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Sedimentological Heterogeneity and Reservoir Quality of the Cretaceous Aradeiba and Bentiu Formations in Simber West Oil Field, Southeast Muglad Rift Basin, Sudan

Ibrahim Yousif[1,2], Matthew Nton[1], Osman Abdullatif[3], Sikiru Amidu[1], Hussam Eldin Elzain[4], Yasir Fadlelmula[1], Yousif Yousif[5]

[1]Pan African University, Institute of Life and Earth Sciences (PAULESI), University of Ibadan, Ibadan, Nigeria; [2]University of Bahri, College of Petroleum Geology and Minerals, Khartoum, Sudan; [3]King Fahd University of Petroleum & Minerals (KFUPM), College of Petroleum Engineering and Geosciences (CPG), Dhahran, Saudi Arabia; [4]Pukyong National University, Busan, South Korea; [5]2B Operating Company, Khartoum, Sudan

ABSTRACT

The Upper Cretaceous Aradeiba and Bentiu Formations are the two main hydrocarbon reservoirs in Muglad Basin of Sudan. The basin has NW-SE trend and straddles Sudan and South Sudan republics. Following the cessation of South Sudan from the northern part, the Northern Sudan Republic has lost huge oil reserves. However, some northern Sudanese oil fields including Simber West field remain less explored and developed. The problem in Simber West field and other northern fields are primarily due to the reservoir heterogeneity of the complex fluvial and fluvio-deltaic systems. This study investigates the multi-scale reservoir heterogeneity of the Aradeiba and Bentiu reservoirs in Simber West field. Analyses of conventional cores, well logs, thin-sections, SEM-EDX, XRD, and Chemo-Scan data were integrated to characterize the Sedimentological, petrographical, and petrophysical aspects. Sedimentological interpretation based on conventional cores and well logs reveals nine major lithofacies types and four main depositional systems. These are fluvial channel, crevasse splay, floodplain, and deltaic/shallow lacustrine systems. The thin-section description shows that most of the samples have moderate and moderate to poor sorting. The quartz content is relatively high and can be classified mostly as subfeldspathic and feldspathic arenites. Well logs and cores analysis show that Aradeiba sand bodies have less vertical continuity and amalgamation compared to Bentiu. However, both formations reflect a general coarsening upward cyclicity with variations in thickness and geometry. The average core porosity of the Aradeiba and Bentiu reservoirs range from 12 to 27.2% and 3.0 to 14.33%, respectively. This is also consistent with higher permeability in Aradeiba up 893 mD than Bentiu of about 1.20 mD. Data from T-sections, SEM-EDX, XRD, and Chemo-Scan show that diagenesis and grain size have significant control on reservoir quality. Both detrital and authigenic clays have influenced the pore throats and reduced the porosity and permeability. In addition, calcite and compaction have also decreased the pore space, particularly in Bentiu Formation. However, different levels of feldspars dissolution were observed which consistent with porosity improvement. The findings of this integrated approach are expected to enhance the reservoir description and prediction. Consequently, that might contribute to the productivity improvement of the Upper Cretaceous reservoirs in the Muglad basin.

Keywords: Sedimentology; Reservoir Heterogeneity and Quality; Aradeiba and Bentiu Formations; Muglad Rift Basin

