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Petroleum system characterization of the northeastern edge of the Termit Basin, eastern Niger: The case of the Boul prospect

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ABSTRACT: Since the discovery of the first oil showings in the Tamesna sub-basin (north-western Niger) in the 1960s, several oil exploration campaigns have been undertaken in the other Niger basins. These are Eastern Niger and Djado basins.
From 2008 onwards, continued oil exploration led to the development of the Goumeri, Sokor and Agadi fields. Thanks to new economically profitable discoveries, Niger has been exporting crude oil since 2024. However, challenges remain, requiring in-depth geological and geophysical studies to increase reserves. Indeed, the Boul-1D well, drilled in 2016 in the Boul prospect on the Bilma block, revealed no hydrocarbons despite promising indications observed during drilling. This lack of productivity is all the more surprising given that the area was covered by a 3D seismic survey and lies in close proximity to the productive Gabobl-1D well. To better understand the reasons for the non-productivity, investigations were carried out to determine the characteristics of the petroleum system at the northeastern end of the Termit Basin, focusing on the Boul prospect, and using seismic and logging data in particular.
Three software packages were used to carry out these investigations. GeoEast was used to analyze seismic data, Techlog to study logging data and Petrel to correlate well data. To deepen the investigations, sample analyses (cuttings and cores) and pressure tests (RFT) were carried out to better identify reservoir levels. An in-depth analysis was then carried out to understand the reasons for the non-productivity of the Boul-1D well, and to determine the key factors for successful drilling in the study area. This study shows that lateral sealing is the main cause of drilling failure in exploration activities in the northeastern part of the Termit Basin. This lateral sealing is the first important factor to which more attention needs to be paid. The phenomenon of hydrocarbon dissipation in the Madama formation is the second factor to be closely monitored when evaluating prospects in this area.

KEYWORDS: Termit basin, Boul prospect, Boul well, non-productivity, lateral sealing, hydrocarbon dissipation.

1 INTRODUCTION

Oil exploration in Niger in the 1960s led to the discovery of the first oil shows in the Tamesna sub-basin (northwestern Niger) (Ministry of Petroleum, Niger). Since then, several oil exploration campaigns have been systematically undertaken in Niger's Iullemmeden, Eastern Niger and Djado basins. Exploration activities include: airborne geophysical surveys (gravimetry and magnetism), seismic reflection, ground geophysical surveys and exploration drilling.

From 2008 onwards, the signing of the production sharing contract with new partner CNPC-NP enabled exploration activities to be stepped up. This led to the development of 3 deposits under the Agadem Phase I contract: Goumeri, Sokor and Agadi. The start-up of these 3 fields in 2011 enabled Niger to join the club of countries not only producing, but also refining oil in Zinder region, with a capacity of 20,000 barrels/day).

Following these initial encouraging results (Agadem phase I), numerous projects undertaken by the operator CNPC-NP led to the discovery of new oil and gas deposits (Gololo, Dougoule, Faringa, Koulélé, Dibeilla, Fana, Tiori, Arianga, etc.), which are technically and economically profitable to exploit. This led to the signing of a second operating contract (Agadem Phase II) in 2018. Since then, Niger has achieved self-sufficiency in refined products, in partnership with China, and began exporting crude oil internationally in 2024, via the Niger-Benin pipeline to the Semé-Kpodji oil terminal.

Despite the above-mentioned discoveries, many challenges remain, particularly with regard to increasing and developing reserves. To meet these challenges, more in-depth geological studies and consequent geophysical research must be undertaken. This will enable to better select the target areas for drilling, so as to remove any ambiguity between areas with high hydrocarbon potential and those without.

For example, a total absence of hydrocarbons has been observed in some well production tests. This is the case of the Boul 1D well, which was drilled in 2016, in the Boul prospect. It is located between the Gabobl-1D well to the east and the Madama E-1D well to the west (Figs. 1 and 2). The Boul prospect, belonging to the Bilma block, is located in the western part of the Araga graben (Fig. 2) and to the northeast of the Gabobl-1D structure. This prospect is covered by the Gabobl-Boul 3D seismic survey.

The non-productivity of the Boul-1D well appears surprising, given the numerous hydrocarbon showings highlighted by the logging data (instantaneous and delayed).

In order to better understand the petroleum system of the Boul-1D well, investigations were carried out in the Boul prospect, where the dry drilling of the Boul-1D well was recorded. With this in mind, this contribution focuses investigations on the theme "**Characterization of the petroleum system of the northeastern end of the Termit Basin: case of the Boul prospect (Termit Basin, eastern Niger)**".

The main objective of this contribution is to analyze the factors responsible for the non-productivity of the Boul-1D well.

Specifically, it aims to:

- Describe the geological and geophysical characteristics of the Boul prospect;
- Identify factors favoring well productivity, as well as their non-productivity in the study area;
- Determine parameters contributing to drilling success.

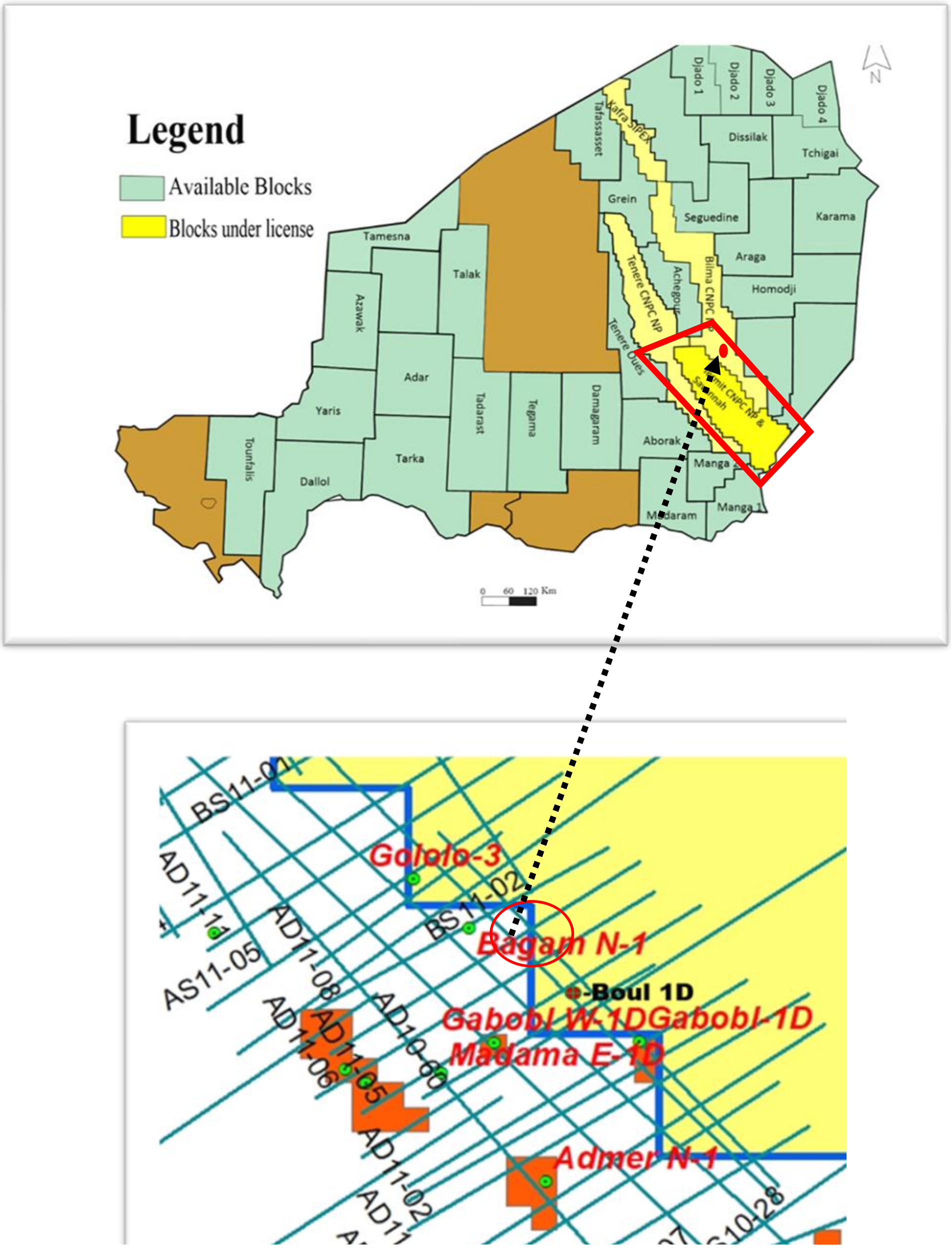

Fig. 1. Location of the Boul prospect in the Bilma Block. The red box indicates the location of the Termit Basin (Ministry of Petroleum, Niger, 2017)

