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New Evidence of the Holokinetic Sequences around Suakin-1 and -2 in the Sudanese Red Sea Area Using Integrated Geophysical Interpretation

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Abstract

Suakin-1 and Suakin-2 wells are in the Sudanese Red Sea segment where the hydrocarbon generation had been proved by previous studies, however, no reasonable reserve was evidenced due to the complexities of the surrounding salt structures. Six seismic lines were tied to Suakin-1 and -2 to delineate the controlling salt tectonics. The salt evacuation (Roho) and other salt bodies were recognized and matched with similar salt structures in analogous stratigraphic conditions as the Gulf of Mexico and Angola margin. While a previous inconsistent interpretation in the study area marked the high amplitude horizon of the Lower Zeit formation as the top of the Dungunab formation. Three seismic features indicated the presence of salt dome (autochthonous): velocity pull-up, dragging of the sedimentary layers forming mini basins around the third feature, which is the relative transparency of the seismic signal in two piercing like bodies. This interpretation similarly demarcated that the salt escaped east-wards, thus the mapped welded salt is believed to be formed after the salt evacuation. A 3D seismic with a far offset and wide range of azimuth is recommended for detailed imaging.

Keywords

Salt Tectonic, Seismic Interpretation, Dungunab, Red Sea

1. Introduction

The Tertiary to Recent Red Sea rift forms part of a rift system that includes the Gulf of Aden and East African Rift in the south at the Afar triple junction and the Gulf of Suez in the north [1]. There is extensive documentation regarding the Red Sea rifting, evolution, stratigraphy, and the associated petroleum prospectivity. These rifts were initiated in the Late Oligocene-Miocene time and fragmented the once continuous Arabian–Nubian Shield [2]. Several geological studies confirmed that the Red Sea basin dominantly preserves Early Miocene to Pleistocene sedimentary successions along the entire length of the basin [3]. In the 1960s, the Deep Sea Drilling Program (DSDP) started new research activities in the Red Sea due to the discovery of hot brines while oil discoveries in the Gulf of Suez raised interest in prospecting elsewhere in the Red Sea [4]. The architecture of rifted continental margins and break-up evolution in the South and North Atlantic and the Red Sea-Gulf of Aden conjugate margins were studied, and a comparison was established by [5] [6]. Their attentive study involved the tectono-sedimentary development of the South Atlantic compared with the Central Atlantic margins during the Mesozoic continental break-up. They considered the Red Sea and the Gulf of Aden as natural laboratories to study the breakup processes and formation of divergent continental margins, therefore they compared the structures observed in incipient stages of basin formation between the African and the Arabian plates with the structures observed in older sedimentary basins associated with the Gondwana break-up. Furthermore, a comprehensive summary of the geological and geophysical studies that have been done along with the Red Sea segments by [7] [8] [9] and how the Red Sea represents an example to understand the processes responsible for early rift-related magmatic systems and ocean basin formation influenced by both active and passive rifting processes (**Figure 1**). [10] studied the shear-controlled evolution of the Red Sea as a zone of structural weakness during the Pan-Africa orogeny and they classified this period into different stages. They discussed the role of the wrench faulting played a key role in generating the linearly arranged pull apart that their spatial distribution was controlled by pre-existing fault systems like Najd shear system, Onib-Hamisana, and Baraka suture zones. Strike-slip motion along the later zones of weakness influenced the Egyptian and Sudanese coastal areas.

Well, data suggest the sediment thickness is up to 4 km in the Red Sea; 3 km or more in some places consists of Miocene evaporites [11] [12] [13]. More lithologic and stratigraphic information has been collected from drill sites along the Red Sea and confirmed the extent of the sedimentary cover to the axial trough zone. The correlation of these stratigraphic units in different sites indicates the middle-late Miocene to Pleistocene deposits with the existence of some anhydrite deposits above recent basaltic volcanic rocks at the axial trough zone [14]. The stratigraphic relationship from these wells suggests prominent unconformities between the Miocene and the post-Miocene sediments [15]. These

