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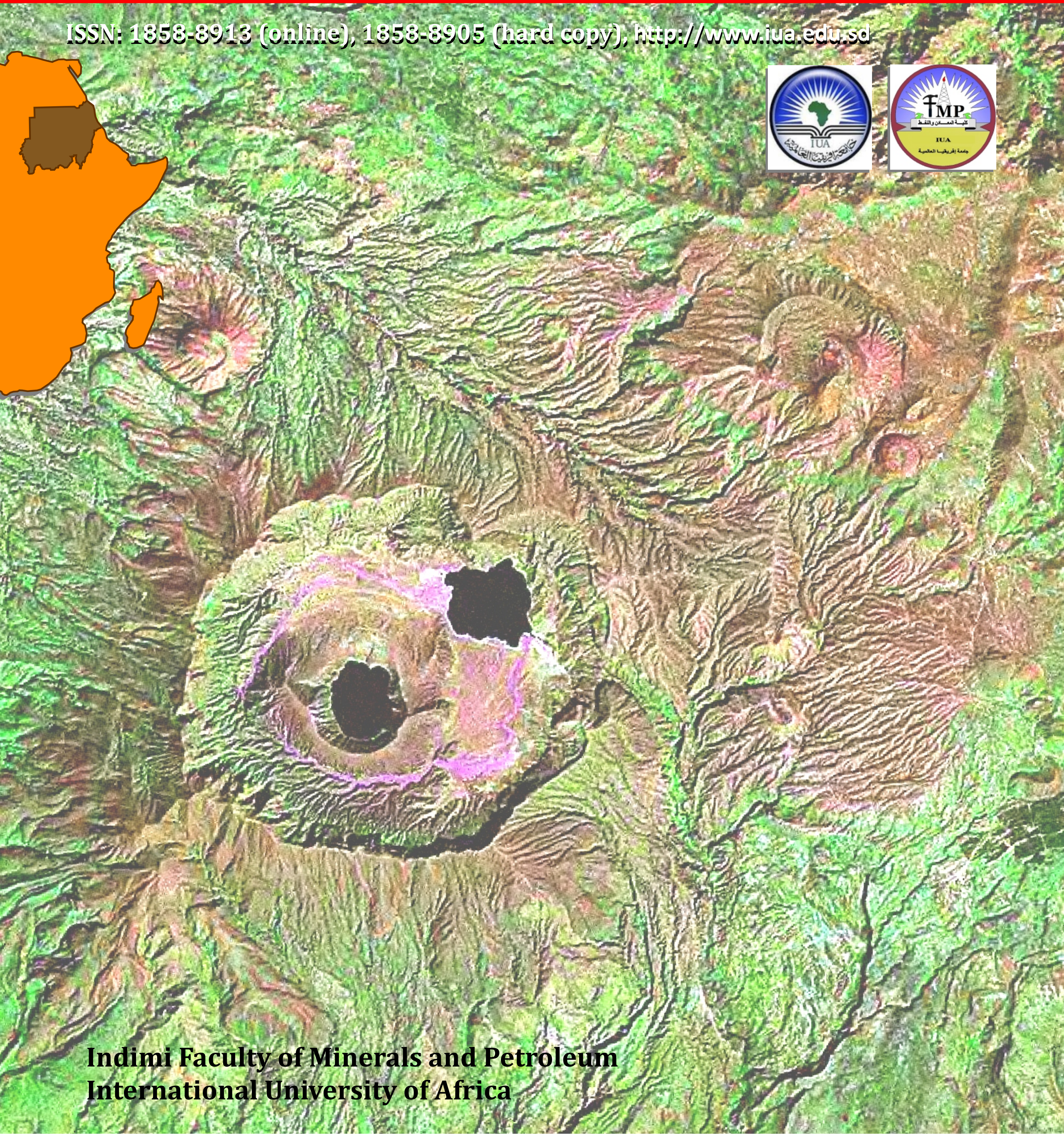

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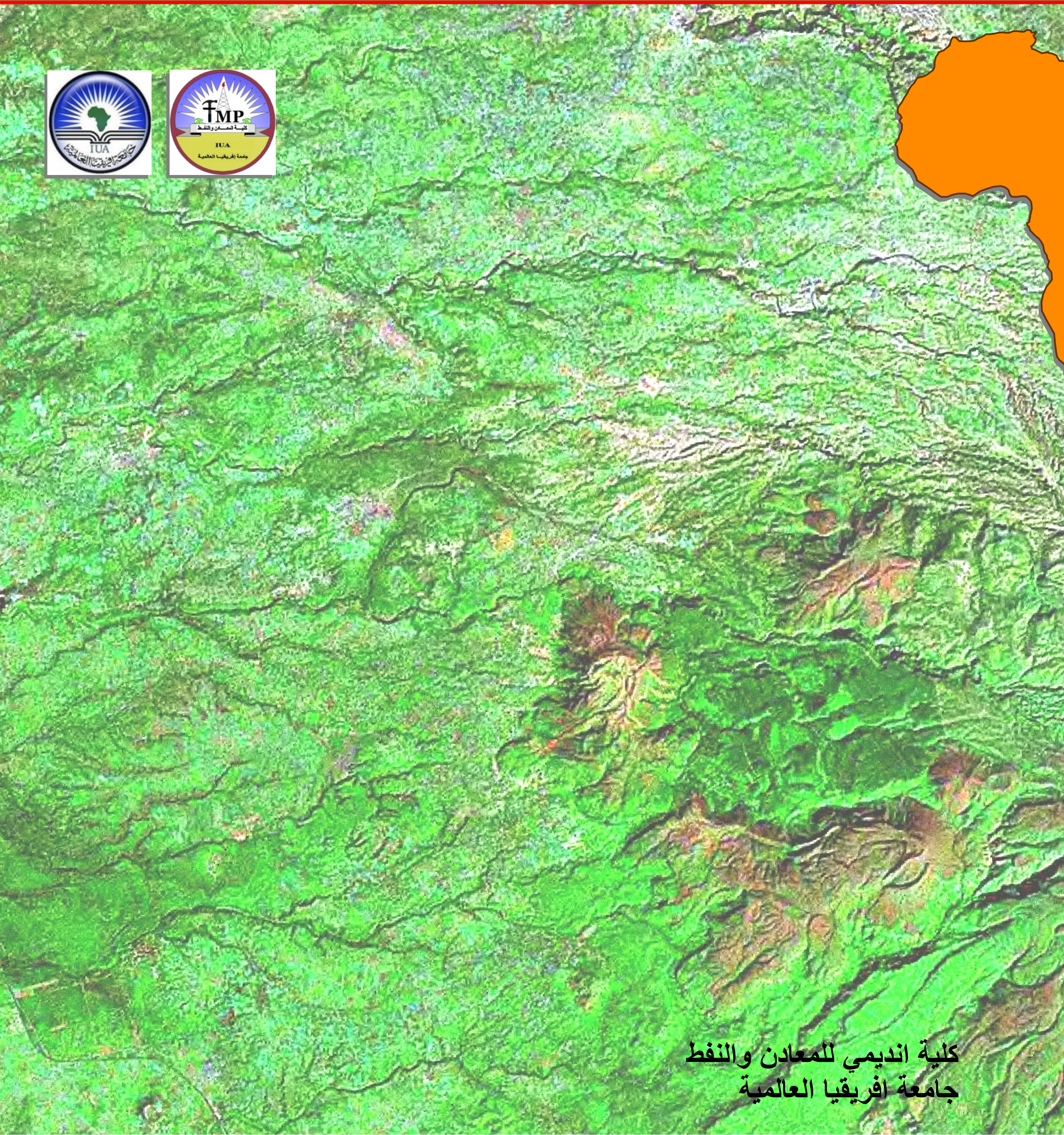

كلية انديمي للمعادن والنفط
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Subsurface Structural Mapping and Hydrocarbon Potentiality Using Seismic Data in Sudanese Red Sea Coastal Plain

Eltayib, S.H.M.[1*], Al-Imam, O.A.O.[2], Abdelrahman, E.M.[3] and Ibrahim, A.S.M.[4]

[1]Dept. of Economic Geology Faculty of Minerals & Petroleum, International University of Africa, Khartoum, Sudan
[2]Dept. of Engineering Geology Faculty of Minerals & Petroleum, International University of Africa, Khartoum, Sudan
[3]Dept. of Mineral Resources, Faculty of Petroleum and Minerals, Al Neelain University Khartoum, Sudan
[4]Oil Fields Researches and Development Administration, Ministry of Petroleum and Minerals, Khartoum, Sudan.