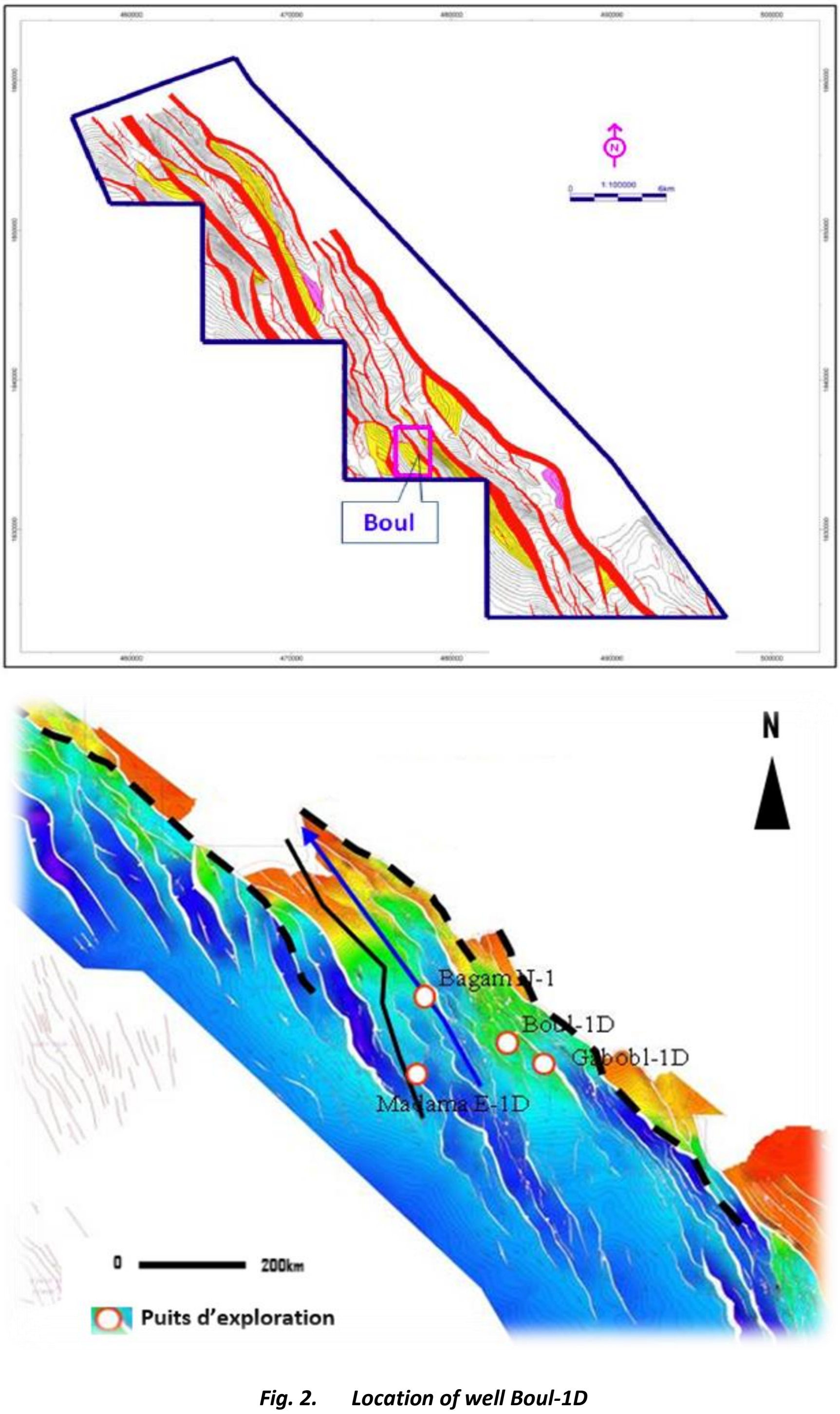

***Fig. 2.** Location of well Boul-1D*

2 GEOLOGICAL CONTEXT OF THE STUDY AREA

Located in eastern Niger, the NW-SE trending Termit basin is part of a set of Cretaceous troughs belonging to the Ténéré graben mega system, extending from southern Algeria towards Lake Chad, over a distance of about 1200 km [1]. The Termit basin is rift-type basin developed on Jurassic bedrock [2], [3]. To the north, it is intersected by the Agadez lineament and is continuous with the Tefidet and Ténéré grabens (Fig.3) [4], [5]. To the south, the Termit basin adjoins the Bornou basin in Nigeria at the northern end of the Bénoué trough. It extends from north to south over a length of around 300 km and a width of 60 km, from east to west. Its surface area is around 30,000 km^2 [6], [7], [8], [9].

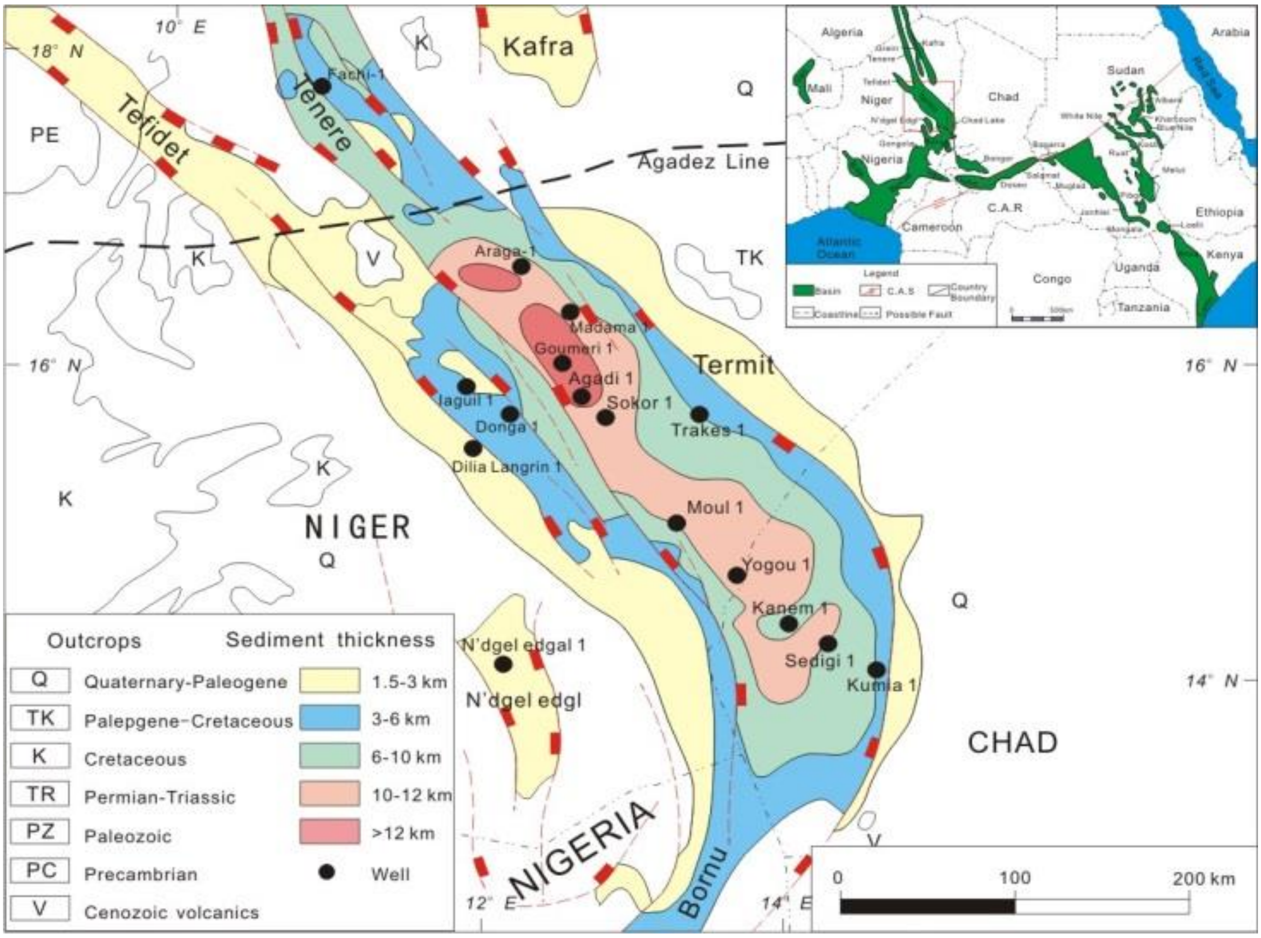

Fig. 3. Synthetic geological map of the Termit Basin (after Maurin and Guiraud, 1993)

2.1 Pre-Rift Period

The pre-rift period extends from the end of the Pan-African orogeny (around 550 Ma) to the Jurassic (around 145 Ma) [10], [11]. This period comprises two episodes: (i) an initial episode of Pan-African crustal assembly, and (ii) a second, relatively stable episode extending from the Cambrian to the Jurassic [10], [11].

2.2 Termit Basin Structuring Period

The Termit basin was structured in 4 main periods: Lower Cretaceous, Upper Cretaceous, Paleogene and Neogene.

2.2.1 Lower Cretaceous Period

During the Lower Cretaceous, the Termit Basin was formed concomitantly to the fragmentation of Gondwana and the opening of the South Atlantic [10], [11]. All authors agree that the Termit Basin was affected by a rifting phase during which fluvial to fluvio-lacustrine deposits were emplaced. This is the rifting phase 1 of Yuan et al. (2023) corresponding to the rifting phase of Wan et al. (2014) [12].

2.2.2 Upper Cretaceous Period

For Wan et al. (2014), this would be a period of subsidence (or downwarping) due to overload subsidence? Whereas Yuan et al. (2023) assume that there is a rifting phase, followed by a post-rift 1 phase. Sedimentation is essentially represented by marine deposits relayed vertically by fluviatile (Yuan et al., 2023) to fluvio-deltaic (Wan et al., 2014) deposits.

2.2.3 Paleogene Period

During this period, there was a rifting phase followed by downwarping (as defined by Wan et al. (2014)). During this Paleogene period, the basic fluvio-deltaic deposits (Sokor 1) are vertically relayed by lacustrine sediments (Sokor 2).

Yuan et al (2023) propose a different interpretation: throughout the Paleogene, there was a rifting phase ("rifting phase II") during which the fluvio-lacustrine deposits of Sokor 1 and then Sokor 2 were emplaced (Fig. 4).

2.2.4 Neogene Period

Wan et al. (2014) and Yuan et al. (2023) agree that the Neogene is a post-rift period during which the fluvio-lacustrine sediments were deposited. This post-rift period corresponds to the basin infilling episode (Fig. 4).

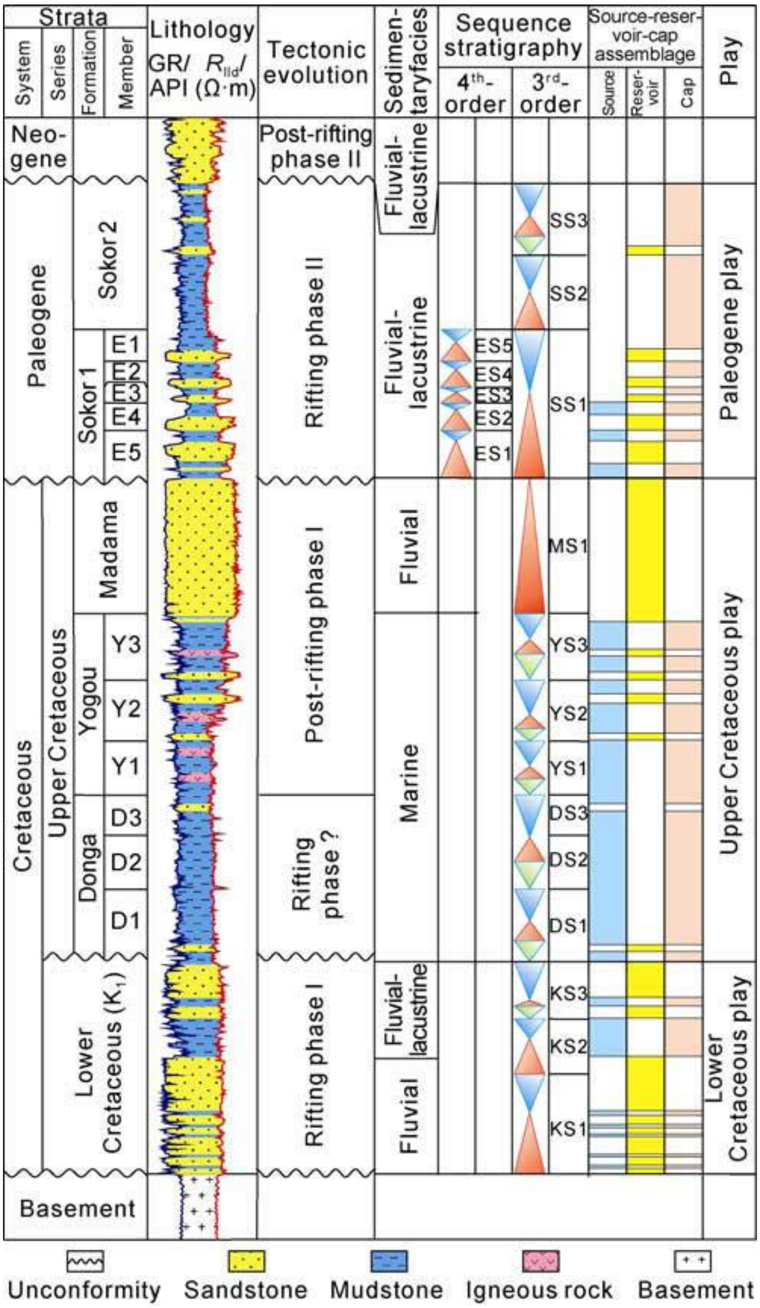

Fig. 4. Lithostratigraphic column of the Termit basin (Yuan et al., 2023)

3 MATERIAL AND METHOD

In addition to the literature review, seismic and logging data, sampling data (cuttings and core samples) and appropriate software were used to characterize the Boul prospect's petroleum system. Thus: (i) GeoEast software was used to analyze and reinterpret the seismic data, (ii) the Techlog program, to analyze and reinterpret the log data (instantaneous and delayed) and, (iii) Petrel software, to correlate the well data.

