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Middle East Oil, Gas and Geosciences Show

19 - 21 February 2023
Exhibition World Bahrain

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New Insights on Stratigraphic Trap Exploration of the Rawat Rift Basin, Sudan

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ABSTRACT

An extensive exploration campaign carried-out by the operator in Rawat Basin in interior Sudan during the last decade resulted in identifications and drilling of most of the structural traps. To increase the hydrocarbon reserves and sustain the production plateau, attention is shifting to identifying non-structural trapping configurations. From petroleum system analysis and modeling, the potential exists for discovery of a sizeable hydrocarbon volumes in combination structural/stratigraphic traps. Rawat Basin is a late Cretaceous to early Tertiary rift basin in interior Sudan. It lies in the northern extension of the elongated NW-SE White Nile rift system, this system (, which) includes the main prolific oil province of Melut basin in the Republic of South Sudan. The basin is filled with continental sediments of fluvial & lacustrine sandstones, mudstones and local tuffs. Facies distribution is influenced by fault-controlled subsidence followed by prolonged episodes of thermal subsidence.

The primary targets for petroleum exploration in the Upper Cretaceous are Galhak Sand & Galhak Oil Units. The Galhak Shale is the main hydrocarbon source rocks in the basin. Tectonic and stratigraphy controls the presence and distribution of oil pools in the basin. To enable exploration for stratigraphic traps, a wide azimuth 3D seismic data was recently acquired over the Rawat Central sub-basin. The new data enabled mapping of reservoir geometries, distribution of the reservoir rock properties as well as mapping of source and seals. Seismic attribute analysis of dense stratal slicing of the target interval permitted the definition of reservoir geometry and the distribution of the rock properties. To de-risk & narrow down the geological uncertainties related to seal & hydrocarbon migration, mitigation work focused on identifying isolated sandstone bodies embedded within the Upper Cretaceous Galhak source rock formation. Prediction of the petroleum system elements was done by building a sequence stratigraphic model that led to an effective prediction of the reservoir quality as well as source and seal rocks.

The combination of chronostratigraphic slicing & sequence stratigraphic work led to the identification of numerous stratigraphic traps, including an example of a sub-lacustrine fan feature that was maturated. Attribute extraction at the target interval of the sub-lacustrine fan exhibited a strong anomaly unlike any other features within the basin. The variation on the attribute maps indicates that reservoir quality, saturation and Net to Gross are likely to vary across the prospects. Geophysical evidence of fluid fill indicates probable down dip conformance of amplitudes with the stratigraphic closure. It also suggested the presence of strong negative amplitude such as (Class III AVO). The trapping mechanism is created by stratigraphic pinch out towards the up-dip direction of the slope area.

EXTENDED ABSTRACT

1. Introduction

An extensive exploration campaigns have been carried-out by the operators in the Rawat Basin in interior Sudan during the last few decades. This effort resulted in identifications, drilling and discovery of hydrocarbons in most of the sizeable structural traps. The remaining potential hydrocarbon volumes are expected to be in small-size structural traps. Recent integrated seismic mapping, petroleum system analysis and modeling studies indicate the potential exist for discovery of sizeable hydrocarbon volumes in combination structural/stratigraphic and in unstructured/stratigraphic traps. Historically these types of traps were avoided due to their high risk of failure. This paper is focused on the central sub-basin of the Rawat. It aims to demonstrate and unlock new stratigraphic trap plays and deal with risk mitigations of these types of traps through integration of seismic attributes, seismic inversion, sequence, and seismic stratigraphy, petrophysics and rock physics.

The study area is in the central part of the Rawat, a late Cretaceous to early Tertiary rift basin in interior Sudan. The basin lies to the north of the prolific NW-SW trending Melut basin that formed due to extensional tectonics in the White Nile Cretaceous rift system in the Republic of South Sudan. Melut basin hosts numerous sizeable oil fields. The Rawat basin is divided into five sub-basins, each is filled with continental sediments of fluvial & lacustrine sandstones, mudstones, and local tuffs (Figure1). Sedimentary facies distribution is mainly controlled by subsidence along faults. The active faulting was followed by a prolonged episode of thermal subsidence. The primary hydrocarbon reservoir targets are in the Upper Cretaceous formations that comprise Galhak Sand, Galhak Oil Units and sands deposited in lacustrine fans at the base of the Galhak Shale source interval (Figure 2). Tectonic subsidence played a primary controlling factor in the maturation of the hydrocarbon source sediments and the distribution of oil pools in the basin especially in the east slope of the central sub-basin. The hanging wall fault blocks are important in the Rawat central sub-basin as proved by the presence of several hydrocarbon discoveries in such setup.