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Abstract

The coastal plain is geologically characterized by Cenozoic siliciclastic and shallow marine rift related sedimentarysequences. Pliocene-Pleistocene is represented by the thick older gravel unit and the emergent linear reef terraces. In this study Petrel Software have been used in seismic interpretation, wells analysis, mapping processing and 2D geological models building of petroleum reservoir environment. The seismic lines interpreted showing time to top basement rocks and depths, time to top of the different sedimentary formations and depths (Hamamit, Rudeis, Kareem, Belayim, Dungunab, Zeit, Wardan and Shagara Formations). Geological structures in the study area are great and deep fault lines. They are mainly normal, reverse, step, graben and horst faults and different salt dome forms. Two main structural regimes are expected for the pre-Miocene salt and post-salt successions. Two main fault systems are noted, normal listric faults trending northwest - southeast, mainly within the Pliocene section and developing gravity sliding structures that include gas and condensate bearing zones in Suakin-1 well, gas in Bashayer-1A well, seismic in Talla-1 and Tokar-1 wells. The ramp - flat listric fault system, a case similar to the post-salt Suakin structures.

Key words: coastal plain, seismic, gas, structures.

1. Introduction

The study areais located in NE Sudan and is situated in the Red Sea State. It isbounded by longitudes 37o 30′ E & 38o 15′ E and latitudes 19o 00′ N & 22o 00′ N. (Fig. 1). A tropical arid climate characterizes the study area. However, the region within which the study area lies has its own peculiarities due to the presence of the Red Sea as an adjacent water body, the Red Sea Hills as an effective physical barrier and the coastal plain as a narrow flat surface (Babikir, 1994). The average temperature is 30oC.It rises up to 46oC during summer (June-September). January is the coldest month during which 23.7ºC is the average temperature (Babikir, 2006). The rain fallof the region is generally low to very low and inconsistent. Two rainy seasons areusually encountered; the first characterizes the coast, starting in October and ends inJanuary,the second lasts July-August and characterizes the high terrainof the Red Sea Hills. Although torrential of season rains are frequent, March-June canbe considered as dry season. The average annual rainfall in the whole region isbetween 100 and 190 mm. The prevailing arid conditions characterizing the region are clearly reflected in the scarce and poorly distributed vegetation cover. Vegetation in the western part of thestudy area is dominated by widely scattered pushes and pannel acacia trees. These trees are confined to the main wadies and their tributaries and to sandy plains. In the coastal plain, in addition to the *acacia* trees, the *leptadiniapyrotechnica dominates*. Moreover, *suaedamonoica* covers extensive areas of the coastal plain. Mangroves are observed growing extensively in some sebkhas of the Red Sea Shore. Geomorphologically, the study area represents part of the high rugged Red Sea Hills terrain, sloping rapidly to the east towards the Red Sea relatively and gently to the west towards the Nile. J. Erba represents the highest peak (2150m) in the study area. This high terrain is an integral part of the upper Eocene uplift of the African-Arabian swell (Eltayib, 2016). This swell was later divided by the East African Rift system into an eastern Arabian and a western Nubian part. The Red Sea Hills terrain is intensively dissected by a complex drainage network. The dominating drainage systems are highly controlled by the prevailing structural elements of the region. Other physiographic features of the area include the coastal strip and the Red Sea.The main physiographic features in the study area which can be considered are the Red Sea Hills in the west and coastal plain in the est. Generally, high elevation in the west and gradually decreases towards the east. Red Sea Hills are classified as a rugged area with high variation in elevation while coastal plain is smooth and level, without raised or hollow areas (Babikir, 1994). The study area is completely depending on drainage system to provide safe water through Khors and Wadies. The annual average rainfall is between 100 and 190 mm. As the drainage system is structurally controlled, the most of khors and wadis are occupied areas of faults, fractures and joints (Babikir, 1994; Basu et al., 1975). Regarding the general topography, the surface water is divided by water shad line to the east. According to the little amount of an annual rainfall and with short season, besides the highly salty soil in coastal area and no perennial streams are known to exist, poor vegetation cover has to be considered. However, bushes and small trees are scattered grown in the wadies (Adams et al., 1995; Fig. 1).

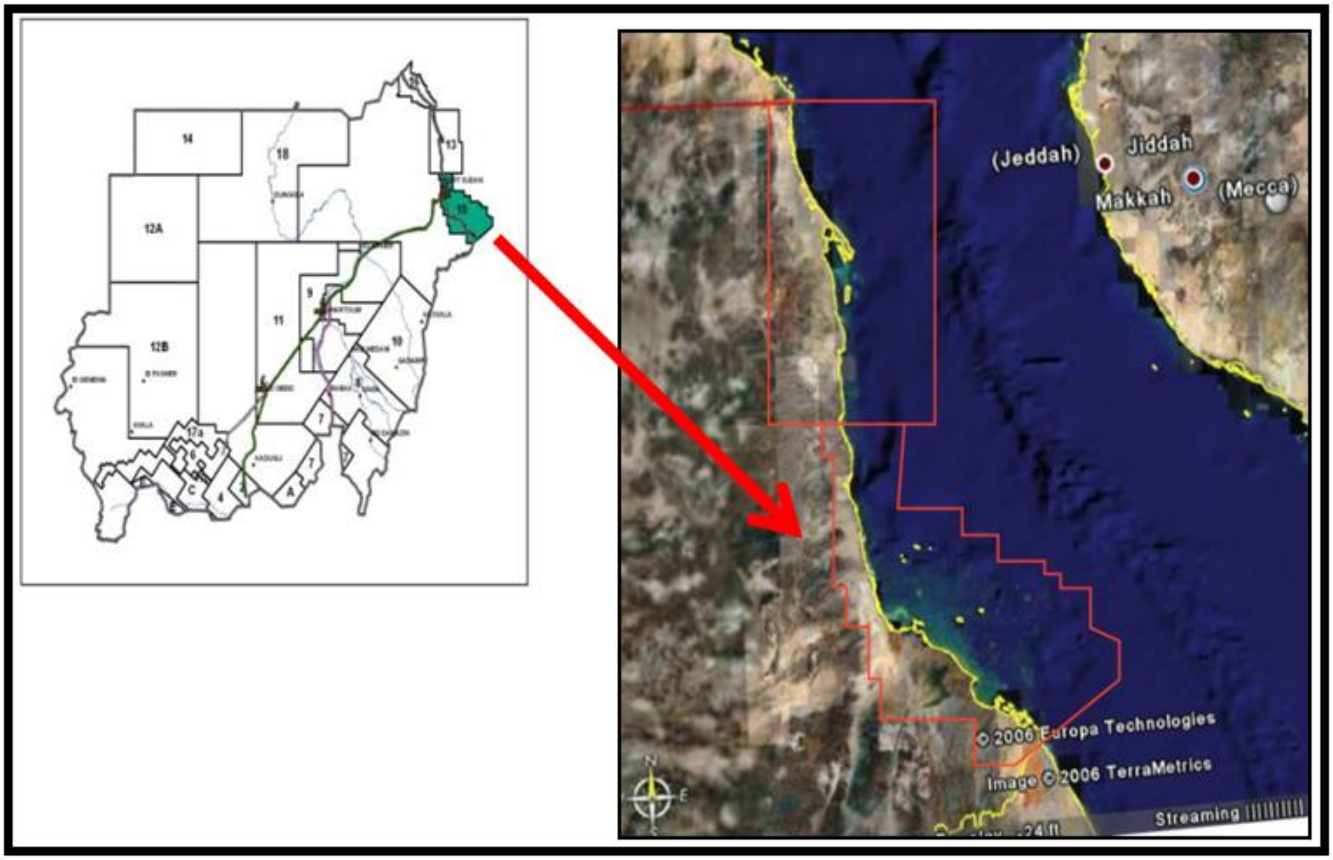

Fig. 1. Location Map of the study area.

2. General Stratigraphy

The stratigraphy of the study area is constituted by the following lithological units from bottom to top (Eltayib, 2016):

(A) Basement Complex: The igneous rocks in Digna-1 well are mainly undeformed but metamorphosed intermediate to basic igneous rocks (lower ampibolite facies). The Basement has been also reached in Durwara-2 well.

(B) Kareem Formation: It is mainly defined in Durwara-2 well represented by sandstone and shale with a thickness of about 542m. The section unconformably overlies metamorphic Basement rocks.

(C) Belayim Formation: It is encountered only in two wells in the studyarea, Durwara-2 and Digna-1 wells with different facies. In the Durwara-2 well, the Belayim Formation is represented by sandstone and shale at the top and two main anhydrite beds at the bottom separated by shale interbeds. It has a thickness of 527m. The lithology changes to mainly carbonate facies intercalated with thin anhydrite and shale beds in well Digna-1 well with a thickness of 429m, dated as undifferentiated Belayim-Kareem.

(D) Dungunab Formation: It is composed of a very thick sequence of evaporites (rock salt and anhydrite) with thin beds of shales. The thickness ranges from 300-900m. The Dungunab Formation is represented in the study area by massive salt section ranging in thickness from 300m in Digna-1 to about 870m in Durwara-2 well.