EXTENDED ABSTRACT

Introduction:
In sandstone reservoirs, heterogeneity develops at different scales (Morad et al., 2010). Therefore, accurate characterization is crucial during exploration and production to assess the productive reservoir zones. In the petroleum industry, it is important to assess the heterogeneity aspects and their influence on the quality of the reservoir (Elzain et al., 2020). The combined effects of the original depositional texture and diagenetic alterations are the two main attributes that control the heterogeneity and quality in sandstone reservoirs (Makeen et al., 2016). Among sedimentary basins in Sudan, those developed in the Mesozoic time are particularly significant since major rift basins including the Muglad rift basin were formed (Figure 1A). These rift basins were developed as the result of the West and Central Africa Rift System (WCARS) (Browne and Fairhead, 1983). The Muglad rift basin has NW-SE orientation with up to 13 Km of thick Cretaceous-Tertiary non-marine clastic deposits (Figure 1B) (Schull, 1988; Torkman et al., 2018). The Simber West oil field (SIW) is located at SE of Muglad basin in Bamboo sub-basin in block 2 (Figure 1C). In SIW, Aradeiba and Bentiu Formations are the two main hydrocarbon reservoirs of the Upper Cretaceous Sequence (Figure 2). The two Formations are widely distributed across the Muglad basin. However, Aradeiba shale represents the major and effective seal of the petroleum system in the Muglad basin. Following the cessation of South Sudan from the northern part, the Northern Sudan Republic has lost huge oil reserves because the bulk of the producing oil fields are located in the Republic of South Sudan. However, some northern Sudanese oil fields including Simber West field remain less explored and developed. The problem in Simber West field and other northern fields are primarily due to the reservoir heterogeneity of the complex fluvial and fluvio-deltaic systems. Additionally, injection wells targeting the Aradeiba reservoir in SIW have failed to displace oil in some producible wells which may raise the question of whether the reservoir facies and properties are continuous or discontinuous in the subsurface. The main objective of this study is to characterize the reservoir heterogeneity and control on its quality in Aradeiba and Bentiu Formations in SIW. The dataset used in the current study consists of two conventional cores and six well logs. Subsurface lithofacies analyses were conducted from the analysis of the conventional cores and wireline logs. Examination of thin-sections, SEM-EDX, XRD, and Chemo-Scan data allows for characterizing the grains, pores, and other authigenic and diagenetic components and their control on the quality of the reservoir.