The Rawat Basin is characterized by having a relatively steeper dips and high relief structural flanks. As such, it is of paramount importance to have competent top, lateral and base seals for successful hydrocarbon entrapment. To maximize our understating and reduce the geological uncertainties related to seal & hydrocarbon migration, our methodology and mitigation work were focused on identifying isolated sandstone bodies embedded within the Upper Cretaceous Galhak source rock formation. Consequently, a Sequence Stratigraphic model was built in the study area to help predict the distribution and the quality of reservoir sands. The sequence stratigraphic model also led to better understanding of the distribution and effectiveness of the other petroleum system elements such as the source, and the seal. The integration of chronostratigraphic slicing and sequence stratigraphic work resulted in identification of potential stratigraphic trap in an area with sub-lacustrine fan-like depositional feature.

To enable effective exploration for stratigraphic traps, a wide azimuth 3D seismic data was recently acquired over the Rawat Central sub-basin. This data permitted better understanding of the stratigraphic architecture and evolution of the sub-basin. It also provided a high-resolution definition of the three-dimensional distribution of sedimentary bodies, their shapes, and their reservoir properties and enhanced our mapping of the seals.

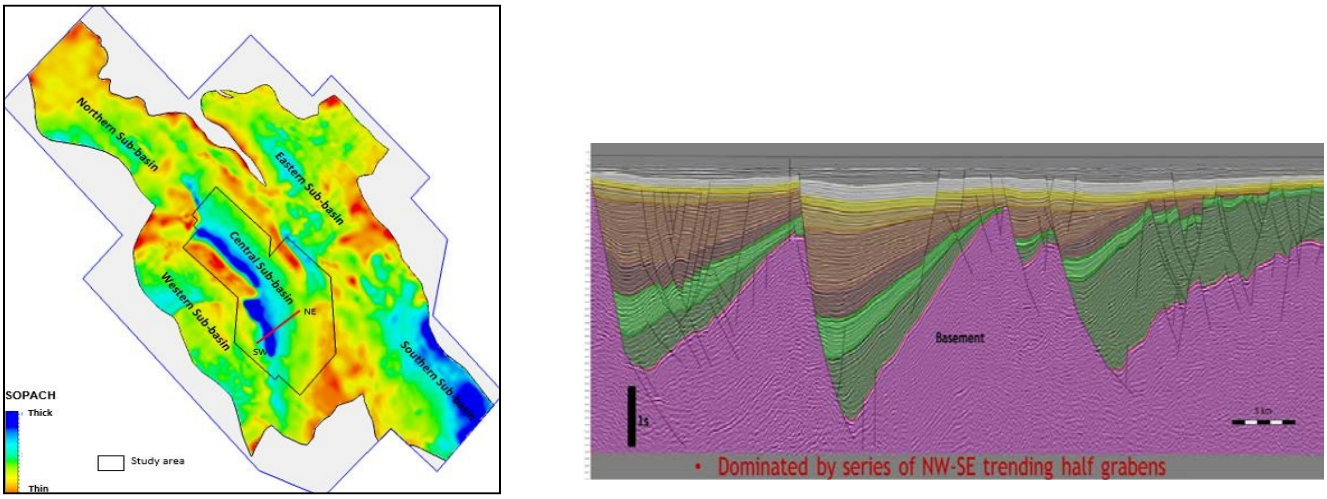

Figure (1): Left: Isopach map of the Upper Cretaceous sediments (Top Galhak to Galhak Oil, see figure 2) showing Rawat subbasins infill. Right: Seismic section illustrating the half-graben architecture of the central sub-basin

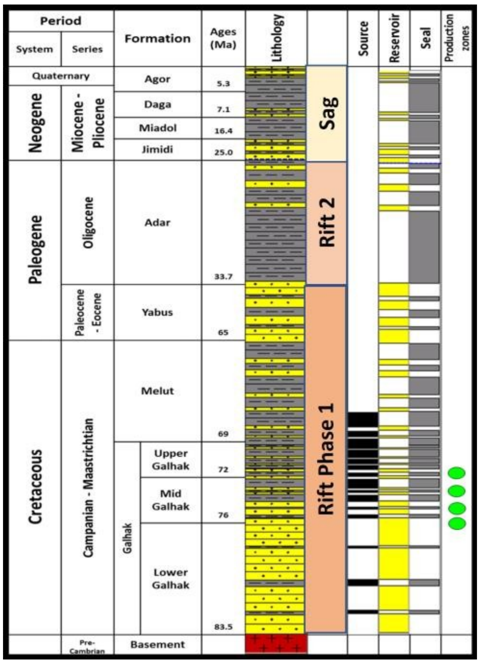

Figure (2): Rawat Basin Stratigraphy and the main Petroleum Systems

2. Seismic Attribute Analysis to Define Sub-Lacustrine Fairway

The seismic interpretation workflow was carried out by generating a dense stratal slicing of attribute maps at the target intervals to identify the most likely sand fairway directions and to assess the likelihood of the presence of the fairway within the study area (Figure 3). The goal was to characterize the fairway in terms of reservoir geometry, and the distribution of its rock properties.