(E) Zeit Formation: Top of the Zeit Formation is defined based on the first thick anhydrite bed. It is represented mainly by rapid intercalations between clastics (shale and sandstone) and evaporites (salt and anhydrite). The average thickness of Zeit Formation is 1800-1900m.

(F) Wardan Formation: It is dominated by sandstones, shales with siltstone, thin carbonate interbeds, and evaporite streaks. The thickness of Wardan Formation ranges between 410-1140m.

(G) Shagara Formation: It is represented by mixed lithotypes consisting of marine sand/sandstone section intercalated with claystone, partially with thin streaks of dolomite, anhydrite and limestone. The thickness of Shagara Formation ranges between 217-1240m.

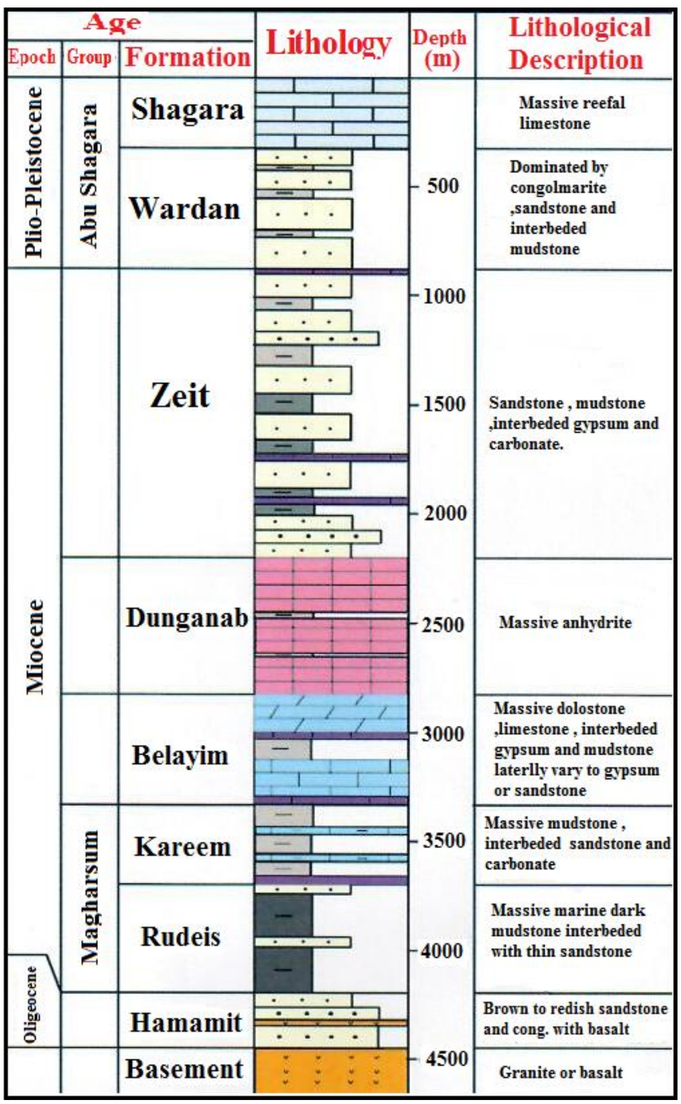

Fig 2. General stratigraphic column of the study area.

3. Objectives

The main objective of this study is mapping of sub surface formations succession, structural evolution and hydrocarbon potentiality in the Red Sea Basinare the main objectives of the study.

4. Methodology

Approximately 6000 km of 2D seismic lines were used to evaluate the accumulation beneath the offshore shallow water and onshore portions of coastal area. This study represents the newly acquired 2D seismic vintage in 2007 (3768 km), PSDM/PSTM reprocessed data (912 KM), the 2008 2D seismic vintage (484 km), part of the 1992 2D seismic vintage (616 km) and with the use of some Lines from SD80 2D seismic vintage and older surveys (210Km). Petrel software that was used in seismic interpretation, wells analysis, mapping processing and 2D geological models building of petroleum reservoirs.

5. Results and Discussion

5.1 Structural Analysis

A set of geoseismic cross sections are constructed to illustrate the subsurface structural features ofthe study area (Fig. 2, 3). The area includes two main structural regimes for the pre-Miocene salt and post salt successions. Two main fault systems are noted, normal listric faults trending northwest- southeast, mainly within the Pliocene section, developing gravitysliding structures that include gas and condensate bearing zones in Suakin-1 well and gas inBashayer-1A well (Fig. 2). Similar features are demonstrated for Talla, Tokar and Tamr plays which are salt related structures.NNE-SSW faults are noted west of Suakin area which might be associated with the development of the Tokar Delta during the drifting stage in Pliocene time. North of the area, north -South fault trends are noticed that are partially parallel to the northern coastal line. At Suakin - Talla structure, ENE-WSW structural trend is illustrated which is also associatedwith gravity high. Cross faults are assumed to be developed during the initiation of the axial trough ofthe Red Sea in the Pliocene time. The effect of these elements is demonstrated by the bendingof faults following the Tokar Delta, change of the shore line direction as well as east andnorth borders of the Delta.The pre-Miocene salt succession is being affected by a series of normal faultstrending northwest - southeast (Clysmic trend) and developing NW-SE tilted fault and horstblocks. Imaging of the pre-Miocene salt section is speculative due to the poor quality of the2D seismic data. These faults are partially extended to the shallow water Pliocene sedimentsparticularly near to the coastal area as a result of younger tectonic activation.

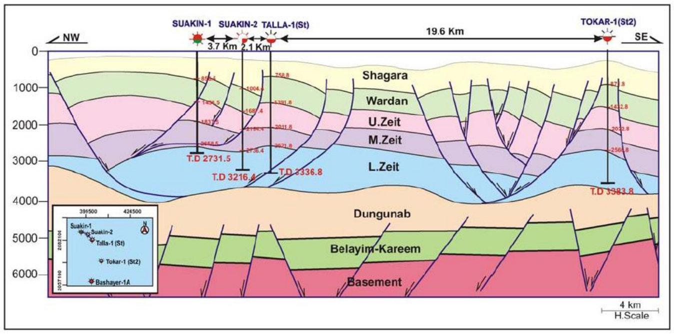

Fig. 3. Structural cross section across Suakin-1, Suakin-2, Talla-1 (St) and Tokar-1 (St2) Wells.

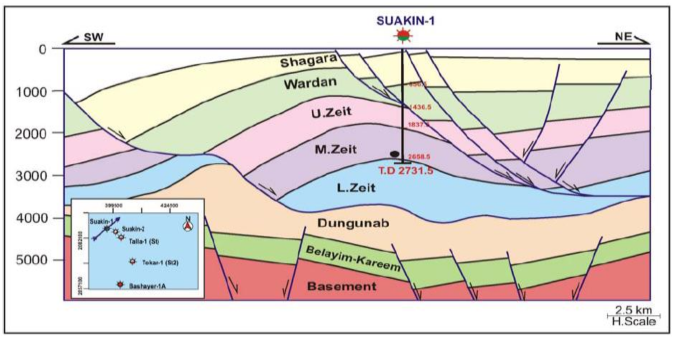

Fig. 4. Structural cross section across Suakin-1 Well.

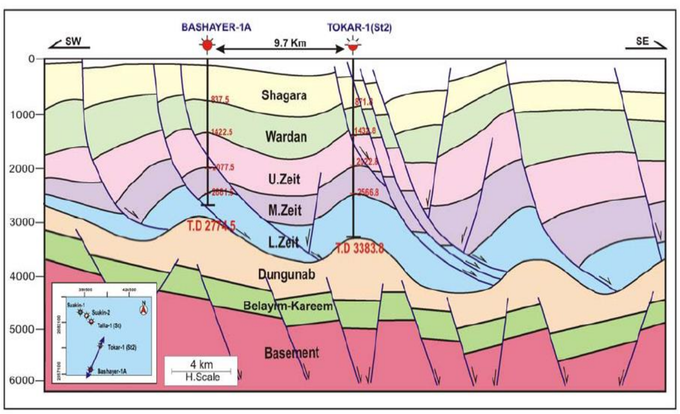

Fig. 5. Structural cross section across Bashayer-1A and Tokar-1 Wells.

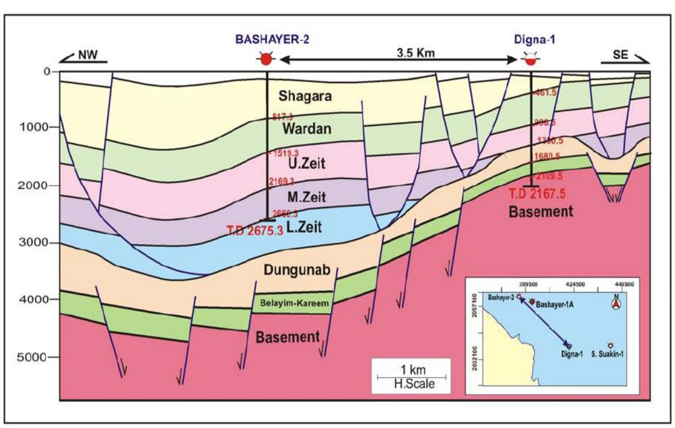

Fig. 6. Structural cross section across Bashayer-2 and Digna-1 Wells.

