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Maturation history modeling of Sufyan Depression, northwest Muglad Basin, Sudan

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ABSTRACT

The Sufyan Depression is located in the northwest of Muglad Basin and is considered as a favorable exploration area by both previous studies and present oil shows. In this study, 16 wells are used or referred, the burial history model was built with new seismic, logging and well data, and the thermal maturity (Ro, %) of proved AG source rocks was predicted based on heat flow calculation and EASY %Ro modeling. The results show that the present heat flow range is 36 mW/m^2~50 mW/m^2 (average 39 mW/m^2) in 13 wells and 15 mW/m^2~55 mW/m^2 in the whole depression. Accordingly, the geothermal gradient is 20 °C/km~26 °C/km and 12 °C/km~30 °C/km, respectively. The paleo-heat flow has three peaks, namely AG-3 period, lower Bentiu period and Early Paleogene, with the value decreases from the first to the last, which is corresponding to the tectonic evolution history. Corresponding to the heat flow distribution feature, the AG source rocks become mature earlier and have higher present marurity in the south area. For AG-2_down and AG-3_up source rocks that are proved to be good-excellent, most of them are mature with Ro as 0.5%–1.1%. But they can only generate plentiful oil and gas to charge reservoirs in the middle and south areas where their Ro is within 0.7%–1.1%, which is consistent with the present oil shows. Besides, the oil shows from AG-2_down reservoir in the middle area of the Sufyan Depression are believed to be contributed by the underlying AG-3_up source rock or the source rocks in the south area.

1. Introduction

The Muglad Basin is an important hydrocarbon exploration and exploitation area with some major oilfields in Sudan and South Sudan. So far, there are many studies on the exploration progress of Muglad Basin but mainly in the middle or south area (Mohamed et al., 2000; Xu et al., 2003; Tong et al., 2004; Li et al., 2010; Makeen et al., 2015). Only a few achievements on petroleum system analysis of the northwest area (Sufyan Depression) were published because only two wells were available (Mohamed et al., 2002; Zhao et al., 2008; Zhang and Gu, 2009). They believed that the Sufyan Depression was a favorable exploration target even though they couldn't provide a comprehensive understanding of the source rock quality in the Sufyan Depression. Moreover, other relative studies (Xue et al., 2004; Zhang and Chen, 2006) and present oil shows also support this viewpoint. Thus, the study on source rock is significant to identify the hydrocarbon potential in the Sufyan Depression.

Before 2007, only 3 wells are drilled in the Sufyan Depression: one dry well, one well with oil shows and one well not reaching AG Formation. Meanwhile, limited seismic data could only produce a very rough stratigraphy model. Until 2014, a more detailed study was carried out in the Sufyan Depression with better seismic data and more well data, which is the essential basis for this study. Therefore, the maturation history and present maturity (Ro, %) feature of the main source rock in the Sufyan Depression, were presented in this study based on burial history modeling and heat flow calculation. And the result can provide important information for the oil and gas exploration in the Sufyan Depression.

2. Geological setting

The Sufyan Depression is located in the northwest area of Muglad Basin, 70 km long and 40 km wide with the total area about 2,800 km^2. It is bounded by Tomat Uplift with boundary fault in the south, connected with Nugara Depression to the east and Babausa

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Uplift to the north and west (Fig. 1). As a relatively independent structural unit in the Muglad Basin, the Sufyan Depression developed many faults that are echelon pattern and mostly trend NW and NWW, which are controlled by the dextral oblique shear movement of the Central Africa Shear Zone.

Nine seismic-stratigraphic sequences were built from bottom to up in the Sufyan Depression, namely Abu Gbra (AG) Formation (AG-5, AG-4, AG-3, AG-2 and AG-1 Members), Bentiu Formation, Darfur Group, Paleogene and Neogene to Quaternary (N + Q) (Figs. 2 and 3). The AG Formation develops the main shale of Sufyan Depression with AG2 and AG3-up Members containing good-excellent source rocks. The Bentiu Formation is a set of thick sandstone and considered as good reservoir bed, but few oil shows was obtained from it. The Darfur Group is regional cap rock rather than source rock in the depression due to very low maturity. Paleogene is mainly sandstone with no oil shows and regarded as overlying strata together with N + Q.

