Geodynamic Framework and Petroleum Potential of the Cap Bon - Gulf of Hammamet Province - Tunisia*

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Abstract

Subsurface analysis of the Cap Bon-Gulf of Hammamet province CGP of Tunisia, based on well logs, seismic data and outcrops reveals the dynamic basin evolution and portrays its hydrocarbon accumulation. Thousands of kilometers of seismic profiles, dozens of well logs as well as gravity measurements together with surface geology were fully examined and integrated in depth. Seismic-based mapping of key horizons of specific sequences illustrate the partition of the dynamic sedimentation all over the strike-slip faulted basins. Selected time slices spanning upper Cretaceous to Tertiary illustrate the spatial environmental and depositional differentiation and allow retracing its geodynamic evolution and its integration into the Mediterranean dynamic evolution. 3D analyses indicate episodes of major regional change in paleogeographic and tectonic setting. These occurred in the late Maastrichtian to lower Paleocene, middle to late Eocene, late Oligocene, early Middle Miocene, late Miocene and late Pliocene to Villafranchian. Episodes were probably induced by the relative motions of the African and Eurasian plates. Plate motions induced discrete steps in the regional kinematics and geodynamics that governed the palaeogeographic evolution of the CGP.

Several of oil and gas fields have been discovered; a great number are accumulated in the Middle Miocene Birsa Formation sands: Tazarka, Birsa, Oudna, Baraka fields. Other hydrocarbon reservoirs were recognized. These are drawn by: the Maamoura field in the Langhian Ain Grab Formation and the Senonian Fractured chalky limestone, the Yasmin oil field producing from the Langhian Ain Grab Formation, the Halk El Menzel oil field reservoired in the Oligocene limestones, the Belli oil field in the intensively fractured Ypresian Bou Dabbous carbonate formation, the Zinia and the Dougga fields reservoired in the

Campanian–Maastrichtian chalky limestone of the Abiod Formation, the Lotus gas field accumulation in the Cretaceous Serdj Formation, the most ancient Cap Bon gas field producing from the Hauterivian-Valanginian M'cherga Formation sands, etc.

The paper intends a regional review of the area through a comprehensive and consistent interpretation and modeling. It illustrates that significant exploration potential still exists in the studied province with quite some sizeable undrilled structures. The dominant play remains within the Neogene. The study is directed toward unraveling and understanding the complexity of the CGP.

Introduction

The Cap Bon (Figure 1) Peninsula is known by the Sidi Abderrhaman gas field discovered in the 1950s, which produced from Lower Cretaceous sands and located on the anticline having with the same name. The Korba anticline follows to the south. This is characterized by a pop-up structure. The Korba and Kelibia wells crossed an entirely carbonate series and no seal was found. Further to the southwest, the anticline has less limestone and presents sufficient seal interval. This is proven by the discoveries of gas in the Abiod fractured limestone at Zinnia and oil in the Lower Eocene Bou Dabbous limestones at Belli. The hydrocarbon indications in the neighbouring wells, such as Neapolis, inspire exploration in the offshore zone: Gulf of Hammamet.

The Gulf of Hammamet (Figure 1) is a complex zone with salt structures, living anticlines, deep Mio-Pliocene depocenters and grabens. Cretaceous and Tertiary reservoirs are interesting with the presence of the main Mesozoic and Cenozoic source rock intervals in the area. Several discoveries have been made during the last decades such as Tazarka, Birsa, Oudna, Yasmin, Cosmos, Zelfa and Baraka oil fields (producing from Mid-Miocene Ain Grab limestones and Birsa sands) and Maamoura (tested oil from the Campanian-Maastrichtian Abiod fractured chalky limestones). Based on a regional consistent evaluation the petroleum geology of CGP area is presented. Earlier studies focused on restricted areas or selected subset of the regional stratigraphy. This paper is an aims to present a consistent structural and stratigraphic evaluation of the CGP area.

Lithostratigraphy

Outcrops are characterized by significant thickness and facies variations. Sedimentary records vary from Eocene to Quaternary age within the study area (Figure 2). Older series are described from neighboring outcrops further to the southwest in central

Tunisia. Surface geology reveals non-depositional or erosional hiatuses witnessing the complexity of the tectono-sedimentary events that controlled the structuring of the region.

The Turonian-Campanian series are represented by the Aleg Formation (Burollet, 1956; Bujalka et al., 1971). It consists of a thick sequence of clays and marls intercalating numerous and thick calcareous, argillaceous limestones and massive gypsum. Within the study area, the Aleg Formation is a deep marine environment deposit (Burollet, 1956) approximately 230m thick.

The upper Campanian-lower Maastrichtian interval is expressed by the Abiod Formation (Burollet, 1956). The interval is made of two chalky and massive limestone ridges interspersed with alternating limestone and marls. The chalky mudstone lower member is rich in foraminifera (*Globigerinidae*, *Globotruncanidae* and *Orbitoides*) together with frequent fragments of pelecypods and echinids. The marly and clayey middle member is rich in benthic foraminifera *Globotruncana stuarti*, *Pseudotextularia*, and *Neoflabellina*. The upper massive carbonate member contains *Inoceramus* prints and echinids (Burollet, 1956). It characterizes an open marine environment within grabens and subsiding areas (Burollet, 1956). In the subsurface, the Abiod Formation was crossed by several wells in the CGP area. It keeps almost the same facies varying in thickness from 36 to 360m.

The upper Maastrichtian-Paleocene is represented by the El Haria formation (Burollet, 1956). It is a succession of clayey and marly layers with limy intercalations. It is a planktonic foraminifera rich formation with *Globigerina Uvigerines*, *Globorotalia* (Burollet, 1956). It was deposited in an open marine environment. Several wells crossed the El Haria Formation in the subsurface. The facies of the El Haria Formation is characterized by lateral changes (clay with some interbedded limestone; clays, interstratified limestones and marls). Its thickness varies from 50 to 370m. Microfauna and nannoflora content of the El Haria Formation show that, in some places, various parts of the formation are missing. In the northeastern part of the CGP area, the El Haria Formation disappears entirely.

An unconformity separates the Campanian-Maastrichtian limestone of the Abiod Formation and the Paleocene marls of the El Haria Formation. This is seen in several wells. This unconformity and sedimentary gap is observed by many authors (Zouari, 1995; Rabhi et al., 2001).

The Lower Eocene is expressed by the Bou Dabbous Formation, which dates the Ypresian. It is made by limestone series intercalated with marly levels (Fournié, 1978). During the Eocene, an infra-neritic sea occupied the Cap Bon region allowing the deposition of limestone, rich with pelagic microfauna represented especially by *Globigerinids*, small corals and brachiopods

(Comte and Dufaure, 1973; Fournié, 1978). The Bou Dabbous formation is crossed by several wells in CGP area. In the SE of the CGP area, this formation is absent; it keeps almost the same facies and its thickness varies from 27 to 348m.