The pre-Miocene salt succession is being affected by a series of normal faults extending northwest- southeast (Clysmic trend) and developing to rotated faults and horst blocks. These faults are assumed to be initiated during the Red Sea Rifting stage in the Oligo-Miocene time and activated during the Pliocene drift phase of the Red Sea (Eltayib, 2016). The rotated and horst blocks representing the main hydrocarbon play in the Gulf of Suez and the northern Red Sea. Miocene salt tectonics form pillows, dome walls of salts when getting away from the shelf area to the deep water as a result of the high heat influx from the axial trough spreading of the Red Sea and the sedimentary supply from the west rift shoulder during the Pliocene time (Eltayib 2016). Accordingly, Pliocene basinal areas, represented by the Zeit Formation and Wardan clastics are developed between the salt pillow structures that are dominated by listric faults. Near the shelf area, the salt is mostly represented by sheet sedimentation where the pre-salt faults are partly extended to the shallow Pliocene sediments as a result of younger tectonic activity. North- South fault trends are partially parallel to the northern coast line, as a result of older faults activation. Cross faults are assumed to be developed during the initiation of the axial trough of the Red Sea in the Pliocene time. The effect of these elements are evidenced by the bending, change of the shore line direction and north and south bounding faults of the Tokar Delta. The structural style relationship of the study area and to the northern Red Sea of Egypt, Saudi Arabia is illustrated in a series of seismic lines. The same phenomena are encountered in the southern Red Sea of Eritrea. Ten main NW-SE structural elements could be recognized on top of Lower Zeit map as being representative to the offshore area from west to east (Fig4.13) as follows: Near-shore shallow water area with no seismic coverage, Bashayer structural Trend (2700-3200m), Bashayer-S. Suakin Trough (3700-4200m), Tokar Structural Trend (3200-3700m) East Tokar Trough (3700-4700), Suakin-Talla Structural Trend (2700-3200m), North Suakin Trough (3800-4200m), Tamr structural Trend (3700-3800m), Agig Structural Trend (2700-3700m), and eastAgig Trough (3700-4700m). The structural style on the pre-salt for possible Basement map is characterized by a series of NW-SE horsts, tilted, rotated fault blocks and grabens as illustrated in (Fig. 7).

5.2 Seismic Interpretation

The seismic interpretation has been carried out on the 2D seismic lines available ofSD75 and older surveys, IPS92, RSM07 and RSL08 vintages. Eight horizons were picked for the shallow water offshore area as follows: Top Wardan Formation, Top Upper Zeit Formation, Top Middle Zeit, and Gas Reservoir Horizon at Suakin-1 structure, Top Lower Zeit, Top Dungunab Formation, Possible Top Belayim Formation and Possible Top Basement.

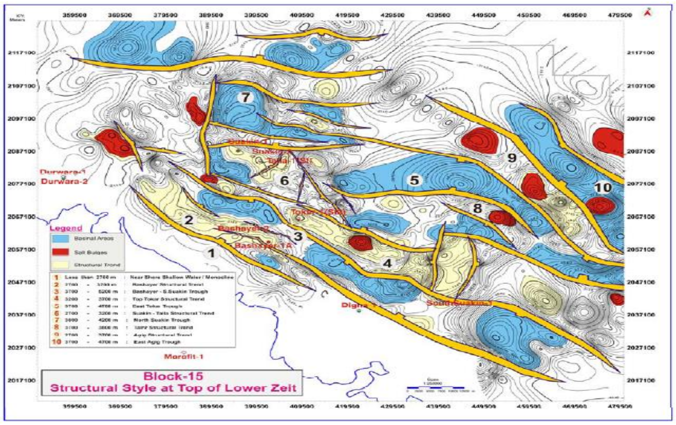

Fig. 7. Structural Map on Top Zeit Formation.

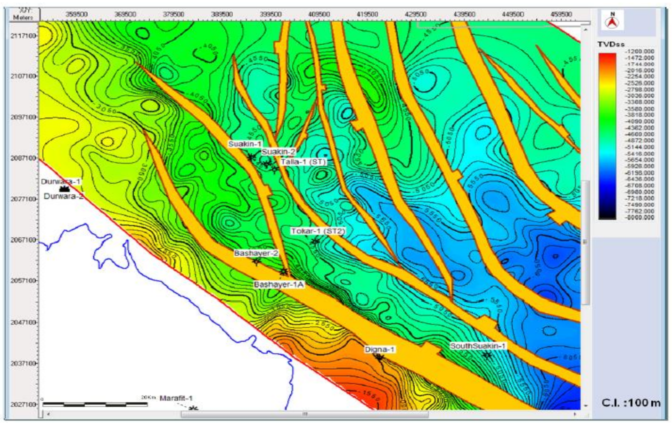

Fig. 8. Structural Map on Top Basement.

The gas reservoir horizon over Suakin-1 well is illustrated on line RSM07-40P1, butit has a limited extension as the reflector is diming away from the Suakin-1 structure. Suakin-1 and Suakin-2 wells are located on the reprocessed seismic dip lines RSM07-040 and RSM07-048. Talla-1 is located on seismic dip line RSM07-052. Bashayer-1Awell is located on the seismic dip line RSM07-071, where the gas horizon is also picked, butnot as clear as in Suakin Area. Bashayer-2 is located on seismic dip line RSM07-007; Tokar-1 well is located on IPS92-006 seismic dip line. Marafit-1 well is located on seismic dip lineRSL08-114 (onshore). The seismic reflectors of the formation tops of those wells were defined from time/depth curves, available velocity and VSP data. The interpreted faults on the different seismic lines were tied and correlated. The faultpolygon for each horizon has been constructed to illustrate the structural setting of the area. It was noticed that the fault trends are characterized by mainly NW-SE (Red Sea fault trend), with some minor E-W fault trends to the north of Suakin structures. The interpretation of the seismic data is considering two separate structural models for post-Dungunab salt and pre-Dungunab Formations. The gravitational and extensional driftingmodel is applied on the post-salt depositional sequence, mainly Zeit, Wardan and Shagara Formations, characterized by the low angle, listric faults, some faults die out within the Zeit Formation, while others smear on top of the Dungunab salt. The extensional rifting model applied for the pre-salt depositional sequences ischaracterized by a series of horsts, tilted, rotated fault blocks and grabens. Deep faults on basement and Belayim levels might extend into the overlying section, particularly near to theshore area where the Dungunab salt might thin or not be present. The Dungunab salt is either sheet like deposition or flow in the form of a series of saltpillows and domes with variable size in different geometry. In some areas, these salt bulgeshave pierced to the sea floor and creates what looks like salt islands.For better correlation of the interpreted seismic horizons, composite seismic tie line(110km), between the drilled wells of Suakin-1, Suakin-2, Talla-1, Tokar-1,Bashayer-1A and Digna-1 has been generated as shown in Figure (11). The line was reprocessedas a Hi Frequency Inverted line across the wells, which have velocity curves as well syntheticseismograms.Selected dip/strike seismic lines across the drilled wells were picked & correlated for theinterpreted horizons as shown in (Fig.11-21)the lines were generated in PSTM & Hi Frequency Inverted PSTM mode.

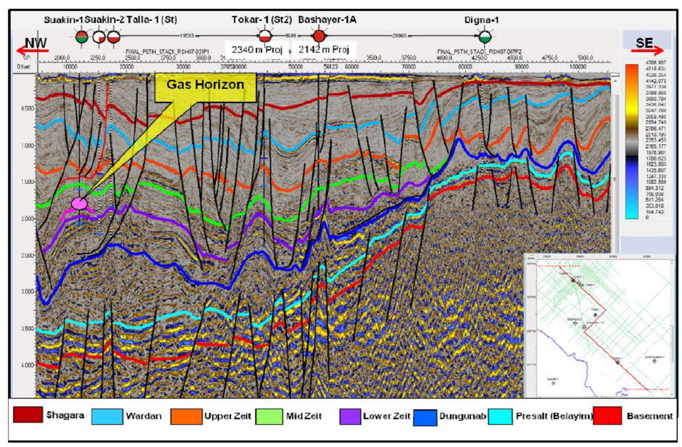

Fig. 9. Arbitrary Hi Frequency Inverted Lines across the Study Area.