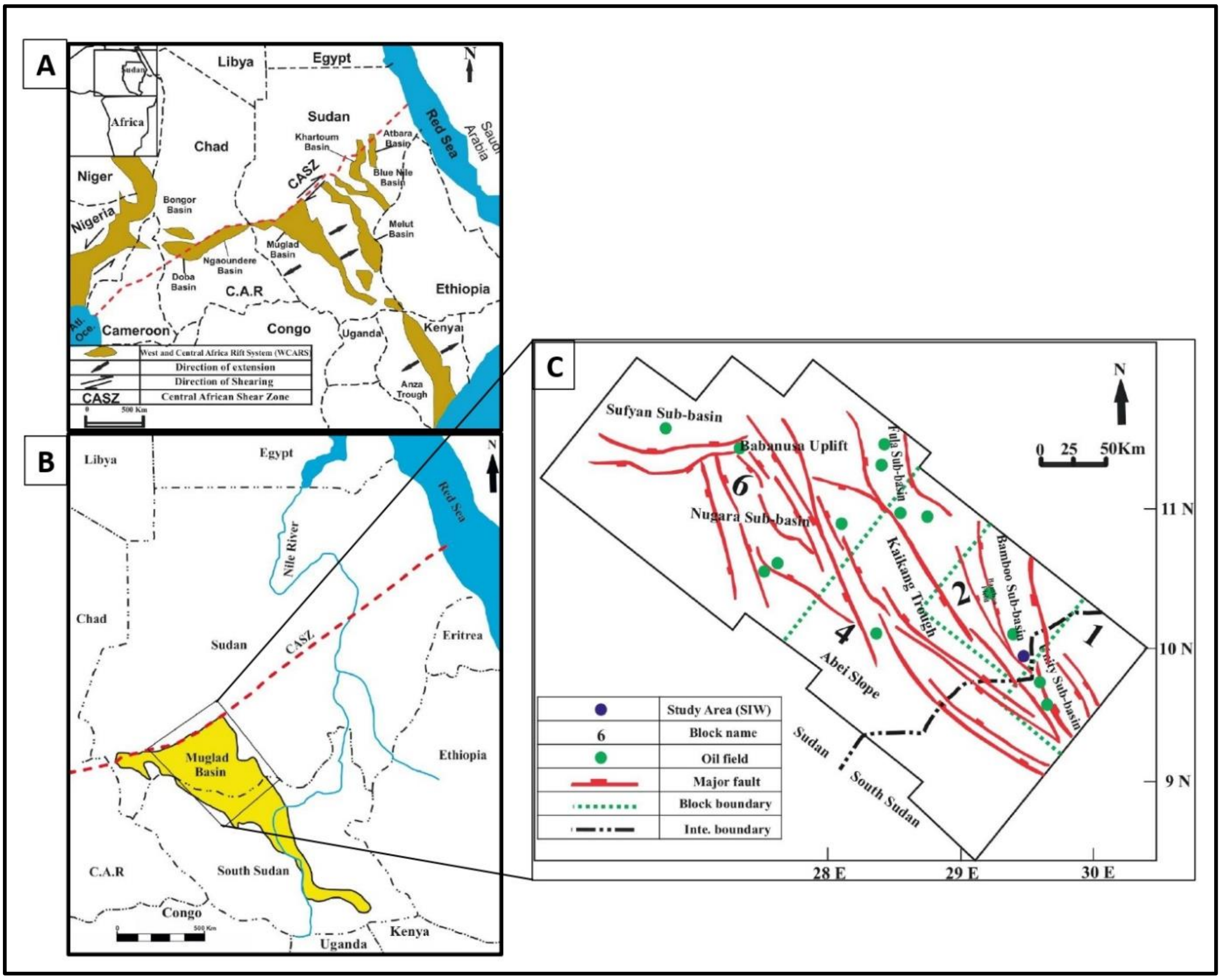

Figure 1A: Tectonic model of the West and Central African rift System (WCARS) (modified after Fairhead, 1988). B: Geographic location of the Muglad rift basin with NW-SE trend which straddles Sudan and South Sudan Republics (modified after Dou et al., 2013). C: Major structures and sub-basins in Muglad basin, the study area (SIW) is located in Bamboo sub-basin (modified after Dou et al., 2013).

Results and Discussion:

The studied cores from Aradeiba and Bentiu reservoirs have been sedimentologically logged. Based on the scope of (Miall, 1978; 1990; 2006), (9) major lithofacies types were defined from the core namely Sm, Sr, Sp, St, SI, Sco, Gm, FcF and Fm (Figure 3). Among these lithofacies types, Sm and Sp are dominant in Aradeiba, whereas in Bentiu reservoir the dominant lithofacies types are Sr, St and Sp. Well log interpretation shows that Sand bodies have good vertical connectivity and amalgamation in Bentiu Formation compared to Aradeiba (Figure 4). Log motifs reveal that Aradeiba Formation was deposited mainly in fluvial (meandering) to deltaic environments, whereas Bentiu Formation was developed in a fluvial setting primarily braided stream. Both Formations reflect coarsening up-ward cyclicity which is typical for fluvial system (Figure 4).

Fine-grained facies deposited in flood-plain and over-bank environments have greatly influenced both vertical and lateral continuity of reservoir units in the Aradeiba Formation with a slight effect on the Bentiu Formation. However, sandstone reservoir units of the Bentiu are vertically and laterally have good continuity compared to Aradeiba (Figure 4). Petrographic analyses from thin-section show that samples contain detrital and authigenic components (Figure 6). The two formations are texturally mature, relatively rich in quartz content up to 47% by volume, and can be classified mostly as subfeldspathic and feldspathic arenites (Figure 5). The grains are moderate and moderate-poor sorted, with dominant primary interparticle pores. Thin-section and SEM-EDX analyses show that fair to good reservoir quality is commonly associated with Aradeiba. Nevertheless, Bentiu reservoir has significantly poor reservoir quality. This is also consistent with the petrophysical evaluation of porosity and permeability measurement from core plugs (Figure 6).