The middle and Upper Eocene is represented by the Souar Formation. It is essentially a series formed by marine clays (Souar A and Souar B) with intercalated beds of limestone rich in *Nummulites* and *Discocyclines* corresponding to the Reinèche member (Burollet, 1956). The Souar Formation corresponds to the oldest terrains exposed in the Cap Bon region that occupy the anticline Jebel Abderrahmane (Burollet 1956, Arnould, 1950; Ben Ismail Lattrache, 1981; Ben Salem, 1992). Towards the northeast, the Souar Formation is replaced by marine bioclastic limestone extending to the Eastern Cap Bon and Gulf of Hammamet: the Halk El Menzel Formation. It denotes a wide stable platform deposit (Bismuth and Bonnefous, 1981). The area south of CGP shows a deep marine area; a bald area where the Eocene series are absent in the eastern coast of Cap Bon and in the southeastern Gulf of Hammamet (Bismuth and Bonnefous, 1981). In subsurface, the Souar Formation keeps almost the same facies; its thickness varies from 46 to 324m.

The Oligocene-Lower Miocene is represented by the Fortuna Formation (Burollet, 1956). It relates to a thick detritic series forming the raised topography of the Cap Bon Peninsula (Ben Salem, 1992). This lithostratigraphic unit is made of two units. The lower unit, called Korbous (Burollet, 1956), is made of shallow limestone deposits; it is around 20m thick (Comte and Dufaure, 1973). The upper part is made of series sandstone bars with coarse quartz. The total thickness of the Fortuna Formation is 800m. At Jebel Abderrahmane, the Fortuna Formation decreases in thickness towards the southeast as reflected in the general morphology of this structure (Ben Salem, 1992). From a paleogeographical point of view, the Fortuna Formation is characterized by a relatively deep marine area that characterizes the southern and central part of Abderrahmane and, a relatively high carbonate zone that characterizes the northern periclinal termination of Jebel Abderrahman and Jebel Korbous (Ben Salem, 1992). In boreholes, the Fortuna Formation is dominantly clay at the base and sandstone at the top with some limy beds. Its thickness varies from 34 to 1,114m and possesses two lateral equivalents: the Ketatna and Salammbo formations.

The Ketatna is formed by limestone rich in bryozoans, algae, *Amphistegina*, mollusks and *Nummulites* (Bismuth, 1973). It characterizes a reefal environment (Fournié, 1978). Few wells crossed the Ketatna Formation. It is formed by limestone and some dolomite beds with a thickness varying from 16 to 235m. The Salammbo Formation was defined by Fournié (1978) in the Gulf of Gabes. It is a shaly equivalent of the Ketatna limestone and Fortuna sandstones. It is a planktonic-foraminifera rich formation including *Globigerina*, *Globorotalia*, *Globigerinae*, *Ciperoensis*, and *Globigerinids* (Fournié, 1978). It characterizes an open marine environment. Within the study area, the Salammbo Formation is crossed by one well and is formed by shale with an 80m thickness.

The middle Miocene series is well developed in the peninsula of Cap Bon. It occupies large anticlinal structures, as well as large synclinal depressions. In the study area, the Cap Bon group consists of four formations: the A level, the Oued El Hammam Formation, the Ain Grab and the Mahmoud Formation. Hooyberghs (1977) defined the A Level on the eastern flank of the Jebel Korbous monocline. This is a metric-scale interval formed by conglomeratic sandstone (El Euch, 2007). In the subsurface, the A level is crossed by one well and is 25m thick. The Oued El Hammam Formation was defined by Hooyberghs (1973) on the northeastern flank of the Jebel Korbous monocline. This formation is formed by green shaly marls rich of planktonic foraminifera (*Globigerinoides sicanus*, *Praeorbulina glomerosa*). It is dated lower Langhian with 20m thickness (Hooyberghs, 1973; 1977). In subsurface, the Oued El Hammam formation is 84m thick.

The Ain Grab Formation is 10 to 15 m thick and is composed of limestone with conglomerate at the base, rich in echinoderms and mollusks (Burollet, 1956). In the Cap Bon area, an unconformity is observed between the transgressive series on the Fortuna Group and the Oued El Hammam Formation (El Euch, 2007). Several wells crossed the Ain Grab formation in subsurface. It keeps almost the same facies. Thicknesses range from 7 to 190m.

The Mahmoud Formation (Biely et al., 1972) is upper Langhian in age (Hooyberghs 1977, Ben Ismail Lattrache 1981, Bismuth, 1994). It accumulates clays, rich with *Orbulina suturalis* and *Orbulina universa* and characterizes open marine environment. It is about 30 m thick. In the subsurface, the Mahmoud Formation was crossed by several wells. Its thickness varies from 30 to 645. The Mahmoud Formation is formed by shale with some sandstone intercallations.

The Middle Miocene continues in the Cap Bon region by the Oum Douil Group. It is a transgressive marine cycle over the continental coarse sandstone summit of the Fortuna Formation (Mejri et al., 2006). It was formed, at the base, by the alternations of clay and sand of the Beglia Formation (Burollet, 1956) with fluvial cross bedding, dune or deltaic (Biely et al., 1972; Blondel, 1991; Tayech-Mannai, 2009). The Beglia Formation is rich with *Ammonia beccarii*, ostracodes, *Hipparion*. It is overlain by the clays of the Mahmoud formation, which are approximately 300m thick. It is attributed to the Serravallian. In the subsurface, the thickness of the Beglia Formation varies from 140 to 1,175m. In the Gulf of Hammamet, the Beglia possesses a lateral equivalent corresponding to the Birsa Formation (Ben Ferjani et al., 1990; Bedir, 1995). It is a sandy clay formation with carbonate levels known as the Intra-Birsa carbonate, recognized in the oil wells drilled in the Gulf of Hammamet. Its thickness varies from 220 to 840m. Beglia is succeeded by the Saouaf Formation. This series presents alternating marl, sandstone and limestone coquina. This formation is composed by marine shoreline facies with frequent cyclic sedimentation. The Saouaf is about 2,000m thick. The age is Serravallian terminal to Tortonian.

The Upper Miocene is characterized by three formations: the Somaa Formation, the Ben Khiar Formation and Bir El Oued Formation. The Somaa formation was defined by Colleuil (1976) as a 250 to 300m thick interval, with alternating yellow or red sands with conglomeratic levels. The Somaa Formation rests unconformably on the Saouaf Formation (Colleuil, 1976; Ben Salem, 1992). In the subsurface, the Somaa Formation varies from 200 to 515m thick. The Beni Khiar Formation is defined near the village of Beni Khiar close to the city of Nabeul (Colleuil, 1976). It is estimated 15m thick and is made of sandstone and clay with some intercalation of limestone and marl. The late Messinian Bir El Oued Formation reaches a thickness of 100m (Colleuil, 1976). This series is formed by sandstone, sand and small banks of limestone. The Pliocene is represented by the continental Segui Formation, which is well developed and conformably overlies the Upper Miocene (Burollet, 1956).

