns: A) the C_{12}–C_{14} group is the major component in the non-source rocks of the Ch 7-1 and Ch 8-1 intervals; B) both groups are abundant and are common in source rocks of the Ch 7-3 interval; and C) the C_{15}–C_{16} group is the major component in source rocks of the Ch 7-3 interval and also in sediments that contain type I or partial sapropel type II_1 organic matter (OM) in the Ch 7-2 and Ch 8-1 intervals. Although thermal maturities of the source rocks in the Ch 7 section are similar, they show significant differences with respect to the drimane isomerisation index, which indicates that the drimane rearrangement is controlled by thermal evolution of the sediments, but may also be closely related to the depositional environment. This study determined that reducing environments are more conducive to preservation of drimane than oxic environments. The drimane isomerisation index and the value of the hopane parameter Tm/Ts are positively correlated. The parameter Tm/Ts varies over a wide range within the sequence, and the large variations may be a result of terrigenous OM input by turbidity currents and/or gravity flows, mixed with the autochthonous sediments. Abundant homodrimane in both source rocks may reflect reducing environments in deep lakes and major input of higher plant OM. Organic-rich shale and oil shale in the Ch 7-3 interval of the Yanchang Formation are the primary sources of oil in reservoirs in the Xifeng area. The crude oil is rich in bicyclic alkanes that are dominated by C_{15}–C_{16} as source rocks with pattern C for bicyclic alkanes, which indicates an origin mainly from the Ch 7-3 interval. The main peaks in all of the crude oils are associated with 8β(H)-drimane and lower abundance of rearranged drimane. However, most of the source rocks have a main peak associated with 8β(H)-homodrimane or rearranged drimane. Weak microbial action, selective degradation and water washing may be the cause of the significant difference in bicyclic sesquiterpane composition between the crude oil and the source rocks. The result suggests that oil-source correlations based on the bicyclic sesquiterpanes are questionable.

1. Introduction

Bicyclic alkanes and bicyclic sesquiterpanes are widely distributed in a variety of sediments and crude oil, but their compositions and distributions differ. Philp et al. (1981) first reported the discovery of bicyclic alkanes in non-marine crude oils of different ages in Australia and interpreted them as products of different levels of bacterial degradation. A series of single unsaturated tricyclic diterpenes ($C_{20}H_{34}$) detected in the crude oil was thought to be the source. The authors concluded that 8β(H)-drimane is synthesised from drimenol and may have a bacterial origin. 4β(H)-eudesmane oil with a C_{15} bicyclic structure is a typical marker of higher plants that are derived from β-eudesmol plant components.

Alexander et al. (1983, 1984) suggest that bicyclic alkanes are

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bacterial metabolic products that form during early diagenesis from degraded bacterial hopanes by ring opening. Many types of isomeric bicyclic alkanes form during late diagenesis by the removal and rearrangement of functional groups. The C_{14}–C_{16} drimane series is usually derived from bacteria and other microbes. 8β(H)–C_{20} homodrimane has been found in algal coal, which indicates that the 8β(H)-drimane series may have a variety of precursors, including bacteria, algae, tricyclic terpanes with long side chains, and the derivatives of 8, 14-secohopane and hopane series by degradation and ring opening (Wang, 1990). Some rearranged drimane may form by degradation of angiosperm oleanoids or ring opening of oleananes (Nytoft et al., 2009; Eiserbeck et al., 2011).

Terrigenous crude oils in northwest China are rich in bicyclic alkanes and bicyclic sesquiterpanes. These biomarkers are generally considered to come from higher plants (Fan et al., 1989; Luo et al., 1991). C_{14}–C_{16}, and C_{20} bicyclic alkanes and C_{15}, C_{16}, and C_{20}-8β(H)-drimane have also been detected in lab-grown *Botryococcus braunii*. This green alga has been recognised as a major contributor of OM in source rocks, and it can be divided into four chemical races on the basis of their hydrocarbon composition and gene sequences, namely A, B, C and S (Metzger et al., 1985, 1990; Zhang et al., 2007; Volkman, 2014). Complete series of tricyclic terpanes with long side chains have been identified from the chemical race A of *B. braunii* from the United States and strains of *B. braunii* from Lake Fuxian in China, although hopanes are rare in *B. braunii* (Song and Li, 1994). Therefore, *B. braunii* is also a possible source of these bicyclic biomarkers in sediments. The terpenes that are produced by *B. braunii* may also form bicyclic biomarkers during diagenesis and bacterial degradation in addition to direct synthesis. This information indicates that bicyclic alkanes originate from a variety of sources, such as bacteria and algae and the products of biological degradation. Preliminary studies indicated that the bicyclic sesquiterpane of source rocks and crude oils in the Yanchang Formation may have more chance to come from the abundant *B. braunii* in the source rocks (Ji et al., 2008, 2010).

