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Tectono-sedimentary evolution of the Termit basin (SE Niger)

Leyla Boubacar Hamidou[1], Mohamed Atmane Abdourahim[1], Aboulwahid Sani[2], Habsatou Ousmane[1], and Moussa Konaté[1]

[1]Université Abdou Moumouni, Faculté des sciences et techniques, Département de Géologie, B.P. 10662, Niamey, Niger

[2]Université d'Agadez, Faculté des Sciences et Techniques, Département de Géologie, PO Box 199 Agadez, Niger

ABSTRACT: Multi-channel seismic and well data from Agadem (Termit Basin), a Mesozoic‑Cenozoic intra-continental rift basin located in the West and Central African Rift System (WCARS), has been analyzed. Regional unconformities, including the top of acoustic basement, have been identified from seismic data.

The correlation of wells in the Agadem Block, as well as the seismic data interpretation, show that the lateral thickness variations of the layers is linked to the synsedimentary normal activation of the N140° to N150° trending fault system of the Termit Basin. The well logs correlation exhibits a high hydrocarbon potential, in the axial zone of the Agadem Block, which is characterized by a strong subsidence rate.

This study shows that the NW-SE-trending graben shaped Termit Basin exhibits a tilted block structuring, controlled by the synsedimentary reactivation of normal faults. Two major periods of structuring characterize the evolution of the Termit Basin:

- The first period, which was an extension stage, including the first rifting stage relayed by a thermal subsidence, occurred from early Cretaceous to Upper Cretaceous, during the south Atlantic opening.
- During the second period, which prevailed from Paleocene to Oligocene, the Termit basin was also affected by a second rifting event, followed by a thermal tectonic subsidence. The NW-SE trending faults was secondly reactivated during a NE-SW extensional regime.

KEYWORDS: Agadem block, tectono-sedimentary, tilted blocks, upper Cretaceous, Paleogene.

1 INTRODUCTION

Niger is composed of two distinct sedimentary domains (West Niger and East Niger), which are separated over a length of about 700 km by the north-south oriented Aïr massif, which is the southern extension of the Hoggar massif [1].

The eastern Niger structure is characterized by two sedimentary basin systems, the Palaeozoic Djado Basin to the NE, and a series of grabens, filled mainly with Cretaceous and Tertiary sedimentary rocks, which extend over a distance of about 1,200 km from southern Algeria towards Lake Chad (Fig.1).

The NNW-SSE trending East Niger Graben System includes the following individual grabens from north to south: Kafra, Grein, Ténéré, Tefidet, Bilma, and Termit, the focus of this paper, which is elongated in a NW-SE direction and covers an area of approximately 30 000 km^2 [2, 3] and N'Guel Edji Graben (Fig. 1).

Exploration in Agadem Block (Termit basin), in the southeastern Niger carried out by Petropar, Petronas, Elf, Esso Exploration and Production Niger Inc, Global Energy and China National Petroleum Corporation (CNPC) consisted mainly of geophysical surveys. These Previous studies shown that Termit Basin experienced two rifting periods:

- The first period of rifting prevailed during the Cretaceous and,
- The second rifting stage occurred during the period ranging from Paleogene to Quaternary

In this study we present a combination of both high-resolution seismic reflection profiles and well data from Agadem Block in Termit basin. Based on these data, we discuss the structural evolution of the study area associated to its sedimentary infilling.

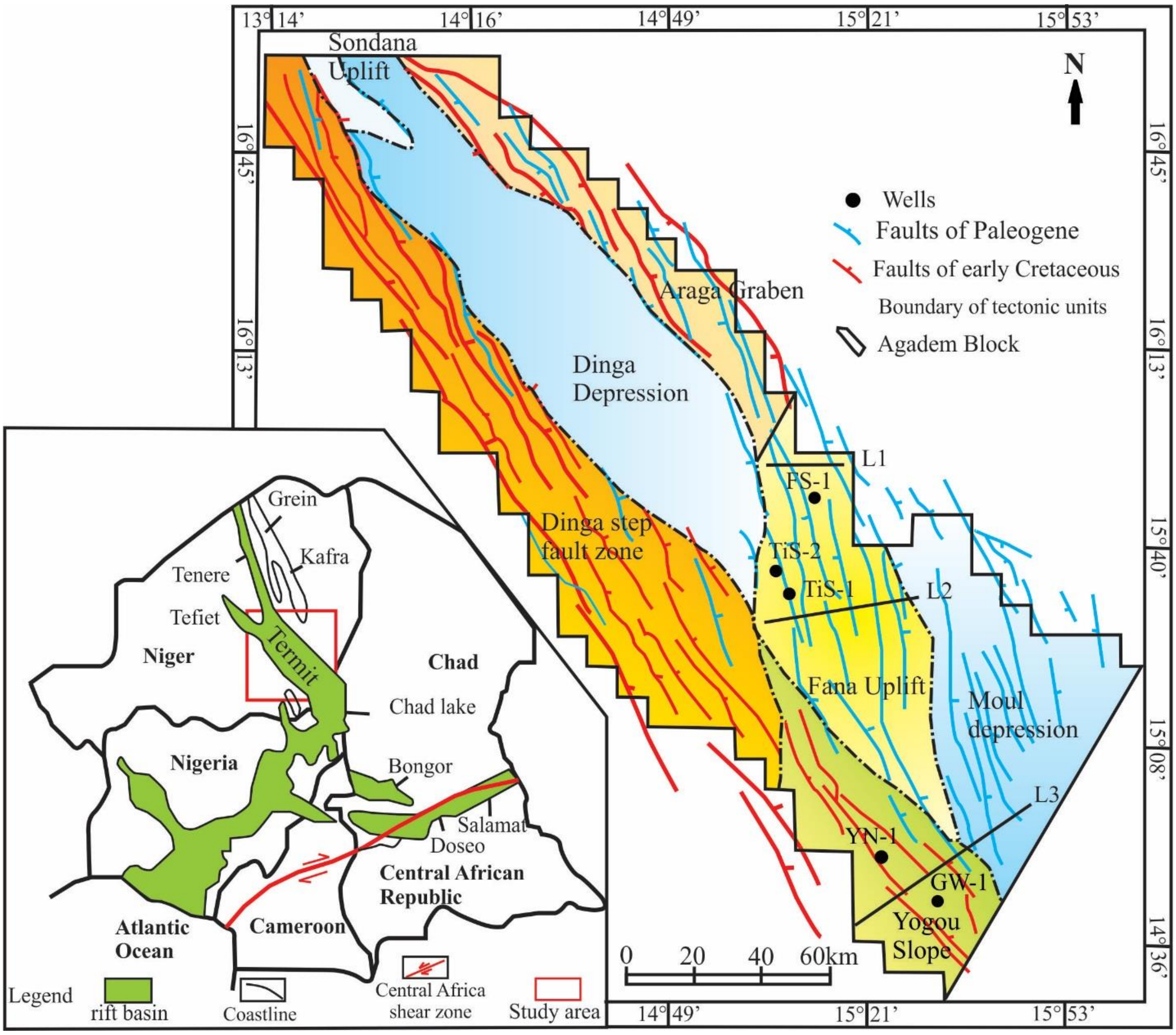

Fig. 1. Location and tectonic units of Termit basin (from Lai et al., 2019)

2 GEOLOGICAL SETTING

The Ténéré rift system extends from south Algeria to Lake Chad, over a distance of about 1200 km [1, 4-6]. It includes a set of coalescent grabens, connecting towards the south with the Nigerian NE-SW trending Benue trough [5, 7].