Structural Evolution

The integrated compilation of seismic and borehole data show that the area of study undergoes great lateral and vertical variations which are induced by the global geodynamic evolution resulting from the Eurasian-African plate convergence. Borehole calibrated seismic sections lead to the following episodes of major tectonic change.

The Lower Cretaceous period is characterized by an NW-SE extensive regime whereas for the Late Cretaceous extension axis is NE- SW (Castany, 1947; Castany 1951; Zouari, 1995; Chikhaoui, 1988). The interpreted seismic section (Figure 3) indicates the onlapping character of the El Haria formation. It underlines the unconformity of the Paleocene intervals. This unconformity is expressed on several boreholes. This sedimentary gap is observed on outcrops by many authors (Zouari, 1995; Rabhi et al., 2001). The late Cretaceous is marked by a general NW-SE directed compression (Zouari, 1995). This compression is recognized on land, in the Grombalia area, by a stratigraphic gap materialized by the absence of the lower Paleocene (Ouahchi, 1993). Several drilled wells expose hiatuses in the lower Paleocene or the lower Maastrichtian ages (Figure 4).

During the early to Middle Eocene period, a compressive regime directed NW-SE took place (Ben Ayed, 1986; Chihi, 1995). This phase is responsible of the major structures observed today (Ben Ayed; 1986). In the Cap Bon area, this compression phase is responsible of the generation of series of NW-SE directed faults. Due to their general orientation, these extensional faults were sealed by the clay and marl deposits of the middle to upper Eocene Souar formation.

The Oligocene is marked by an NNE-SSW directed extensional regime (Ben Ayed, 1986; El Euch et al., 2004; Melki et al., 2010). This extensional period allowed the development of grabens and half-grabens making the available space for the Fortuna deposition. The latter exhibits lateral thickness and facies changes (sandstone and clay in sandstone and marl). A correlation between five wells located on the Cap Bon province, after a flattening on top of Fortuna formation expresses the shape of the depositional environment of this formation (Figure 5). It relates to a thick detritic series, which are forming in the present time the raised topography of the Cap Bon peninsula (Ben Salem, 1992). Interpreted seismic sections express the prograding behavior of this siliciclastic interval.

The Ain Grab Formation represents a transgressive system and this interval displays a high-amplitude reflecting horizon with remarkable continuity and seismic frequency. It is on a regional reference helping to correlate the network of seismic data (Sebei et al., 2007). In the Gulf of Hammamet, the Ain Grab Formation was unconformably deposited on earlier series. During the Serravalian age, the northeastern part of Tunisia was marked by a NW-SE compressive period as seen in the Saouaf region by reverses faults series trending NW-SE (Saadi, 1997). The maximum shortening is directed NE-SW (Letouzey and Trémolières, 1980).

During the Tortonian stage, the whole region was affected by a major compressive phase known as the Atlassic phase (Burollet, 1956; Zargouni, 1979; Zouari, 1995). This NW-SE directed phase resulted on NE-SW trending folds (Korbous and Abderrahmane anticlines separated by Takelsa and Dakhla Korba synclines) and the occurrence of normal faults directed NW-SE (Figure 6).

An important tectonic unconformity is highlighted by seismic sections, which seals the folded, faulted and partially eroded Neogene deposits. This unconformity is the major regional tectonic event of Late Miocene-upper Pliocene (Ben Ayed 1986; Ben Salem 1992; Chihi 1995). Due to this NW directed compression event, the basin underwent folding and inversion. This environment led to the creation of the available space for the deposition of the late upper Miocene Somaa Formation. The interpreted seismic section (Figure 7) shows the Somaa Formation laying unconformably on the upper Miocene Saouaf Formation.

The interpreted calibrated seismic profile in the Gulf of Hammamet show clear expression of the Miocene unconformity (Figure 8). The Pliocene compression induced the inversion of the Hammamet basin and the uplift of Cap Bon area forming thus the Abderrahman anticline (Messoudi and Hamouda, 1994).

The interpreted calibrated seismic profile in the Cap Bon area trending NW-SE (Figure 9) shows a thickness variation between both flanks of the Abdurrahman anticline. This variation expresses the tectonic inversion occurred in the area. The basin area becomes a high zone. It is conventional to involve a relaxation phase following a compressional regime. This corresponds to the transgression of the Middle Pliocene and a subsidence around Nabeul-Hammamet, which promotes the healthy development of these series. The rest of the Cap Bon could correspond to a relatively high area explained by the absence of similar deposits in the Miocene and Pliocene (Ben Salem, 1992).

Petroleum System and Play

The Tunisian stratigraphic column presents many source rock intervals with good potential; these are spread from Paleozoic to Cenozoic. A number of source rock intervals were identified in the area through studies and analyses based on outcrops and borehole data samples. The main proven source rocks here are the Albian Fahdene Formation, the Cenomanian to Turonian Bahloul Formation and the Ypresian BouDabbous Formation.

The Albian shales and limestones cover northeastern Tunisia. It is an organic rich interval with good TOC values varying from 0.65 % to 4 %, reaching 400m thickness in the CGP area. The Late-Upper Cenomanian Bahloul Horizon is one of the main source rocks in Tunisia; it consists of laminated and marly limestone with large Globigerinids of Late Cenomanian age (Robaszynsky et al. 1990a and 1990b). The Bahloul Formation has been recently documented by Zagrarni et al. (2008). Surface sections offered TOC values varying from 1.1% to 3.6% in central Tunisia. Borehole samples within the organic rich part of the Bahloul Horizon lead to a TOC ranging from 0.8 to 6.4%. The hydrocarbon potential may reach 33g/kg at Oued Bahloul.

The BouDabbous Formation is made up of a well-bedded mudstone with abundant planktonic foraminifers. It covers the Gulf of Hammamet and parts of the Pelagian Sea. With a thickness varying between 50m to 350m, the TOC content of the BouDabbous ranges between 0.5 and 2.5% (Fournié, 1978; Burollet and Oudin, 1980). Due to its proximity, the BouDabbous sourced the Nummulite packstone of the Sidi EI Itayem and Ashtart oil fields.

Most hydrocarbon accumulations are reservoired within the Mid-Miocene Birsa Formation sandstones, such as Dougga, Tazarka, Oudna, Birsa, Cosmos and Yasmin fields. These sands exhibit excellent reservoir quality (Figure 4). The Ain Grab limestones flowed some 3,500 bopd on test on Maamoura. Eocene reservoirs include the Halk el Menzel Formation and the Lower Eocene BouDabbous Formation. Fractured BouDabbous Formation is the significant reservoir onshore Cap Bon province such as at Belli, Al Manzah and Beni Khalled fields. The Abiod Formation possesses reasonable matrix porosity with typically low permeability. Fracture porosity and connected pore volume is required for the Abiod Formation to be a viable reservoir. The critical moment of the CGP petroleum systems is the late Miocene to early Pliocene where peak hydrocarbon migration has occurred. Trap retention since this time appears not to be an issue in the studied area.

