Organic geochemical and petrographic characteristics of the Miocene Salif organic-rich shales in the Tihama Basin, Red Sea of Yemen: Implications for paleoenvironmental conditions and oil-generation potential

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ABSTRACT

This study is the first investigation which provides information regarding the organic geochemical and petrographic characteristics of Miocene Salif organic-rich shales from Tihama Basin in the Red Sea, Yemen. We evaluate organic matter content, type, maturity, and oil-generation potential as well as depositional environmental conditions. The total organic carbon (TOC) contents of the Miocene Salif shales vary between 0.59% and 5.40%, indicating fair to very good source rock potential. The Salif shales have hydrogen index values in the range of 64–576 mg HC/g TOC. The organic matter in the Salif shales are dominated by Type II kerogen and mixed II–III kerogens with a minor contribution of Type III kerogen, as supported by kerogen microscopy. This is also confirmed by their biomarker and carbon isotope results, which indicate that the Salif shales were deposited in highly reducing marine conditions and received high contributions of aquatic organic matter (e.g., algal and microbial) and terrigenous organic matter. Consequently, the Salif Formation is likely to be an oil-source rock. Maturity indicators such as vitrinite reflectance and pyrolysis data (i.e., T_{max} and PI) indicate that most of the Salif shale samples are generally thermally mature, at the early-mature to peak oil window stage. The new data presented in this paper suggest that early-mature oil has been generated from Miocene Salif organic-rich shales, so exploration strategies should focus on the known location of Miocene Salif organic-rich shales for predicting the location of the source kitchen.

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1. Introduction

The study area for this paper is the Tihama Basin of the Yemeni Red Sea (Fig. 1). The Yemeni Red Sea portion is situated in south-east Red Sea extending from the Saudi Arabian border in the north and to the Ethiopian border in the west (Fig. 1). The Yemeni Red Sea like the Red Sea as a whole is undergoing hydrocarbon exploration and research (e.g, Cole et al., 1995; Hughes et al., 2005; Hadad and Abdullah, 2015). Recently, the Tihama Basin in the Yemeni Red Sea has seen increasing exploration interest, with 12 wells already drilled (Fig. 1), some of which have been petroleum discoveries (gas and condensate with oil shows). Exploration activities commenced in 1960 with 12 wells drilled along the basin. The drilling results range from gas and condensate, to oil shows to dry holes. In addition, oil seeps are reported on the Red Sea coast, especially on the Farasan and Dahlak Islands of Saudi Arabia (e.g., Ahmed, 1972; Cole et al., 1995). Therefore, these scattered discoveries have encouraged study of the source rock potential and hydrocarbon generation for use in further exploration drilling along the Yemeni Red Sea.

The Tihama Basin is the hydrocarbon exploration frontier in the Yemeni Red Sea where minimal data are available for adequate assessment of hydrocarbon potential. The present study is a comprehensive study on the source rock characteristics of the Miocene Salif organic-rich shales in the Tihama Basin, in order to investigate a potentially significant oil-source rock and describe organic matter input and depositional environment conditions. This study is expected to provide information and spark regional interest in the Yemeni Red Sea and provide a basis for further exploration success and resource assessment in the whole basin.

2. Geologic setting

The Tihama Basin developed in the south-eastern part of the Yemeni Red Sea as a result of the Tertiary rifting process related to the evolution of Red Sea and Gulf of Aden (Redfern and Jones, 1995). The rifting of the Red Sea and Gulf of Aden commenced in the late Oligocene to late Miocene (Redfern and Jones, 1995), accompanied by volcanic activities (Mattash, 1994; Al-Kadasi, 1994; Nasher, 2010). The stratigraphic section of the Tihama Basin is dominated by a thick Cenozoic sedimentary successions (late Oligocene to Pleistocene time) and can be classified into two megasequences: syn-rift (late Oligocene to late Miocene) and
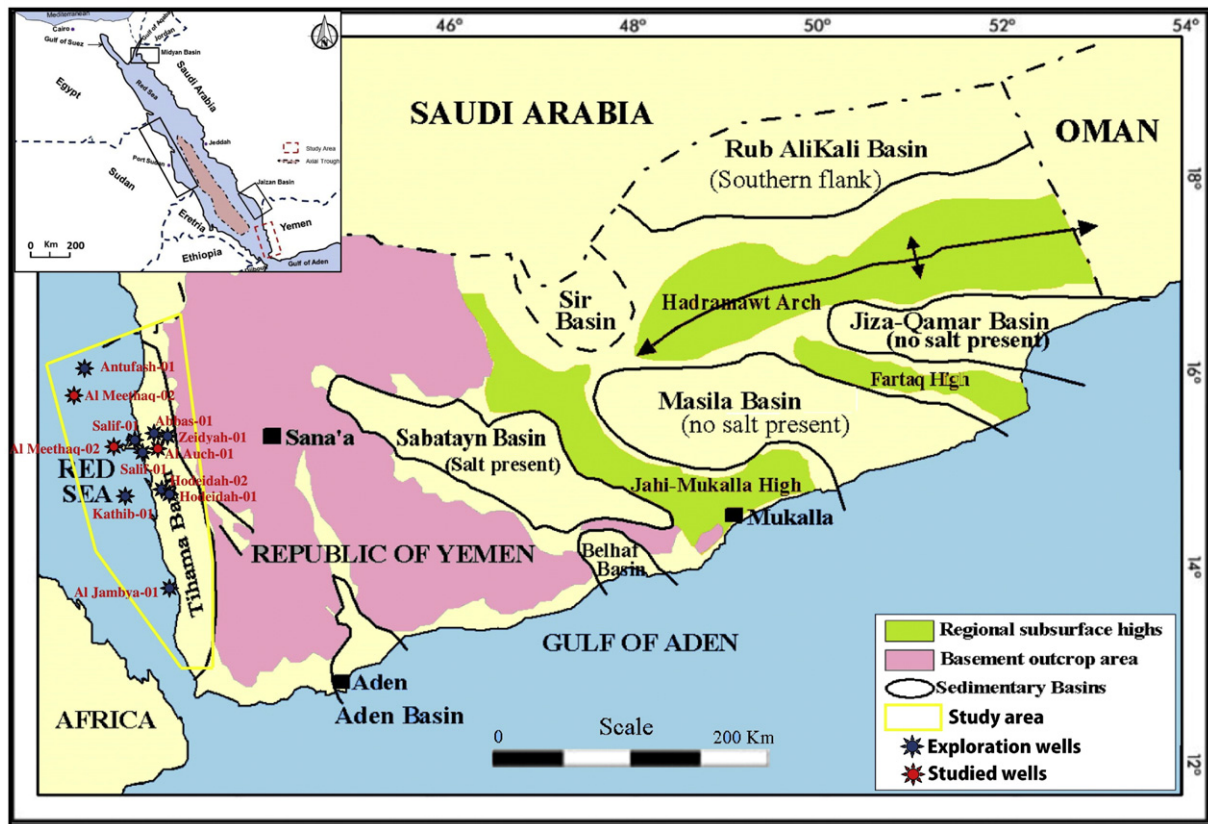
Fig. 1. Location map of the main sedimentary basins in Republic of Yemen (modified after Beydoun et al., 1998), showing location of the Tihama Basin including studied wells.