The Termit Basin is an extensional asymmetric rift basin belonging to the West and Central Africa rift system (WCARS) [8-11]. Controlled by NW-SE to NNW–SSE trending border faults, the Termit basin was developed on Precambrian basement. Six tectonic units (two negative tectonic units and four positive tectonic units) composed the basin. These are: Dinga and Moul depressions, Dinga step-fault zone, Araga Graben, Fana Uplift, and Yogou Slope. (Fig. 1).

The tectonic evolution of the Termit basin is characterized by 3 major phases: a pre-rift stage, a first synrift phase (from Early Cretaceous to Paleogene) which can be divided into three sub-phases, and a post-rift stage (Fig. 2) [9, 10]. Termit basin was developed during the first synrift phase linked to the breakup of Gondwana and the opening of the South Atlantic [2, 9, 10, 12-17].

During the second rifting phase, the deposition consists of fluviatile to lacustrine sediments [1, 18-20]. The Donga and the Yogou formations consisted of marine clastic rocks, while the Madama is composed of braided fluvial sandstones and mudstones. All these formations were deposited during the second rifting phase (Fig. 2) [21]. During this phase, the basin underwent a period of subsidence caused by tectonic subsidence and the worldwide Late Cretaceous eustatic sea-level highstand [22]. According to [23] and [24] the second rifting phase was ended by a regional unconformity. Sokor-1 and Sokor-2 formations which consist of Cenozoic continental sediments from alluvial, fluvial, and lacustrine depositional environment, were deposited during the second rifting phase [9, 10, 25]. The post rifting thermal subsidence phase in the Termit basin occurred during the Neogene – Quaternary period. During this time, mainly fluvial-alluvial plain sediments were deposited.

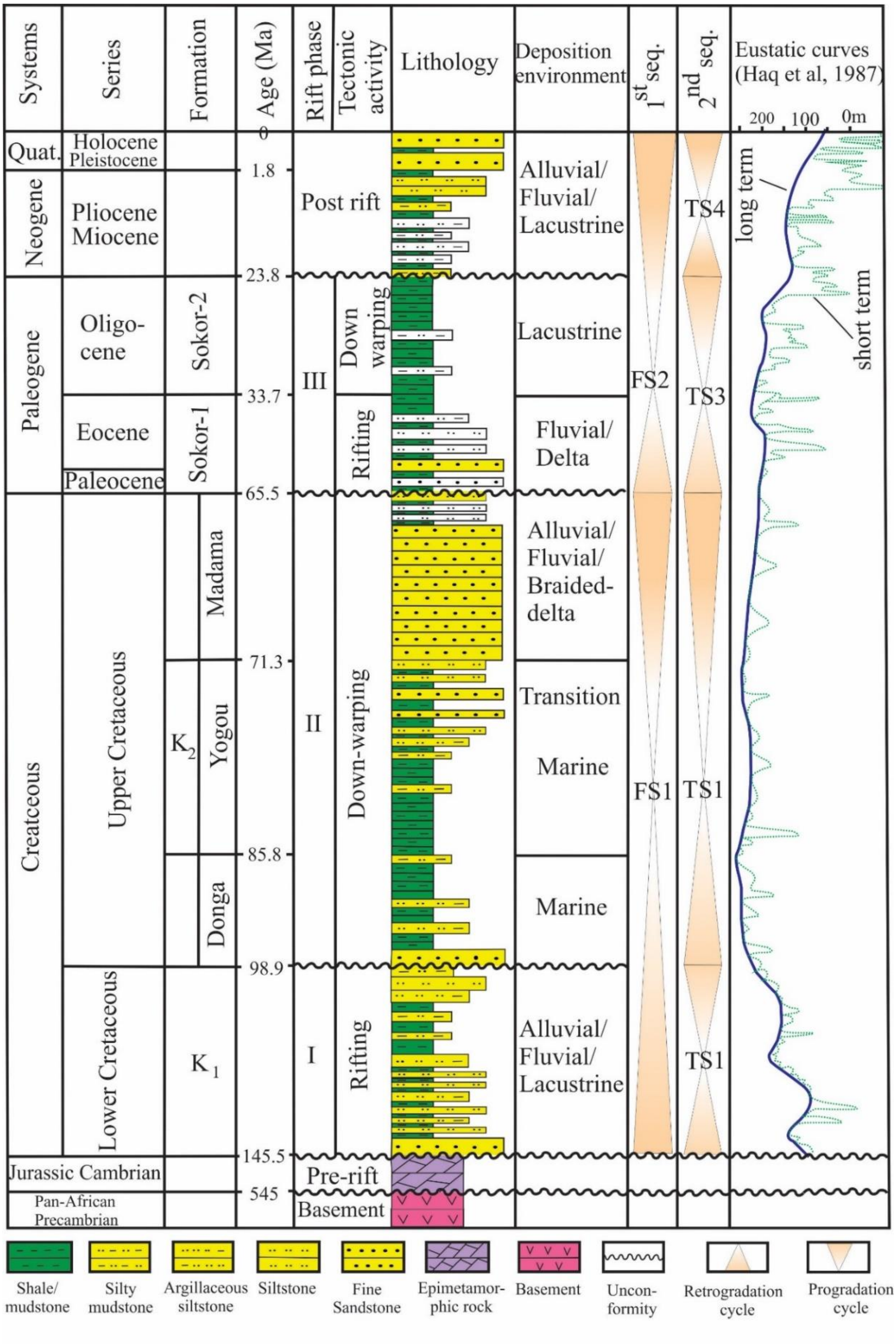

Fig. 2. Stratigraphic column and sequence division of the Termit Basin (modified after [9, 26])

3 MATERIALS AND METHODS

The data used in this study consist of seismic profiles and wells (FS-1, TiS-1, TiS-2, YN-1 and GW-1) kindly provided by CDP (*"Centre de Documentation Pétrolière"*). Well logs in the basin were used to verify our interpretation of the key horizons depth. The data were interpreted using the Petrel software produced by Schlumberger (2009). The vertical scale for all of the seismic profiles is a two-way travel time. Correlation of the seismic sections and well data led to the identification of four sequences. After building up the stratigraphic succession, we studied the distribution of the formations, by well correlation and by analysis of further tectonic and depositional evolution in the basin.