Conclusion

This is a compilation based on surface geology, borehole data (well logs and subsurface geology), and surface seismic data covering the CGP area. The region expresses imbricate extensive and compressive structures with complicated arrangements. Across-calibrated structural and stratigraphic consistent interpretation and assessment show that significant exploration potential still exists within the Gulf of Hammamet. The dominant exploration plays within the CGP area remain within the upper cretaceous tertiary interval while focusing on the lower to middle Miocene series. These results quality are well supported with the abundance of source rocks. Finally, due to the structural complexity of the area, detailed geological modeling using 3D seismic survey is well recommended.

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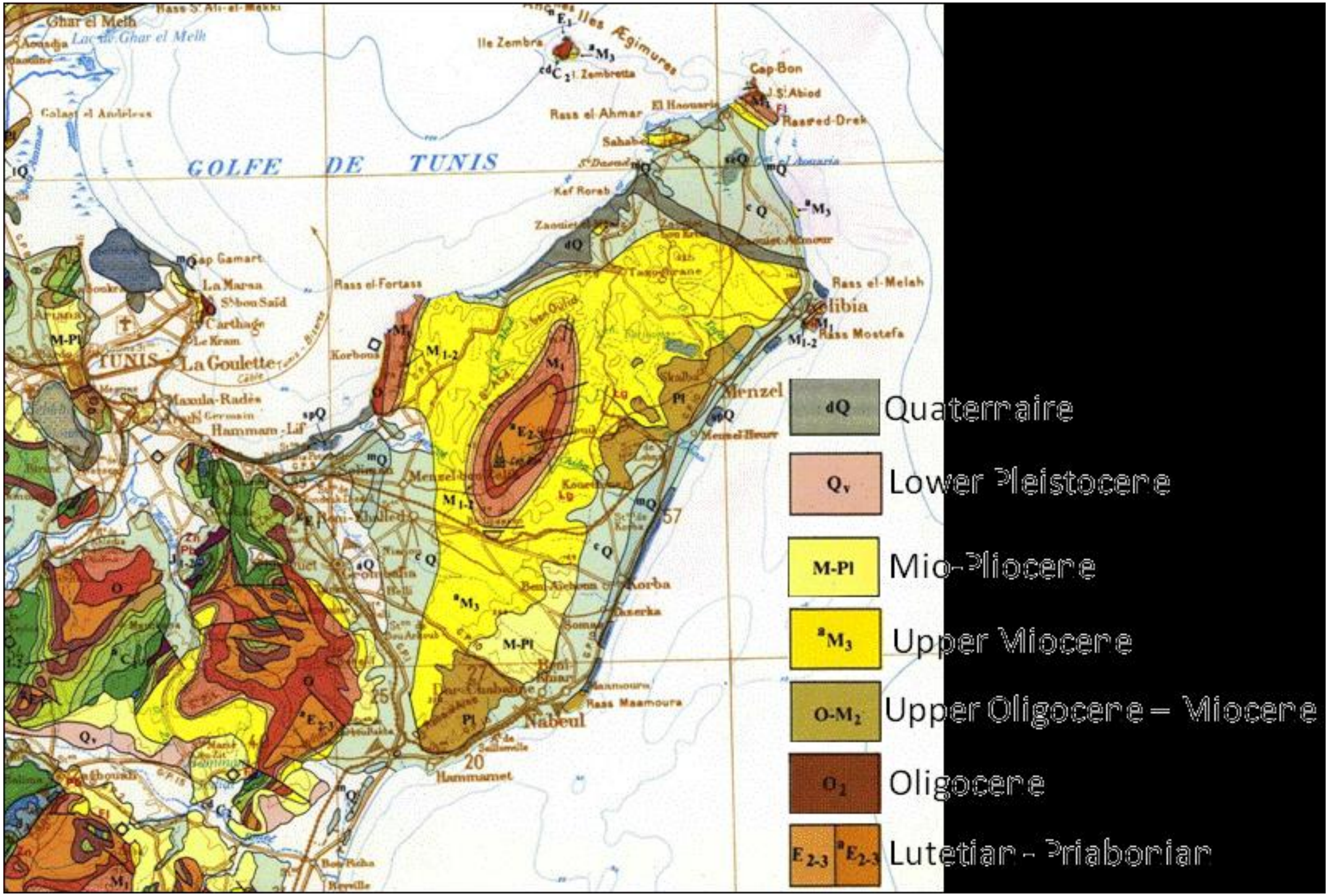

Figure 1. Geological map of the Cap Bon area (map 1/500,000).