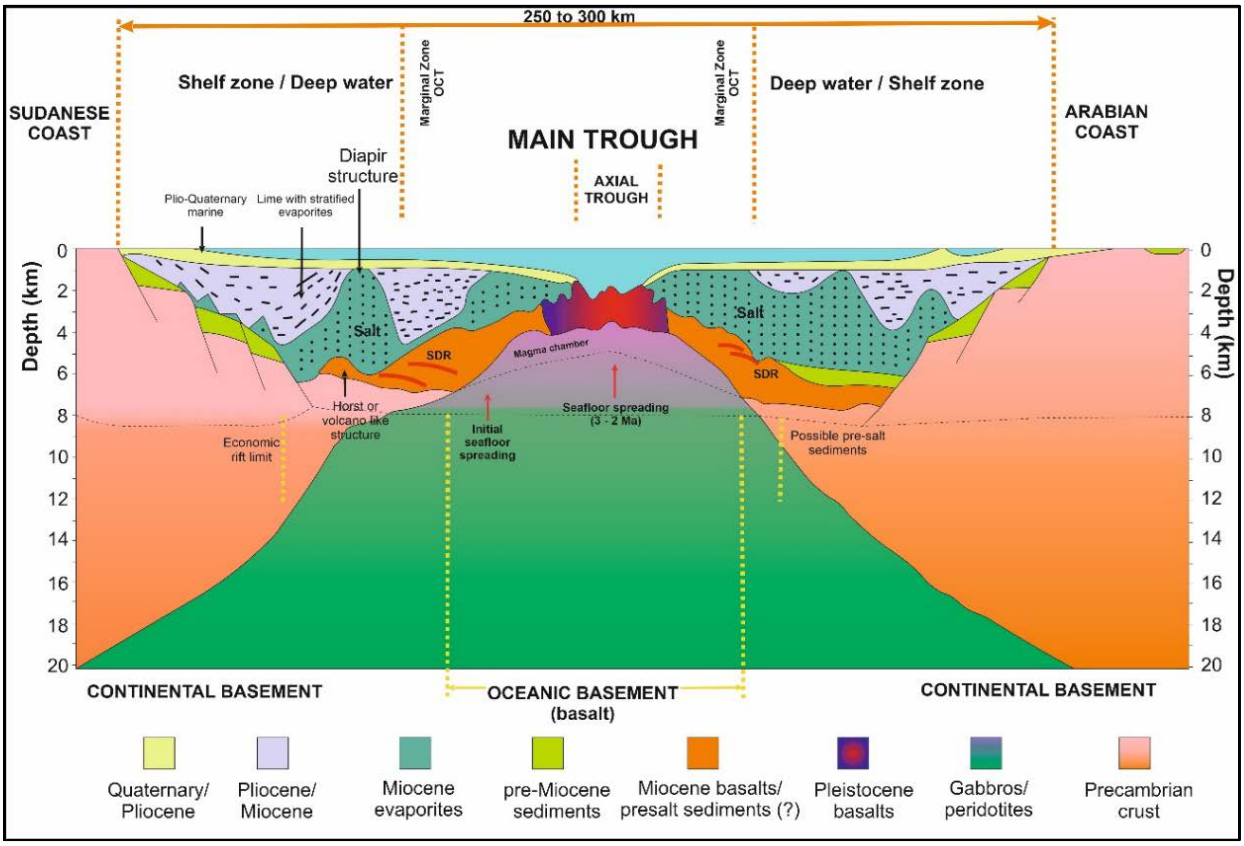


Figure 1. Conceptual tectonic model for break-up in the Red Sea between Sudan and Saudi Arabia. Incipient spreading is observed in the axial trough, separating two Late Miocene salt basins [6].

findings are compatible with the Saudi Sudanese Commission in 1976, as they collected over 4000 km of deep-water marine and 645 km of shallow marine seismic profiles at the central Red Sea area between 18˚N and 24˚, with 1.7 to 4.6 km/sec average velocity for the sedimentary cover and up to 3 km thickness in over the main trough area, thinning towards the axis [9] [16].

The stratigraphy and sedimentation of the Sudanese Red Sea can be placed tectonically into two major phases: Pre-Rift stratigraphy and Syn-Rift stratigraphy while the latter is divided into three phases: pre-salt, salt, and post-salt (**Figure 2**). The pre-salt phase is found at the lowermost sequence of the stratigraphical column to include Mukawar, Hamamit, and Mughersum group overlies and on laps of the Basement complex that is uniform throughout the area. The salt phase represents the evaporate sequence and is composed of Belayim and Dungunab formations, which were deposited during the cycle of the sea level rise and fall, indicating a change in climate and a prolonged period of desiccation The salt tectonics and the controlling structures will be discussed separately. The overall sequence is overlain by a thick sedimentary unit that represents the post-salt phase and is composed of a mixture of clastic and carbonate sediments of the Abu Shagara Group.

In spite of their limited analytical data, [8] concluded the petroleum potentiality in the Sudanese Red Sea segment that the upper Cretaceous-Cenozoic

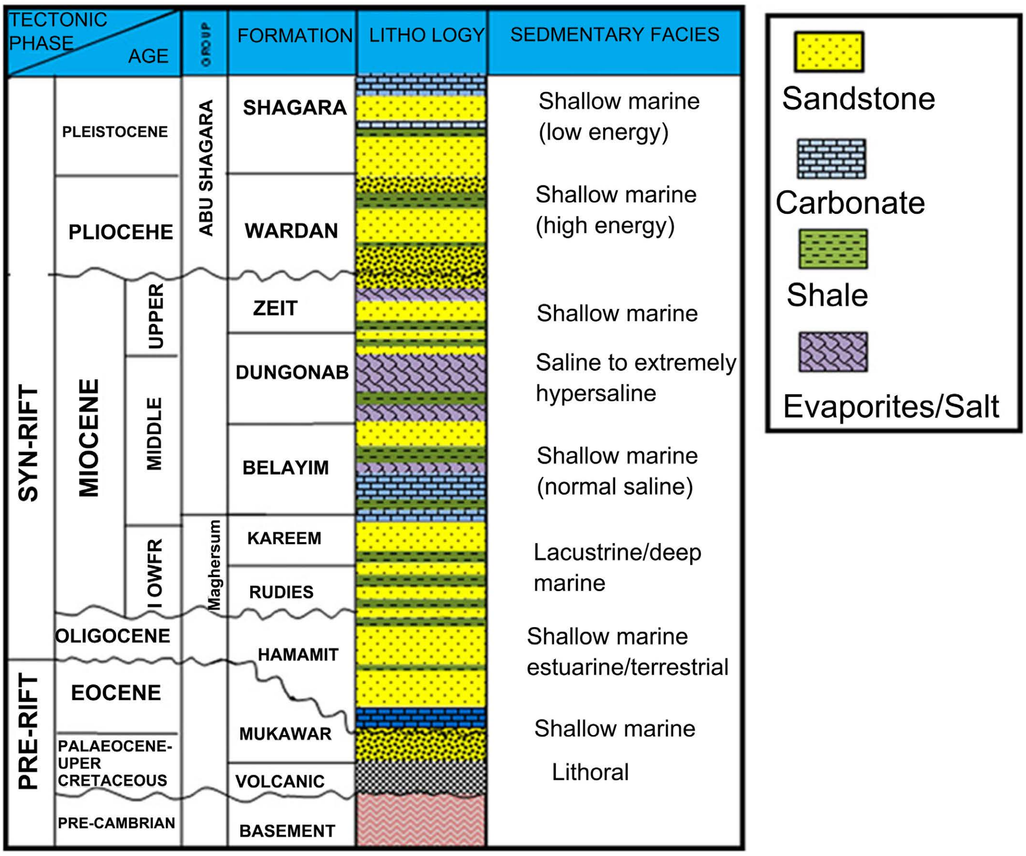


Figure 2. Stratigraphic column for the Sudanese Red Sea, based on surface geology and limited coastal exploration wells, after [8].