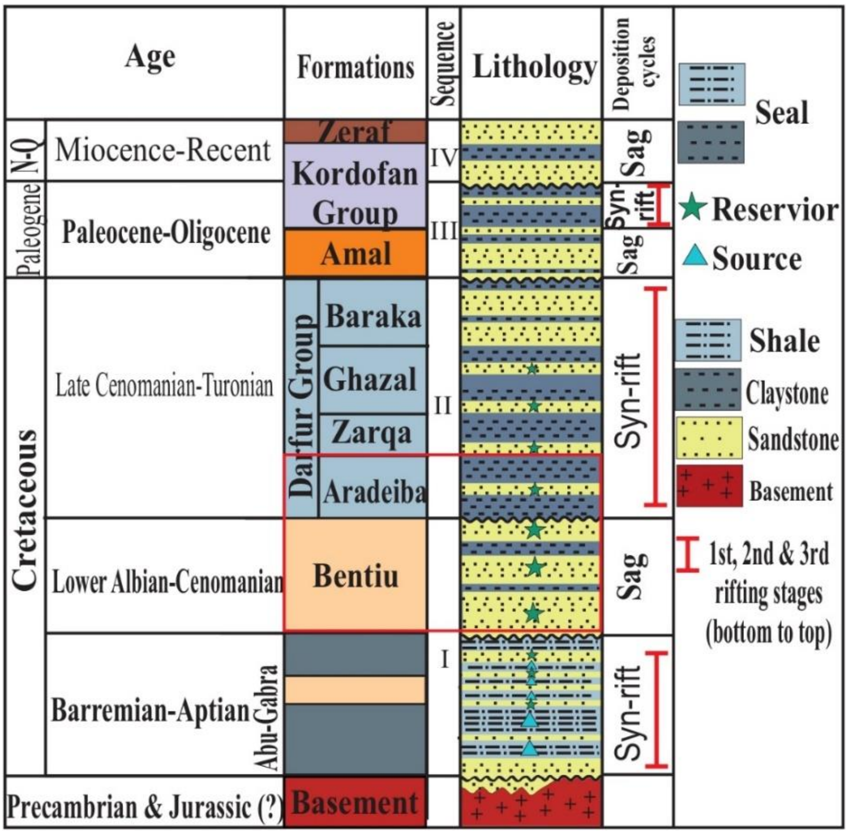

Figure 2. Muglad's basin Stratigraphic Column showing formations, petroleum elements, and rifting episodes. Aradeiba and Bentiu Formations are highlighted with red square (modified after Shull, 1988; Makeen et al., 2021).

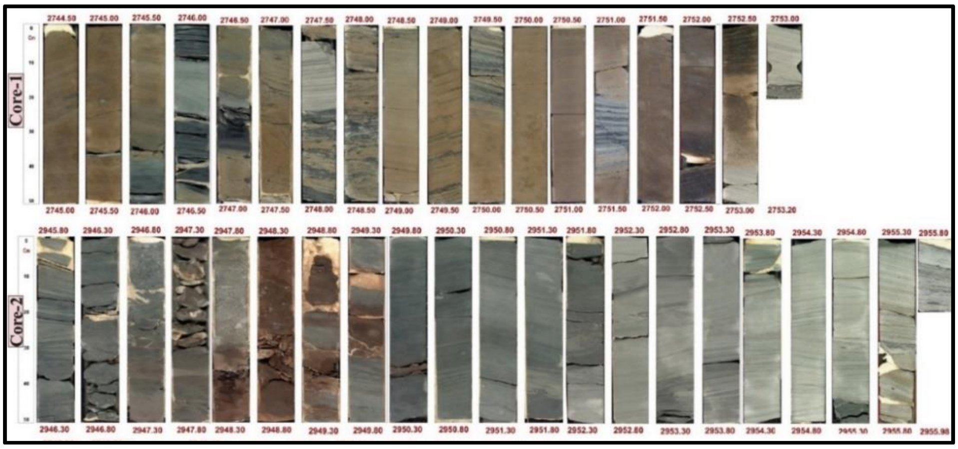

Figure 3. Conventional Cores photos for Aradeiba (Core#1) and Bentiu (Core#2) Formations in well SIW-2. (9) main lithofacies types were recognized.