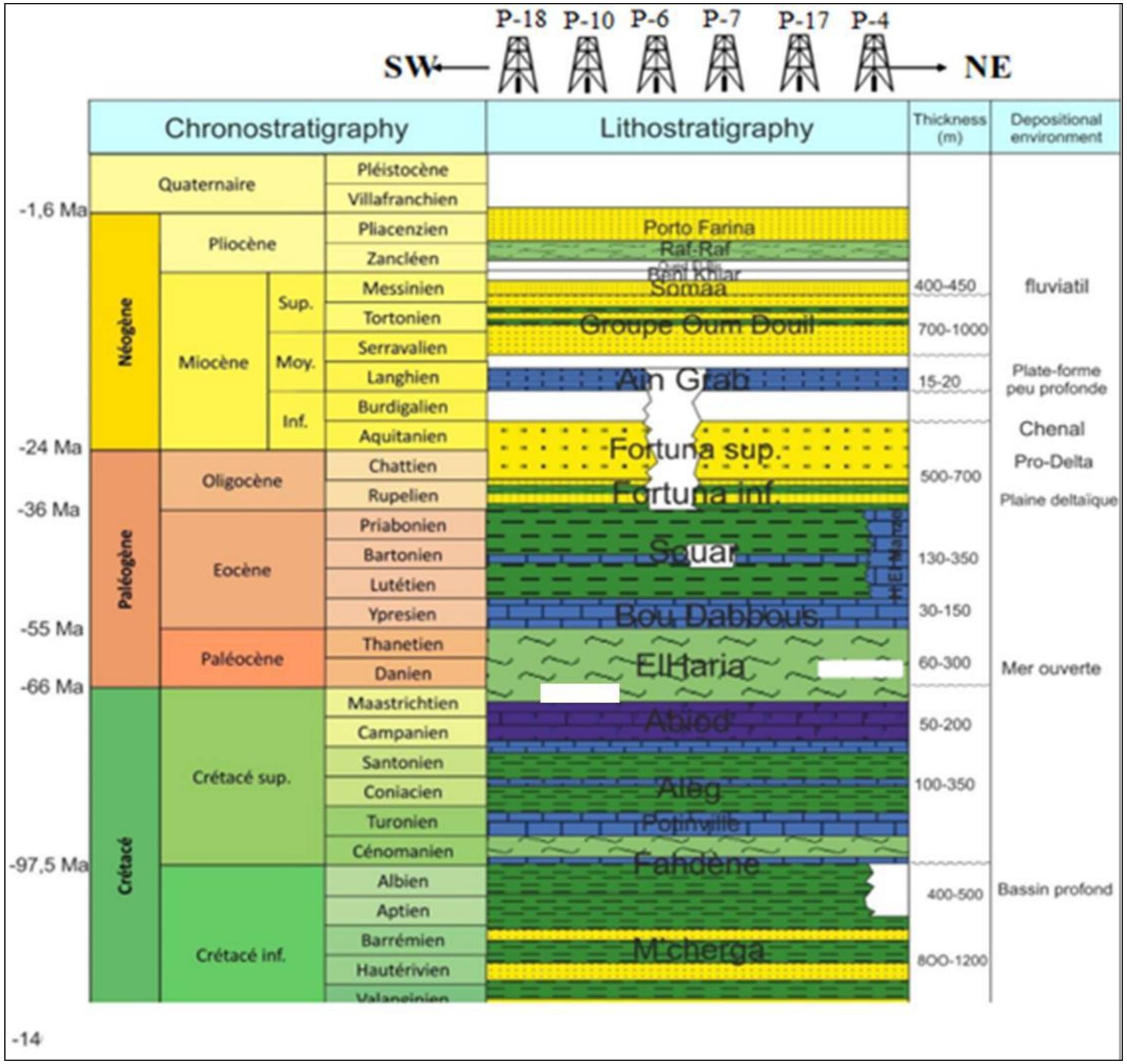

Figure 2. Synthetic lithostratigraphic chart for the study area.

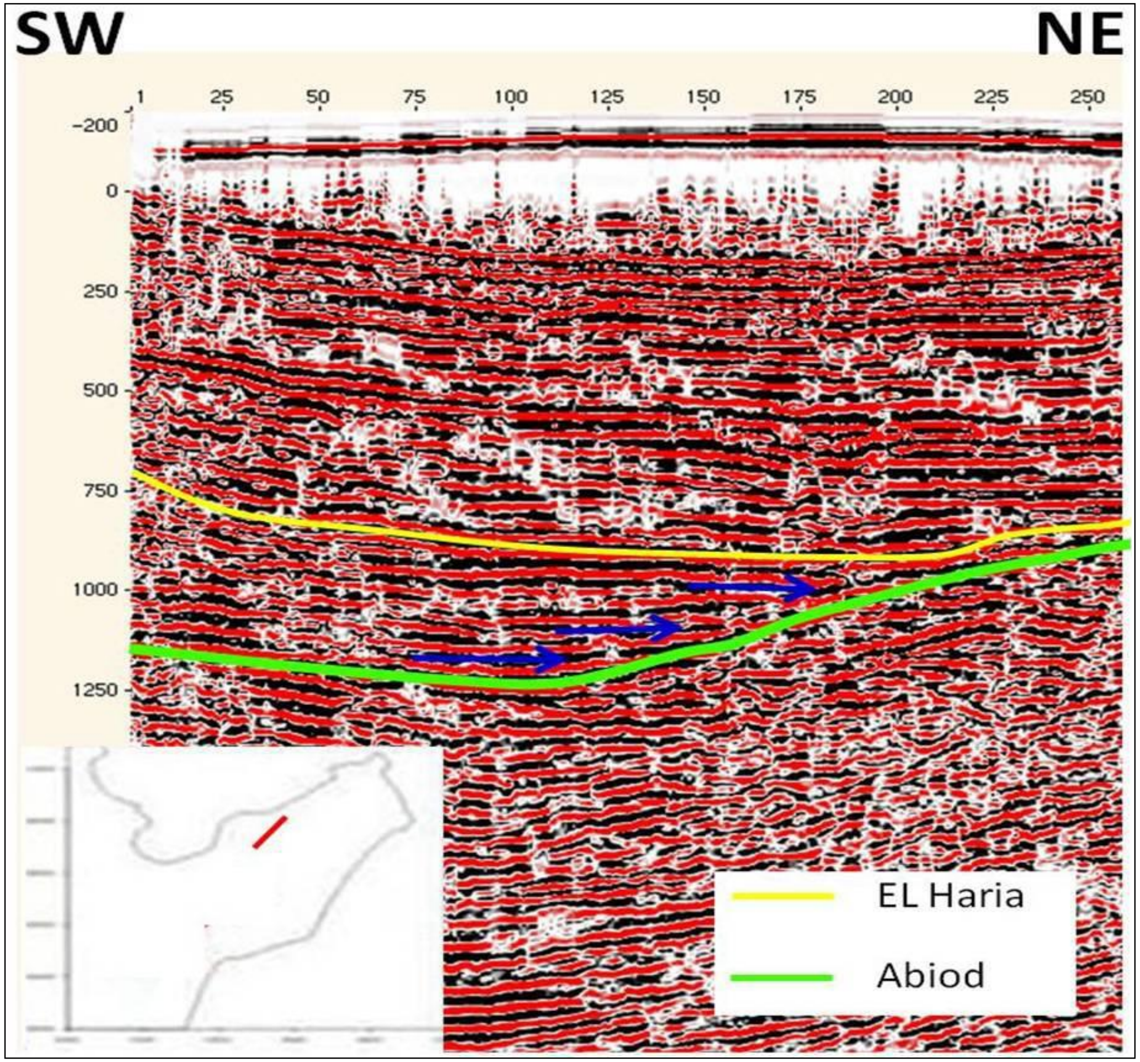

Figure 3. Seismic section located in the North of the Cap Bon area. The seismic response characterizes the onlaps of the Paleocene El Haria Formation.