4 RESULTS AND DISCUSSION

4.1 SEDIMENTARY FEATURES

4.1.1 EARLY CRETACEOUS SEQUENCE K1

The K1 sequence is composed of sandstone, kaolinite, and quartz sandstone associated with siltstone and mudstone. Termit Basin started to develop during the break-up of Gondwana from Upper Jurassic to Lower Cretaceous [2, 13-17] and subsequent seafloor spreading resulted in the formation of the South Atlantic Ocean. Fluviatile to lacustrine sediments are deposited in Termit and nearby grabens in the early to Late Albian period during the rifting, associated to a rapid subsidence [1, 4, 18, 19]. The sediments deposited during this time in the Termit Basin are up to 2500 m [27].

4.1.2 UPPER CRETACEOUS SEQUENCE K2

The upper cretaceous sequence K2 consists of 3 formations: Donga, Yogou and Madama. From well YN-1, the lower interval of Donga formation Turonian-Coniacian in age marks the beginning of the Turonian Neolobites, Nigericeras and Pseudotissatia transgression [2].

The Donga formation is dominated by shallow marine shales interbedded with thin and fine sands deposits, which are highlighted by the high values of gamma-ray (135 API) (Fig. 3a). Locally, the gamma-ray values show the presence limestone deposits. According to [9] and [8], shallow marine depositional environment was affected by marine transgression in the Western Africa Rift System during the Late Cretaceous.

Yogou formation in the well GW-1 (Fig. 3b), is characterized by alternances of high gamma-ray values (120 API) and low values (40 API), due to the interbedded sandstones and mudstones. These sediments are deposited in a transitional environment [9] including lamellibranch fossils [2]. Due to regression during the Late Campanian, seawater returned to the Niger Basin [9]. Interbedded sandstones and mudstones represent the upper part of Yogou formation (Campanian) which was deposited in a marine to terrestrial transitional environment [9, 28].

The **Madama** Formation which consists of sandstones and mudstones was deposited during the Maastrichtian. This period is characterized by a regression in Agadem area [29]. The sediments were characterized by the logging response from well GW-1 with relatively low value of GR (40 API), indicating a sandstone-rich depositional environment (Fig. 3c). This observation is consistent with the description of geological log which shows sandstone interbedded with thin layers of mudstone. According to [1, 9], the madama Formation was deposited in braided stream environments. The resistivity log values indicate low porosity.

4.1.3 PALEOGENE SEQUENCE

The paleogene sequence known as Sokor is made up of continental deposits, mainly fluvio-lacustrine deposits [9, 28]. It can be divided into two formations: Sokor-1 at the bottom and Sokor-2 to the top.

The Paleogene-Eocene Sokor-1 formation ("Sokor alternances") consists of fluvio-deltaic sediments deposits [9] with vertebrate fossils, [2]. This formation consists of sandstones interbedded with mudstones in the uppermost deposits, while the lowermost sediments consists of sandstones and schists. This formation represents the reservoir rock in Agadem Block and has high porosity and permeability. In eastern Niger, a second rifting stage occurred from the Paleocene to the middle Eocene and resulted in deposition of the Sokor-1 Formation sandstones [28].

The lithology of the Oligocene Sokor-2 Member is mainly lacustrine mudstone, interbedded by thin sandstone layers. (Fig. 3d). The oligocene Sokor-2 formation consists of lacustrine deposits [9], with plant fossils [2].

The Sokor-2 formation composed from bottom to top by low velocity shales and claystones deposits. The low velocity deposits consist mainly of shales with a high GR value (120 API) and sandy clays with an average GR value (75 API) (Fig.3e). These observations are consistent with the predominance of low velocity shales in the lower deposits of Sokor-2. This formation represents a regional top seal for reservoirs in the Sokor-1 Formation [9, 30]. The Neogene and Quaternary mainly consist of fluvial deposits (Fig. 3f).