Mukawar and Hamamit sandy formations have little or no hydrocarbon source potential [13], and the lower to middle Miocene Rudeis. Kareem and Belayim Formations that have been penetrated in several wells have more potential for generating black oil. Whereas the middle-upper Miocene Dungunab Formation contains thin regionally early mature intra-evaporite shales in coastal areas, that if developed deeper offshore are likely to generate hydrocarbons. The concentrated deltaic sedimentation in Zeit Formation is more likely to provide gas-prone source rocks. The Plio-Pleistocene Abu Shagara Group has no oil source potential in the nearshore areas, nevertheless, potentially may improve further offshore and shows richer organic matter if it has been subjected to higher heat flow. Oil and gas seeps and shows have been published on the Saudi Red Sea margin which is the analog of the mirror image of the Sudanese Red Sea. The hydrocarbon system in the Sudanese segment was also proven in both well sites of Bashayer-A1 and Suakin-1 as confirmed gas and condensate discoveries, the latter well site has been used in the current study to tie the seismic lines for reliable interpretation.

2. Salt Occurances and the User Data in the Red Sea

The fluid rheology of salt and its incompressibility make it inherently unstable under a wide range of geologic conditions at such low temperatures and differential stresses [17]. The primary driving force for salt tectonics (Halokinesis) is differential loading, while two factors resist salt flow: strength of the overburden, and boundary drag along the edges of the salt body. [18] found that the spatial relationship between the faulting beneath the salt and the overburden depends on the salt thickness. In areas of thrust tectonics, salt layers act as preferred detachment planes [19]. When a salt layer becomes too thin to be an effective detachment layer, the overburden and the underlying sub-salt basement are effectively welded together due to salt movement, dissolution, or removal by faulting.

Salt welds can be classified into three types: primary, secondary, and tertiary welds, in which the difference in location and moving behavior. The primary type joins strata originally separated by autochthonous salt, and it gently adopts the general dipping sub-salt strata with supra-salt sediments which imitates the angular unconformity. The recognized pitfalls produced by this process are the apparent down laps and the pseudo-turtle back structure. The secondary type joins strata originally separated by steep-sided salt diapirs, while the tertiary type joins strata originally separated by a higher allochthonous salt sheet (**Figure 3**).

[20] studied the attributes and evolution of an exhumed salt weld in the La Popa basin in northeastern Mexico and they presented that salt weld may cause the development of new faults in the cover sequence and these salt welds may also develop in the vertical direction by putting the sides of a former diapir in contact. This assumption was adopted later by [21] in their study to elucidate the origin of Jabal Sanam in Southern Iraq with a detailed geomorphological, geological, and tectonic description of the feature and this assumption helped in explaining the development of the faults. The term roho was derived in mock

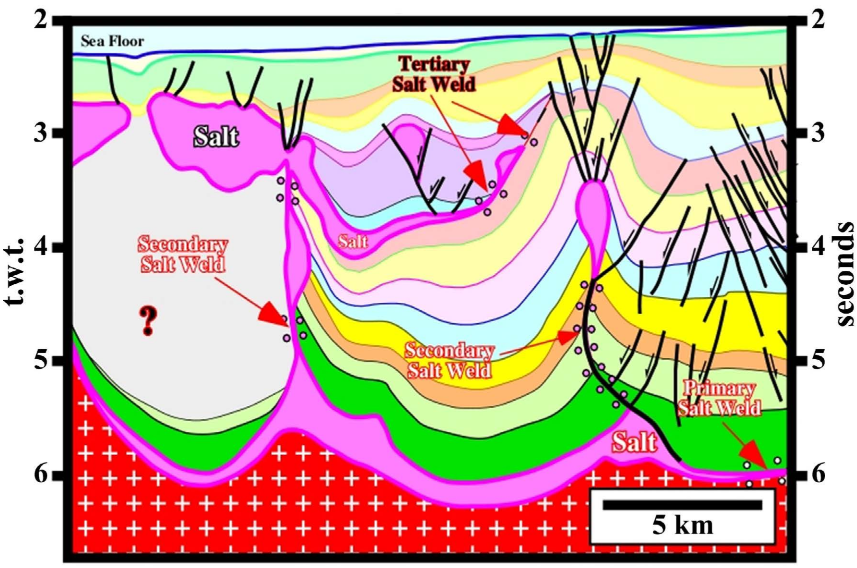
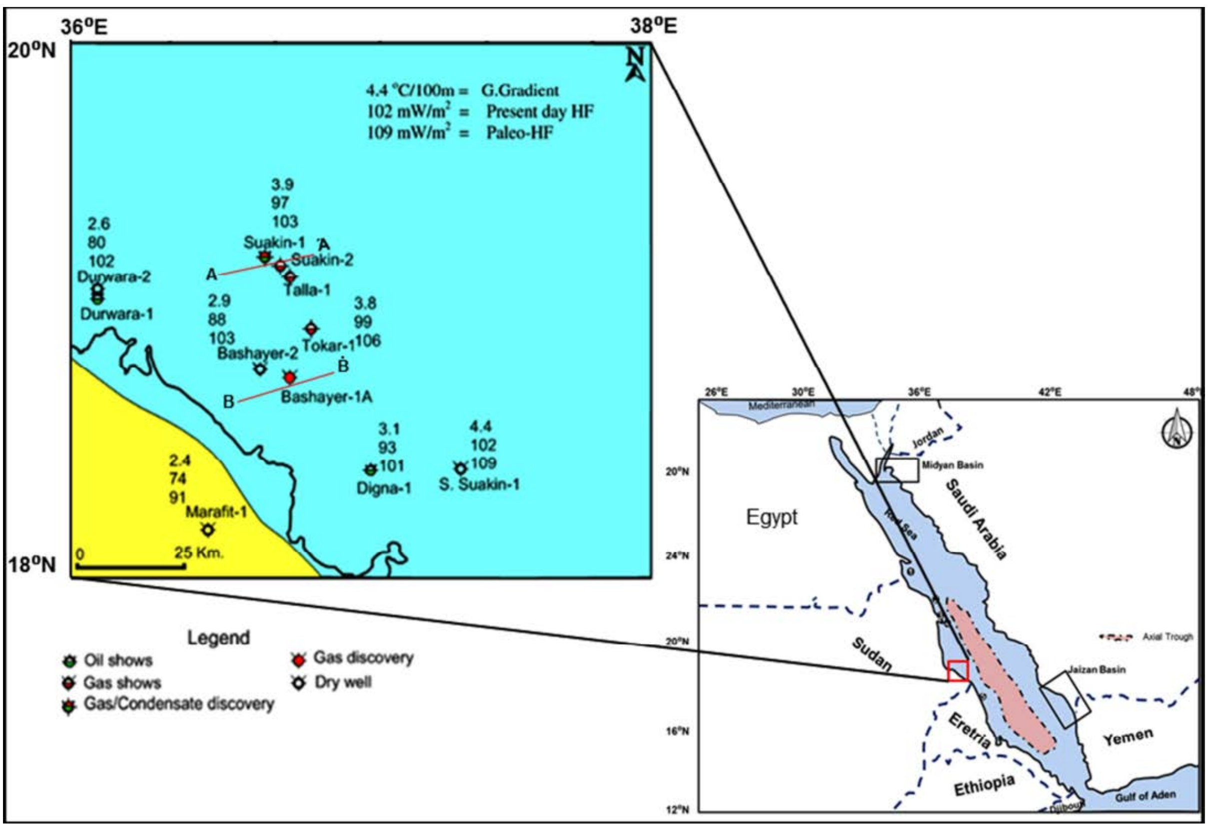


