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Research paper

Hydrocarbon source rock generative potential of the Sudanese Red Sea basin

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ABSTRACT

To date, the Sudanese Red Sea like the Red Sea as a whole, represents a grossly under-explored basin. Recently, the basin has seen increased exploration interest, with more than 15 wells being drilled, some of which have been petroleum discoveries (gas and condensate with oil shows). A similar exploration trend has been seen in the Saudi, Eriteria and Egyptian sectors of the Red Sea. The Red Sea rift marks the break-up of the Afro-Arabian plate in Eocene–Oligocene time. The tectonostratigraphic evolution can be subdivided into three major phases: Pre-rift, Syn-rift and Post-rift phase. Generally, terrestrials and marginal to deep marine sediments were deposited with both good reservoir quality and potential source rocks being present. The pre-Salt Rudeis/Kareem shales are expected to be good petroleum source rocks for the basin. Moreover, shales of base Zeit (post-Salt) are considered the main source of the known accumulated hydrocarbon (gas and condensate) in the shallow targets with the condensate charge also expected from intra-evaporites shales and pre-salt sources along the salt windows. The measured amount of TOC, HI, and hydrocarbon generation from pyrolysis of kerogen of the examined samples indicate source rock generative potential of these intervals. The TOC contents for base Zeit, and inter-beded shales of Dungnab Formations, range from 0.60& to 5.40 wt. %, while the hydrogen index (HI) values are in the range of 50-600mg HC/gTOC suggesting dominantly type III-II kerogen. The high TOC (>1.5) and HI (>300) values of base Zeit and Dungnab Formations are limited to some intervals within these formations. Consequently, the base Zeit source rocks are considered very good for condensate and gas generation. In comparison to their equivalents Burqan and Maqna Group sources (HI = 350–600 mg HC/gTOC) on the Saudi Red Sea sector, Rudeis/Kareem shales could perhaps possess good quality type-II kerogen. The Red Sea's high pressure and temperature regimes have a significant impact on hydrocarbon maturation, generation and the quality of the preserved accumlations. Presently, the Zeit source varies in maturity across the basin and within the oil window in the Suakin and Bashayer areas and at gas window elsewhere to the east towards offshore. On the other hand, the pre-salt Rudies/Kareem Formations are currently in the late oil to wet gas zone and probably out of gas phase distally offshore. However, the salt tectonics makes for challenging exploration. The salt movement is considered recent as it is only the recent sediments that appear to be controlled by salt movement.

1. Introduction

The Red Sea occupies an elongate depression over 2000 km long, with a width varying from 200 to 350 km. The Sudanese portion of the Red Sea (Fig. 1) extends 700 km from the Egyptian border in the north to the Eritrean border in the south. The Sudanese Red Sea is an underexplored basin (as is the Red Sea as a whole) with only 15wells being drilled. Six of these wells were drilled during the 1960's and were located, drilled, logged, tested and evaluated using outdated technology. Of the 15 wells drilled to date, ten were wildcats drilled along the coast, at least two of which were subsequently showing to be off-structure at the prospective horizons. It was reported that of the eight structurally valid wells, one was not properly evaluated, three did not penetrate the objectives due to operational failure, and one was not properly located stratigraphically. Two of the 15 wells were discoveries, namely Suakin-1 and Bashayer-1A and encountered both rich, wet gas/condensate and dry gas. The Suakin-1 wet gas/condensate

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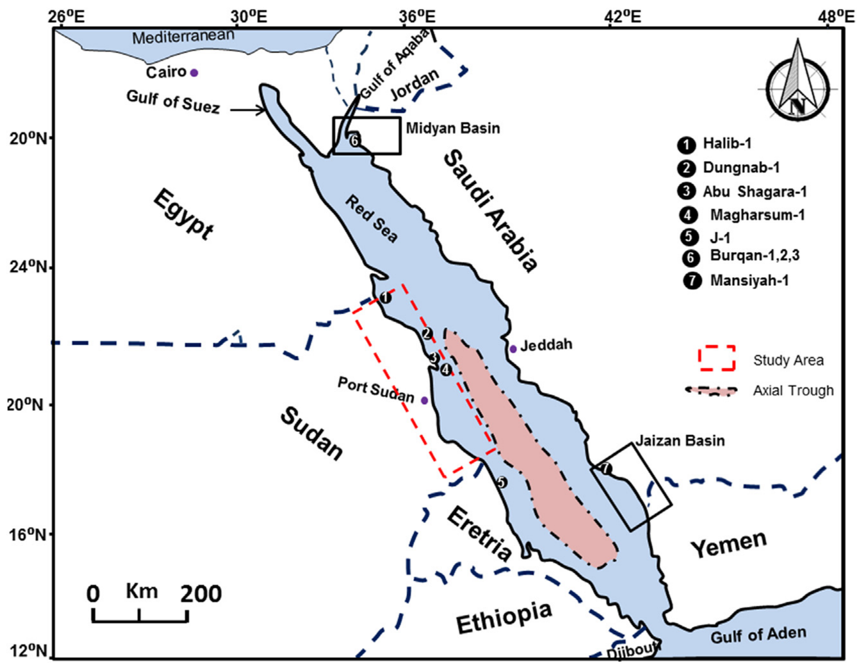