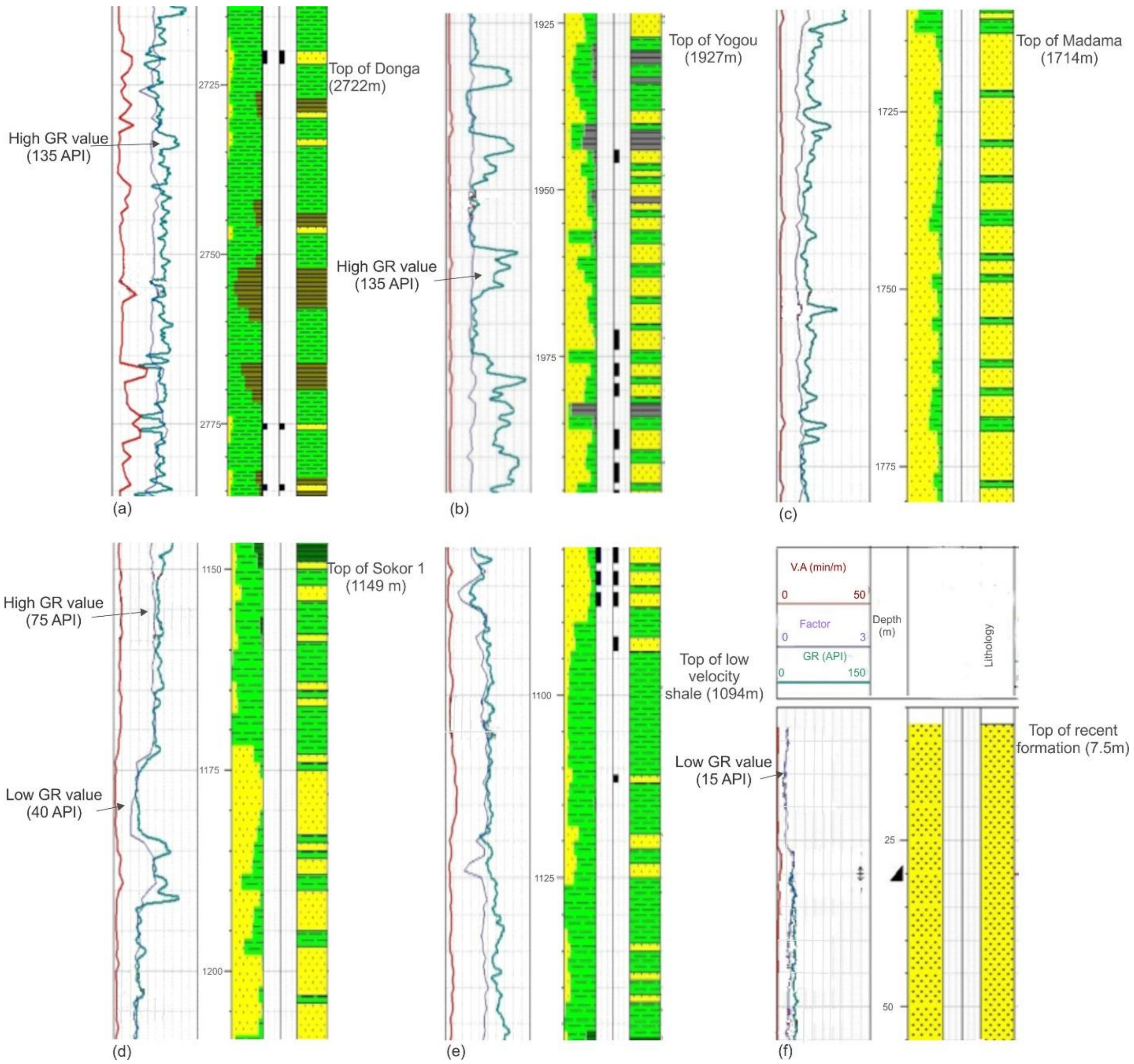

Fig. 3. Donga, Yogou (well Yogou N-1), Madama, Sokor-1, Sokor-2 and recent formations in well Garana W-1 (CNPC, 2012)

4.2 WELL CORRELATION

Donga formation (Fig. 4) is located between 3475 m -2722 m (753m thick) at YN-1. **Yogou** formation is observed in two wells, and Donga formation in one well. The thicknesses are 447m (2722 m - 2275 m depth) and 373m (2300 m - 1927 m) respectively at YN-1 and GW-1. This formation is thickest in the well YN-1.

The results (Fig. 3) show that in the well FS-1, the formation of **Madama** is located between depths 1980 m - 1910 m (70 m thick), in the well TiS-2 between 2150 m - 2094 m (56 m thick), in the well TiS-1 between 2130 m - 2086 m (44 m thick), in the well YN-1 between 2275 m - 1923 m (1698 m thick) and in the well GW-1 between 1927 m - 1714 m (213 m thick). Madama formation is thickest in the well YN-1.

Sokor-1 formation (Fig. 4): in the well FS-1, Sokor-1 is located between depths 1910 m - 1240 m (670 m thick), in the well TiS-2 between 2094- 1410 (684 m thick), in the well TiS-1 between 2086 m - 1404m (682 m thick), in the well YN-1 between 1923 m - 1260 m (663 m thick) and in the well GW-1 between 1714 m - 1140 m (574 m thick). Sokor-1 is thickest in the well TiS-1.

Low velocity shale was identified in all the wells between 1240 m - 1178 m (62m thick) in the well FS-1, 1410 m – 1347m (63m thick) at TiS-2, between 1404 m - 1202 m (202m thick) in the well TiS-1, between 1260 m -1255 m (5m thick) in the well YN-1 and between 1140 m - 1100 m (40m thick) in the well GW-1.

Sokor-2 formation (Fig. 4) is located between depths 1178 m – 915m (263 m) in the well FS-1, in the well TiS-2 between 1347 m - 1100 m (247 m thick), in the well TiS-1 between 1202 m - 986 m (216 m thick), in the well YN-1 between 1255 m - 802 m (453 m thick) and in the well GW-1 between 1100 m - 536 m (564 m thick). Sokor-2 is thickest in the well GW-1.

Neogene and Quaternary sequence: in the well FS-1 (Fig. 4), this sequence is located between depths 915 m - 7.5 m (707.5 m thick), in the well TiS-2 between 1100 m -7.5 m (1092.5 m thick), in the well TiS-1 between 986 m - 7.5 m (978.5 m thick), in the well YN-1 between 802 m - 9 m (793 m thick) and in the well GW-1 between 536 m - 7,5 m (528.5574 m thick). The Neogene and Quaternary sequence are thickest in the well TiS-2 (Fig. 4).

The delimitation of the main formation has allowed correlating the different sequences which were previously defined. Five lithostratigraphic logs distributed in several sectors of the basin were correlated in a NE-SW direction (Fig. 4).

The result of the correlation shows a variation in the thickness in all the sequences. The sediment's thicknes in the Sokor-1 formation (Paleogene sequence) gradually increases from the border to the center, while it becomes thinner from the border to the basin center for the Sokor-2 formation. The strata of Neogene-Quaternary sequence are subject to a thickening from the border towards the center of the basin (Fig. 4). The thickness variations observed on both sides of the secondary faults are attributable to the control of tectonics on the sedimentation.

During the deposition of Paleogene and Neogene-Quaternary sequences, the high thickness of sediments in the axial zone of the basin reflect a migration of depocenter towards the central part of Agadem area related to a high subsidence rate.

The five well logs studied show hydrocarbon potential for wells TiS-1 and TiS-2 compared to the wells GW-1, YN-1 and FS-1 (Fig. 4). These hydrocarbons potential have been highlighted in Sokor-1 formation exhibiting alternating reservoirs rocks. The wells TiS-1 and TiS-2 which have high hydrocarbon potential are located in the axial zone of Agadem where the subsidence is very strong. This strong subsidence is related to the fault activity (tectonic subsidence) which would favor the hydrocarbon accumulation in these wells.