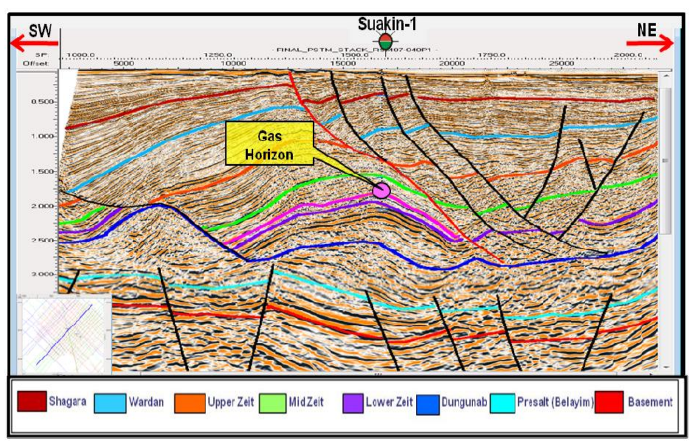

Fig. 10. Seismic Line across Suakin -1 Well.

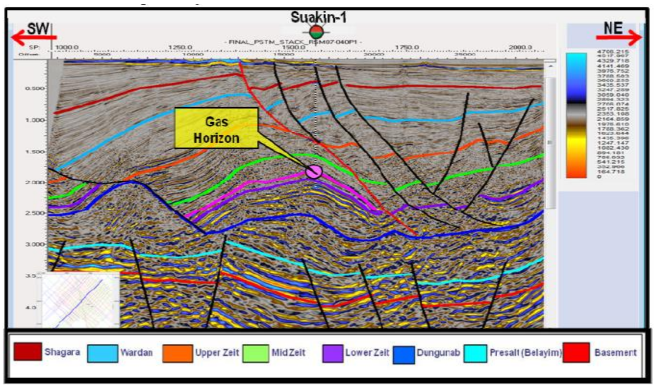

Fig. 11. Hi Frequency Inverted across Suakin -1 Well.

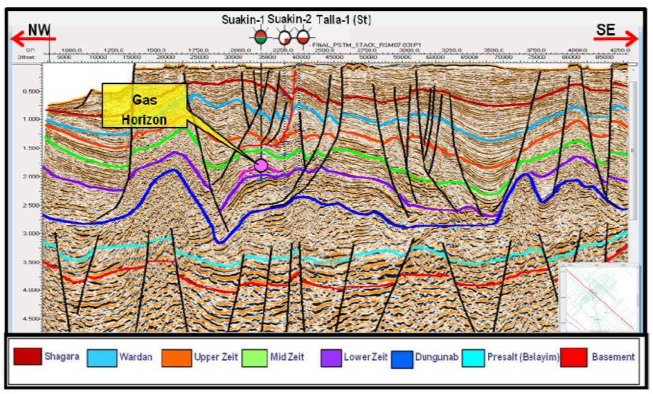

Fig. 12. Seismic Line across Suakin -1, Suakin -2 and Talla -1Wells.

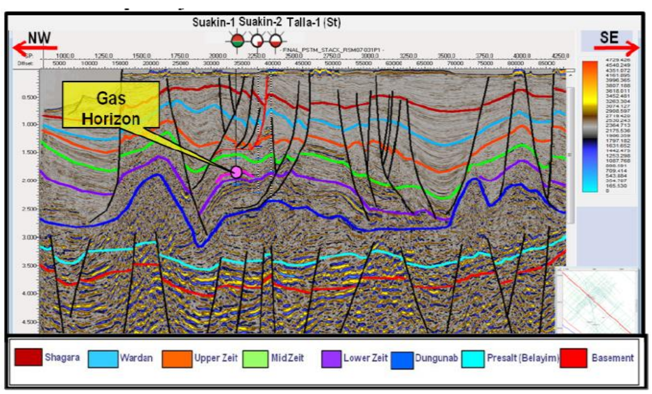

Fig. 13. Hi Frequency Inverted Strike across Suakin-1, Suakin-2 and Talla-1Wells.

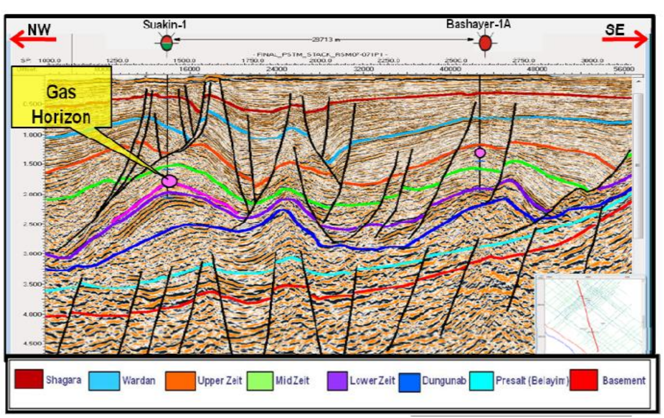

Fig. 14. Seismic line across between Suakin-1 and Bashayer-1A wells.

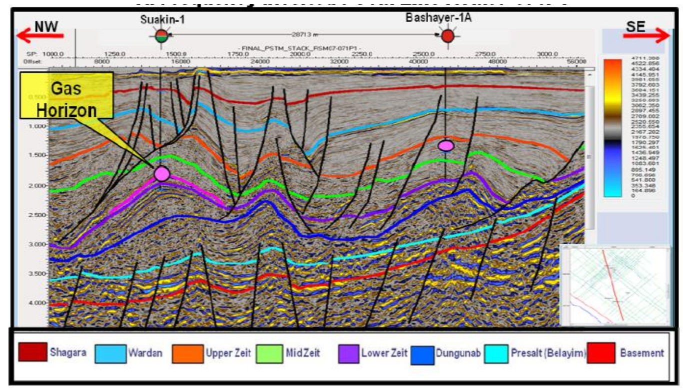

Fig. 15. Hi Frequency Inverted Line Between Suakin -1 and Bashayer-1A wells.

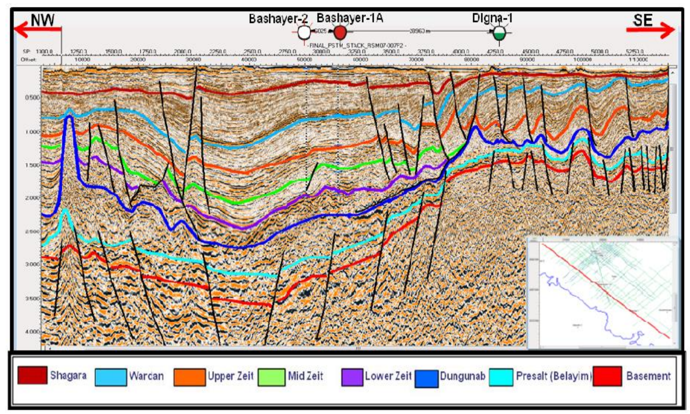

Fig. 16. Seismic line across Between Bashayer-1, 2 and Digna-1 wells.

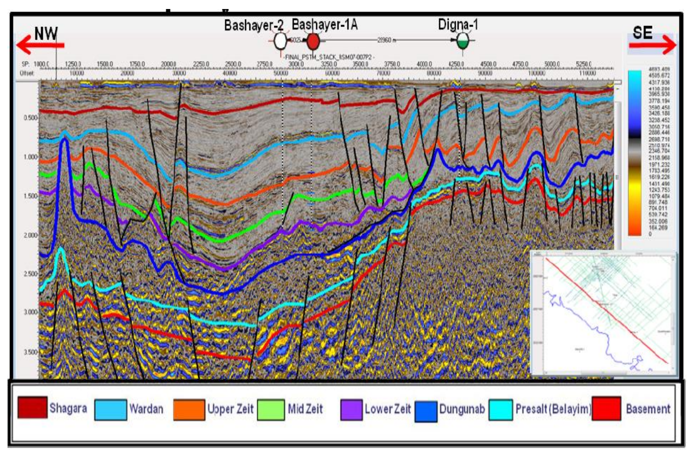

Fig. 17. Hi Frequency Inverted Line Between Bashayer-1, 2 and Digna-1 wells.

The mapping of the Lower Zeit horizon shows the Suakin-Talla as one big structure with culminations at different structural levels which would have merits to be defined by 3D seismic survey. Suakin-2 well appears to be located in a saddle within this structure. The Suakin-1 gas horizon is located at the lower part of the Middle Zeit unit. The Suakin Upper Zeit closure is shifted to the south. The Talla structure is mapped as a closure on Upper, Middle and Lower Zeit horizons. The Tokar structure is still valid on Upper, Middle and Lower Zeit horizons. The East Talla structural high is a SW tilted fault block, mapped on Top Zeit, up-dip of Talla-1well. This structure could be merits if confirmed by 3D seismic data. Several features are mapped in direction of east, north and west of Suakin structure. Other features are developed as trap door structures to the west and up-thrown side from Bashayer-1A well which could be prospective. The Tamr Leads is also mapped down-dip, east of Tokar structure. The Belayim Formation would be deep to about 4.0sec or more. Imaging of Belayim and basement horizons below the Suakin-Talla regional structure are unreliable. However, the interpretation is subject to two scenarios. They show fault block and low structural relief. On the other hand, the definition of the reflectors of the onshore seismic data is made by jump correlation with couple of offshore seismic lines.