To determine reservoir levels, drilling data (cuttings and core) and pressure data (RFT-Repeat Formation Testing) were analyzed. To determine the reasons for the non-productivity of the Boul-1D well, a detailed analysis of the results was carried out. Investigations then focused on the parameters to be taken into account for successful drilling in the study area.

4 RESULTS AND DISCUSSION

4.1 SOURCE ROCK

The Boul prospect lies to the West of the Araga Graben, not far from the Dibeilla-1 zone, belonging to the same tectonic unit (Araga Graben), adjacent to the Dinga Depression.

Modelling of the hydrocarbon genesis process shows that the depth of the oil window for the source rocks of the Yogou formation lies between 2,800 and 4,500 m. At present, most of these zones have reached maturity, and the Dinga graben has entered the gas generation phase. During the rifting phase of the Paleogene, the source rocks of the Yogou Formation had matured over a wide area, which is in good agreement with the existence of traps (notably faults), the presence of regional caprock (Figs. 5 and 6). The maturity zone of the source rocks of the Yogou Formation, during deposition of the Sokor 1 Formation, is limited to the west of the Araga graben. It reaches greater maturity during the deposition phase of the Sokor 2 formation, which is associated with the main period of hydrocarbon generation and expulsion. The Dibeilla zone corresponds to an area with high hydrocarbon potential. The Total Organic Carbon (TOC) is mainly between 1.0% and 1.95%. The types of organic matter are primarily algae, plants, and animals, accounting for 95%. The organic matter types are mainly Type Ⅱ2–Ⅲ (African Institute of RIPED, 2010). The Boul prospect, located to the north of the Dibeilla zone, corresponds to a zone favorable to hydrocarbon accumulation.

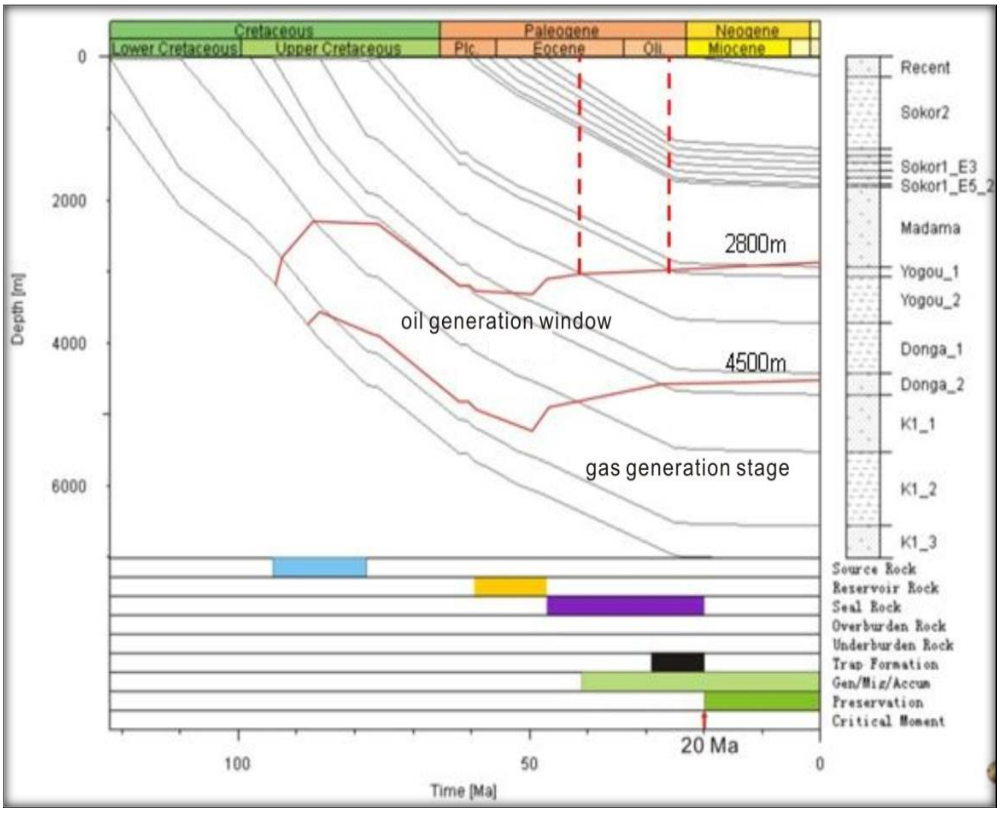

Fig. 5. Modeling the different stages of hydrocarbon formation in the Agadem Dibeilla-1 well

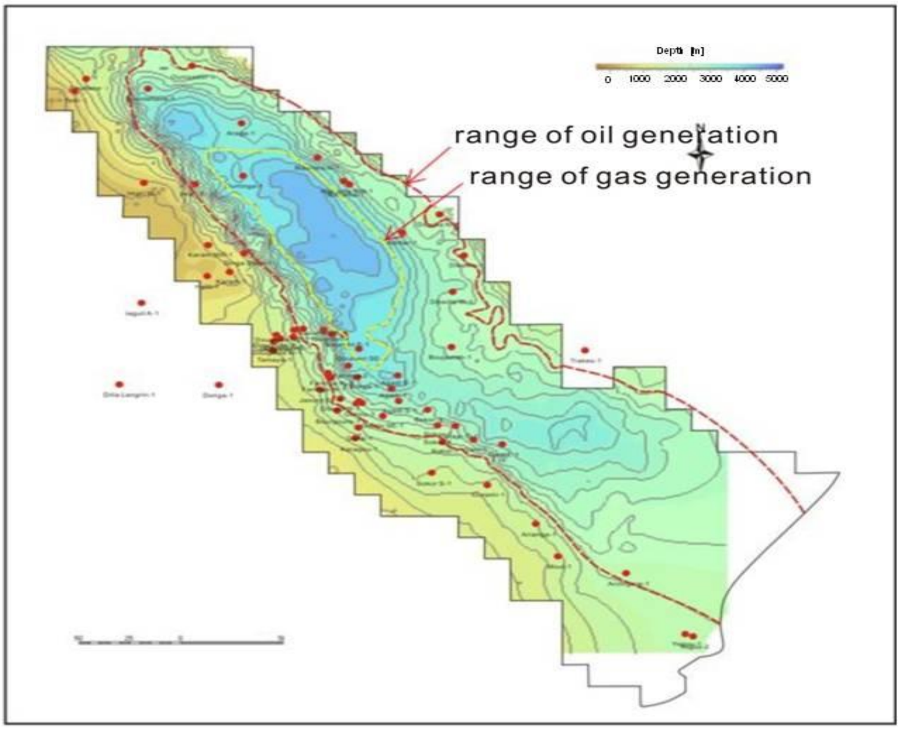

Fig. 6. Current limit of source rock maturation in the Yogou formation in the Agadem block

4.2 RESERVOIR ROCK

Research into seismic features shows that the E5 sand group in the Boul prospect area is a major sandstone reservoir in the Sokor formation of the Boul-1D well (Fig. 7-A). The main characteristics of the lithology of this formation are as follows:

- Heterogeneous formation, with alternating sandstones, argillites, shales, siltstones, and gravels,
- Sandstones (47.36%): fine to medium-grained, well sorted, moderately porous, low fluorescence, no visible oil,
- Argillites (46.79%): consolidated, sometimes sandy,
- Carbonates shales with platelet flow,
- Siltstones: low porosity, very weak fluorescence,
- Gravels: good porosity, weak fluorescence, no visible oil.

The average porosity of this zone is 20.4% with an average permeability of 410 md.

Research into regional sedimentary features indicates that during the deposition of sand group E5, the Boul prospect was located in a distributary channel-type sedimentary sub-environment (Fig. 7-B).