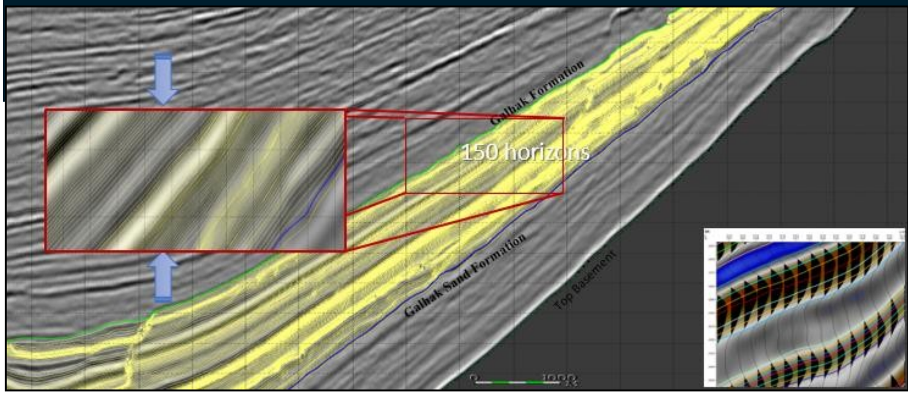

Figure (3): Horizon stack (Slice) generations showing strata slicing at the target interval

At the target, a series of seismic attributes were produced. Most of the attributes exhibited a strong seismic anomaly unlike any other feature within the central sub-basin (Figure 4). They further indicate that the main depositional fairway, with better stacked reservoir sands, lies further to the downthrown of the main fault. Three wells were previously drilled: Well A and Well B drilled up-dip and Well C drilled further down dip on strike and in the same trend of Wells A & B. These three wells targeted structural traps that did not exhibit seismic amplitude anomalies. These wells did not encounter good quality sands indicating the wells lie within a sediment bypass area off the depositional fairway.

The generated seismic horizon slices permitted the definition of reservoir geometries, stratigraphic patterns, and the distribution of the rock properties. They also allowed identification of the most likely depositional fairway and enhanced our definition and understanding of the subtle stratigraphic traps. Most of the attribute maps on the Upper Cretaceous (near base Galhak Shale interval) confirmed the sub-lacustrine fairway pattern geometry. They showed three sand lobes cutting across the central sub-basin as slope channels extending SW towards the synclinal area and they deposited in a confined low. There is only monoclinal dip but no obvious structural trap in the area where the fan lobes were developed. For this reason, the trap is a combination structural/litho-stratigraphic one with reservoirs pinching-out up dip towards the slope area to the east. The variation in the intensity of the seismic amplitude maps is most likely indicative of heterogeneity in the reservoir quality, and or due to saturation or Net to Gross (N/G) across the sub-lacustrine fan body.

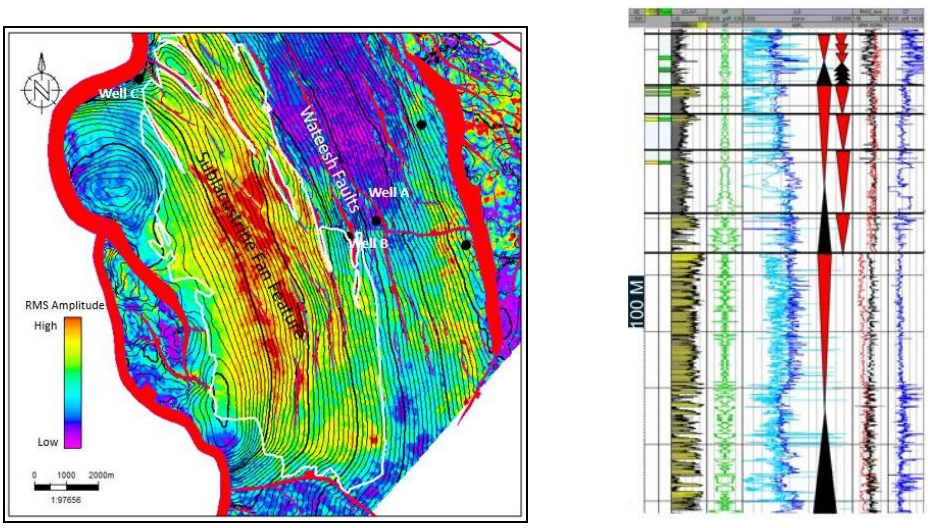

Figure (4): Left: Perspective view of the RMS amplitude map showing the confined nature of the Upper Cretaceous (Near Base Upper Galhak) sub-lacustrine fan geometry. Right: The analysis of a select logs from a borehole showing systems tracts recognition

3. Characterizations of the Sub-Lacustrine Fan Fairway

Characterization of the sub-lacustrine reservoirs were carried out using various 3D seismic attributes and inversion volumes. The new datasets contributed to greater understanding of the lateral connectivity and characterizations of the sub-lacustrine sands and enabled geo-body extraction for stratigraphic trap identification and delineation.

Rock physics analysis was conducted to determine whether lithology and fluid type could be predicted with some degree of confidence using the WAZ 3D seismic dataset. This is to validate the seismic response in the areas tested by Well A, Well B and Well C. Apparently, the wells lie outside of the depositional fairway of the sub-lacustrine fan litho-stratigraphic trap.