Figure 3. A-line from deepwater Angola recognizes the three principal types of salt welds: the tertiary salt weld is quite evident on the allochthonous sheet, in the upper part. The central part indicates two vertical secondary welds, which suggests the diapiric salt bodies were shortened. While the primary salt weld is visible on the right bottom of the line.

comparison to the moho based on seismic refraction experiments in this province during the late 1960s, however, it was recognized that the high-amplitude discontinuous reflectors were residual salt on evacuation surfaces. Recently, Roho's term was restricted by [22] to the discontinuous, high-amplitude seismic reflections caused by remnant salt along welds, also called salt-evacuation surfaces or salt-withdrawal surfaces. The current study adopts this assumption in revealing the salt structures in the study area.

The complexity of salt structures makes any interpretation challenging since they vary rapidly in space therefore the salt geometry cannot be projected into a poor-data zone. In addition, salt structures create steep salt interfaces and can deform nearby sediments into equally steep orientations with poorly imaged dips, as they can modify stresses and pore pressures in wall rocks potentially change their velocities and cause velocity anisotropy. As they can be faster or slower than the surrounding sediments, Salt velocity complications can distort the seismic wavefield and make it harder to produce a correct image [23]. Hereafter, pre-Stack depth migration is a principal technique for solving these challenges that require an accurate velocity model. A large part of modern salt interpretation is directed at the velocity-model building for pre-stack depth migration.

The study area covers both onshore and offshore parts of the Sudanese Red Sea. One sonic log, two check shots of Suakin 1 and Suakin 2 (**Figure 4**), addition



(A) (B)

Figure 4. (A) Locations of the used wells in the study area, (B) location of the study area along the Sudanese Red Sea.

to six 2D seismic lines (four SW-NE in lines and two NW-SE crosslines) are used in this study. The seismic lines are provided by Oil Exploration and Production Administration (OEPA) with the following parameters: recording length is 8000 ms, sample interval 2 ms, channel 480, shot point interval 25 m, and group interval 12.5 m.

A conventional quality control and data check was continuously done during the data loading process to emphasize their consistency to delineate the salt structures associated with the extensional tectonics and determine the salt movement's direction. Two synthetic seismograms, from both wells (Suakin 1 and Suakin 2), were generated using extracted wavelets from the stacked seismic and were utilized to precisely pick the formation tops as shown in **Table 1**. Although log depths were not deeper enough to penetrate the Belayim formation, five formation tops were picked accurately: Seabed, Shagara (Pleistocene), Wardan (Pliocene), and the Upper-Miocene formations of Zeit and Dungunab. Based on the stratigraphy of the deeper formations added to the seismic characteristics, the seismic interpretation succeeded to pick a deeper horizon with high amplitude at an average depth of 3700 meters that represents the boundary of Belayim and Kareem formations at the lower part of the Syn-rift sequence as shown in **Figure 5**.

3. Results

The overall quality of the used seismic data fulfilled the delineation of the reflectors within the sedimentary package, which was mostly strong. More than a few commonalities were observed in interpreting the in-line sections: a high amplitude reflector represents, according to well-tops information, the top of lower Zeit formation (**Figure 6(a)** and **Figure 6(b)**) stating a high grade of sedimentation, while the anticlinal shape conceivably refers to individual faults, whereas an extensional fault is mapped as a reactivated fault in the opposite direction to its

Table 1. Well tops data from Suakin 1 and 2.

Well ID	Formation	Measured Depth (meter)
Suakin-1	Shagara	398
	Wardan	869
	Upper Zeit	1449
	Middle Zeit	1850
	Lower Zeit	2671
Suakin-2	Shagara	531
	Wardan	1019
	Upper Zeit	1702
	Middle Zeit	2169
	Lower Zeit	2751