Figure 1. Location map shows the study area in the Red Sea. Exploration wells on the Sudan, Eritrea and Saudi margins are shown (after Bunter and Abdel Magid (1989), Beydoun (1992) and Hughes et al. (1999)).

discovery flowed at a rate of 1158STB/day of 52° API condensate and 6.89 MMSCFG/day reportedly from the thick upper Miocene sandstone of Zeit Formation (unpublished report). All other wells encountered shows (gas and oil) or were dry holes.

This paper presents and evaluates the results of organic petrological and organic geochemical analyses of more than 13 exploration wells in the Sudanese Red Sea portion. Comparison of source potential is also made to the Saudi, Eritrean Red Sea and the well explored hydrocarbon province Gulf of Suez.

2. Tectonostratigraphic setting

The Red Sea rift was formed by Arabia being split away from Africa. This break up started in the Eocene and accelerated during the Oligocene (Cochran, 1983; Bunter and Abdel Magid, 1989a; Mitchell et al., 1992; Coleman, 1993; Ghebreab, 1998; Bosworth et al., 2005). In the mid Late Cretaceous, prior to the rifting, the Tethys Ocean transgressed the study area southward resulting in the deposition of marine sediments. Some continental sediment (Fig. 2) also occurred across the Red Sea area (Ahmed, 1972; Bunter and Abdel Magid, 1989a). In the Sudanese Red Sea, these represent the pre-rift sediments of Mukawar and Hamamit Formations (Fig. 3), and consist of sandstone with minor interbeds of shale (Bunter and Abdel Magid, 1989a). During the Oligocene, strong rifting initiated with block faulting, followed by local erosion of the Hamamit Formation (Ahmed, 1972; Bunter and Abdel Magid, 1989a). The early–middle Miocene Rudeis-Kareem and Belayim Formations constitute the Syn-rift, pre-salt clastic and carbonate sediments. During late middle Miocene, the Red Sea/Gulf of Suez became isolated from the Mediterranean and the limited influx of water resulted in thick deposits of anhydrite, salt, shales, and sandstone forming the Dungnab Formation. The Zeit Formation of clastic sediments, deposited on top of the Dungnab Formation, mark the end of the Miocene. In the early Pliocene (5Ma), the Red Sea opened and, oceanic crust was emplaced. This resulted in deposition of the Plio-Pleistecene post-rift Abu Shagara Group, consisting of coarse clastics and carbonates. During this time the Red Sea attained its current shape (Ahmed, 1972; Bunter and Abdel Magid, 1989a; Beydoun and Sikander, 1992).

2.1. Methodology of hydrocarbon source rocks evaluation

In this study, the source rocks have been evaluated based on the three main geochemical parameters of quantity (TOC), quality (kerogen type), and thermal maturity of kerogen. Routine geochemical methods comprising Rock-Eval pyrolysis, Total Organic Carbon (TOC) content determination, petrography and biomarker analysis have been performed on the Sudanese Red Sea wells. A total of (89) rock cuttings and cores samples have been crushed into fine powder and analysed using Rock-Eval pyrolysis method to examine their potential hydrocarbon abundance and quality. Solvent wash extraction has also been performed on these crushed samples using a Soxhlet apparatus applying a mixture of Dichloromethane (DCM) and Methanol (93:7). The extracted organic matters (EOM) have been separated into their three main fractions: aliphatic, aromatic and NSO by liquid column chromatography applying petroleum benzene, DCM and Methanol respectively. The saturated fractions have been analysed using gas chromatography mass spectrometry (GCMS) acquiring the total ion currents (TIC), m/z 217 and m/z 191 fragmentograms. These fragmentograms were then used to predict and identify the nature of the organic matter based on biomarker signatures.

In the petrographic study, visual kerogen typing was performed on the sample blocks made by mounting the rock fragments and cuttings in a mixture of resin and resin hardener. Once solidified, the blocks were ground flat on a diamond polishing lap to provide a highly reflecting surface. Further polishing was carried out using silicon carbide paper of different grades and eventually finer alumina suspension was used for final surface smoothing. Subsequently, microscopic visual kerogen investigation was conducted using a *LEICA DM6000M* microscope. These investigations were run under normal polarized reflected light and ultraviolet (UV) light