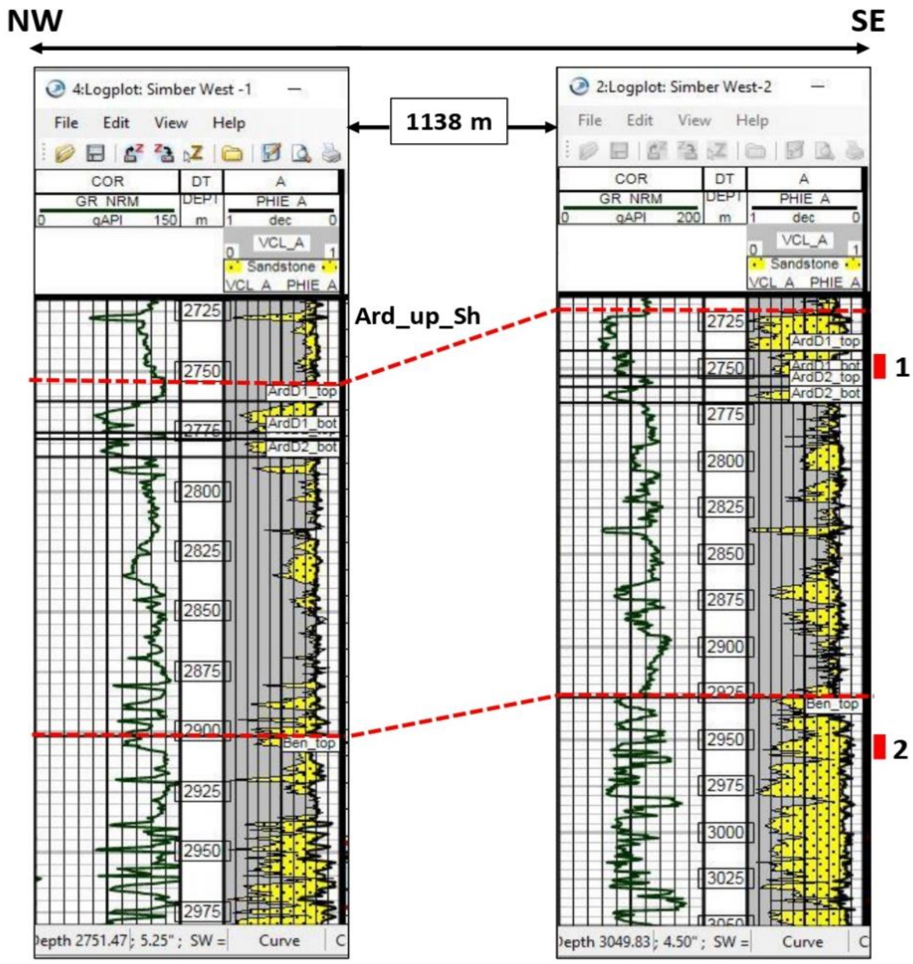

Figure 4. Well log response shows lateral and vertical reservoir connectivity through wells SIW-1 and SIW-2 from the NW to SE. The Well SIW-1 is located at the down-dip part of the structure. Aradeiba reservoir shows poor vertical continuity and amalgamation compared to the underlain Bentiu reservoir. Both Formations reflect a coarsening upward pattern.

From the thin-section petrographic study combined with Chemo-scan data, it is possible to recognize four types of porosity interconnectivity classes, which include good, fair-good, fair, and poor interconnectivity (Figure 6). The dominant pore types are primary interparticle pores. The estimated total visual porosity in Aradeiba and Bentiu reservoirs samples reaches up to 27.5% and 11.5%, respectively. Most of the Aradeiba samples show good and good to fair porosities. However, Bentiu samples are described to have mainly poor porosity (Figure 6). The petrophysical assessment from core plugs shows that porosity and permeability values are higher in Aradeiba than in Bentiu reservoir (Figure 6). In the Aradeiba reservoir, the measured helium porosities range from 12% to 27% with an average of 21%, while in Bentiu Formation range from 3.0% to 14.33% with an average of 7.0%. This trend of porosity is also consistent with nitrogen permeability in both formations. It ranges in Aradeiba from 0.3 mD to 114 mD with an average of 24.6 mD. In Bentiu Formation, these values are significantly low with an average of 0.06 mD. These variabilities in petrophysical properties are the result of depositional facies and diagenetic alteration. From the analyzed core samples, good to fair reservoir quality is usually associated with the Sm and Sp lithofacies types. Coarse- medium grained sands with moderate to well sorting commonly have less cement and matrix, and therefore, good quality. Integrated chemo-scan analyses with SEM-EDX results show that reservoir quality has been decreased by the presence of chlorite, illite, kaolinite, and calcite. Moreover, compaction has also played a significant role to decrease the porosity and permeability, particularly in Bentiu Formation. However, different levels of grains dissolution have been observed and contributed to the porosity enhancement (Figure 6).