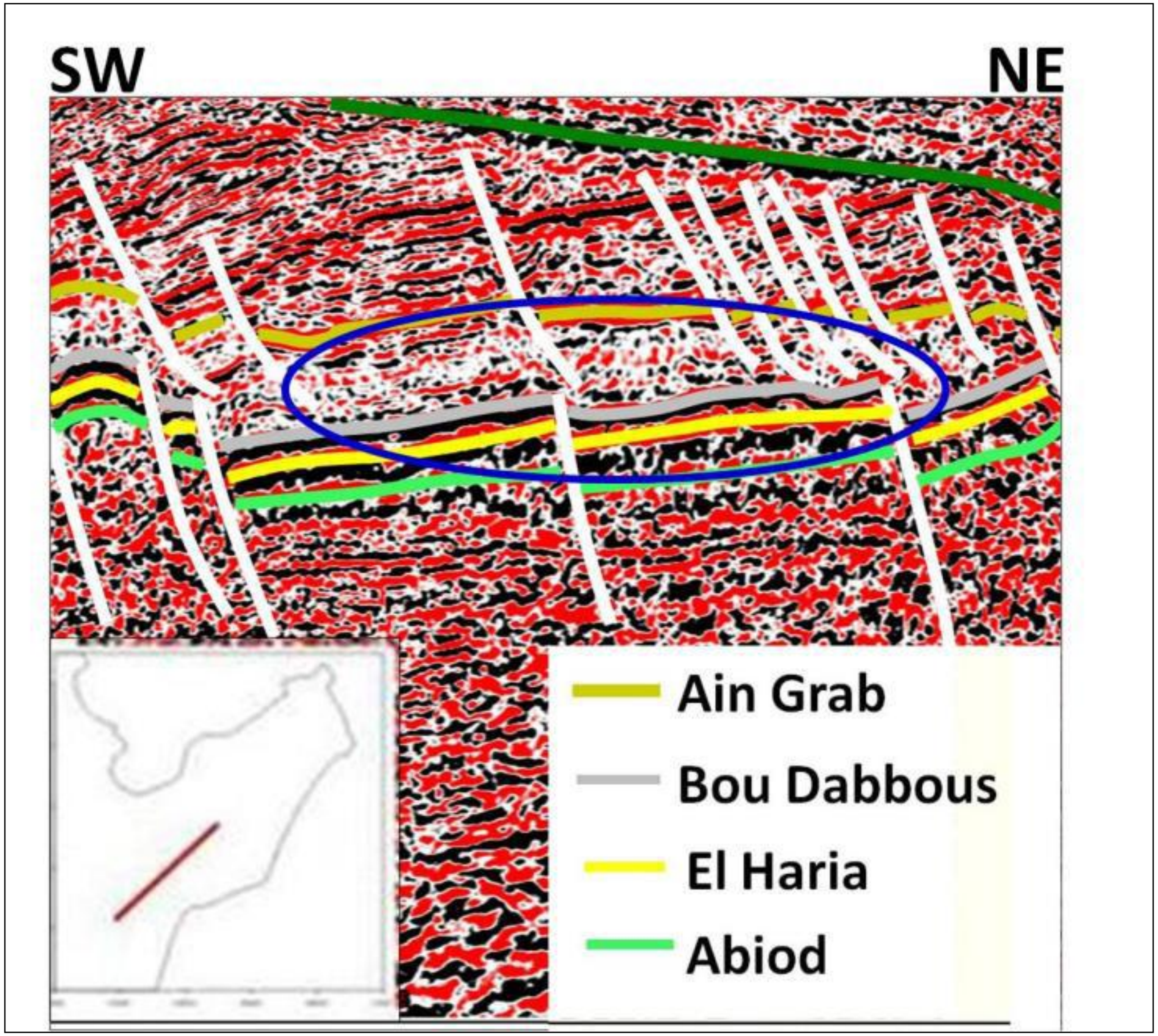

Figure 4. Seismic section located near Grombalia. The seismic response characterizes the normal faulting of the Ypresian (grey) and older series.

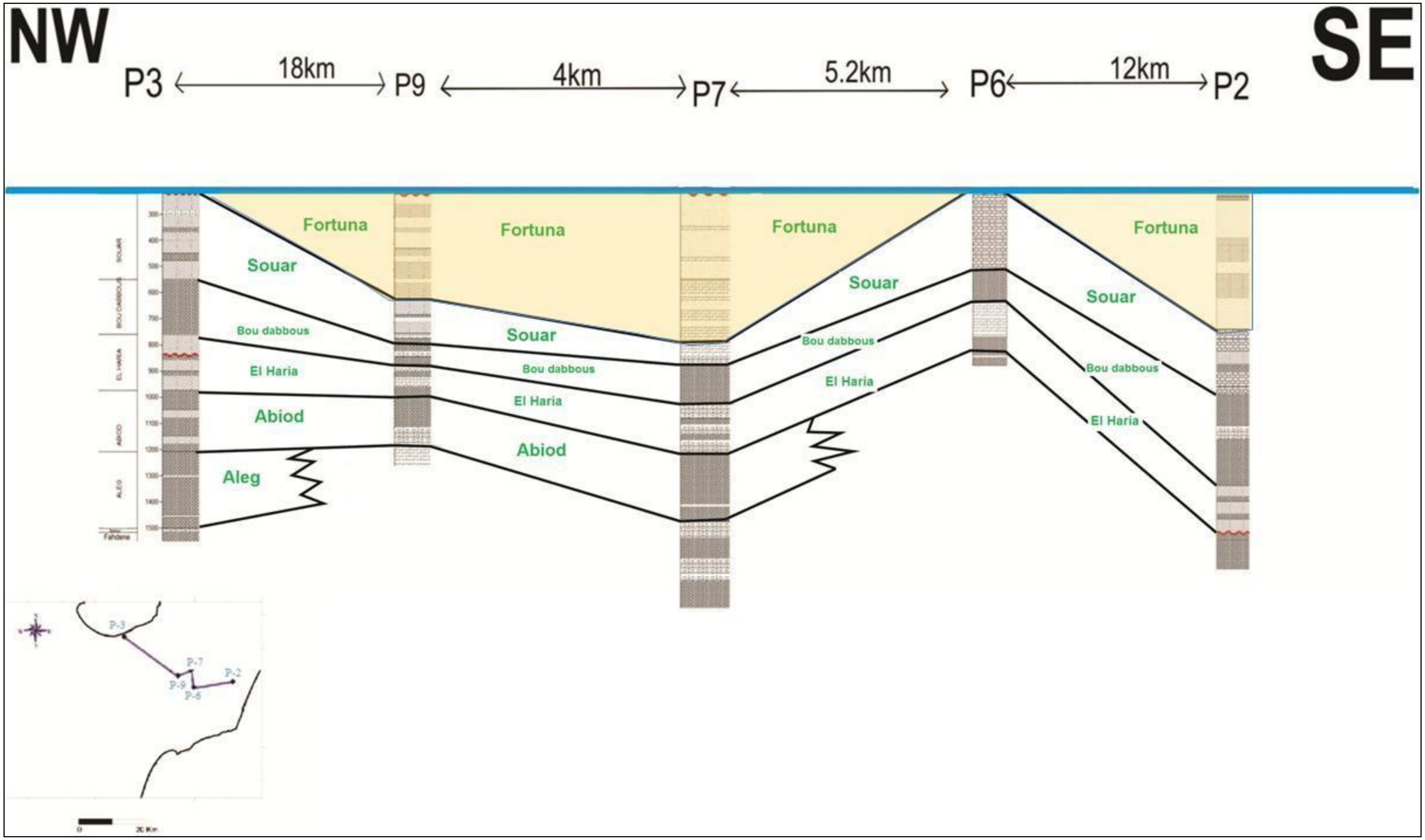

Figure 5. Lateral correction between five wells drilled in the Cap Bon peninsula. A flattening on the top of the Fortuna Formation expresses the available space and the shape of the depositional unit.