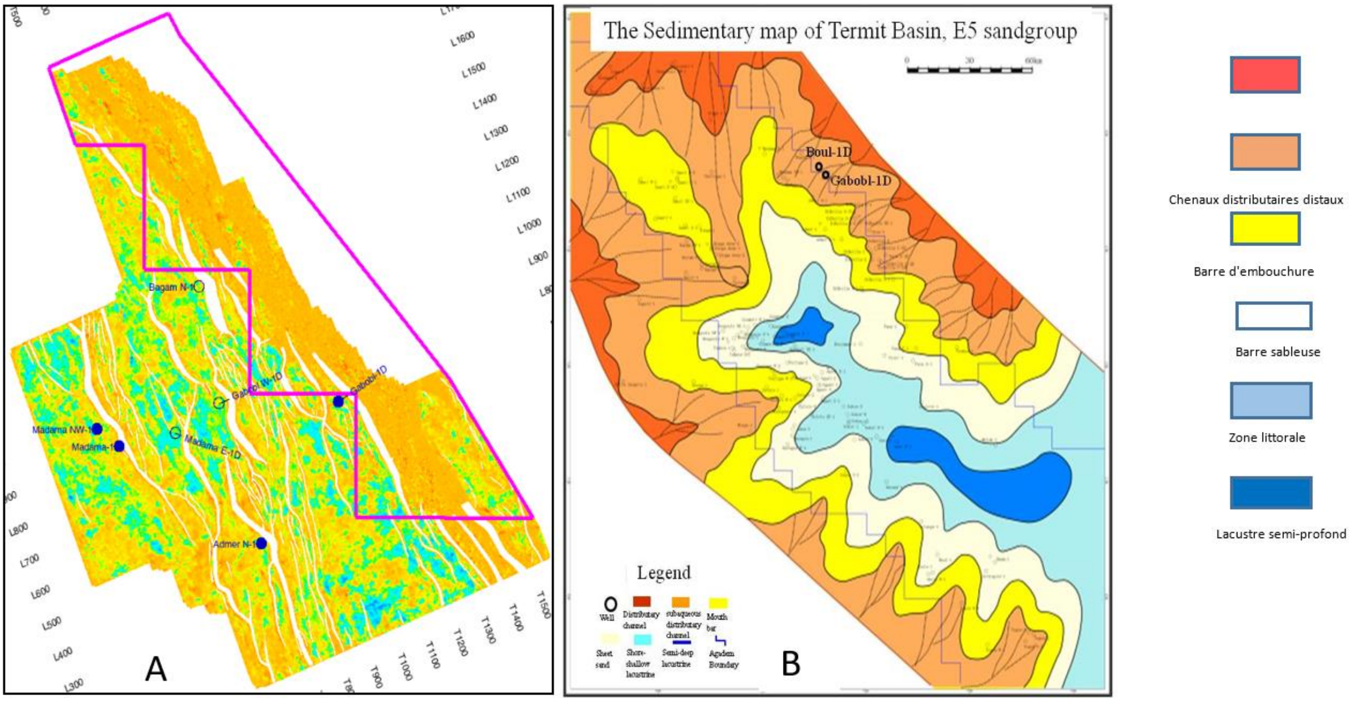

Fig. 7. *Gabobl-Boul 3D seismic attributes in sand group E5 (A): the dark yellow hue indicates sandstone levels, while the blue hue represents mudstones. Sedimentary map of the Termit Basin, sand group E5 (B) (Modified from Ministry of Petroleum, Niger, 2016)*

Correlation with the surrounding wells (Madama E-1D; Gabobl W-1D; Gabobl-1D) confirms that sandstones are quite well developed in the Sokor formation at the Boul-1D well (Fig.8).

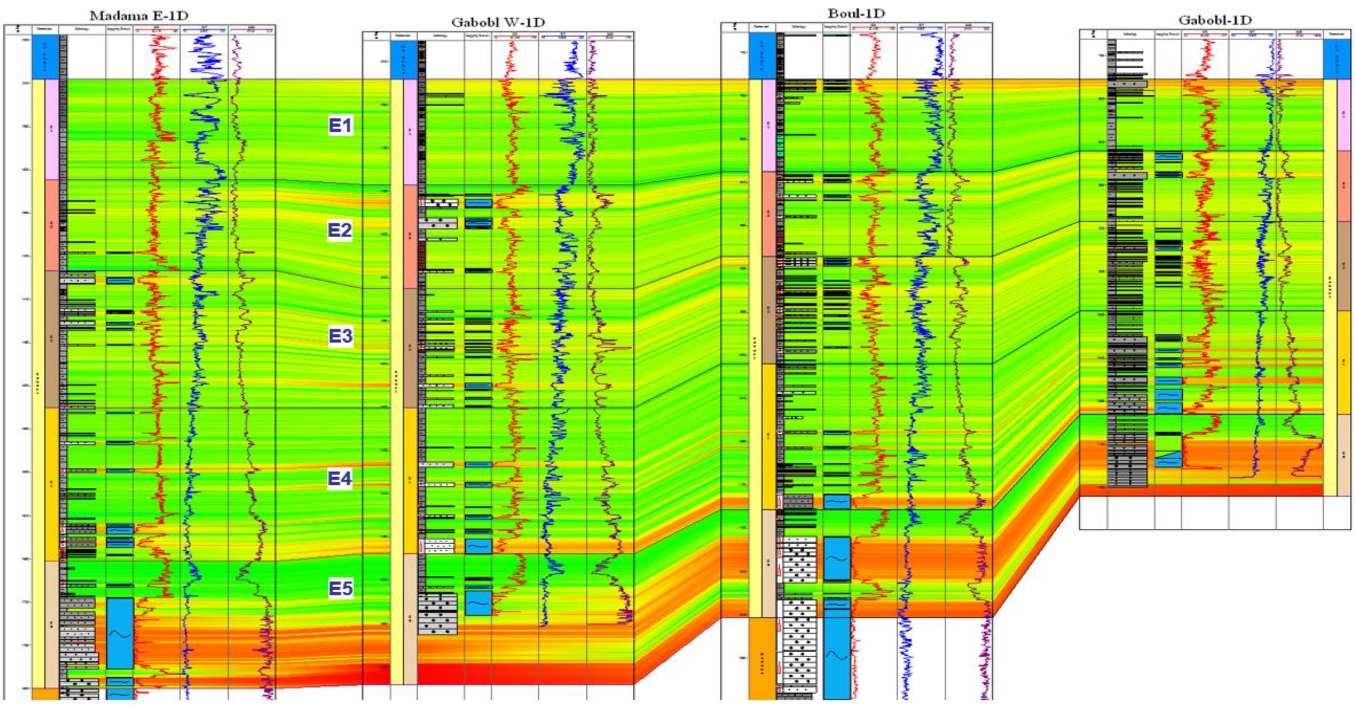

Fig. 8. *Correlation of the Madama E-1D, Gabobl W-1D, Boul-1D and Gabobl-1D wells, showing that the Boul-1D well, like the other wells, has the characteristics of a good reservoir*

To describe the lithology of the Madama Formation reservoir and to examine the presence of hydrocarbon shows, core samples were taken at depths corresponding to the different peaks of the gas curves. These samples were observed macroscopically, then analyzed by fluorescence (Fig. 9). The analytical results are presented in Table 1. The main characteristics of this formation (1399 to 1560 m) are as follows:

- Formation dominated by coarse to very coarse sandstones, with good porosity,
- Sandstones (82.98%): generally unconsolidated, with pure quartz and more pronounced fluorescence than in the Sokor Formation,
- Weakly consolidated shales (17.02%).

The average porosity of this zone is about 21.63% with an average permeability of 305 md.

Table 1. Core analysis results for the Boul-1D well

Core	Interval (m)	REC (cm)	Lithology and description of showings
A	1396,5	1,7	Medium sandstones, olive gray, moderately consolidated (Fig.9, A1)
B	1399,0	1,1	Fine, moderately consolidated sandstones with well-sorted and rounded to subrounded grains, light-gray in color. The matrix is sometimes clayey. Porosity is medium. No evidence of oil. (Fig.9, B1).
C	1401,0	1,4	Very fine, light gray, moderately consolidated sandstones. Quartz grains are rounded to subrounded, and well sorted. The matrix is sometimes clayey. Porosity is moderate and there is no visible oil staining. There is no direct fluorescence (Fig.9, C2), implying an absence of residual oil.
D	1404,0	1,8	Fine to medium, moderately sorted sandstones, subrounded to subangular quartz grain, dark brown in color, moderately consolidated,. Porosity is average. Traces of dark-gray oil are present, with slight fluorescence and abundant blooming. Light-brown residual oil is visible (Fig.9, D3).
E	1406.0	1,3	Fine to medium-grained moderately consolidated sandstones, dark-brown, with subrounded to subangular quartz grains, moderately sorted. The matrix is clayey. Porosity is medium. The sample shows traces of dark gray oil, characterized by pale yellow direct fluorescence. The residual oil is light brown in color (Fig. 9, E3).
F	1412.5	0,5	Very fine, moderately consolidated sandstones with rounded to subrounded, moderately sorted quartz grains, dark-brown in color. The matrix is sometimes clayey. Porosity is medium. These sandstones show traces of dark-gray oil, with a slight pale-yellow fluorescence. The residual oil is light brown in color (Fig. 9, F3).

Analysis of these cores has revealed the existence of reservoir rock and confirmed the presence of hydrocarbon showings.

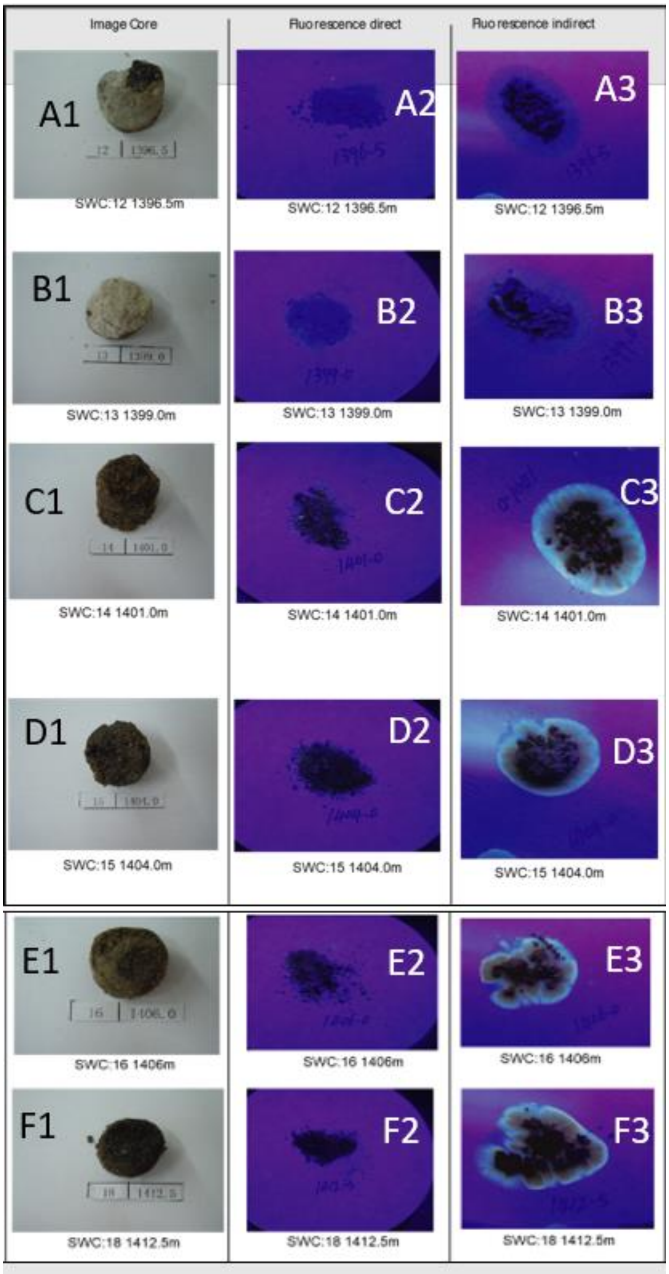

Fig. 9. Photographs of analyzed core samples

(1) A1 to F1: Unanalyzed raw samples,

(2) A2 to F2: Samples observed by direct fluorescence,

(3) A3 to F3: Samples observed by indirect fluorescence.