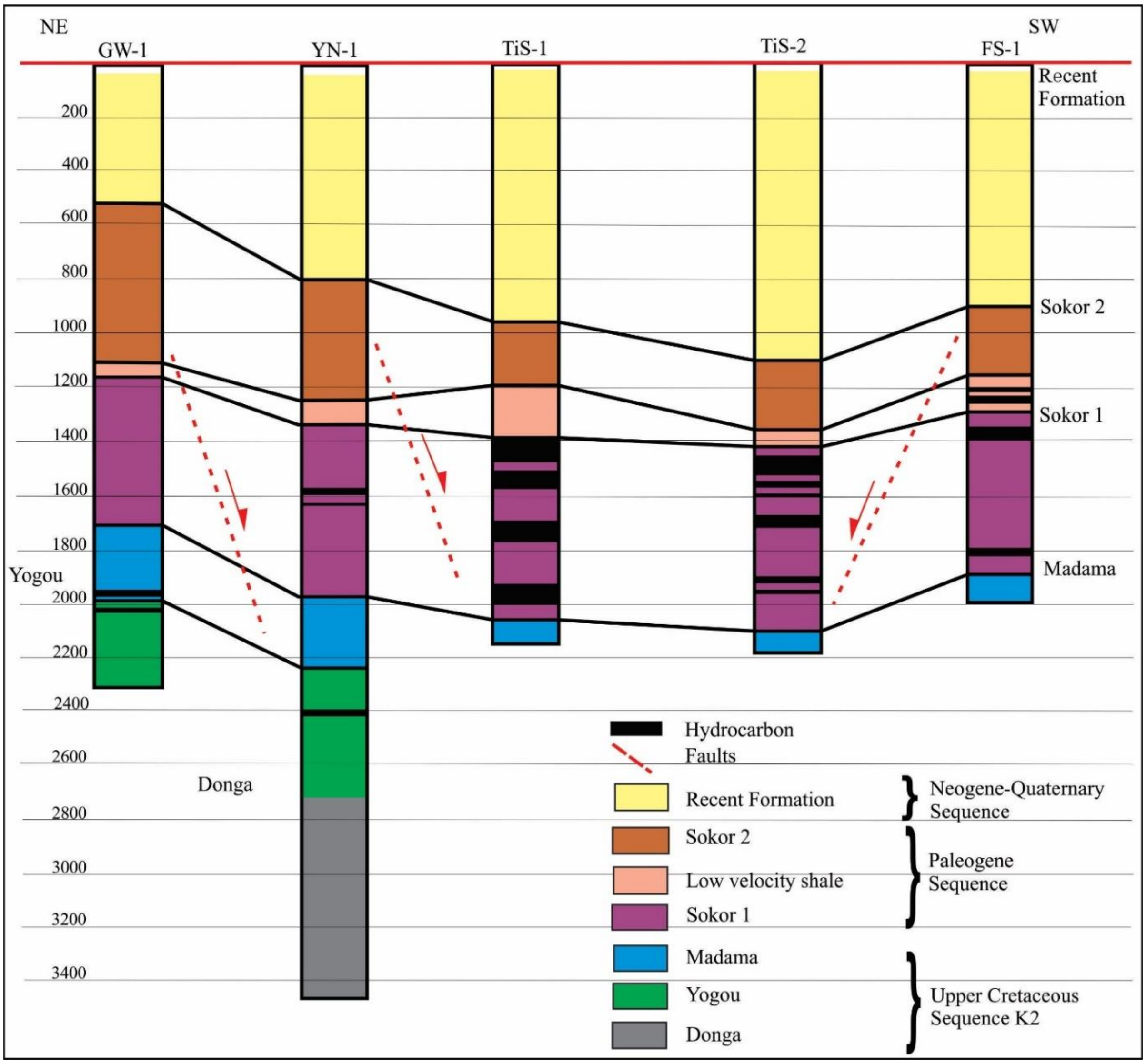

Fig. 4. Lithostratigraphic correlation (GW-1, YN-1, TiS-1, TiS-2, FS-1)

4.3 SEISMIC INTERPRETATION AND BASIN STRUCTURE

Seismic profiles were interpreted in this study to highlight the structure of the Termit Basin. The first step toward the interpretation was to recognize and delineate major seismic unconformities. The seismic reflector configuration analysis combined with well data has allowed identifying four main seismic sequences on the seismic sections. We have identified three regional unconformities or sequence boundaries which delineate four sequences, including the top of the acoustic basement. They are referred from bottom to top as: the early cretaceous sequence K1, the upper cretaceous sequence K2, the Paleogene sequence and the Neogene and Quaternary sequence in decreasing in age (Fig. 5). All these sequences are affected by normal faulting (Figs. 5, 6, 7). The lower boundary of K1 sequence is the deepest traceable unconformity and is characterized by a strong reflection overlying a zone of chaotic reflections interpreted to represent massive rock (Fig. 5). The upper boundary of K1 lays in angular unconformity onto the Precambrian basement.