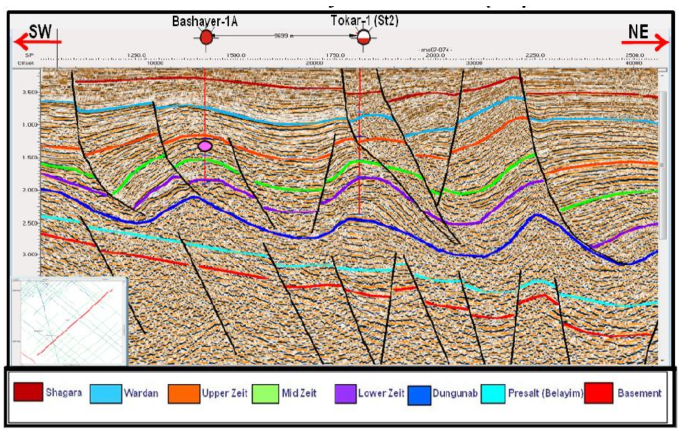

Fig. 18. Seismic line across between Bashayer-1A and Tokar-1 wells.

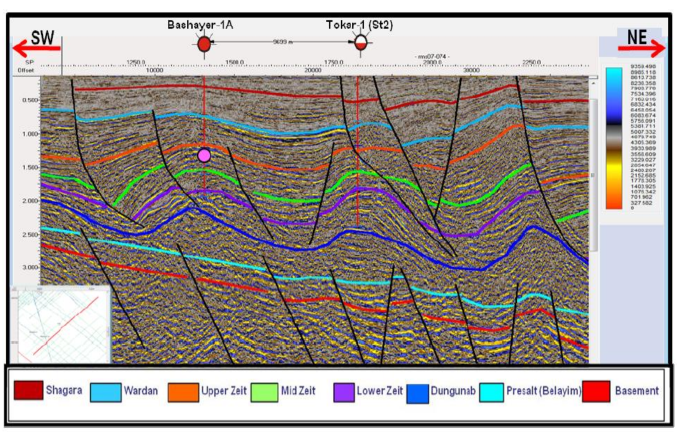

Fig. 19. Hi Frequency Inverted Line Between Bashayer-1A and Tokar-1 wells.

Considering the reported formation tops by RRI in 1988, the strong seismic reflector would be Belayim Formation that overlies a thick Kareem/Rudeis section on top of basement. The second scenario is honoring the seismic onshore to offshore correlation, where in such case this strong reflector would be top Zeit. The underlying section shows an angular unconformity with this horizon. The subdivision of the Zeit section in the onshore area to Upper, Middle and Lower units are not possible. However, a horizon was picked and mapped near the top of this section named as Intra-Upper Zeit Horizon. The onshore Basement horizon is correlated well in both cases with the offshore. At the basement level, a possible lead is shown on one dip seismic line to the east of Marafit-1 well and couple possible leads west to the well (Fig. 20,21) .The mapping also shows a trough to the west of Marafit-1 well which would have merits to act as a hydrocarbon kitchen. It is recommended to acquire more seismic lines around Marafit-1 area to confirm the existence of those leads. For the Onshore area, the following maps were constructed: Top Wardan Formation, Top Zeit Formation, Top Intra-Upper Zeit Horizon and Possible Top Basement.

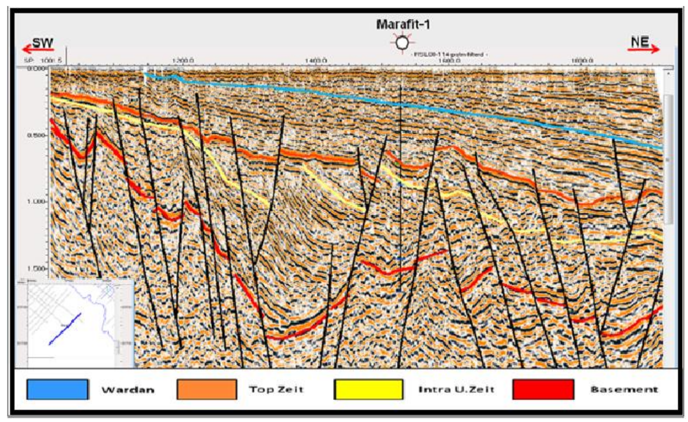

Fig. 20. Seismic Line across Marafit-1 well.

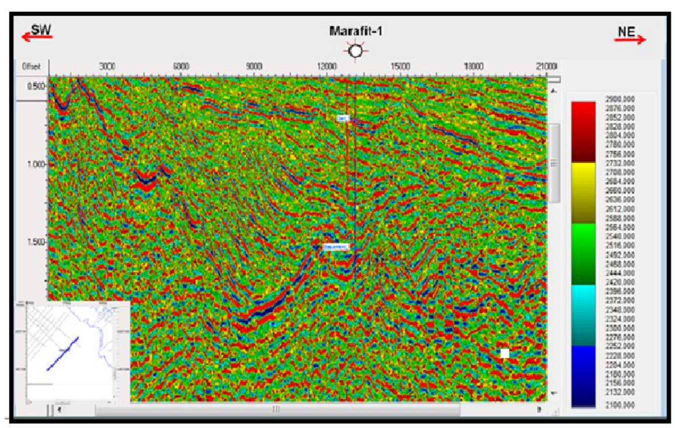

Fig. 21. Hi Frequency Inverted line across Marafit-1 well.

5.3 Time Maps

TWT maps were constructed in the offshore area for seven seismic horizons from Basement upward to Wardan Formation. The contour interval from Wardan down to Lower Zeit unit is 20ms, however from Dungunab salt down to Basement is 50ms. Time and depth maps were created for the following horizons for the shallow water area: Top Wardan Formation, Top Zeit Formation, Top Middle Zeit Unit, Top Gas Reservoir in Suakin-1 Area, Top Lower Zeit Unit, Possible Top Dungunab Formation, Possible Top Belayim Formation and Possible Top Basement. The structural setting of the mapped horizons for the pre-salt horizons, possible Belayim and possible Basement horizons is not conformable with the post-salt structural setting/type. The Belayim& Basement maps illustrates dominotype fault blocks oriented mainly to the NW- SE direction. On the other hand, the Zeit and Wardan maps show 4-way & 3-way dip closures on gravitational listric faults with variable amplitudes from the Upper Zeit down to Lower Zeit units. The time maps of the Zeit units confirm the structural closure of the Suakin-1 and Bashayer-1A discoveries. It shows the Talla-1 well is being located on a closure for top Upper Zeit, Middle Zeit and Lower Zeit. The closure of the Tokar well is also confirmed on the three levels. Other structures are identified to be subject for further exploration. Several troughs are mapped within the Zeit section that could act as hydrocarbon kitchen areas, as North Suakin, East Bashayer, East Tokar, and SE Suakin.

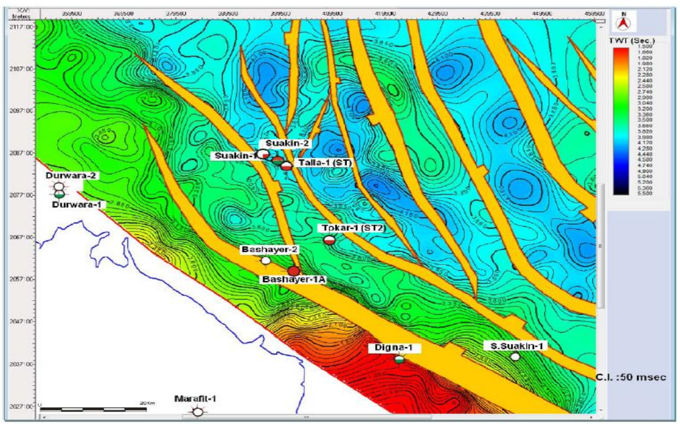

Fig. 22. Top Basement TWT Map Offshore Area.