With a view to further investigations to confirm reservoir zones, the density of the fluids present was estimated. This involved plotting the pressure curve along the zones identified as porous and permeable. The pressure data (Table 2) were used to produce the RFT curve (Fig. 10). From this curve, the pressure gradient was determined (equation below). This gradient is used to calculate both the density of the fluid present and the pressure of the medium. This approach enabled to identify the nature of the fluids (oil, gas or water).

Table 2. Pressure measurements (RFT) (Ministry of Petroleum, Niger, 2017)

n° Test	Profondeur (m)	Gauge Type	Pression hydrostatique initiale (psi)	Pression mesurée (psi)	Pression hydrostatique finale (psi)	Temp. (°C)
1	940.5	10K	1698.2	1259.6	1697.5	53.88
2	942	10K	1699.9	1261.9	1700.3	54.05
3	943	10K	1701.7	1264.0	1702.0	54.22
4	1268	10K	2273.7	1719.6	2275.0	57.23
5	1269	10K	2277.3	1720.7	2277.4	57.77
6	1270	10k	2279.1	1723.7	2279.2	58.19
7	1271	10K	2280.8	1724.7	2281.1	58.49
8	1305	10K	2340.2	1774.7	2340.2	59.12
9	1306	10K	2341.9	1777.5	2342.6	59.33
10'	1306.7	10K	2343.0	1778.2	2342.8	59.53
11	1326	10K	2375.1	1803.9	2374.8	60.04
12	1327	10K	2376.8	1806.0	2376.0	60.23
13	1329	10K	2379.5	1808.6	2378.7	60.39
14	1338	10K	2394.6	1922.0	2394.5	60.44
14'	1338.3	10K	2395.0	1822.1	2394.8	60.47
15	1340	10K	2397.9	1824.4	2396.8	60.60
16	1341	10K	2398.9	1826.5	2398.3	60.66
17	1343	10K	2401.7	1829.3	2401.4	60.73
18	1370	10K	2448.4	1868.0	2448.1	60.77
19	1372	10K	2451.5	1870.8	2451.5	60.84
20	1374	10K	2454.6	1874.0	2454.4	60.96
21	1376	10K	2458.2	1877.1	2458.0	61.06
22	1390	10K	2482.1	1897.0	2481.7	61.18
23	1395	10K	2490.1	1903.9	2490.0	61.28
24	1400	10K	2499.0	1911.5	2498.6	61.35
25	1405	10K	2506.9	1918.7	2506.6	61.48
26	1475	10K	2628.8	2018.7	2629.6	61.73
27	1600	10K	2848.1	2195.4	2849.0	62.45
28	1900	10K	3376.3	2618.8	3377.1	63.40

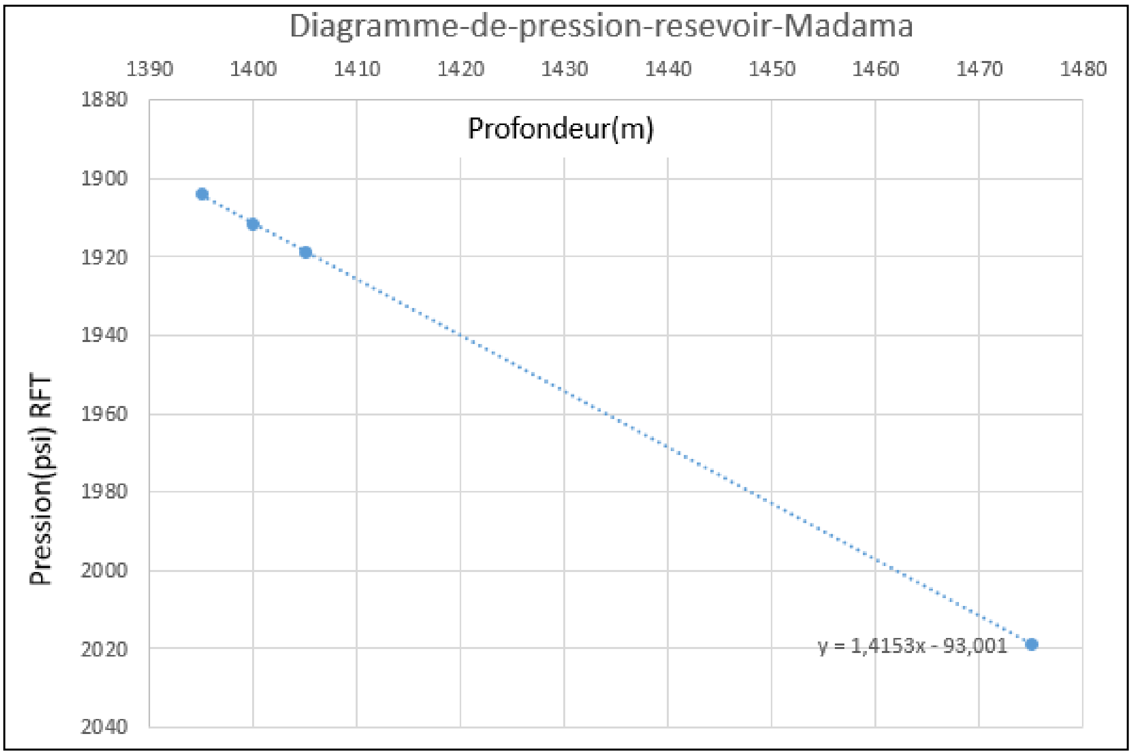

Fig. 10. RFT diagram of the Madama reservoir interval between 1398.5 to 1410.3 m (Boul-1D)

The RFT curve plots pressure versus depth in the target zone corresponding to the Madama formation. The curve thus obtained has the equation: **Y= ax+c,** with **a** the directing coefficient giving the pressure gradient, and **c** the y-intercept. After projecting the pressure data from the Boul-1D well into Excel, the equation of the straight line is directly obtained (y=1.4153x-93.001), giving the value of the coefficient a, which is 1.41. Density is calculated in standard petroleum practice by the formula: Density = $\frac{a}{1,422}$ = $\frac{1,41}{1,422}$ = 0,99 g/cm3, a being the pressure gradient and 1.422 a conversion constant from psi/m to g/cm^3.

The density value obtained is close to 1, which corresponds to the density of a heavy oil. So, at the Boul-1D well, the Madama reservoir would be saturated with heavy oil.

4.3 Cap Rock

In the Termit basin, the middle and lower parts of the Sokor2 formation were formed close to the maximum flooding surface. A vast zone of thick, continuous Sokor lacustrine argillites developed (Fig. 11), constituting the main basin-wide cap rocks. These argillites strata range in thickness from 300 to 1000 m in most areas of the basin. These layers are distributed continuously throughout the basin (Fig. 12) and has only been eroded in: (i) the northern parts of the Soudana “structural uplift”, (ii) the Termit West Platform and, (iii) the Termit East Slope.

The Araga tectonic unit, in which the Boul prospect is located, is marked by a consequent thickness of lacustrine argillites, enabling them to play the role of cap rock. This is illustrated by the correlation of wells in the Gabobl-Boul3D, which shows that the argillites in the lower part of the Sokor formation and the Low Velocity Sand (LVS) group are over 350 m thick, covering the entire Sokor1 formation, thus forming a good cap rock at basin scale (Fig.12).

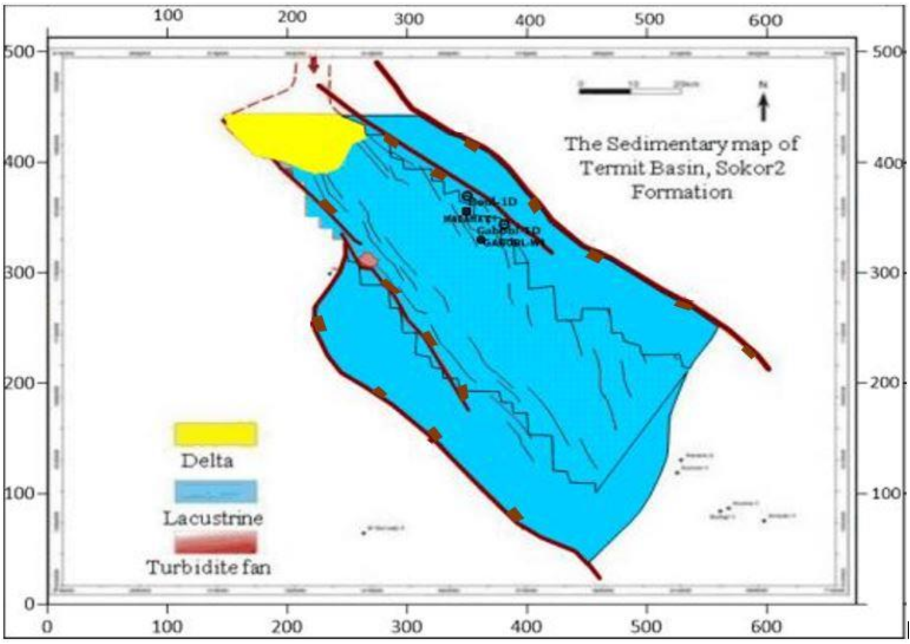

Fig. 11. Lateral variation of depositional environments in the Sokor 2 formation.

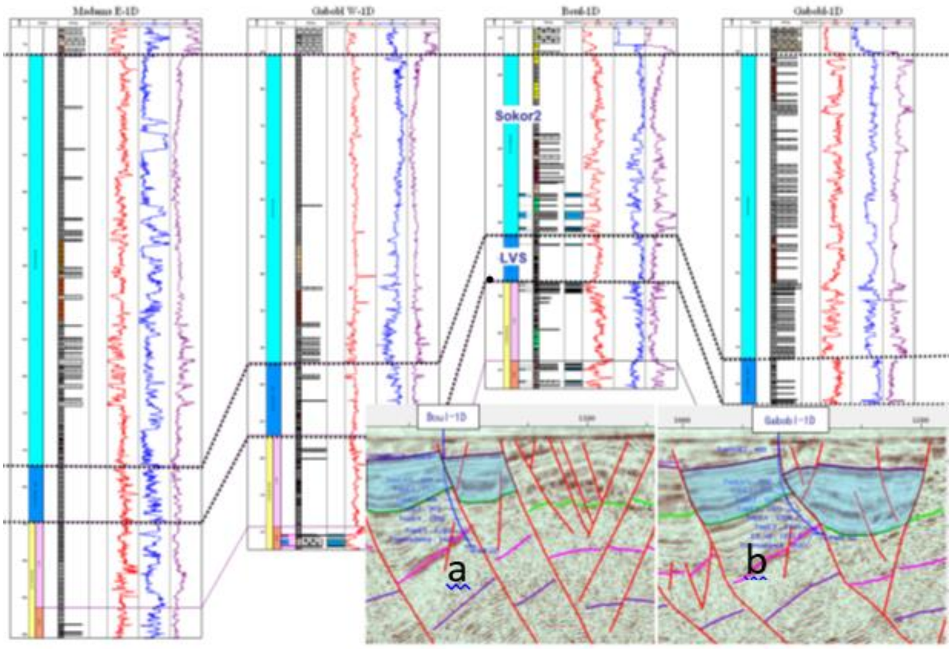

Fig. 12. Correlation of wells (Madama E-1D, Gabobl W1-D, Boul 1-D and Gabobl 1-D) showing the presence of cap rocks in the Boul-1D well

4.4 THE TRAPS

The Boul-1D and Gabobl-1D well traps are structural traps, closely associated with synsedimentary normal faults (Figs. 12 a and b). These are antithetic fault blocks that can be observed on the seismic profiles in Figs. 12 a and b. The seismic profiles show a continuity of reflectors implying a reliability of the traps (Figs. 13 and 14).