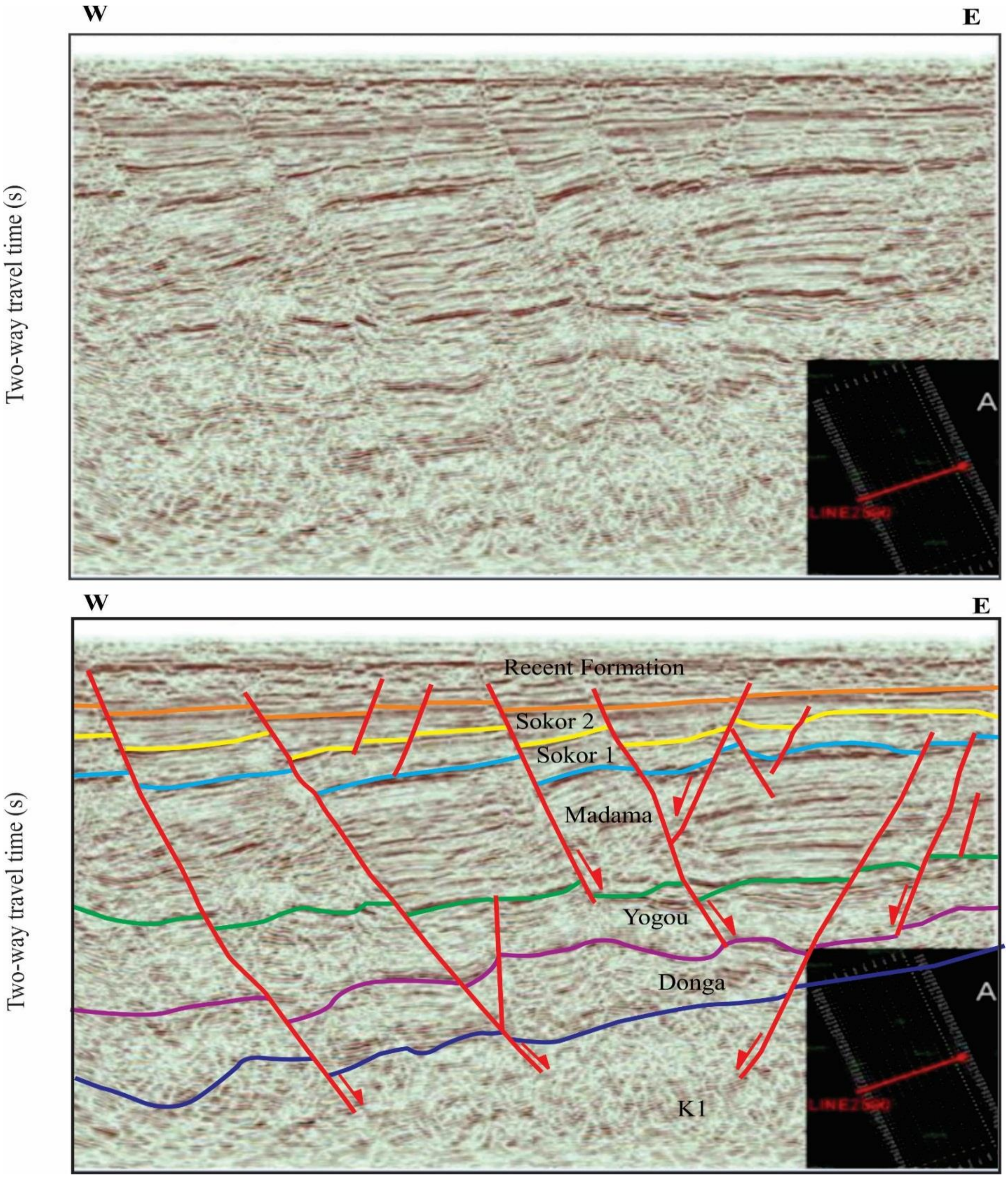

Fig. 5. Structural interpretation of seismic line 1 (L1) in Agadem block

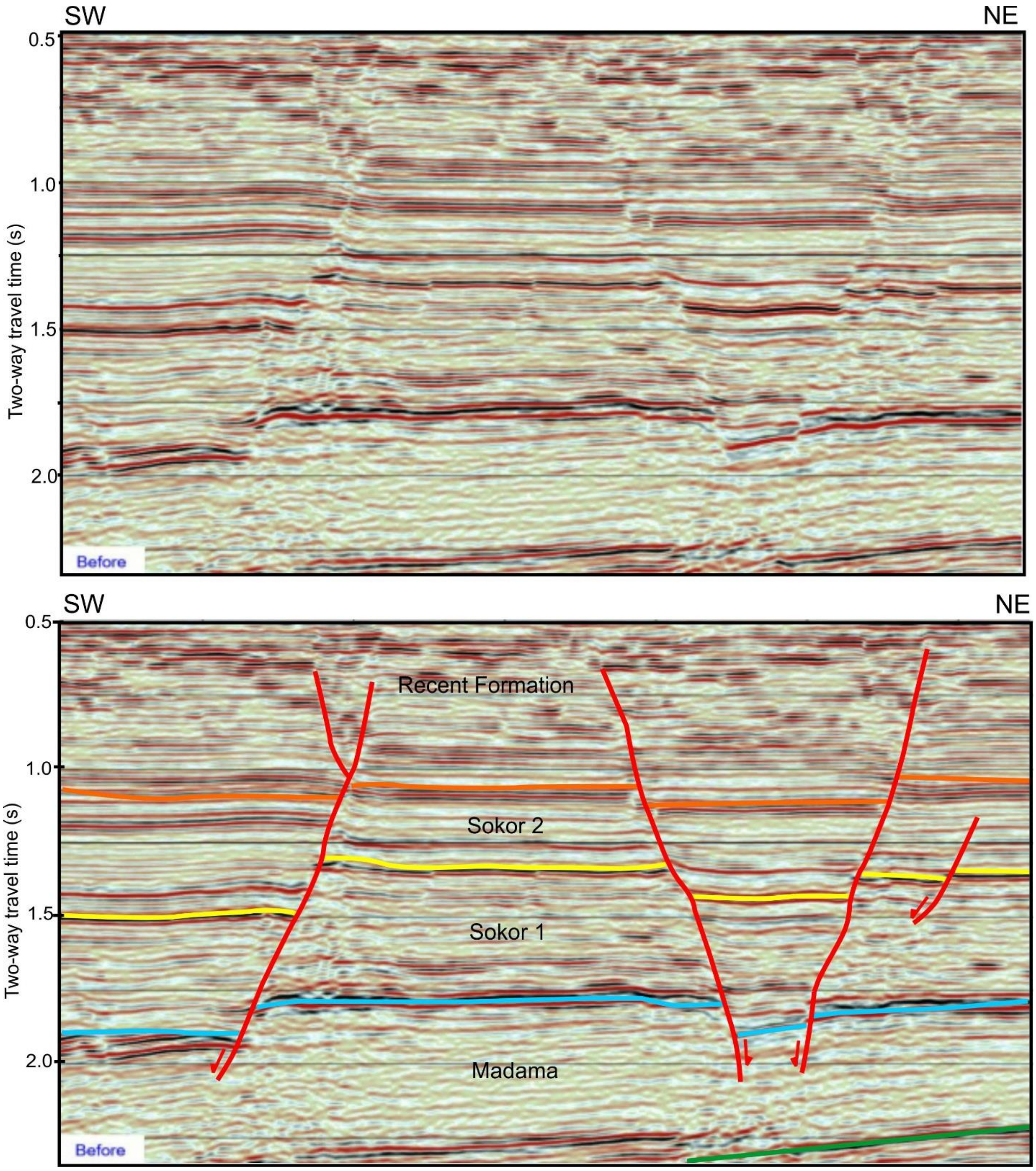

Fig. 6. Structural interpretation of seismic line 2 in Agadem Block (see figure 1 for location)

The Upper Cretaceous sequence in the basin can be divided into three formations: Donga, Yogou and Madama formations from bottom to top (Figs. 5, 7). This sequence is characterized by a low continuity and parallel reflections on seismic sections, and is affected by normal faults with NW-SE trending, and NE-SW trending (Fig. 5). The faults have variable displacement.

Deep-penetration profiles illustrate that the Agadem block is characterized by tilted blocks, bounded by large-scale normal listric faults. The area is also characterized by small scale grabens and half-grabens. The thickness variation and the decametric to hectometric scale anisopachous fold in the Donga formation show the synsedimentary nature of these structures (Fig. 8).

The Paleogene sequence in the basin is divided into two parts: Sokor-1 and Sokor-2 (Figs. 5, 6, 7). The seismic unit corresponding to this sequence consists of low-to good continuity reflection patterns. Erosion unconformity occasionally occurs beneath that sequence with the underlying Upper Cretaceous formation. In this sequence, NW-SW to NNW-SSE trending faults displacement developed tilted blocks structures. The extensional faults within the Sokor-1 and Sokor-2 sequences generated large accommodation space in the basin with high sediment thickness, which indicates that faults reactivation strongly influenced the sedimentation. The faults control on deposition was very strong at that time.

The Neogene-Quaternary recent formation is characterized by seismic reflectors less marked than those of the previous sequence (Figs. 5, 6, 7). This sequence shows attenuation and sometimes the lack of seismic reflectors, meaning a weak tectonic activity at this time. This attenuation of tectonic activity during the Neogene-Quaternary period, according to [9], is followed by a post-rift thermal subsidence, concomitantly with the deposition of alluvial plains deposits of the recent formations.