Throughout the tectonic evolution history, three obvious rifting—sagging cycles can be identified in the Sufyan Depression: (1) AG period, with strong faults movement during AG-3 period; (2) Bentiu—Darfur period, with relatively weak tectonic movement; (3) Paleogene—present period, with the third as well as the weakest rifting stage in Early Paleogene (Fig. 2). Corresponding to this tectonic background, there are three water-level cycles with the maximum water level appeared in the middle of AG-2 period.

Along the section AA′ from south to north of the Sufyan Depression, it's clear to see that the strata are thicker in the south and thinning towards north (Fig. 3). The sedimentary facies distribution of AG Formation is semi-deep lake in the south area with fan deltas on the south edge, shallow lake in the middle and shore with deltas in the north. In spite of lacking well data and samples, AG3_down, AG4 and AG5 shales are speculated as potential source rocks according to the sedimentary evolution history and seismic interpretation. They could generate more hydrocarbons than upper AG source rocks due to their higher maturity, but it still remains to be confirmed. The oils shows occurrence manifests that the AG-2 petroleum system (AG-2 & AG-3 source + AG-2 reservoir + AG-1 & AG-2 cap) is the main target (Fig. 3).

3. Database

In total, 16 wildcats and appraisal wells in the Sufyan Depression are used or referred in this study: all the wells have sand content, density, porosity and permeability data from logging data interpretation; 13 wells have formation temperature data; only 5 wells from SW and SE wells have Ro data, so the Well SW-4 and Well SE-2 that have comprehensive data are chosen to present the main model results. All the data are from unpublished reports (RIPED & Sudapet, 2007; BGP, 2015).

4. Basin modeling results

4.1. Burial history

Updated stratigraphy model is built from more detailed seismic data and more well data (Table 1). The deposition time of each layer is given based on the equal proportion of layer thickness over each formation. The lithology used in the model is mainly sandstone and shale, and the sequence strata can be subdivided into layers according to their lithologic features. The physical properties such as sand content, density and porosity of each lithology for each layer are identified from logging data interpretation (Table 2). Both present seismic and logging data show that there is no obvious erosion in the Sufyan Depression though unconformities were found in the other areas of Muglad Basin (Schull, 1988; McHargue et al., 1992; Mohamed et al., 2002, 2000). The burial history curves of all the wells were drawn according to the burial depth of each sequence stratum from logging results and their deposition time. The results show that the deposition rate is very fast before AG-2 period and then decreases to a stable rate until present.

4.2. Thermal model

The present formation temperature is used to identify the present heat flow at each well location, and the heat flow history is predicted according to the Ro (%) data from 5 wells.

4.2.1. Present heat flow

The present heat flow at each well location is calculated by combing the thermal conductivity of each layer and geothermal gradient. Firstly, the matrix thermal conductivity of each lithology is got from mix of the thermal conductivity of pure sandstone and pure shale according to its sand content ratio (Table 2). And then, the bulk thermal conductivity of each layer is calculated from water and matrix conductivities and porosity with the equation as follows:

$$K_b = K_w^{\varnothing} \times K_m^{1-\varnothing}$$

where K_b, K_w and K_m are thermal conductivities of bulk, water and matrix, respectively.

Secondly, the geothermal gradients were determined by the present formation temperature with a constant surface temperature as 29 °C. While the bottom hole temperature from 13 wells are

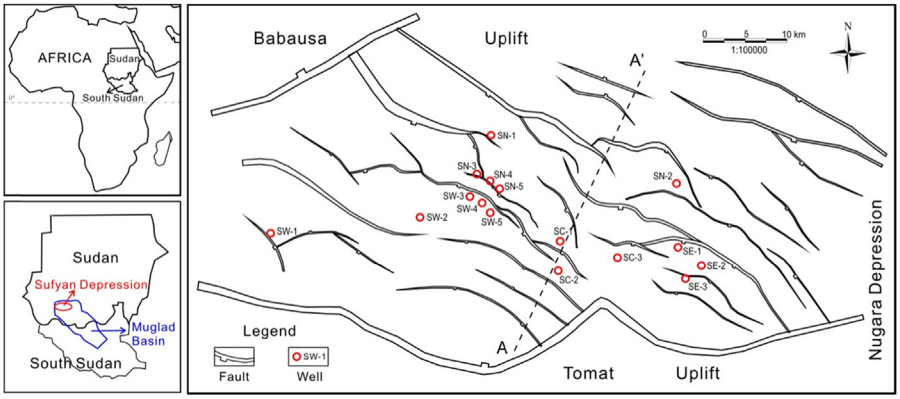

Fig. 1. Regional location map of Sufyan Depression, Muglad Basin.