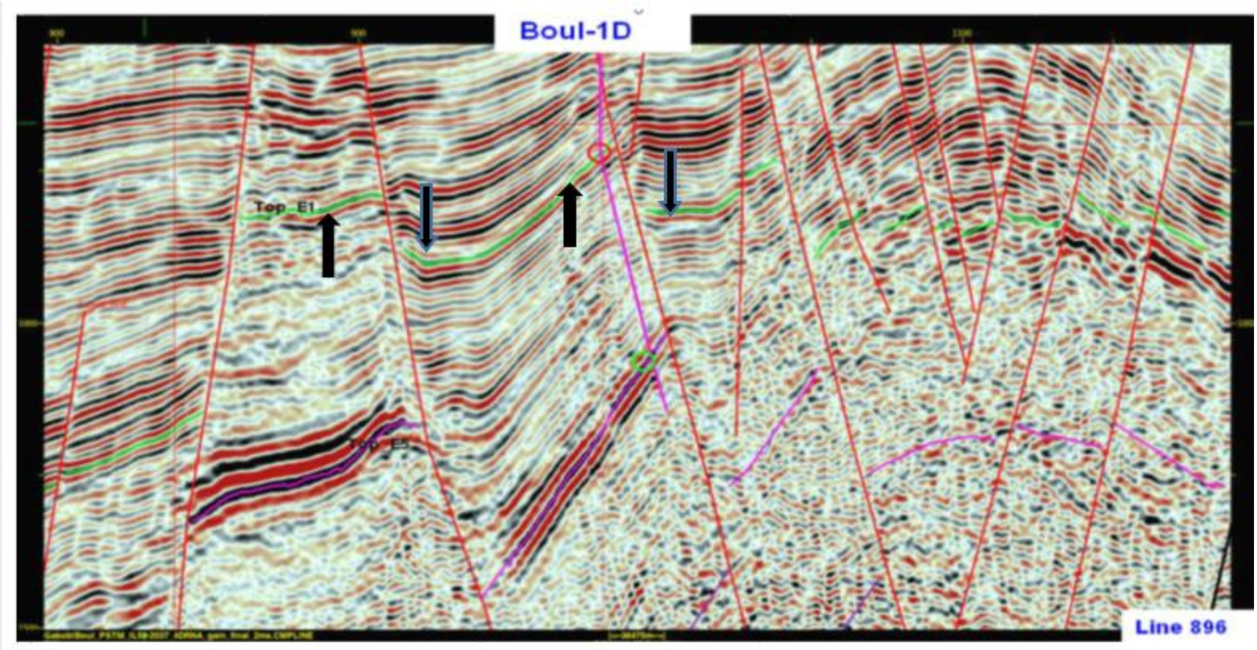

Fig. 13. Boul-1D seismic line 896 profile

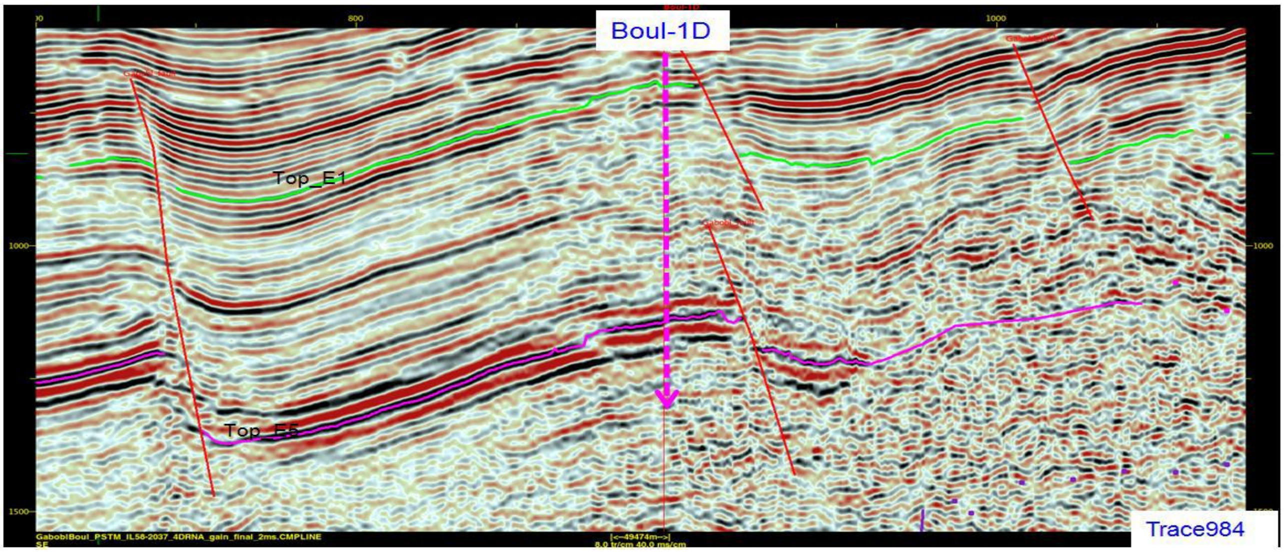

Fig. 14. Boul-1D seismic line 984 profile

4.5 HYDROCARBON MIGRATION

Research into hydrocarbon migration in the Araga graben, including the Boul prospect, indicates that:

- The maturity ranges of the Yogou Formation source rocks, during deposition of the Sokor1 Formation, can be seen to the west of the graben. It reaches maximum maturity during deposition of the Sokor2 formation, corresponding to the hydrocarbon generation and expulsion phase (Fig. 15).
- The hydrocarbons thus generated, in the bedrock of the Yogou Formation, begin their migration after emplacement of the Madama Formation. They migrate from the western part of the graben towards the east. The emplacement of the Sokor 2 Formation is contemporaneous with the graben-wide migration of hydrocarbons (Figs. 16 and 17).

The simulation results are consistent with the current distribution of oil and gas reservoirs. Faults are the main routes for hydrocarbon migration. They also act as traps in the Sokor 1 and Madama reservoirs. In view of the above, we can deduce that the Boul prospect also corresponds to a zone favorable to hydrocarbon accumulation.

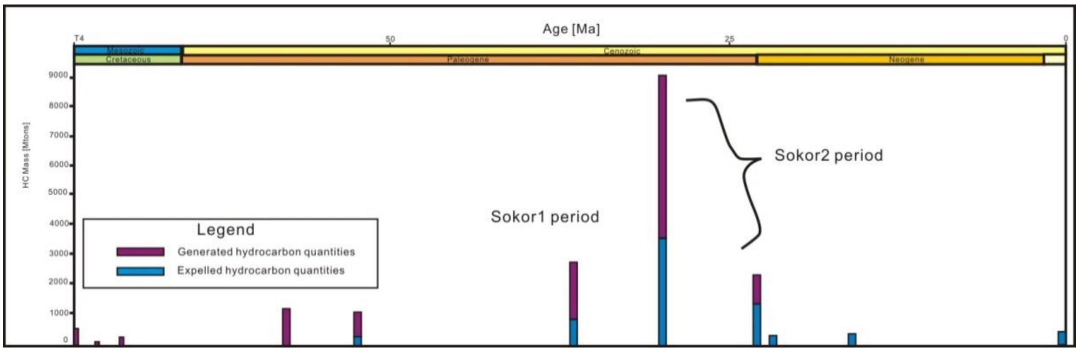

Fig. 15. Simulation of the quantities of hydrocarbons generated and expelled at different times in the Araga graben

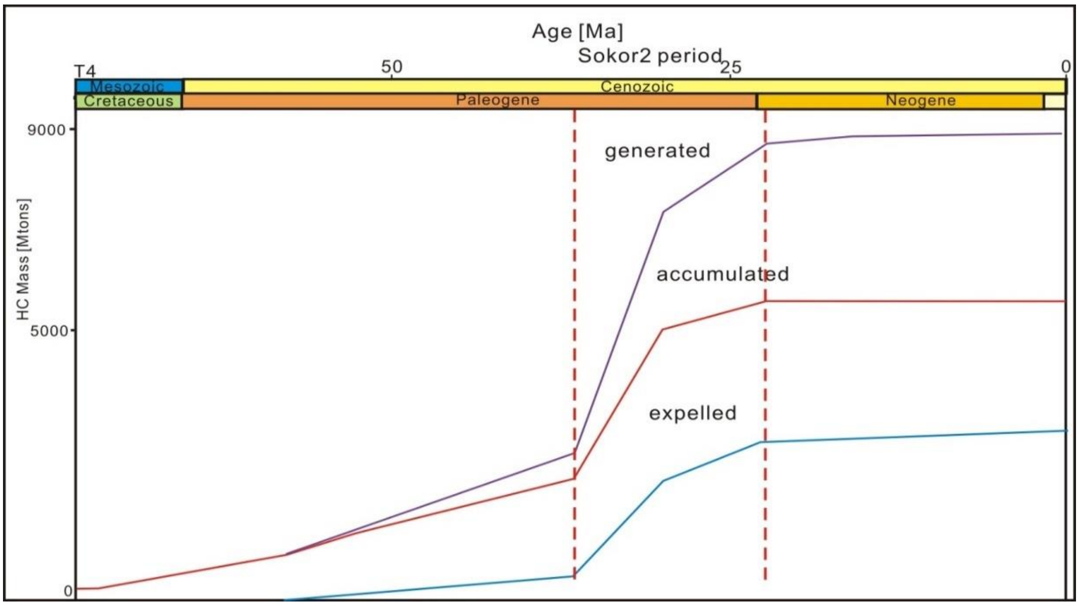

Fig. 16. Simulation of the quantities of hydrocarbons generated and expelled by the source rock of the Yogou Formation in the Araga graben