Well log analysis shows that sands can be discriminated from shales using VP/VS, P- Impedance and S-impedance, which are commonly used as a lithology indicator. Discrimination of oil bearing from brine bearing reservoirs are relatively hard. Simultaneous, geostatistical, and genetic seismic inversion were performed on the 3D seismic dataset. The inverted seismic deliverables such as P- Impedance, S- Impedance, VP/VS, most probable lithology, Total porosity, Volume of Shale, and oil probability were used in horizon slicing generation and the characterization of the sub-lacustrine litho-stratigraphic trap.

Horizon slicing generated from the inverted datasets at the target of interest of the Upper Cretaceous (near base Upper Galhak Formation) clearly discriminate between the area where the sub-lacustrine combination structural/litho-stratigraphic trap developed and the areas where Wells A, B, and C were drilled. A calculated Volume of Shale (V-Shale) of less than 30% has been used as a cutoff to delineate the reservoir (Figure 5). The target interval has estimated porosity between 13 to 27% with oil probability values of more than 75% (Figures 6).

Seismic response at the top of the litho-stratigraphic trap at Upper Cretaceous (near base Upper Galhak Shale) is represented by a soft kick with lower impedance values and probable down dip conformance of seismic amplitudes with the stratigraphic closure (Figure 7). AVO shows a clear increase of negative seismic amplitudes with increasing offsets corresponding to a type III AVO response. The trapping mechanism is setup by structural dip on a monoclinal ramp and stratigraphic pinch-out towards the up-dip direction of the slope area (towards the east).

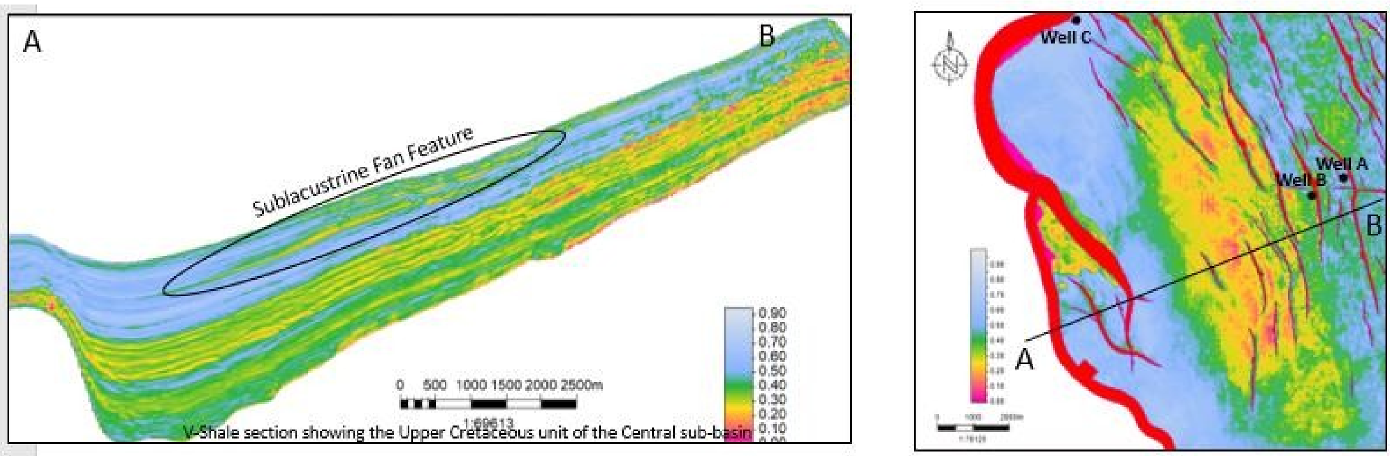

Figure (5): A vertical section on the left and a map on the right showing Volume of Shale Attribute. Observe how well this attribute discriminates between sands in the litho-stratigraphic trap from the surroundings area.