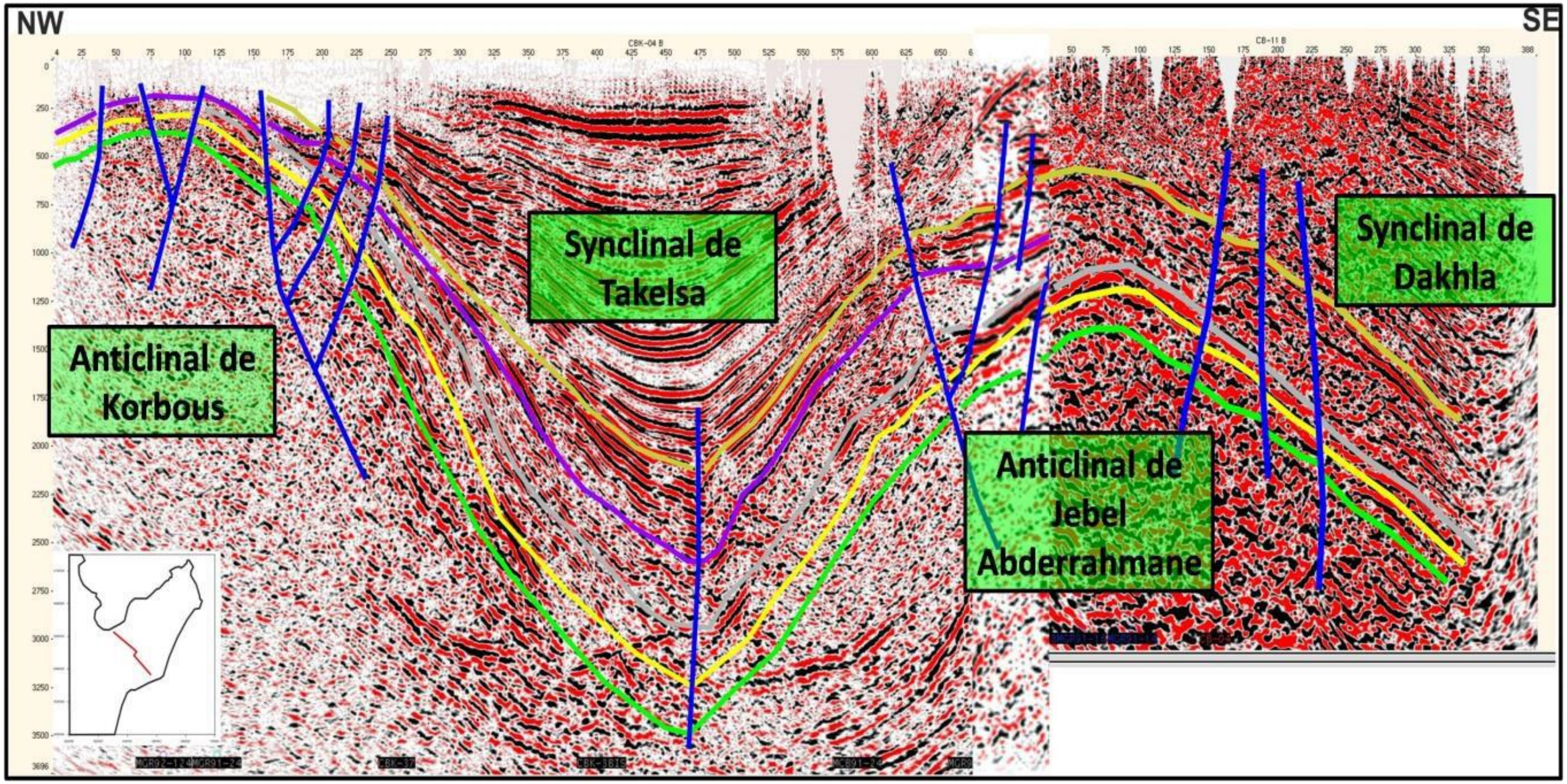

Figure 6. Seismic section located near Grombalia. The seismic response characterizes the folding occurred in the area after the deposition of the Miocene series.

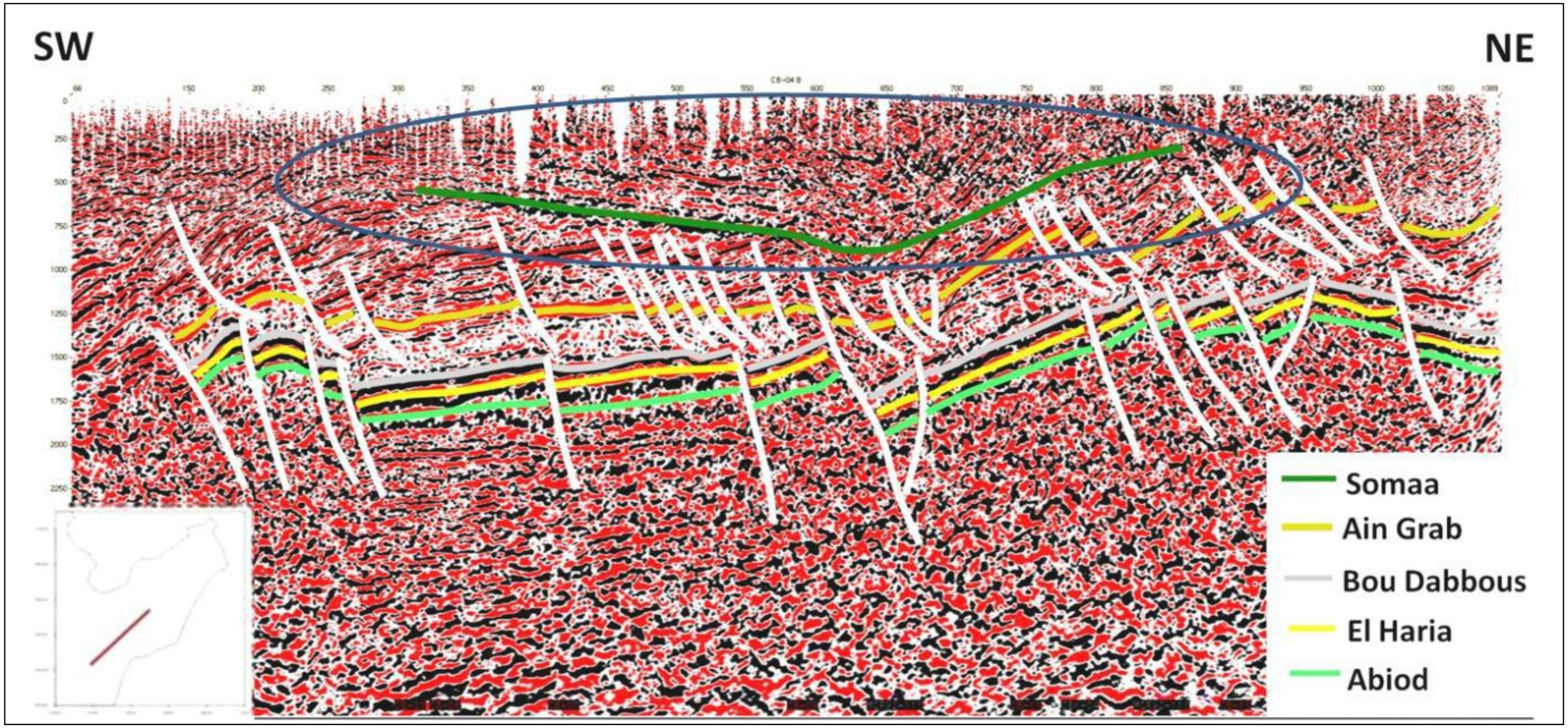

Figure 7. Interpreted seismic section expressing the Somaa Formation trough.