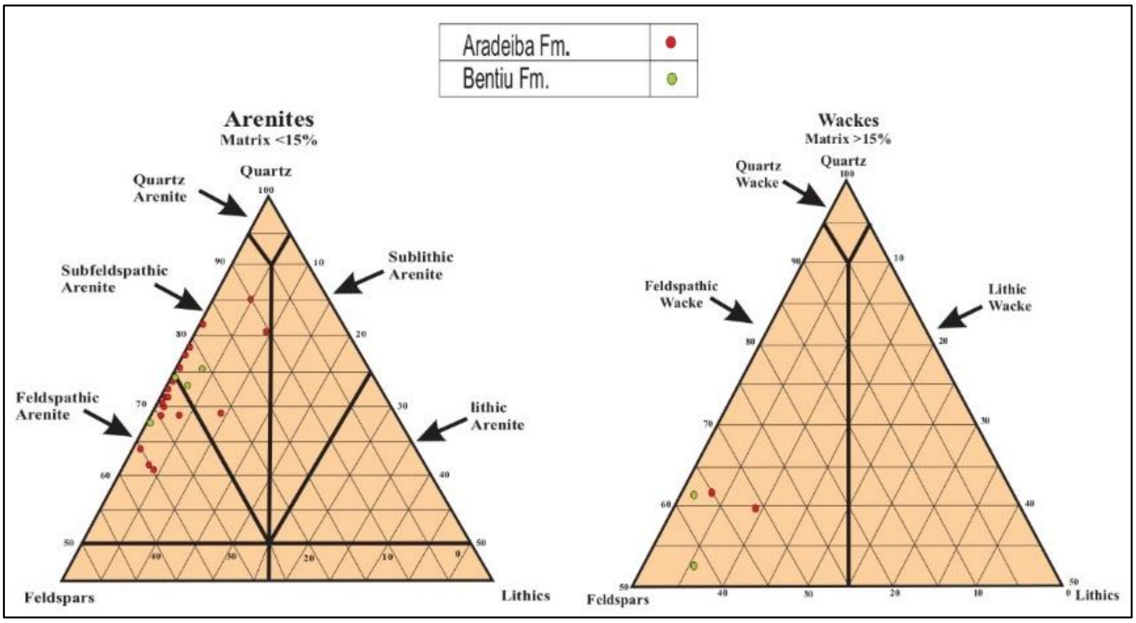

Figure 5. QFL graph shows the plotted percentages of Quartz, Feldspars, and Rock fragment for the Aradeiba and Bentiu Formations. Most samples have matrix less than 15% and being classified as feldsphatic and sub-feldspatic arenites (after Dott, 1964 and Pettijohn et al., (1987).