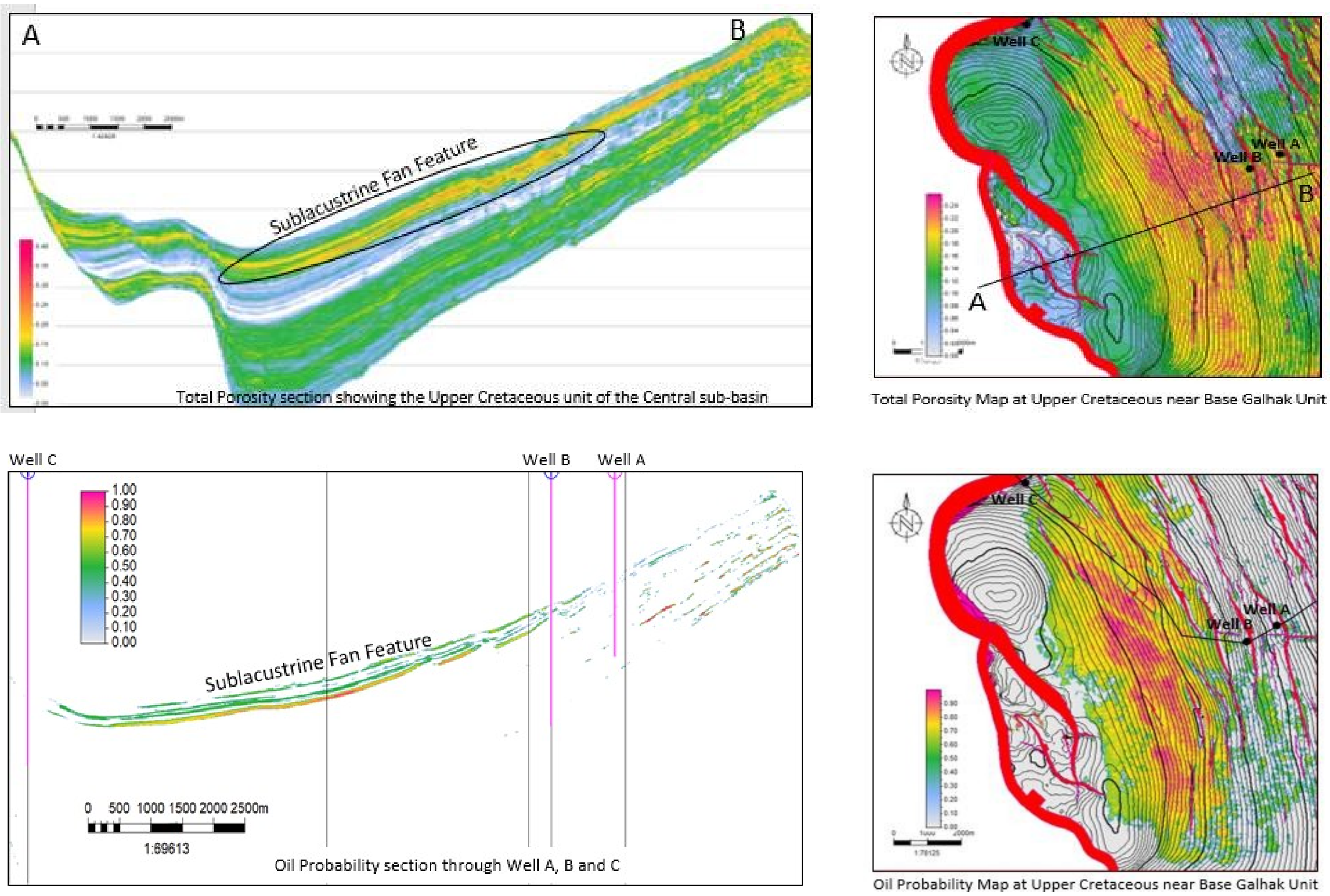

Figure (6): Total Porosity and Oil Probability attributes showing clear definition and characterization of the litho-stratigraphic closure of the sub-lacustrine fan feature. Well A, B and C clearly drilled outside the sand fairway

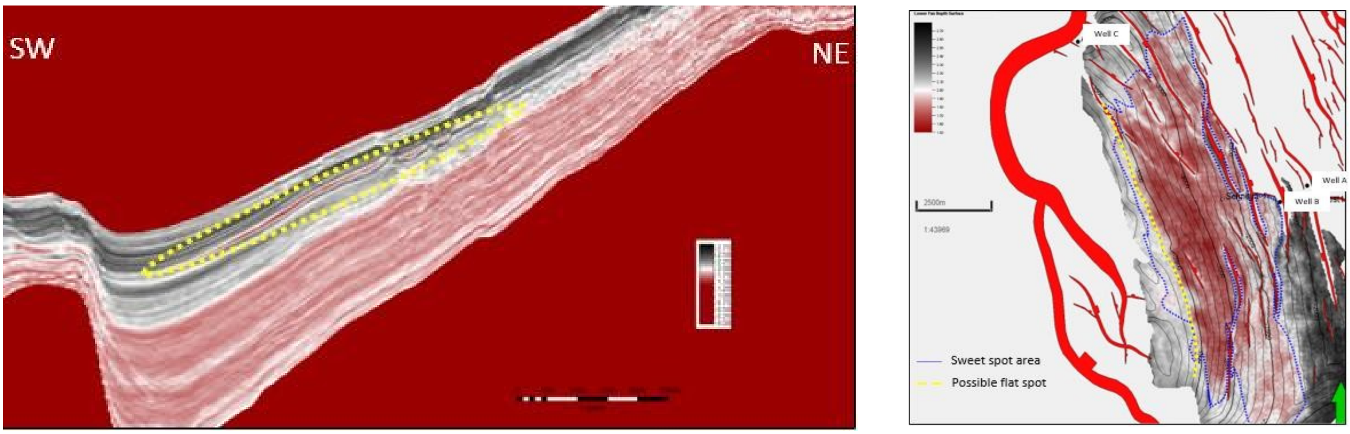

Figure (7): VP/VS showing probable down dip conformance of seismic amplitudes with the litho-stratigraphic closure of the sub-lacustrine fan feature.