post-rift (Pliocene to Pleistocene) as shown in Fig. 2. The syn- and post-rift sedimentary rocks are represented by the Tihama Group (marine, transitional, and continental depositional environments). The syn-rift sequence comprises predominately clastic sediments and evaporites that were developed during Early to Late Miocene time (Fig. 2). During the Early Miocene time, early syn-rift sediments of the Zaydiyah and Maqna formations were deposited. The Zaydiyah Formation is in turn underlain unconformably by Tertiary volcanic rocks (Fig. 2). The Zaydiyah Formation is predominantly clastic sediments overlain conformably by marine sediments of Maqna Formation (Fig. 2). The Maqna Formation is mainly shale with interbedded sandstone (Fig. 2). The Late–Middle Miocene Salif Formation is underlain conformably by marine Maqna sediments, composed of evaporites with subordinate shales and sandstones (Fig. 2). The post-rift sequence is represented by the Abbas Formation (Pliocene), which consists predominantly of sandstone and mudstone with vertical variations of thickness and lateral facies changes in other subsurface locations. During the Pleistocene, the Abbas Formation developed along the shore of the Yemeni Red Sea and contains the Kamaran Member. The Kamaran Member is composed of reefal limestone, is similar to the organic reef of the Farasan Islands of the Southern Red Sea coast of the Saudi Arabia.

3. Samples and methods

Thirty-seven (37) cutting shale samples of the Miocene Salif Formation were collected from three wells in the onshore Al Auch-01 and coastal Al Meethag-02 wells through offshore Al Meethag-01 well of the Tihama Basin, Red Sea of Yemen (Fig. 1). Organic geochemical and petrology analyses were performed on the Salif shale samples to investigate the source rock characterization and petroleum generation potential. Most of organic geochemical and petrographic analyses were

carried out at Simon Petroleum Technology Limited Laboratories, United Kingdom.

The organic geochemical analyses include total organic carbon content, Rock-Eval pyrolysis, bitumen extraction, and biomarker distributions. All the samples were crushed to powder and analyzed by a Rock-Eval-II instrument that can provide measurements of the total organic carbon (TOC) content and Rock-Eval pyrolysis parameters. Pyrolysis analysis was performed on whole crushed samples, which were heated to 600 °C in a helium atmosphere and several parameters such as TOC, S_1, S_2, S_3, and temperature of maximum pyrolysis yield (T_{max}) were measured. Hydrogen (HI), oxygen (OI), production (PI) indexes, and petroleum potential yield (PY) were then calculated.

Six powdered samples were subsequently extracted with a mixture of dichloromethane (DCM) and methanol (CH3OH) (93:7 v/v) for 72 h using a conventional Soxhlet apparatus. The extracts were separated into aliphatic and aromatic hydrocarbons, and NSO compounds using a long liquid column chromatography on silica gel topped with alumina oxide and the asphaltenes were left on the column. The saturated fractions were then analyzed using gas chromatography (GC) and gas chromatography–mass spectrometry (GC–MS). Gas chromatograph (GC) equipped with a flame ionization detector (FID) was used. A FID gas chromatograph with AMS-92 column, temperature programmed from 70 to 270 °C at a rate of 3 °C/min, and then held for 20 min at 290 °C, was used for GC analysis. The GC–MS experiments were performed on a Finnegan 4000 mass spectrometer with a gas chromatograph attached directly to the ion source using temperature programmed from 60 to 300 °C at a rate of 3 °C/min, and then held for 20 min at 300 °C. The biomarker compounds were then identified through retention time and published works (e.g., Philp, 1985; Peters et al., 2005; Hakimi et al., 2012a). Peaks assignments are as listed in Appendix 1 and the derived parameters were calculated by measuring peak heights.