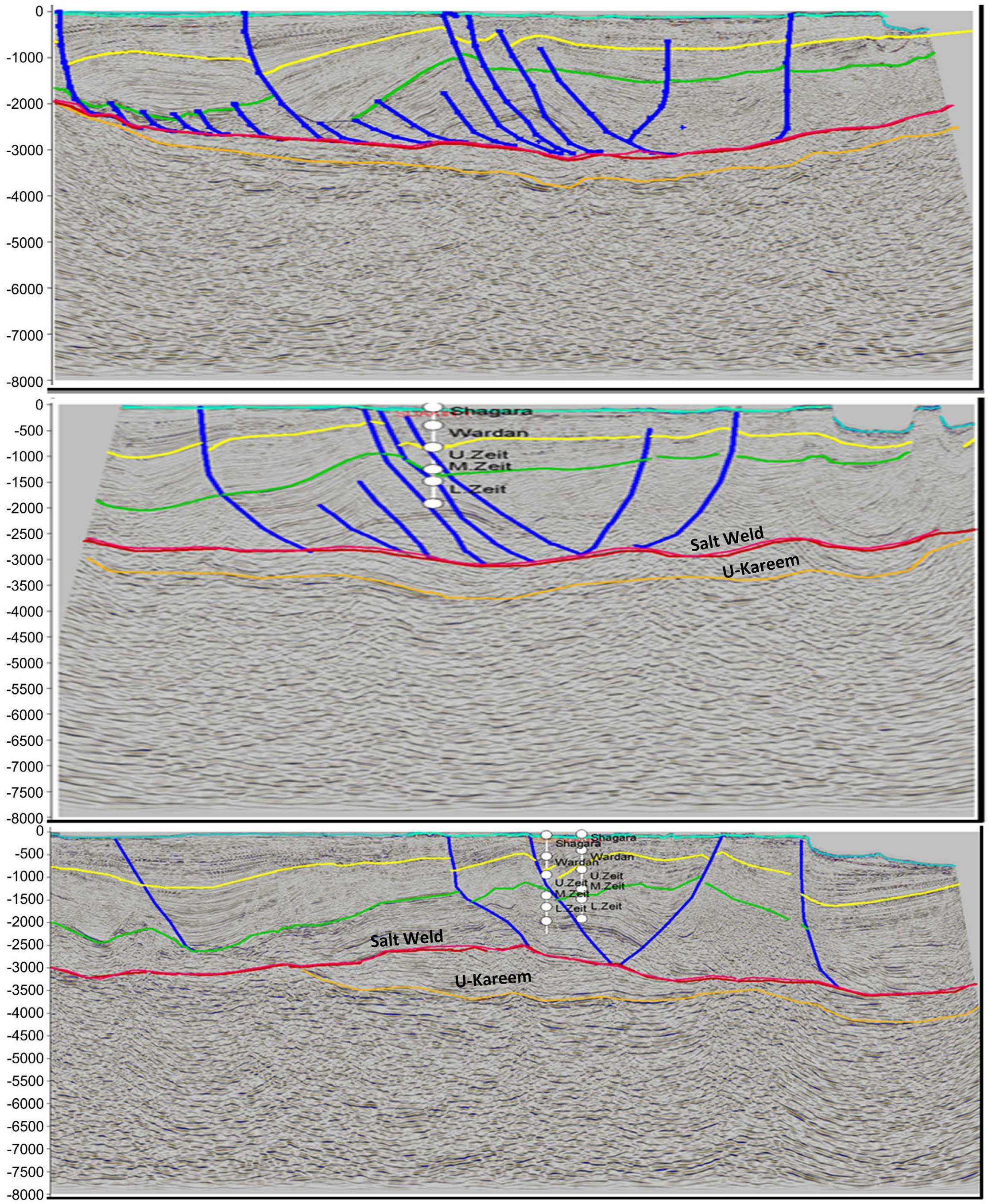


Figure 5. Interpreted seismic in-lines and horizons picking based on well-tops data, the stratigraphy of the deeper formations, added to the seismic data characteristics. The deeper high amplitude at an average depth of 3700 meters shown in a brown-colored horizon represents the boundary of Belayim and Kareem formations (lower Syn-rift sequence).

original movement forming structural inversion. The interpretation of the seismic data was conducted for post-Dungunab salt, and the extensional drifting model on the post-salt depositional sequence that was characterized by the low angle listric faults. It was noticed that mainly NW-SE characterized the fault trends, parallel to the Red Sea ridge axis, detached from the Dungunab formation.

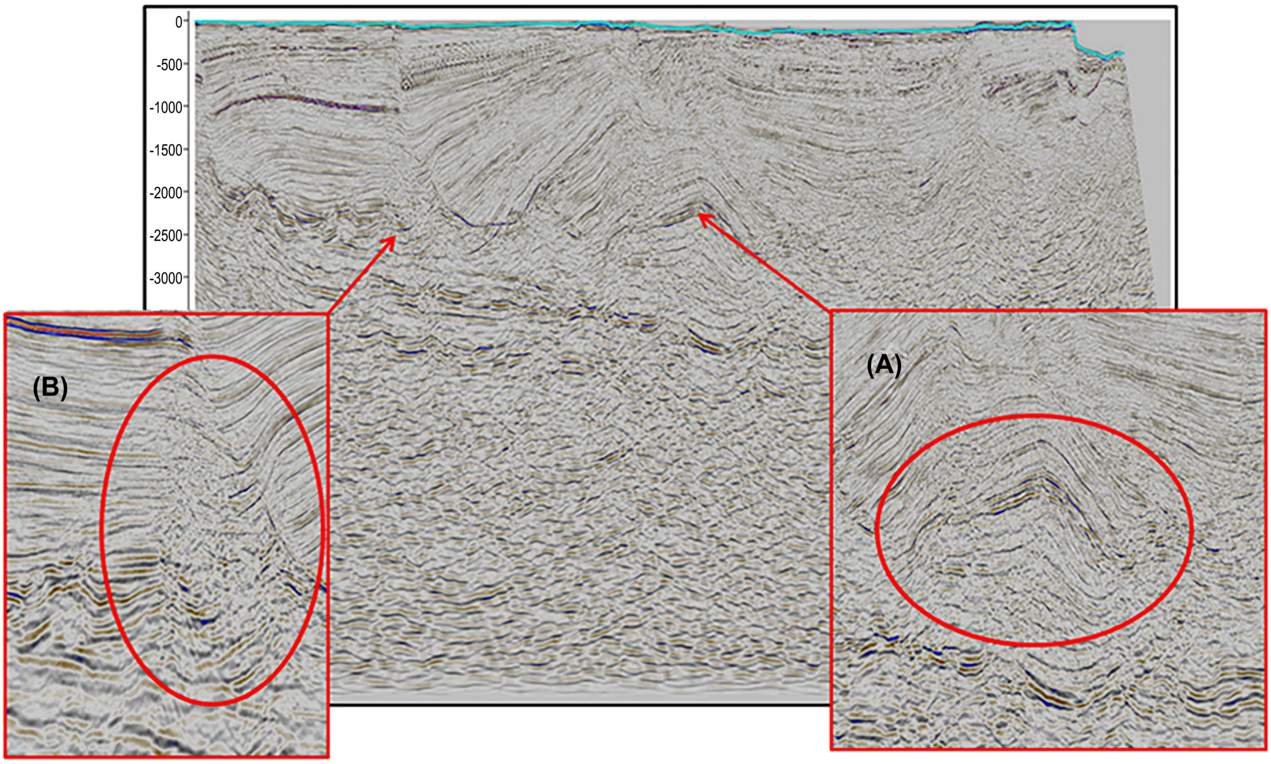


Figure 6. (A) and (B) Show commonalities that were observed in interpreting the in-line sections and detected a high-amplitude reflector that according to well top information represented the top of lower Zeit formation stating a high grade of sedimentation.