4. Sequence and Seismic Stratigraphy of the Rawat Central Sub-basin

To understand the depositional patterns for targeting stratigraphic traps, a sequence stratigraphic model for the Upper Cretaceous (Galhak formation) in the Central sub-basin of the Rawat rift basin was built using wells (cores and logs) and 3D seismic data (seismic attributes, stratal slicing, seismic inversion).

Application of the principles of sequence and seismic stratigraphy in Rawat basin permitted prediction of the presence and quality of reservoirs, source, and seal rocks. However, characterization of the thinner sands from thicker sands in a mud-rich environment is challenging. Therefore, it was essential to identify the main depositional fairways of sub- lacustrine fan to better define where thicker sands are likely to be found. Seismic data, well logging and core data showed that the braided delta, semi-deep, shallow lacustrine deposits, delta plain, delta front, pro-delta and fan delta are mainly developed during the various rift phases with the sediment deposition mainly coming from the NE to SW direction.

An integrated analysis of well logs, extraction of seismic amplitudes and inversion attributes from the reprocessed seismic volumes, and the cores revealed two sub-sequences (SQ1, and SQ2) within Upper Cretaceous formations. Each sequence represents a cycle of rising and falling lake level producing lowstand, transgressive, and highstand systems tracts. The lithfacies in the Upper Cretaceous (Galhak Oil sequence (SQ1)) contain excellent reservoir properties as it is deposited in fluvial – fluvio deltaic and fan delta environments. In the second sub sequence within the Upper Cretaceous (Upper Galhak Sequence (SQ2)), the Lowstand Systems Tracts (LST) include the sub-Lacustrine fan sand bodies. We believed these spreads widely along the west of the slope area into the basin center. The TST and HST contain the main source and seal rocks in the Rawat Central sub-basin (Figures 8).

The analysis results indicate that the Lowstand Systems Tract (LST) of the Slope and Basin Floor areas contain numerous high quality reservoir sands in the Central Sub-basin of the Rawat Rift Basin. This includes high and low-density deposits and channel levee complexes. The high-density deposits form the thicker and better-quality reservoirs.

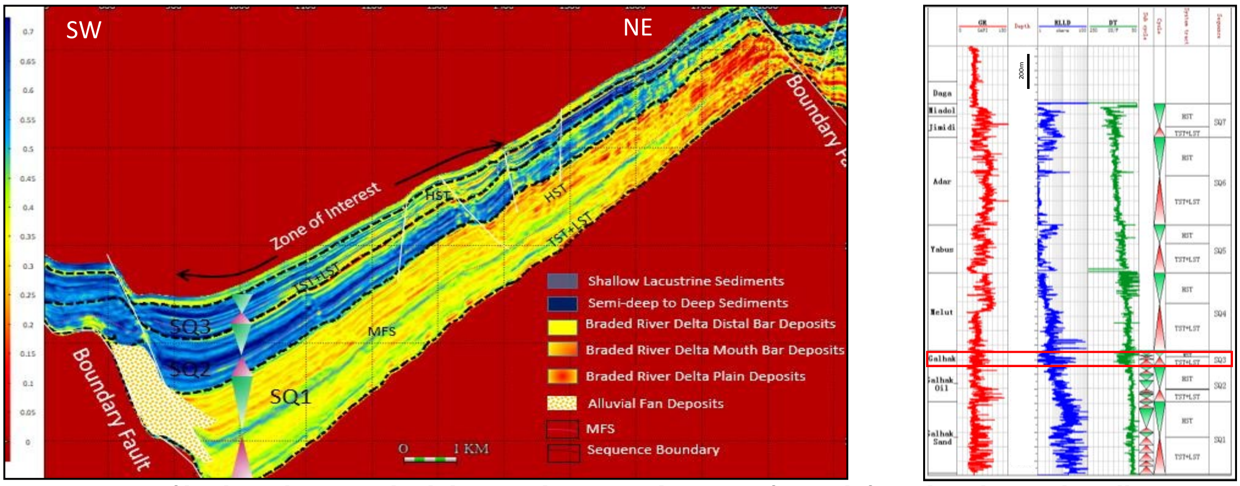

Figure (8): Profile along the Central sub-basin indicating sedimentary facies (left) and (right) single well sequence interpretation, SB: Sequence Boundary, HST: High Stand System Tract, TST: Transgressive System Tract, LST: Low Stand System Tract and MSF: Maximum Flooding Surface

Syn- depositional faults controlled the development of the sedimentary environment, and the distribution of the lowstand systems tracts within the central sub-basin. The facies interpretation from the slope in the east to the combination structural/litho-stratigraphic trap area to the west, towards the depocenter, show the potential for deposition of stacked reservoirs in synclinal area as shown in figure (9 and 10).