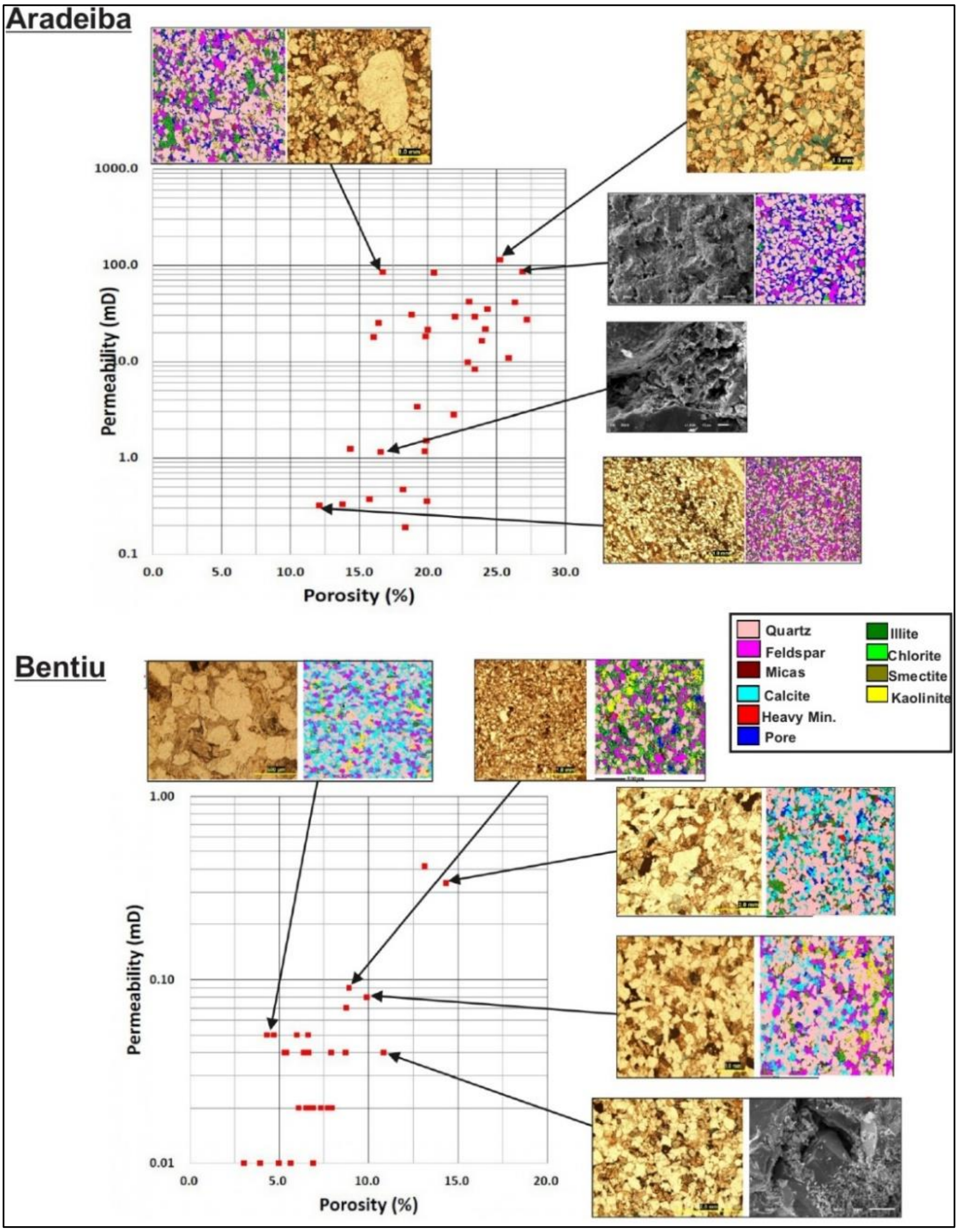

Figure 6. Reservoir quality in Aradeiba and Bentiu reservoirs as inferred from thin-section, Chemo-scan, and SEM-EDX analyses. Both depositional and diagenetic attributes affect the reservoir quality. Detrital and authigenic clays and intensive calcite cementation were found to be responsible for porosity reduction along with the effect of compaction. Aradeiba reservoir shows good reservoir quality compared to Bentiu reservoir.

Conclusions:

In this study, we characterized the reservoir heterogeneity and quality of the Aradeiba and Bentiu Formations in Simber West oil field through the study of their sedimentological, petrographical, and the petrophysical aspects. Aradeiba Formation was mainly deposited in fluvial (meandering) to deltaic setting, whereas the underlain Bentiu Formation was developed in braided streams. The sandstone reservoir bodies of Aradeiba Formation show low vertical connectivity and amalgamation compared to the Bentiu reservoir. However, petrophysical analyses from core plugs, thin-section, Chemo-scan, and SEM-EDX shows that the reservoir quality of Aradeiba is good to fair, particularly in the Upper Aradeiba Formation. Although grain size have significant control on reservoir quality, diagenesis has significant role on reservoir quality as well. The reservoir porosity and permeability are significantly low for the underlain Bentiu Formation. Factors decreasing porosity and permeability include detrital and authigenic clays, calcite cement, and compaction. Common clays are chlorite, illite, and kaolinite. Different levels of grain dissolution have been observed and contributed to the porosity improvement. The findings of this integrated approach are expected to enhance the reservoir description and prediction. Consequently, that might contribute to the efforts of productivity improvement of the Upper Cretaceous reservoirs in the Muglad rift basin.

Acknowledgements:

We are so grateful to the Pan-African University, University of Ibadan, Nigeria and the African Union (AU) for the opportunity and funds to conduct this research. Special thanks to Sudan Ministry of Petroleum and Energy for providing the data, and their kind permission to publish this work. We also highly appreciate the King Fahd University of Petroleum & Minerals (KFUPM) for the technical support and laboratory analyses.

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