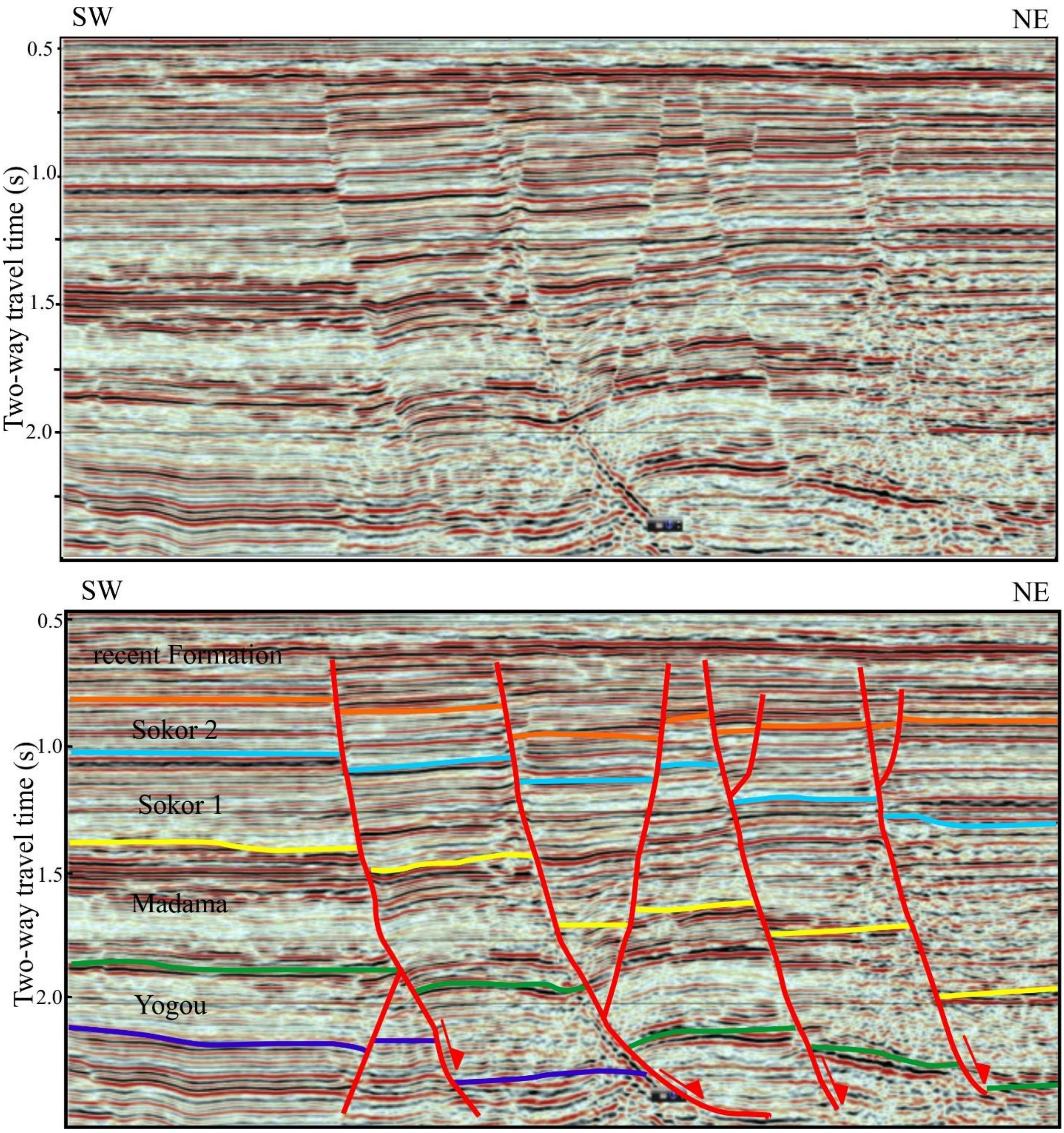

Fig. 7. Structural interpretation of seismic line (L3) in Agadem Block (see figure 1 for location)

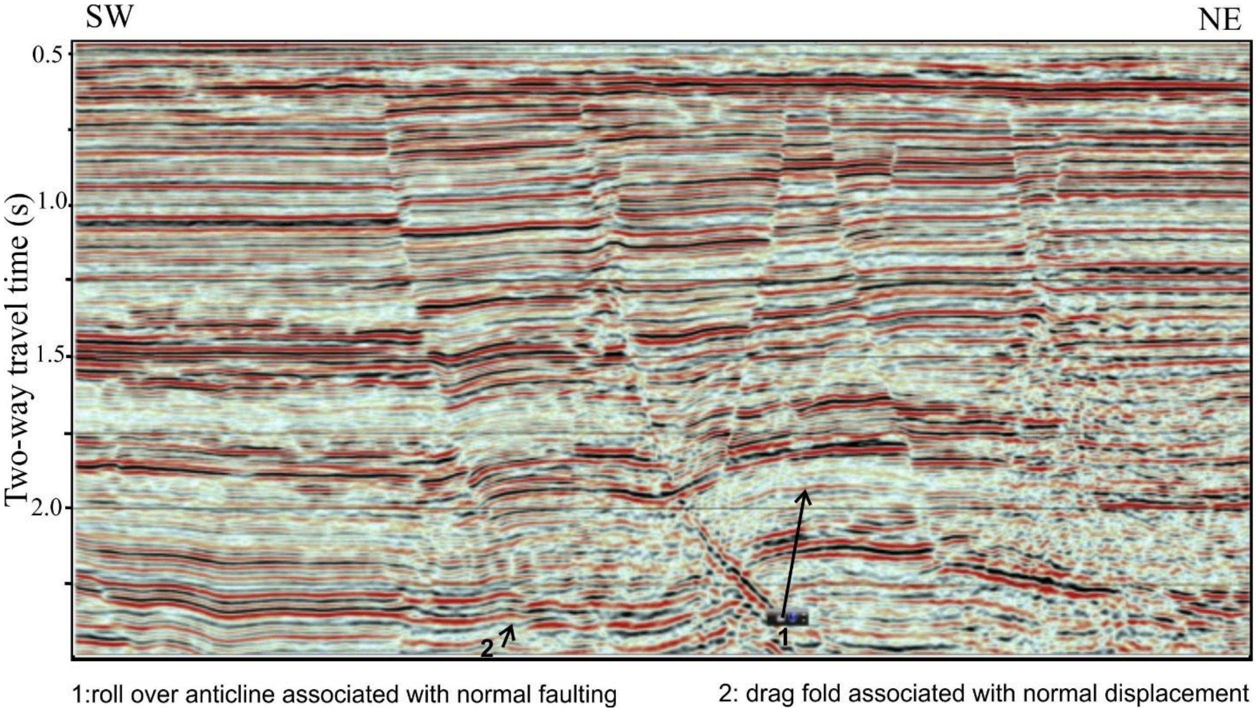

Fig. 8. Seismic line 3 (L3) showing micro-fold in the area (see figure 1 for location)