Bicyclic sesquiterpanes have been found in a variety of sediments and crude oil, and their geochemical properties have been widely exploited in petroleum exploration. For example, the relative abundances of rearranged drimane and homodrimane are used to investigate the thermal evolution and migration direction of crude oil (Luo et al., 1991; Trindade and Brassell, 1992; Zhang et al., 2004), and the fingerprints of bicyclic sesquiterpanes are applied in oil-source correlation (Al-Arouri et al., 1998; Okunova et al., 2010). However, because the sources of bicyclic biomarkers are complex and their diagenetic evolution is not well understood, the reliability of the applications of bicyclic biomarkers needs to be explored further.

Over the past 10 years, a series of oil reservoirs in lithological traps have been found in the Triassic Yanchang Formation in the Xifeng area, southwest Ordos Basin, northern China. The source of the oil in these reservoirs is the organic-rich Ch 7 section (Ji et al., 2007a; Duan et al., 2008; Yu et al., 2010). The source rocks and crude oil of the Yanchang Formation in the area are rich in bicyclic alkanes, and significant amounts of *B. braunii* have been found in the source rocks. Intervals with high fossil abundance appear to be the main source rock layers in the Ch 7 section (Ji et al., 2010), which indicates that *B. braunii* is not only an important hydrocarbon parent material in the source rocks, but is also likely the source of the bicyclic alkanes in the source rocks and crude oil.

In this study, the applications of the geochemical properties of bicyclic alkanes in studies on the depositional environment of source rocks are extended by a detailed analysis and descriptions of the distribution and characteristics of bicyclic alkanes in different environments. Possible changes undergone by bicyclic sesquiterpanes during the migration and accumulation of petroleum and the reliability of their applications in oil-source correlations are evaluated through a comparative study of the source rocks and crude oil.

2. Geological setting

The Ordos Basin is a large Mesozoic depression located in north–central China (Fig. 1). This basin was part of the North China Craton that formed prior to the Paleozoic (Kusky et al., 2007) and became an isolated lake basin in the Middle and Late Triassic. A series of lacustrine and deltaic clastic sediments more than 1000 m thick was deposited in the basin during this time. These sedimentary rocks, which are known as the Yanchang Formation, became the dominant source rocks for Mesozoic oil due to the presence of organic-rich mudstone, carbonaceous shale and oil shale. Sandstone and sand bodies of various sizes tend to form oil reservoirs (Yu et al., 2010; Guo et al., 2012). The Yanchang Formation features 10 oil-bearing beds (from Ch 1 to Ch 10 sections), the lithologies of which are in Table 1. Each oil bed can be further divided into 2 to 3 intervals based on sedimentary cycles and lithologic combinations. Sections Ch 10–Ch 8 are Middle Triassic in age, and sections Ch 7–Ch 1 are considered to be of the Late Triassic based on examinations of sporopollen fossils and determination of zircon U–Pb age (Ji and Meng, 2006; Wang et al., 2014).

The sediments of the Yanchang Formation in the Ordos Basin were clearly controlled by regional tectonic activities. Table 1 shows the complete sedimentary cycle from the beginning of basin development in Ch 10 to the demise of the basin in Ch 1. Three lake transgressions are represented by the Ch 9, Ch 7 and Ch 4 + 5 periods. Maximum flooding occurred in Ch 7 and resulted in the source rocks that are widely distributed within the basin (Li et al., 2012). Sandstone layers in different sections of the Yanchang Formation may form Mesozoic petroleum reservoirs in different regions of the basin due to the migration of lake sedimentary center (Yu et al., 2010). An ancient lake can is divided into lakeside, shallow lake, moderately deep lake and deep lake according to water depth, and the moderately deep lake refers to the area between deep lake and shallow lake (Jiang et al., 2007). The main sources of oil in the Xifeng oilfield are the deep and moderately deep lake organic-rich mudstone and oil shale in the Ch 7 section (Ji et al., 2007a). Sandstone in the Ch 8-1 interval beneath Ch 7 forms major petroleum reservoirs in the region. The source rocks are located immediately above the reservoirs (Yang et al., 2004; Guo et al., 2012).

3. Material and methods

Oil exploration in the Xifeng area is focused on the Ch 8 to Ch 6 sections of the Yanchang Formation, and wells X30 and X44 are the most complete core drilling in the study area. The majority of samples were collected from the Ch 8 and Ch 7 sections in wells X30 and X44. They not only have higher petroleum potential, also cover various sedimentary environments including lakeside, shallow lake, moderately deep lake and deep lake in the longitudinal based on previous studies (Yang et al., 2004; Ji et al., 2007a; Guo et al., 2012) (Fig. 1). Seventy-two and sixty-two core samples were collected from Ch 8 and Ch 7, respectively. Supplementary samples from the Ch 7-3 interval were collected mainly from wells X40, N4, Zh5, Zh42 and M9 in the adjacent region. The stratigraphic positions of all of the samples were confirmed by correlations between each section. Crude oil samples were collected from eight wells in the Xifeng area. The main reservoir is the Ch 8-1 interval of the Yanchang Formation.

Lipid biomarkers in the samples were extracted using the Soxhlet method. To eliminate potential contaminants, the outer