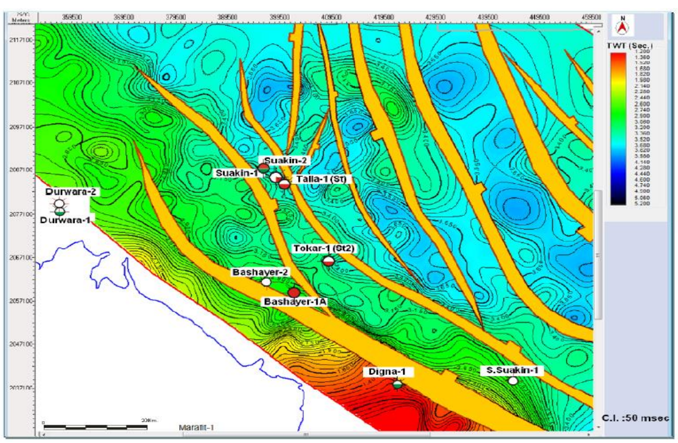

Fig. 23. Top Pre- Salt (Belayim) TWT Map Offshore Area.

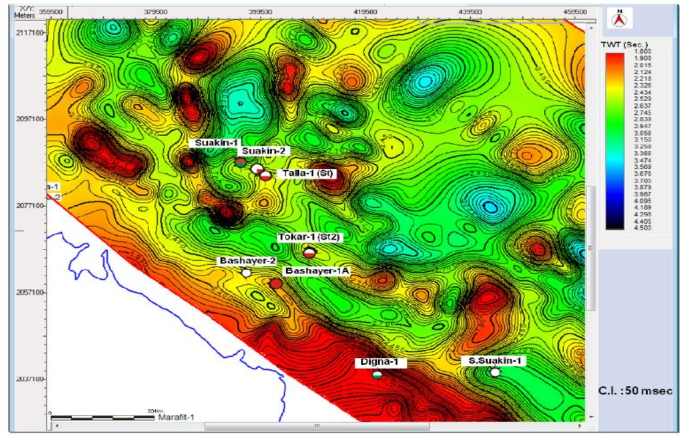

Fig. 24. Top Dungunab Salt TWT Map Offshore Area.

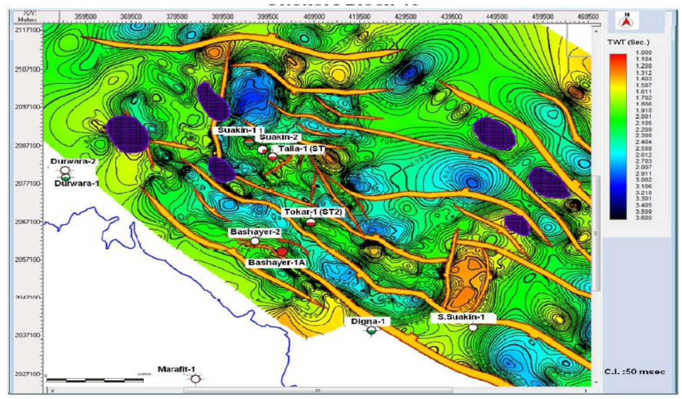

Fig. 25. Top Lower Zeit TWT Map Offshore Area.

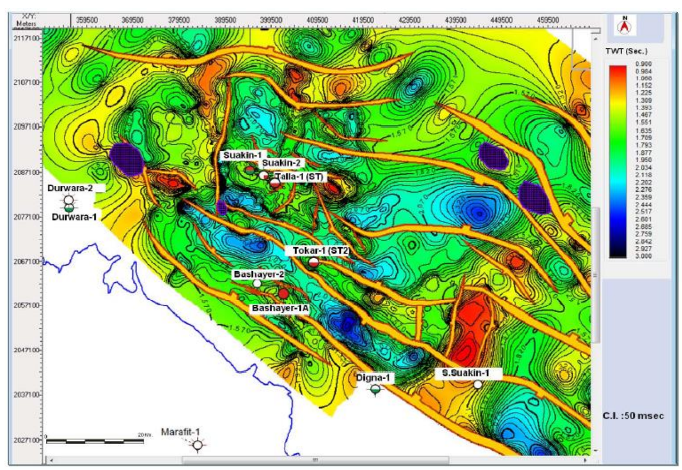

Fig. 26. Top Middle Zeit TWT Map Offshore Area.

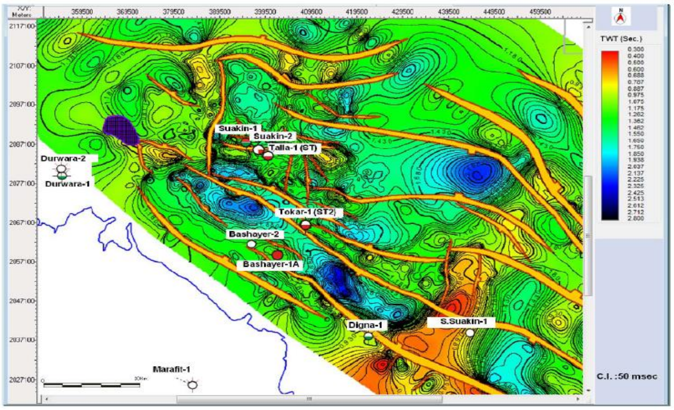

Fig. 27. Top Upper Zeit TWT Map Offshore Area.

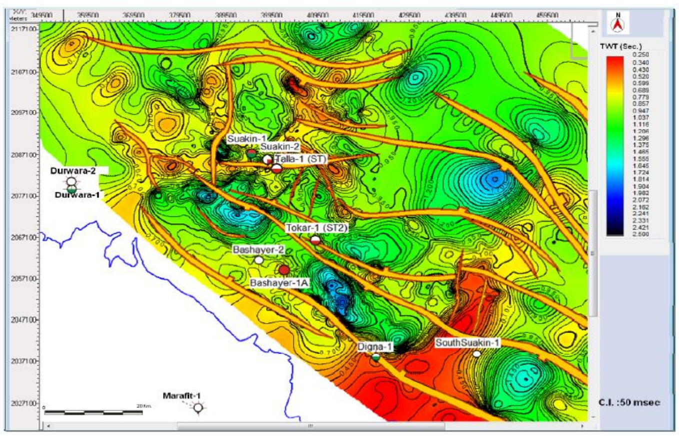

Fig. 28. Top Wardan TWT Map Offshore Area.

5.4 Depth Maps

Time to depth conversion for all the mapped horizon was done by using the averagevelocity created by the available stacking velocity data around well Marafit-1.In general, the top Zeit and Basement maps show a series of NW-SE faults stepping downfrom west to east towards the basinal area to the east.The Basement map shows the Marafit-1 wells was drilled on a down-step fault block of anintra-basinal high, where the uplifted block is the east. However, this feature is onlyillustrated on one seismic dip line (RSL08-114). The nearest line is 6Km to the north. On the Zeit level, there is also a horst feature based on one dip seismic line RSL08-114 to thenorthwest of Marafit-1 well as shown (Fig. 32) two other features were mapped on the West of Marafit-1 well, one of which is present onboth Basement and Intra-upper Zeit horizons, the other is just available on the Intra-upper Zeit Horizon.

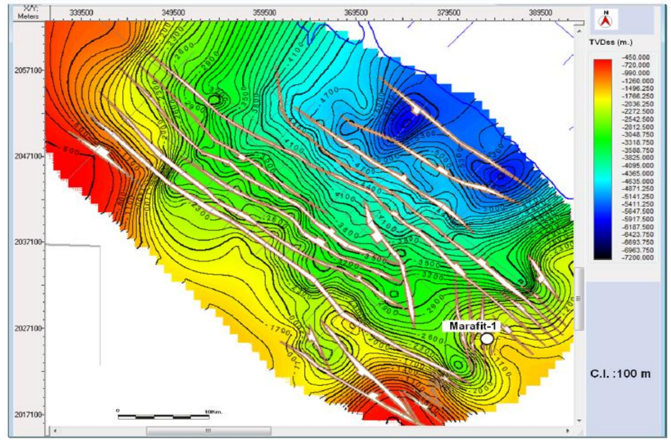

Fig. 29. Top Basement Depth Map.

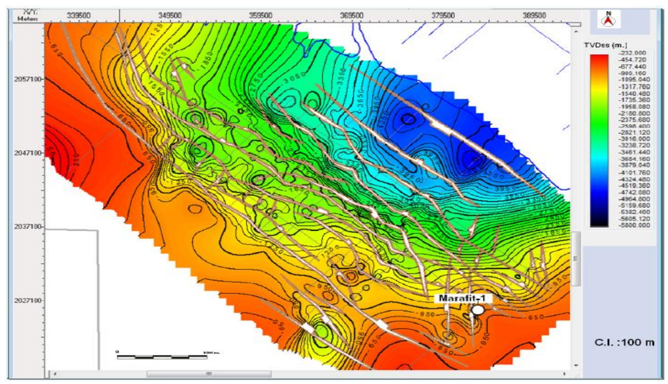

Fig. 30. Top Intra Upper Zeit Depth Map.