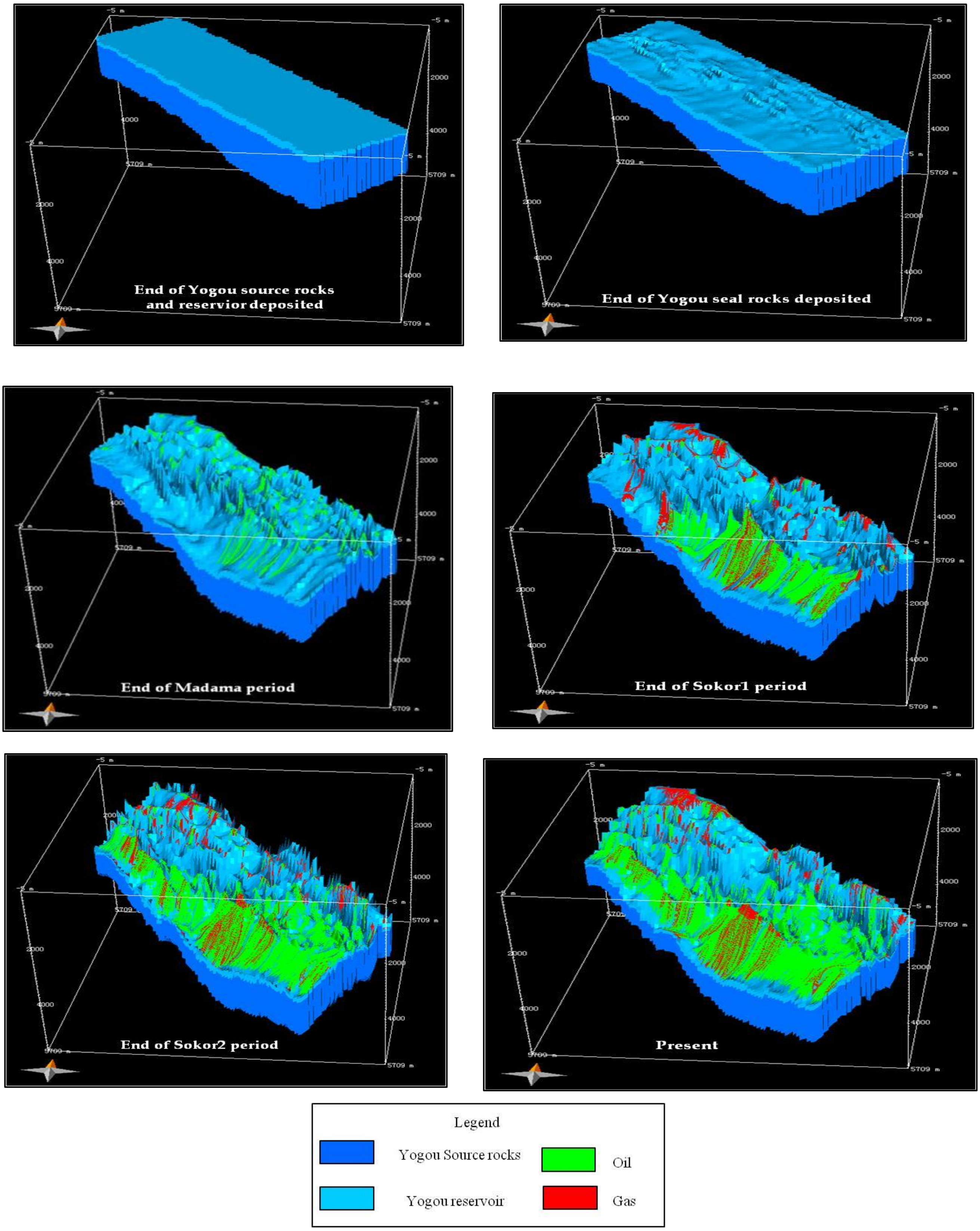

Fig. 17. Simulation of 3D hydrocarbon accumulations in the Yogou Formation, (Araga graben)

4.6 PRESERVATION (LATERAL SEALING)

Lateral sealing research shows that there is a high risk for the Boul prospect, as the main target sandstone layers E4 and E5 in the upper compartment are juxtaposed with E3 and E4 in the lower compartment (Fig. 18). From a lithological point of view, the E3, E4 and E5 sandstone layers lack sufficient interbedded argilites levels, presenting a high risk of hydrocarbon leakage (Fig. 18).

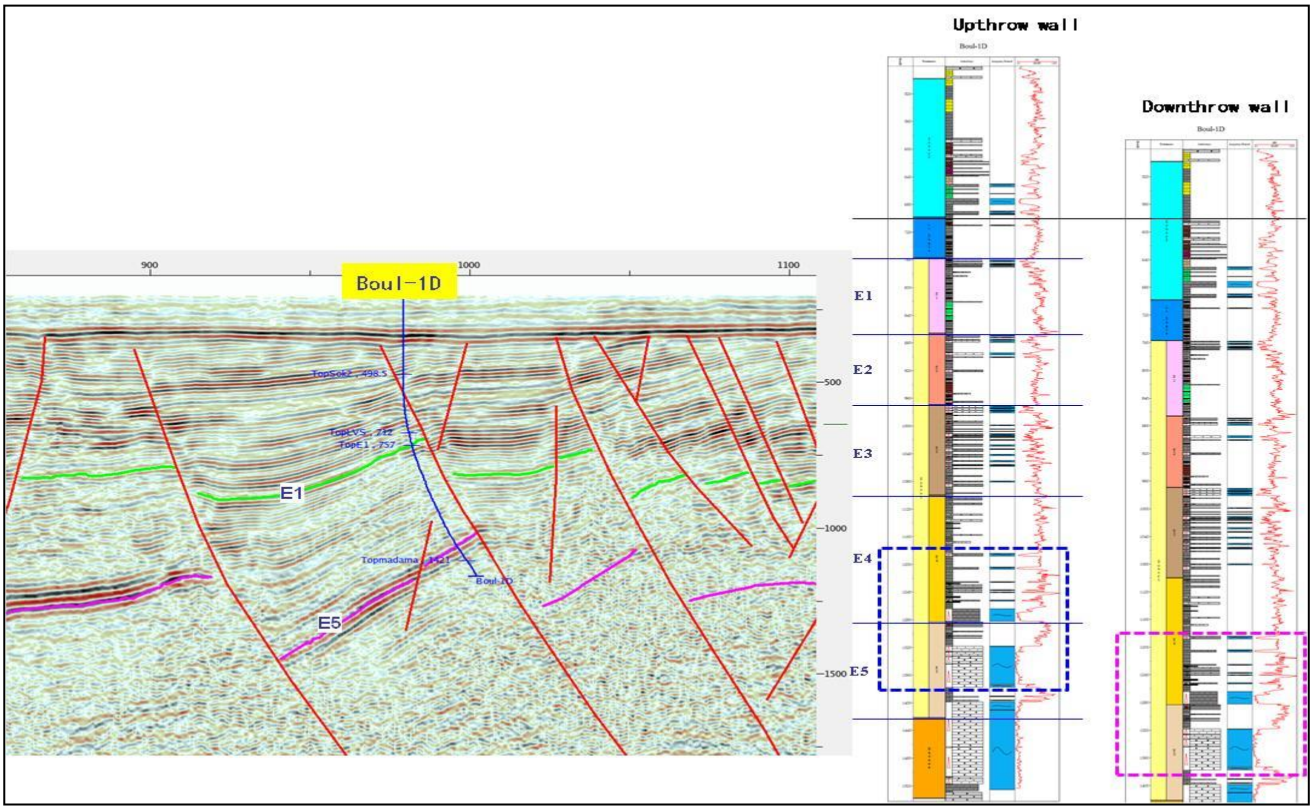

Fig. 18. Lithological juxtaposition for the Boul-1D Structure

It should be remembered that, in the Agadem block, most of the cap rocks have a shale percentage (cut off) assumed to be greater than or equal to 40% (Vshale≥40%). This means that the cap rocks must have a shale content significantly higher than this value.

The Shale Gauge Ratio (SGR or % shale volume), representing the total shale volume in relation to the vertical rejection of a given fault in the reservoir zone compartment, and its inverse, the Smear Shale Factor (expressing the shale volume in the juxtaposition zone compartment), are essential tools for characterizing the tightness of a fault.

The reference SGR value, expressing the volume of shales required to act as cap rock to the reservoir layers in this part of the Agadem block, is greater than 0.4 (40%). For the Boul prospect, the value is around 0.2 (i.e. 20%). This value indicates that tightness along the fault plane is compromised, resulting in a risk of lateral hydrocarbon migration (Fig. 19).

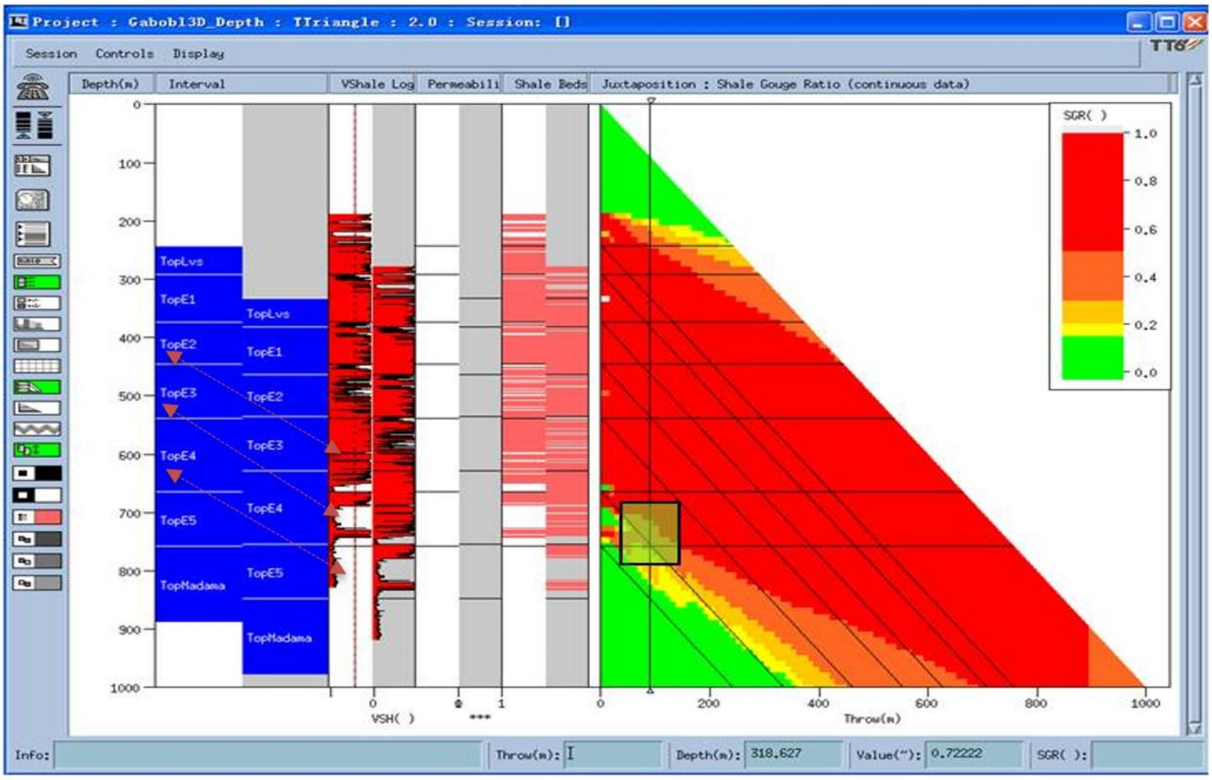

Fig. 19. Schematic of the triangular SGR liner on the Boul-1D shale

4.7 EXISTENCE OF A DISSIPATION SYSTEM

Geological analysis and interpretation of the Boul-1D well reveals the existence of a hydrocarbon dissipation system on the west side of the Boul Prospect. This is due to the fact that the Madama sandstones outcrop directly at surface. Consequently, the conditions for oil and gas accumulation are not met in this zone (Fig. 20).