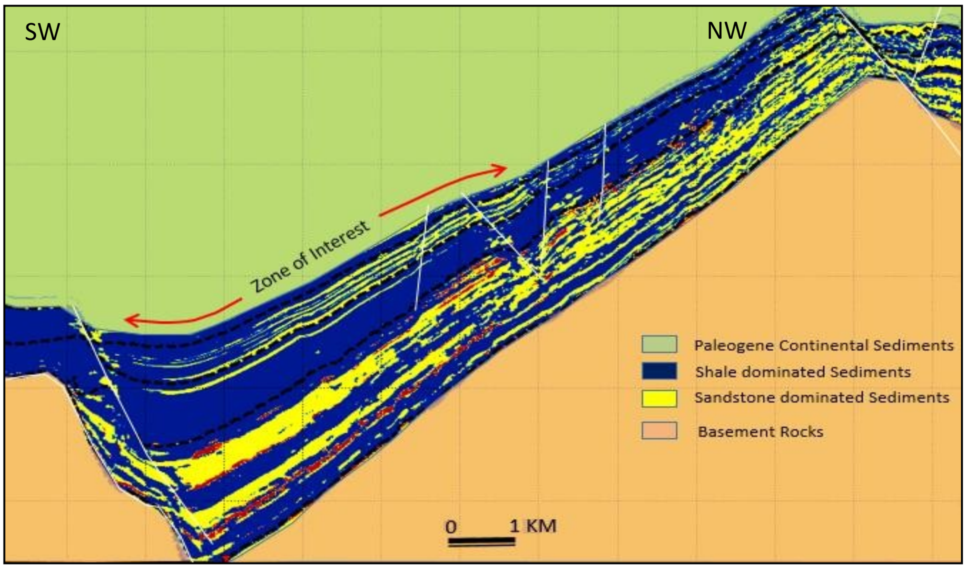

Figure (9): Facies interpretation Profile along the Central sub-basin showing the stratigraphic trap target.

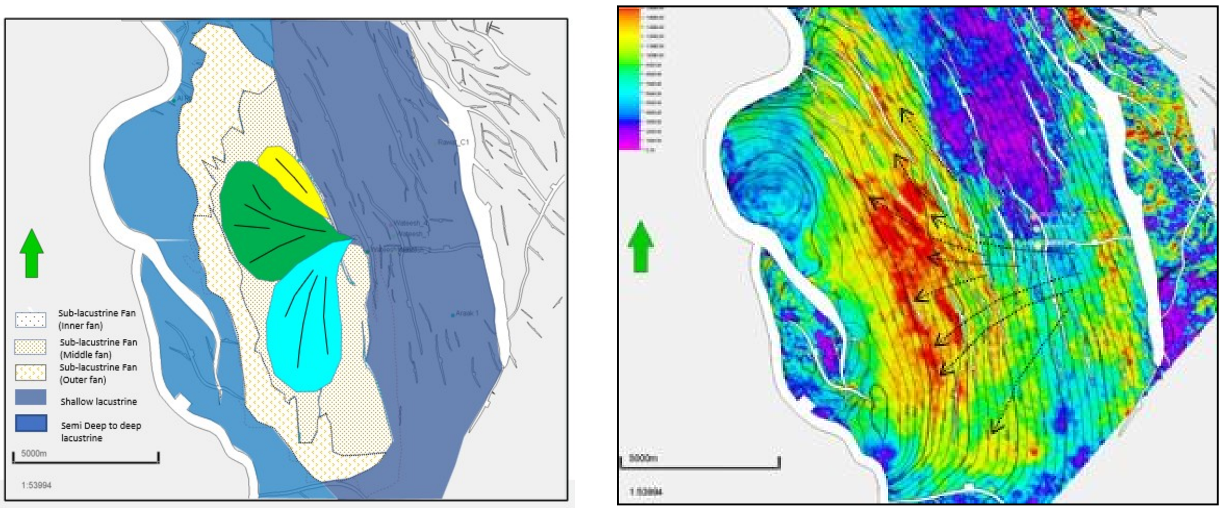

Figure (10): Map view of the Depositional system of the sub-lacustrine Fan during the Lowstand Prograding Complex

During the late Cretaceous period, the area was affected by progradation of regressive clastic deltas. Instability of the margin resulted in sands by-passing the high areas to the east through feeder channels. Episodic failure of the slope occurred at the Upper Cretaceous (Galhak intervals) during the lowstand period. This caused the clastic sediments especially the sub-lacustrine fan to flow over a long distance. Eventually, the sediments settled in depocenter areas. During this period, the potential sandstone reservoirs formed in a lowstand systems tract environment (Figures 11 and 12). Two types of basin floor fans are expected, (a)incised channels and unconfined sub-lacustrine fans where they were controlled by slope inclination alone and were not diverted by structural barriers. This was observed in the area towards the north part of the central sub-basin. (b) confined sub-lacustrine fans controlled by NW-SE trending faults. These presented by our current litho-stratigraphic trap closure under investigation.