Nevertheless, two interpretation limitations were observed. Continuity loss on top of the middle Miocene strata of the Dungunab formation stands as structural complexity where uncertain features were present. This is due to velocity pull-ups and affects determining proper velocity for migration in seismic processing. The inadequate quality of the lower seismic section was due to low signal to noise (S/N) ratio and low frequency and thus was tremendously challenging to demarcate the lower syn-rift and pre-rift sedimentary layers of lower Miocene to upper Cretaceous (*i.e.*, Rudies, Mukawar, and Hamamit formations).

4. Discussion

The upper surface of the salt layer of Dungunab formation occurs below zones of normal faulting in the overlying sediments that had been recognized in association with tilted blocks that combined with listric fault rollover systems. Also, an absence of the total transparency of seismic events in the salt zone explains that the salt had been squeezed out; this proves that the salt structure that had been detected in the seismic data is a typical salt roller (roho) system or salt evacuation (**Figure 7(a)** and **Figure 7(b)**).

[24] studied the Cenozoic structural evolution and the tectonostratigraphic framework of the Northern Gulf Coast Continental Margin. They followed [22] and restricted the term roho to the characteristic discontinuous, high-amplitude seismic reflections caused by remnant salt along welds as well as additional terms

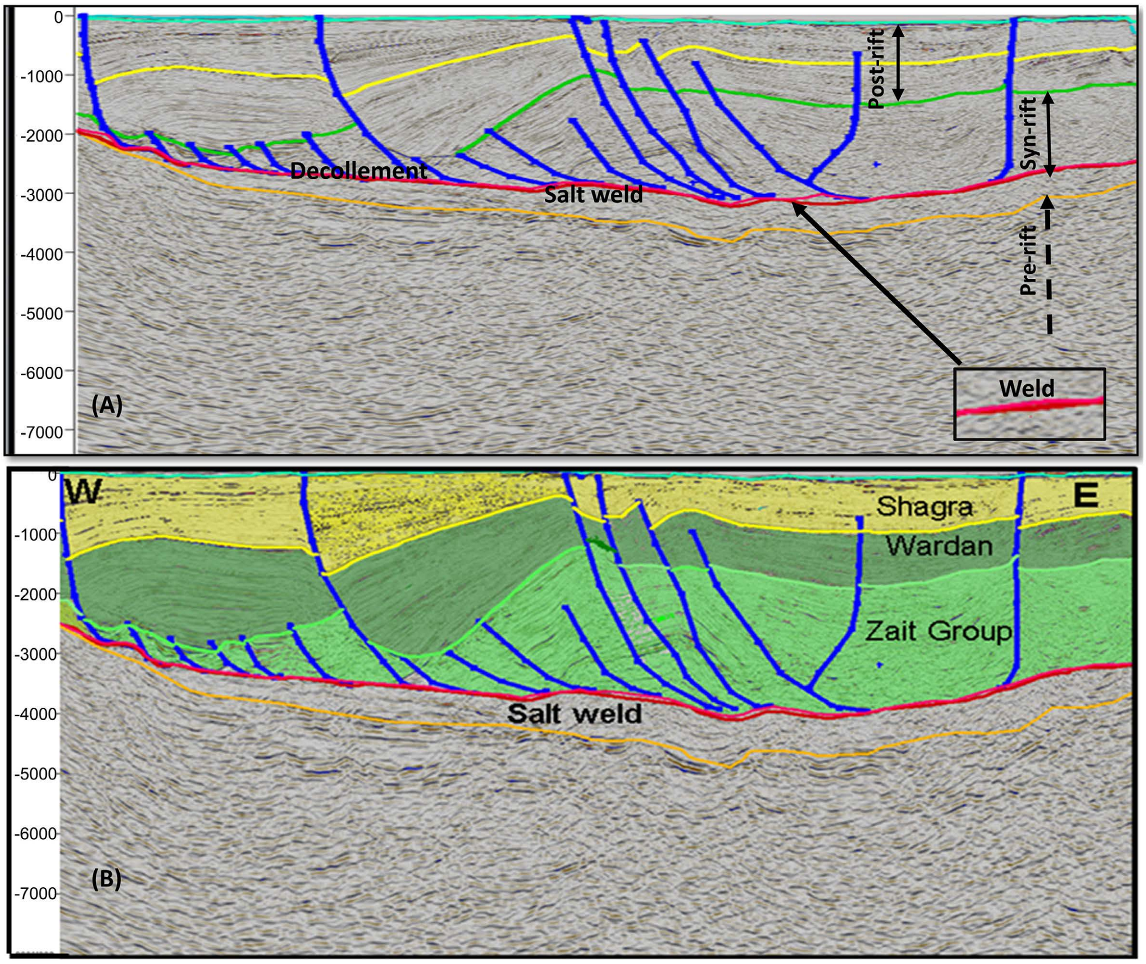


Figure 7. (A) Seismic profile interpretation shows sedimentation, and associated listric growth faults collapsed the west end of a salt body to produce a weld (red). A zoomed-in window illustrates that the base salt (deep red) and top salt (red) had completely welded. (B) Sedimentary formations above the Middle-Upper Miocene Salt weld in Dungunab formation.

such as salt-evacuation surfaces or salt-withdrawal surfaces. Among all extensional and compressional salt structures expected to be observed in the Red Sea, only the salt Roho system is detected in the seismic sections of the study area showing similarity to section from the Gulf of Mexico [24] as shown in **Figure 8**.