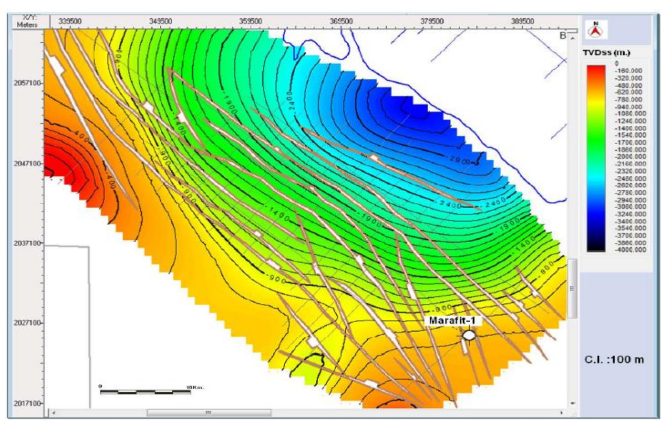

Fig. 31. Top Zeit Depth Map.

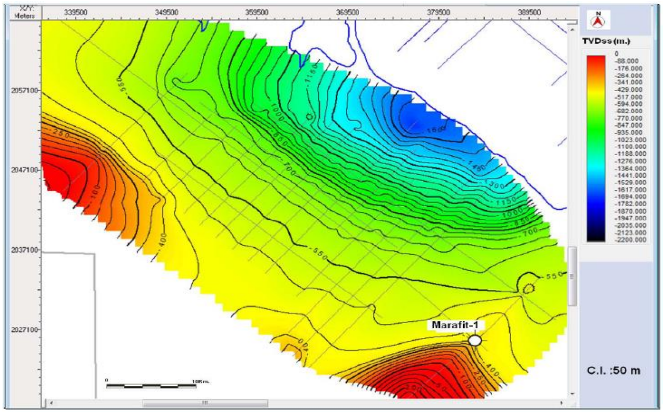

Fig. 32. Top Wardan Depth Map.

5.5 Isopach Maps

A set of regional isopach maps was constructed from the depth maps between the following horizons: Pre-salt (Belayim) and Top Basement, Top Upper Zeit & Top Dungunab, Top Lower Zeit & Top Dungunab, Top Middle Zeit & Top Lower Zeit, Top Upper Zeit & Top Middle Zeitand Top Wardan & Top Upper Zeit.

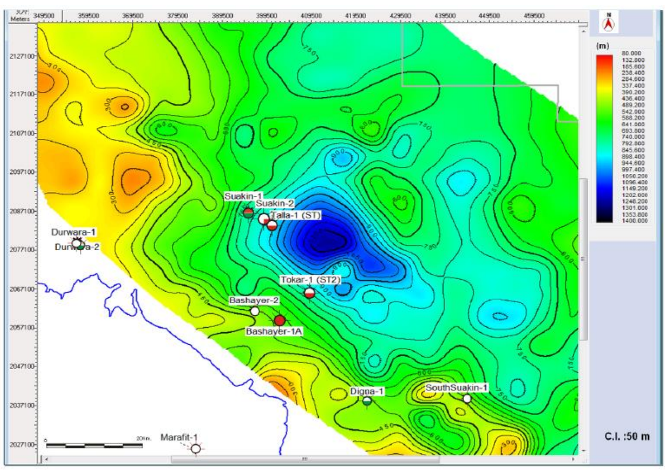

Fig. 33. Isopach map of pre-salt (Belayim) Formation.

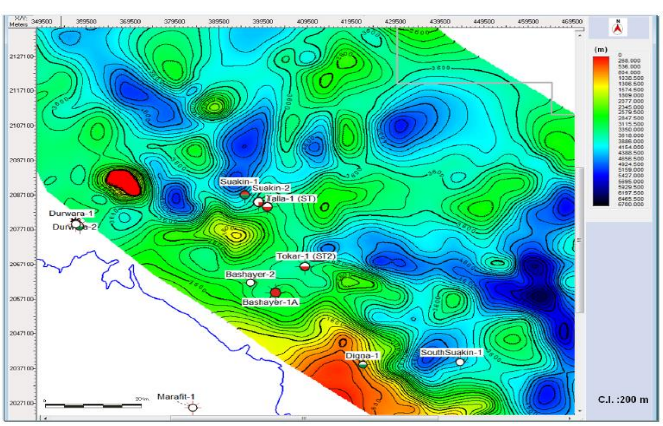

Fig. 34. Isopach map of Total Zeit Formation.

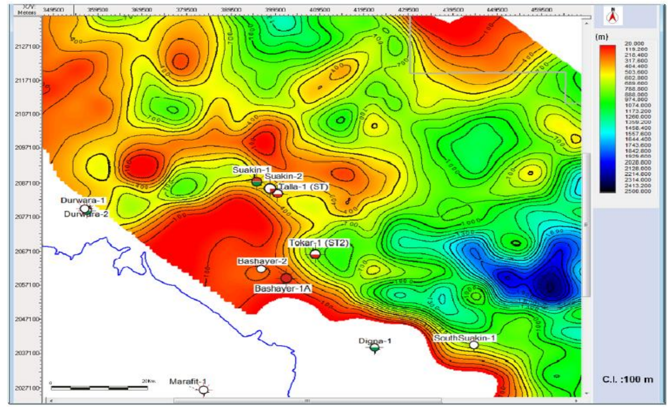

Fig. 35. Isopach map of Lower Zeit Formation.

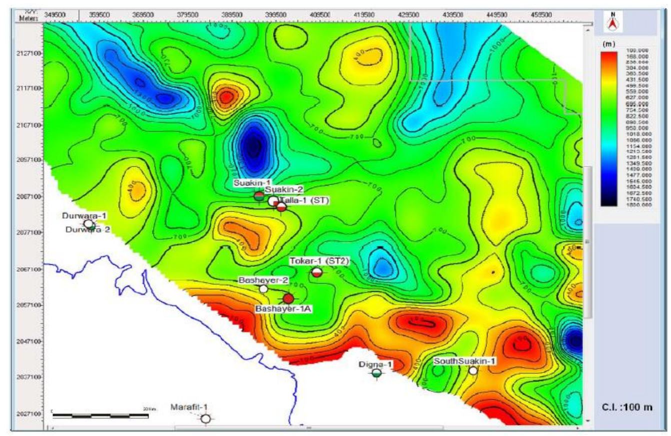

Fig. 36. Isopach map of Middle Zeit Formation.

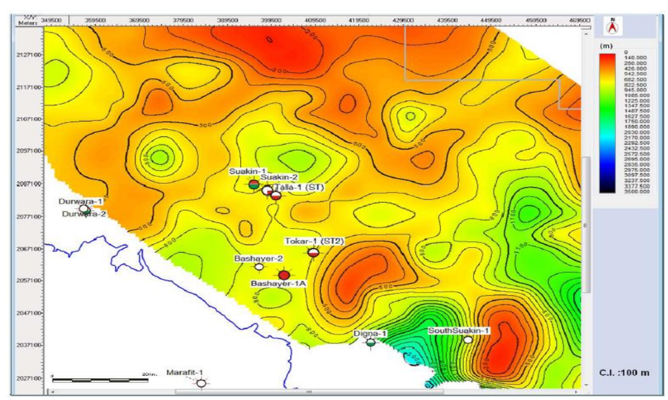

Fig. 37. Isopach map of Upper Zeit Formation.

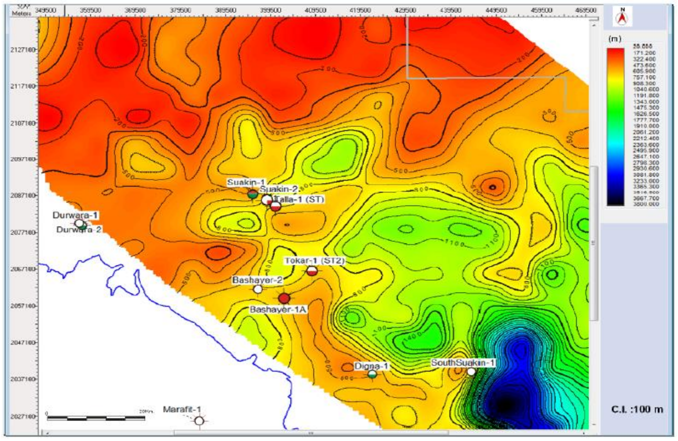

Fig. 38. Isopach map of Wardan Formation.

6. Conclusions and Recommendations

The seismic lines interpreted showing time to top basement rocks and depths, time to top of the different sedimentary formations and depths (Hamamit, Rudeis, Kareem, Belayim, Dungunab, Zeit, Wardan and Shagara Formations). Geological structures in the study area are great and deep fault lines. They are mainly normal, reverse, step, graben and horst faults and different salt forms. The study area its potential for gas and condensate exploration and/or development of existing discoveries particularly Suakin-1. However, it is recommended to acquire 3D seismic surveys on the defined discoveries, prospects or leads before any further drilling in the area.

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