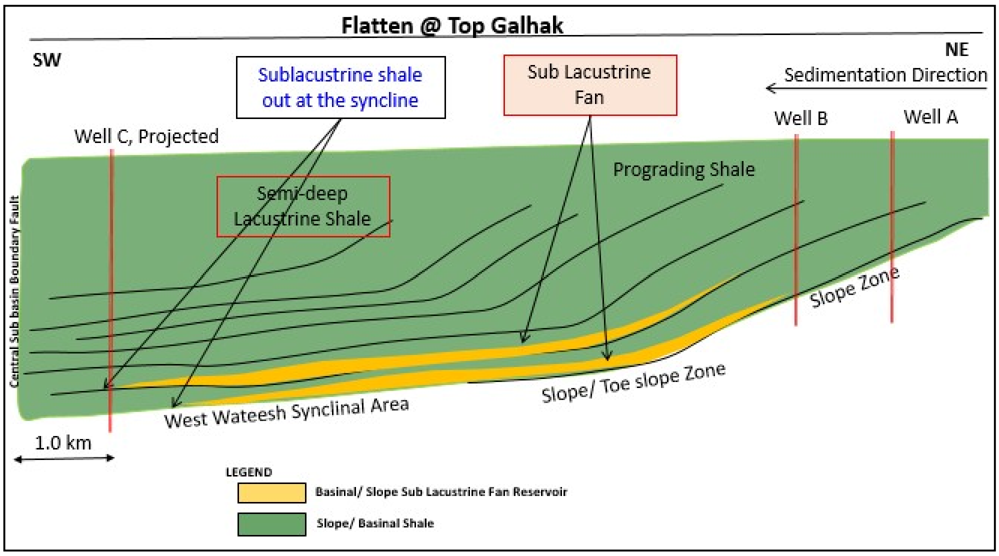

Figure (11): Deposition of sub-lacustrine fan during Lowstand Prograding Complex

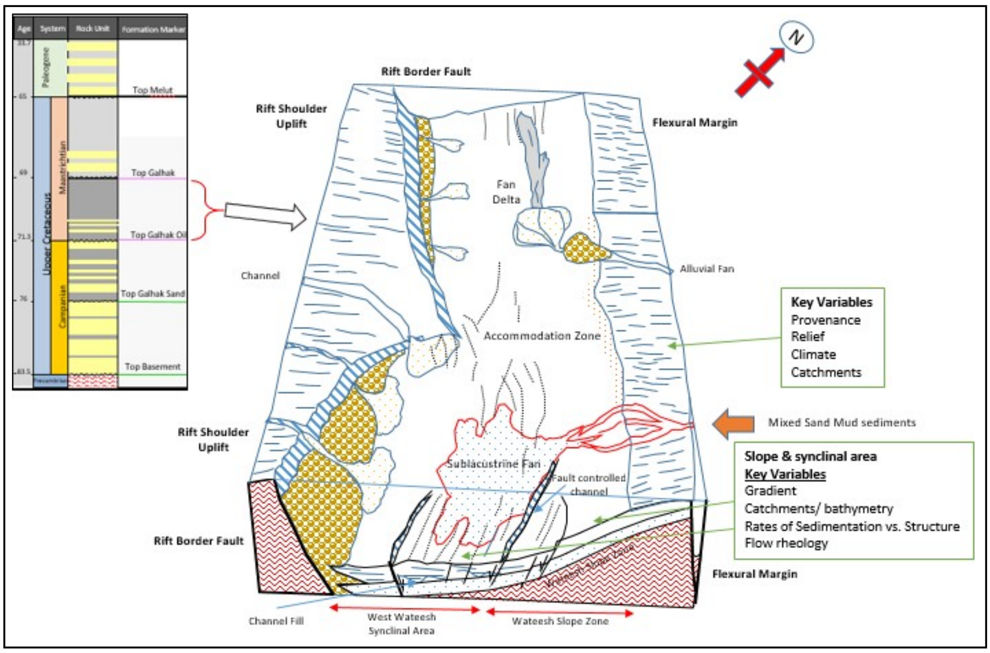

Figure (12): Depositional model of Upper Cretaceous (Galhak Shale) in the Rawat Central Sub-basin. It shows rift geometry, accommodation zones, sedimentation patterns and lithologies.

5. Conclusions

In this study, we focused on the Central sub-basin of the Rawat Cretaceous rift basin in Sudan. Integration of seismic attributes, seismic inversion, and sequence and seismic stratigraphy provided a robust approach for the identification and description of a combination structural/litho-stratigraphic trap. A sub-lacustrine fan system near the base of the Upper Cretaceous (Upper Galhak Shale Unit) deposited during a Lowstand Systems Tract, has been identified and evaluated for prospect maturation. The trap was setup by up-dip pinch-out of sandstones or isolated sands bodies within otherwise shaly unit of the Upper Cretaceous (Galhak Shale Unit). The trap integrity of the identified prospect is dependent on the sealing capacity of faults in the up-dip direction (towards the east). This constitutes the most critical risk for hydrocarbon entrapment. The result of this study underscores the importance of exploring for hydrocarbons in combination structural/stratigraphic and unstructured traps in the Rawat rift basin.

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