Seismic interpretation in this study observed three features that indicate the presence of salt dome (autochthonous): velocity pull-up, dragging of the sedimentary layers forming mini basins around the third feature, which is the relative transparency of the seismic signal in two piercing like bodies (**Figure 9**). The seismic interpretation similarly demarcates that the salt escaped east-wards, thus welded salt that was mapped presently is to be formed after salt evacuation. Further studies are required in the eastern part of the current study area to delineate and predict on-base ground salt structures.

A broad comparison of the present results was done with a seismic profile from the Angola margin [25] indicating the similarity of the structure that appears in both seismic sections (**Figure 10**). There can be considerable certainty

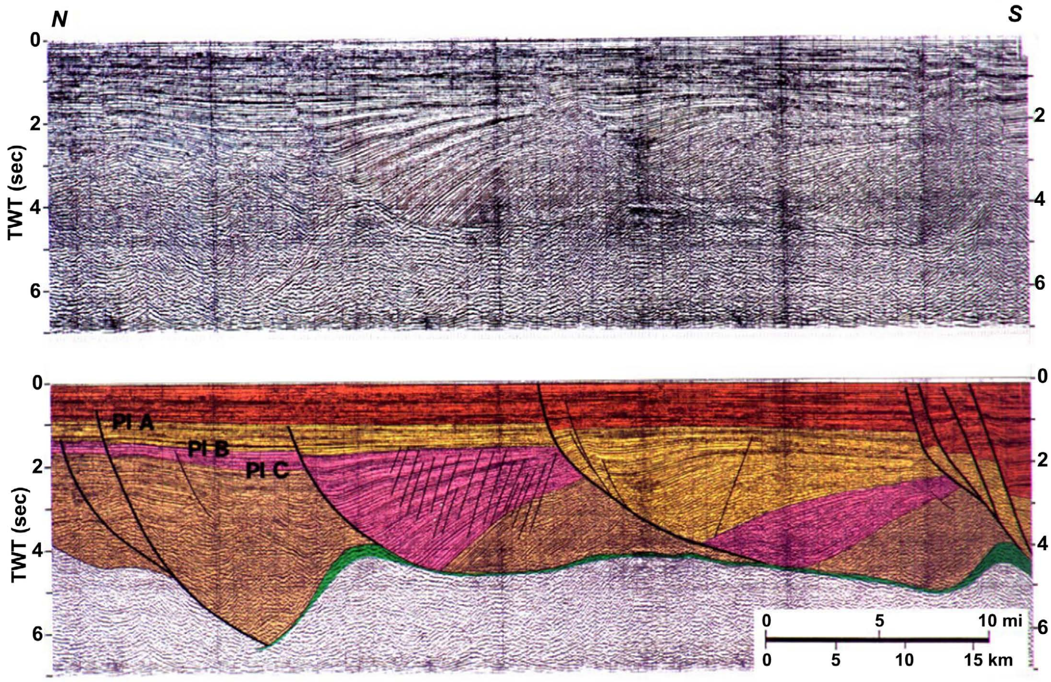


Figure 8. Un-interpreted (top) and interpreted (bottom) seismic profile across an organized roho system, western Louisiana outer shelf of Gulf of Mexico. Roho reflections were shown along with the detachment for Pliocene–Pleistocene listric growth faults from [24].

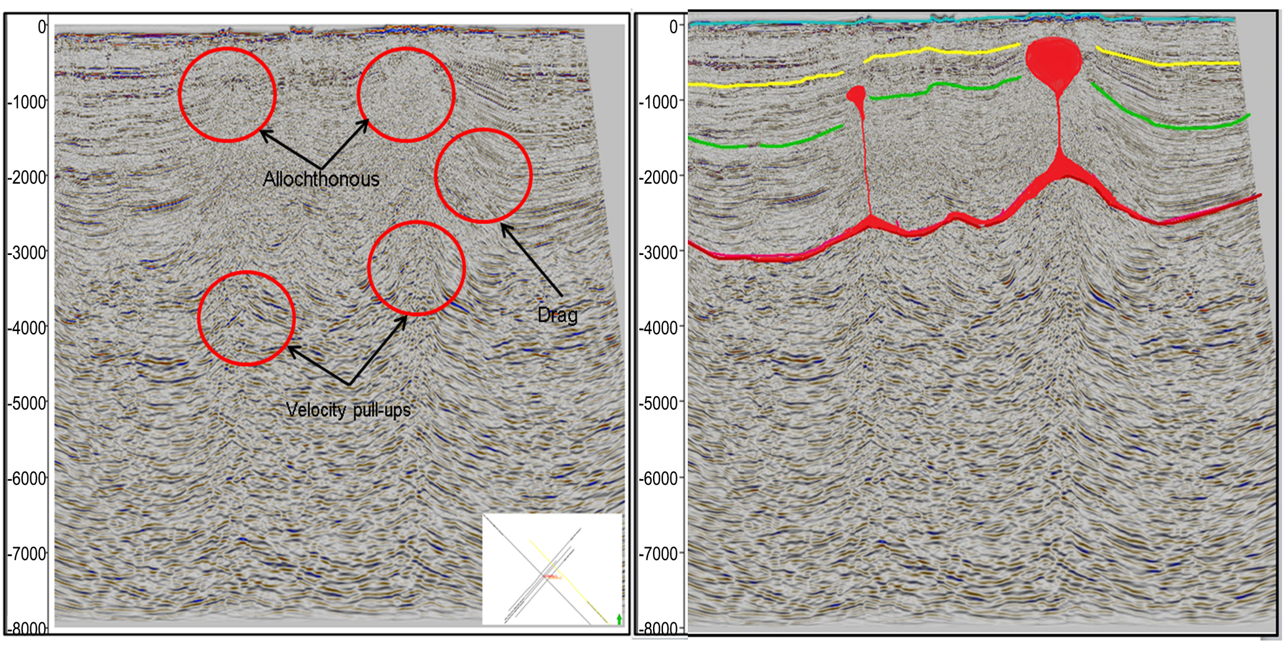


Figure 9. (left) Three observed features of the salt dome (autochthonous), velocity pull-up, is the drag of the sedimentary layers forming a mini-basins, and transparency of the seismic signal in two piercing like bodies. (right) Highlighted seismic interpretation designed for the observed salt behavior.