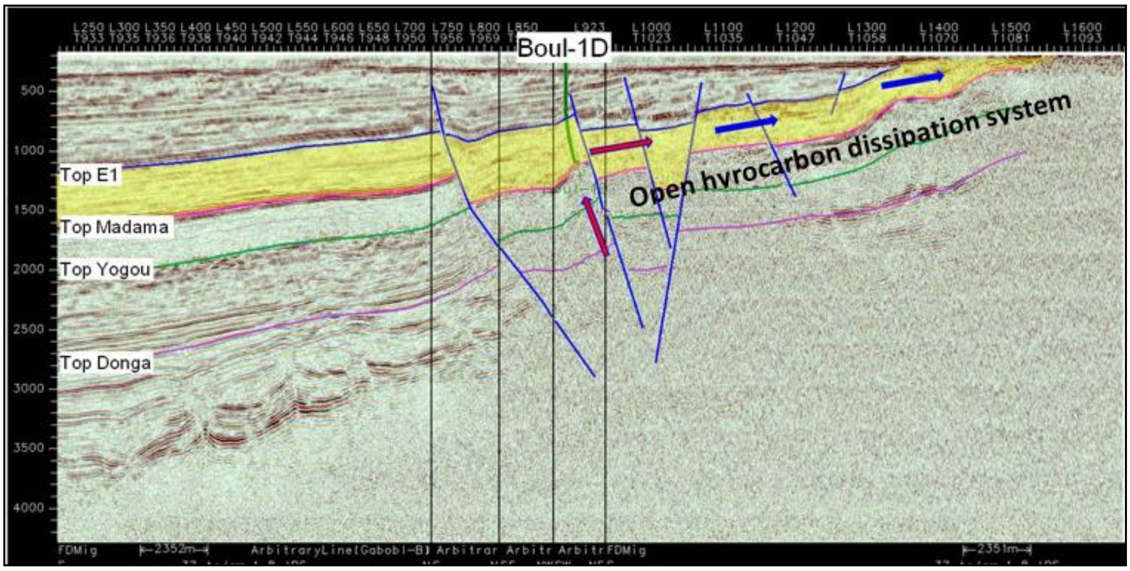

Fig. 20. Interpretation of the seismic line crossing the Boul-1D well

To further investigate this dissipation phenomenon, these results were compared with those from the Madama E-1D and Bagam N-1 wells, which lie in the same tectonic unit (Araga Graben) as the Boul-1D well. The same dissipation problem was observed in these wells, which are dry (Figs. 21, 22 and 23).

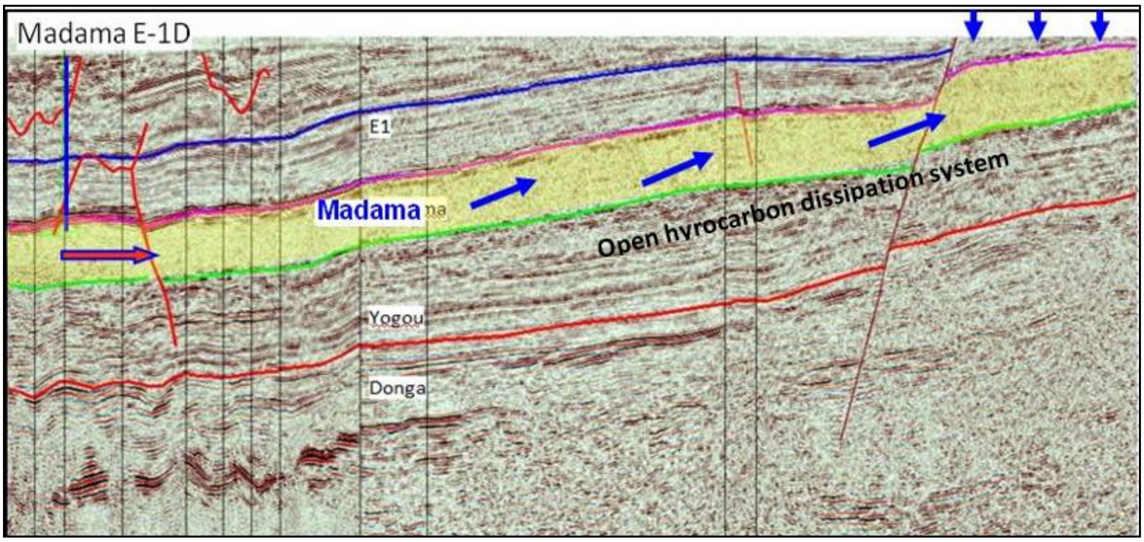

Fig. 21. Interpretation of the seismic line crossing the Madama E-1D well near the Boul prospect

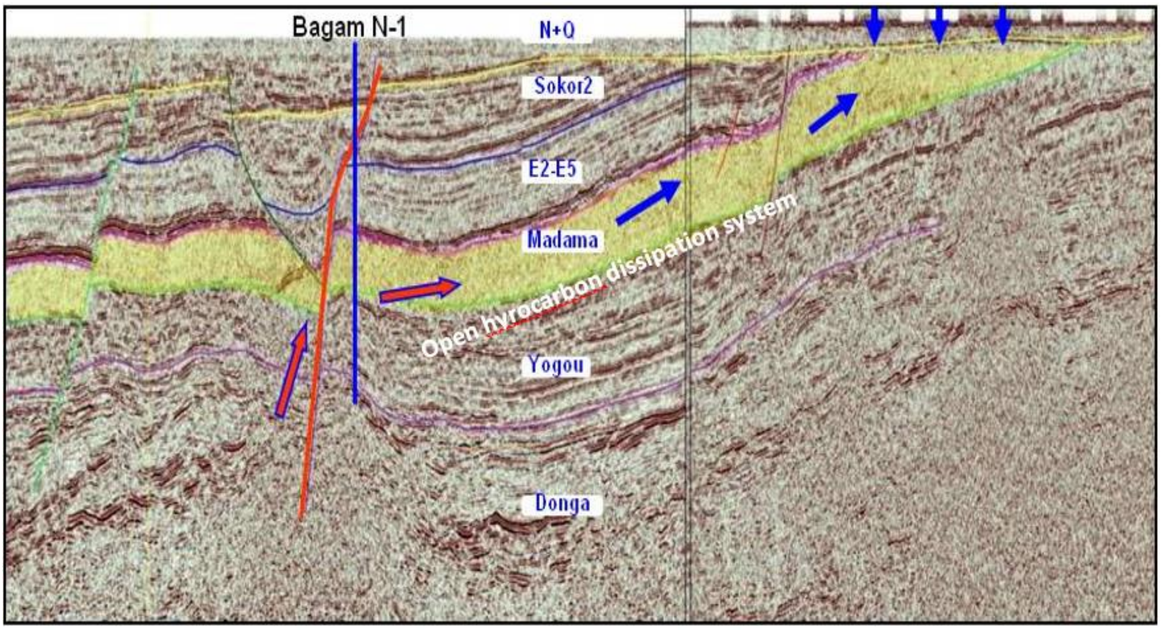

Fig. 22. Interpretation of the seismic line crossing the Bagam-1D well near the Boul prospect

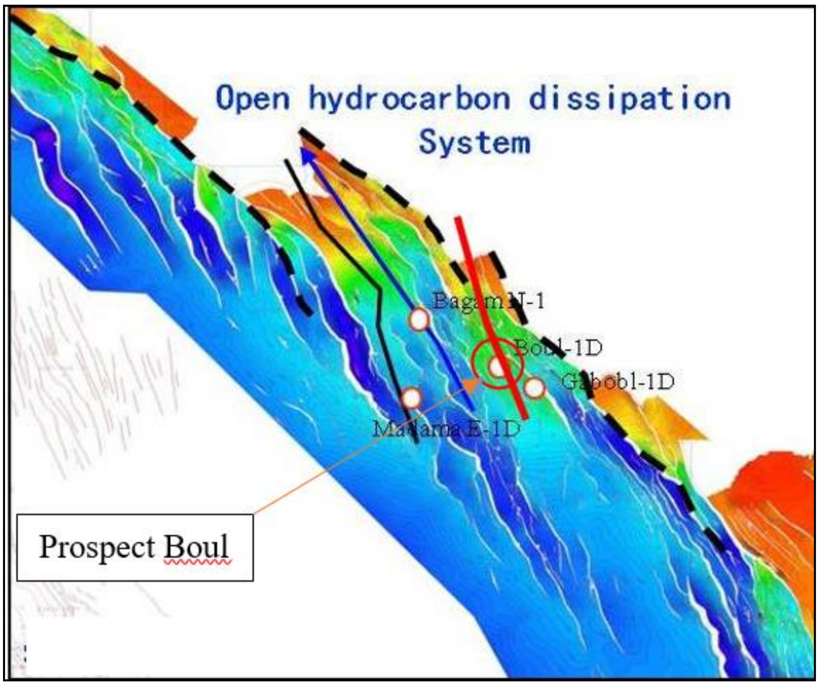

Fig. 23. Open hydrocarbon dissipation system on the western of the Boul prospect.

5 Conclusion

As a result of this study, the following conclusions have been drawn:

- The petroleum system (source rock, reservoir rock, cap rock, migration, and accumulation) of the Boul-1D well has many similarities with other positive wells;
- From a structural point of view, the lateral seal integrity of the faults in the Boul trap is deficient, which does not favor hydrocarbon accumulation;
- To the west of the Boul prospect, the NW-SE trending fractures affecting the Madama Formation act as hydrocarbon dissipation drains.

The lateral seal integrity is the primary cause of drilling failures in exploration activities in the northeastern part of the Termit Basin. It is the most critical factor that requires greater attention. The phenomenon of hydrocarbon dissipation is the second key factor that should be closely monitored when evaluating prospects in this area.

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