The detailed analysis of these seismic sections revealed the depth structure of the Agadem block, which is characterized by a graben system controlled by a series of NW-SE and NNW-SSE trending fault. These faults were active at different times and at different locations (Fig. 5). Evidence for synsedimentary deformation observed on seismic profiles is provided by the micro-folds in the sequences and the highly laterally variable sediment distribution created by the extensional faults displacements (Fig. 4). Another structural feature observed in this basin is the presence of tilted bocks controlled by listric faults, with NE-SW trending. According to [9], the basin's structural style in the West African System (WAS) is dominated by large tilted, normally faulted blocks which were active during the Early Cretaceous and Palaeogene. On seismic profiles most of the faults exhibit normal displacements which show that the area was dominated by an extensional tectonic regime (Figs. 5, 6, 7). These normal faults induce thickness variations, associated with displacements attenuation towards the top.

The faults can be divided into two sets based on the time of formation and reactivation. In one hand, the Early Cretaceous NW-SE-trending faults that was reactivated in the Paleogene, these kind of faults are linked to the opening of the South Atlantic [9], and on the other hand, the NNW-SSE-trending normal faults were formed in the Paleogene [9], (Fig. 1).

The evolution of Agadem Block is characterized by a low subsidence rate during the early Cretaceous (Neocomian to Albian), associated to the first episode of rifting, accompanied by fluviatile to lacustrine sedimentation which correspond to the Early Cretaceous sequence K1.

The evolution of the Agadem Block, during the Upper Cretaceous, is characterized by an increase of the subsidence rate, which favors the deposition of Donga, Yogou and Madama formations representing K2 sequence.

The Paleogene series in Agadem Block is dominated by the second phase of extension with NE-SW trending, which resulted in the reactivation of NW-SE trending faults and the formation of NNW-SSE-trending faults. These faults controlled the sedimentary infilling consisting of delta-lacustrine sediments of Paleogene sequence (Sokor-1 and Sokor-2 formation) [9].

A second cycle of rifting started when the African-Arabian Plate collided to Eurasian Plate. This rifting cycle includes the Paleogene syn-rift phase and the Neogene–Quaternary post-rift phase [8]. During this last period of rifting, the area experienced regional uplift [8], followed by post-rift thermal subsidence [29], which is in favor of the deposition of alluvial plain sediments of the Neogene-Quaternary sequence [9].

The detailed analysis of these four seismic sections revealed the depth structure of the Agadem Block. Evidence for synsedimentary deformation observed on seismic profiles is provided by the micro-folds (Fig. 8) in the sequences and the highly laterally variable sediment distribution created by the extensional faults. Another structural feature observed in this basin is the presence of tilted bocks controlled by synthetic and antithetic NE-SW trending listric faults. According to [9], The basin's structural style in the West African System

(WAS) is dominated by large tilted, normally faulted blocks, which were active during the Early Cretaceous and Paleogene. On seismic profiles most of the faults exhibit normal displacement, implying that the Termit basin was affected by an extensional tectonic regime (Fig. 5, 6, 7). These normal faults induce thickness variations, associated with displacements attenuation towards the top.

The Agadem block is an extensional asymmetric syncline graben bounded by NW-SE to NNW-SSE trending faults. These faults can be divided into two sets based on time of formation and/reactivation: the Early Cretaceous NW-SE-trending faults that was reactivated in the Paleogene, and the NNW-SSE-trending faults formed in Paleogene (Fig. 1) [9].

The evolution of Agadem block is characterized by a low subsidence rate during the Early Cretaceous allowing fluvio-lacustrine deposits which correspond to K1 sequence. The first episode of rifting in the Early Cretaceous (Neocomian to Albian) was accompanied by fluviatile to lacustrine sedimentation which corresponds to the Early Cretaceous sequence K1.

The evolution of the Agadem block in the Upper Cretaceous is characterized by an increase in the subsidence rate which favored the deposition of Donga, Yogou and Madama formations representing the K2 sequence.

The Paleogene in Agadem Block is characterized by a second phase of extension with NE-SW trending which resulted in the reactivation of NW-SE trending faults and the formation of NNW-SSE trending faults. These faults controlled the sedimentary infilling consisting of deltaic-lacustrine sediments of Paleogene sequence (Sokor-1 and Sokor-2 formation) [9].

A second cycle of rifting started when the African-Arabian Plate collided to the Eurasian Plate. This second rifting cycle consists of a Paleogene syn-rift phase and a Neogene–Quaternary post-rift phase [8]. During this last period, the area experienced regional uplift [8], followed by post-rift thermal subsidence [29], which is in favor for the deposition of alluvial plain deposits of the Neogene-Quaternary sequence [9].

5 Conclusion

The tectono-sedimentary analysis of the Termit trough, based on the combined use of well data seismic profiles, allow to reconstruct the sedimentary and structural basin evolution. The analysis of the well logs shows that the sedimentary infilling of Agadem Block with 4000 m in thickness on average, include from bottom to top:

- The Early Cretaceous sequence K1, consisting of continental fluvio-lacustrine sediments;
- The Upper Cretaceous sequence K2, comprising marine sediments (Donga, and Yogou formation) and fluvial to fluvio-deltaic sediments (Madama formation);
- The Paleogene sequence, including the fluvio-deltaic deposits of Sokor-1 and Sokor-2;
- Neogene and Quaternary sequence with alluvial plain deposits

The correlation of the geological logs of the five wells of the Agadem block highlights, on the one hand, lateral variations in the thickness of the layers attributed to the activity of the faults and, on the other hand, identifying the wells with high hydrocarbon potential.

The seismic profiles interpretation reveals that tilted block structures were associated with normal syn-sedimentary listric faults of the Agadem block. The correlation of the seismic data with the geological logs allowed to calibrate chronologically the seismic sequences to the main stratigraphic sequences.

The tectono-sedimentary analysis reveals that the sedimentary infilling is controlled by NW-SE and NNW-SSE trending faults. Thus, based on the structural evolution, two major periods have been distinguished:

- The first period, which was a rifting and subsidence stage, prevailed from the Lower Cretaceous to the Upper Cretaceous. The extension dominantly produced NW-SE trending normal faults.
- The second period was also a rifting and subsidence time that occurred during the Paleogene. The extensional regime reactivated NW-SE faults and generated NNW-SSE trending faults.

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