to adopt this interpretation if additional parallel in-line seismic data are used to confirm the existence of the same salt structure in the study area. A comparison with the previous interpretation done by [26] for the same line (**Figure 11**)

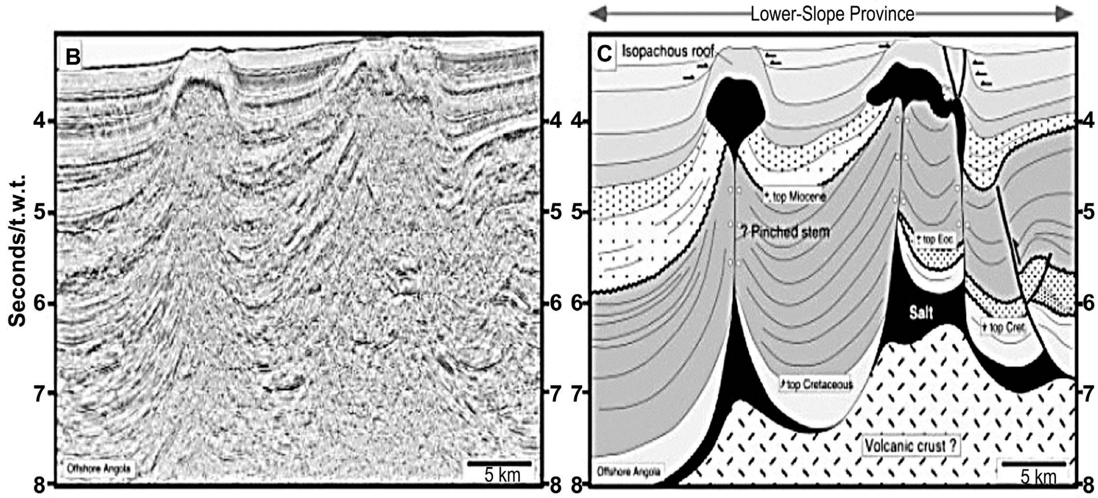


Figure 10. To compare the observed salt structures that are shown in **Figure 9**, both un-interpreted and interpreted seismic profiles from the Angola margin show similar structures of passive salt diapirs and some coalesced into a small canopy [25].

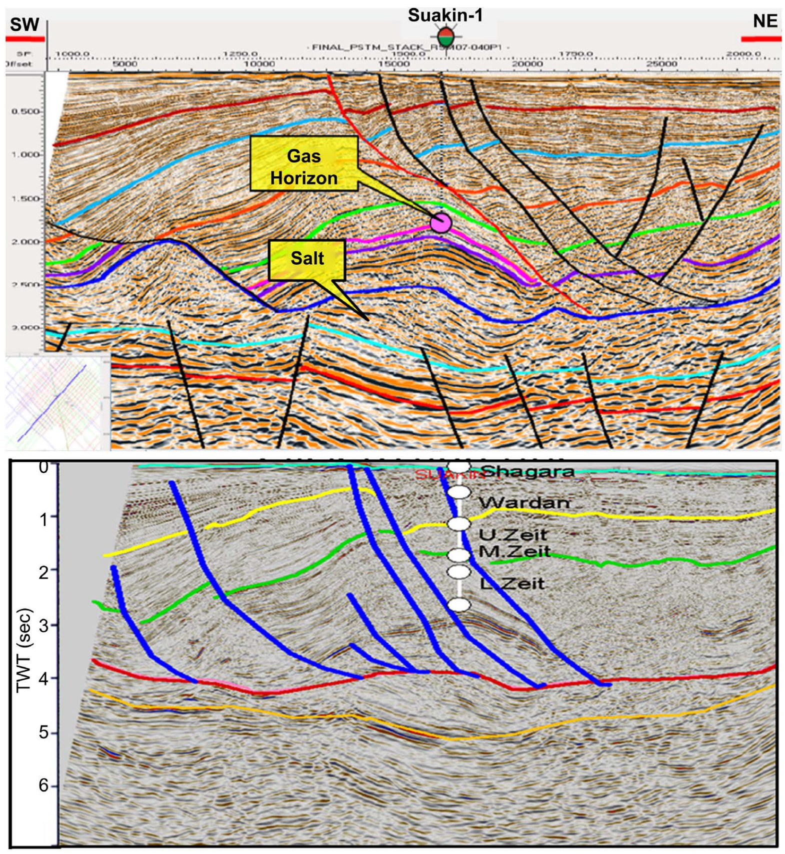


Figure 11. Two different interpretations of the same seismic section cross Suakin-1 and show the main subsurface structure elements. (above): [26] interpretation shows anticlinal (doming) features created by the salt movement of Dungunab formation due to high thermal regimes and sliding of sediments through the listric faults. Compared to (below): the present re-interpretation shows Dungunab salt is delineated as welded and moved east-wards (Red horizon) along the entire sections, while the anticlinal structure is identified by the discontinuous, high-amplitude seismic reflections representing the top of the lower-Zeit formation.

suggested the Dungunab formation as a salt dome structure, while the current interpretation is clarified it is entirely welded and the dome structure represents the top of the lower Zeit formation.

5. Conclusions

The upper-Middle Miocene Salt layer in terms of its structure-dominated tectonics, and movement direction is the main objective of this study. Integration of six seismic lines and two wells, Suakin 1 and 2, is used to re-interpret the seismic data that were no previous studies on that matter thus far to relay on. Despite both wells didn't penetrate fully the salt layer, they confirmed precisely picking the horizons associated with the post-salt formations and overlain the salt layer.

Utilizing the stratigraphy and the seismic characteristics, adding to the logs data, the final interpretation had been matched with salt evacuation (Roho) and salt body structures that are similar to what had been mapped in previous studies of similar stratigraphic conditions in the Gulf of Mexico and Angola margin. The additional comparison shows the inconsistency of interpreting the same data by a national study in 2012 and that they observed the high amplitude horizon of anticlinal shape as the top of Dungunab formations whereas in the current study, this horizon is identified as top of lower Zeit. Thus, to enhance the subsurface imaging and for comprehensive delineation of the salt structures and their flow direction along the Sudanese Red Sea area, a 3D Seismic with a far offset and wide range of azimuth is recommended.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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