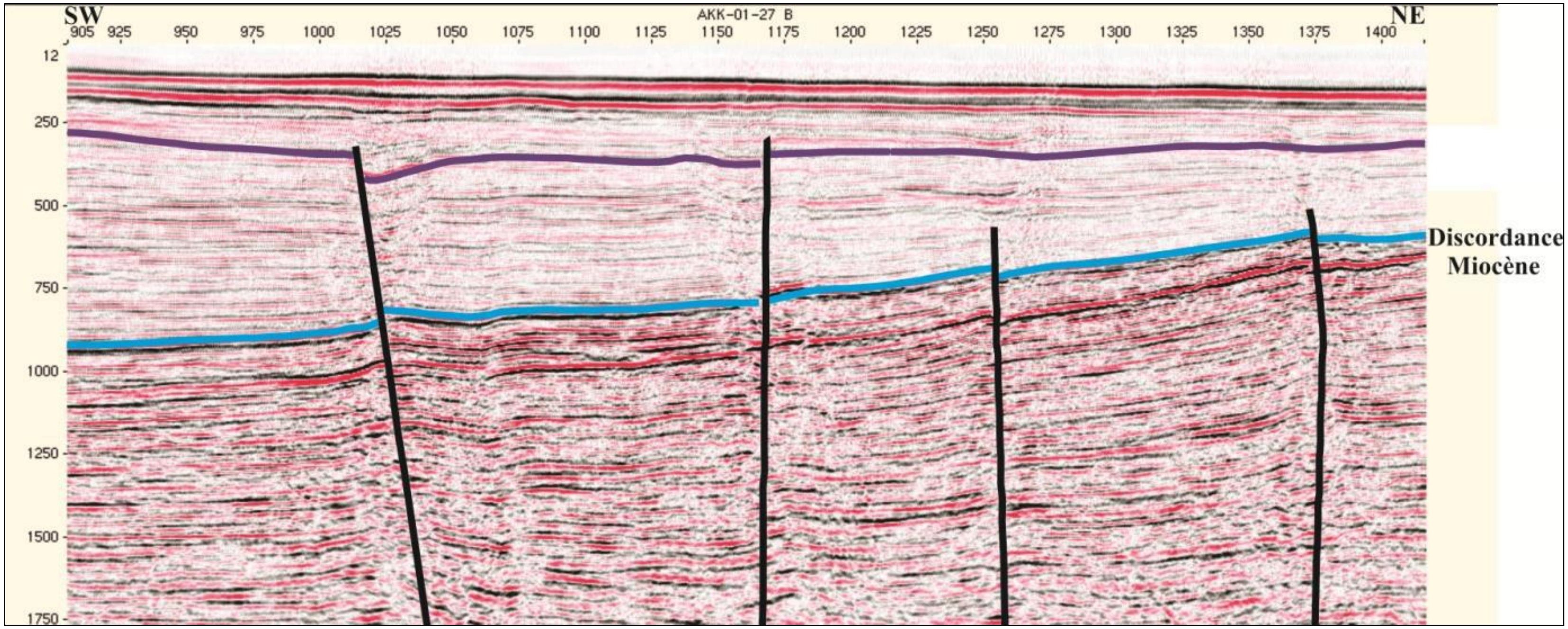

Figure 8. Interpreted seismic section expressing the Pliocene Rafraf Formation laying unconformably on the Miocene series.

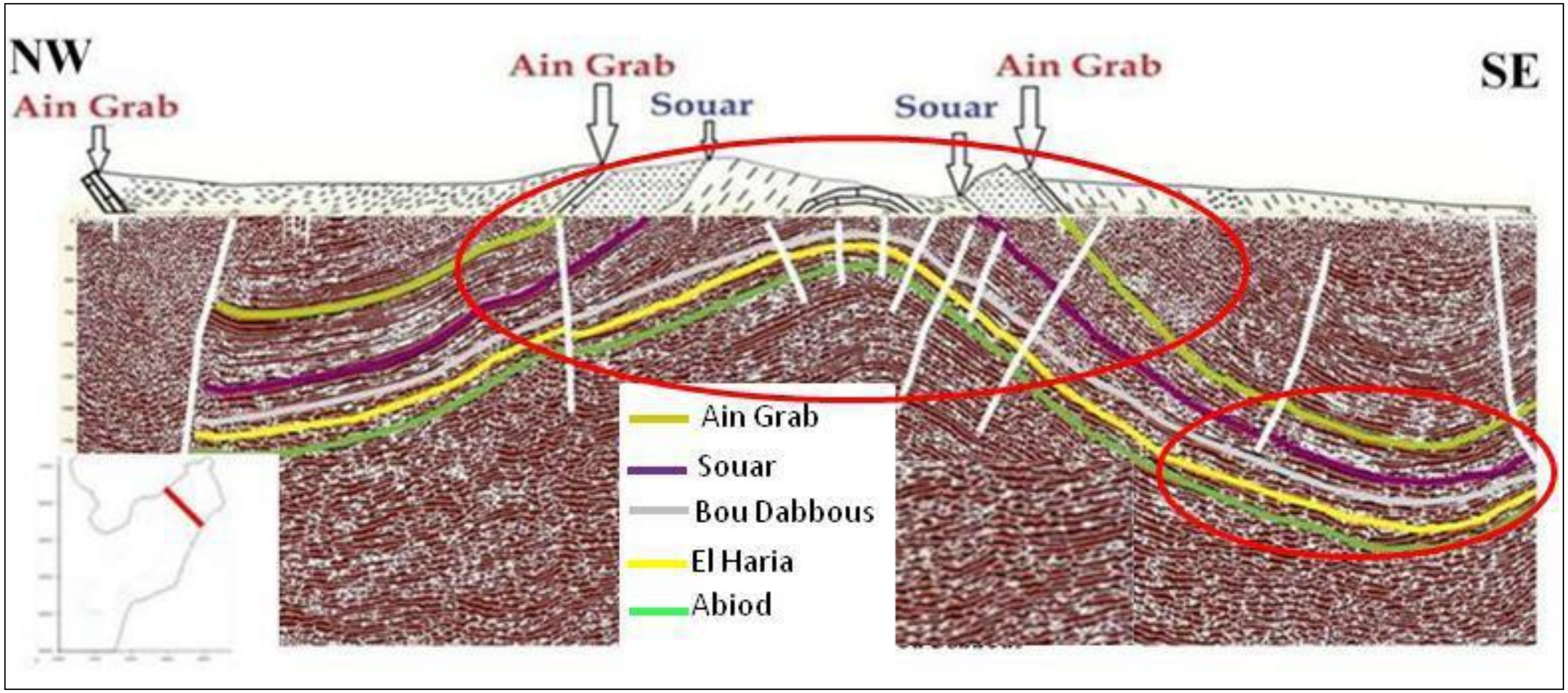

Figure 9. Interpreted seismic section compared to the outcropping geology over the Cap Bon area.