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STRUCTURAL STYLE AND ITS IMPACT ON TRAP FORMATION AND HYDROCARBON DISTRIBUTION IN MUGLAD RIFT BASIN, SUDAN

ALI ABD ELKAREAM OMER

DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE

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Abstrak

Muglad Basin diiktiraf untuk menjadi sebahagian utama Sudan lembangan perselisihan dalaman. Ia adalah salah satu produk utama zon Afrika Tengah ricih. Ia mempunyai ciri-ciri urutan tebal bukan marin clastic daripadalewat Jurassic / Awal Cretaceous umur Tertiari. Lebih daripada 15 km seksyen sedimen telah disimpulkan daripada data seismic dalam palungutama. Tiga episod perselisihan utama didokumenkan dalam lembangan. Acara perselisihan pertama dianggarkan telah berlaku dalam lewat Jurassic / Awal Cretaceous, yang kedua masuk lewat Cretaceous kali Coniacian-Santonian dan berterusan sehingga akhir Cretaceous dan yang ketiga semasa Tertiary. Rangka kerja struktur lembangan dikawal oleh dua set sesar: seluas kira-kira utara-selatan tren set kesalahan Cretaceous dan barat laut-tenggara tren kesalahan Tinggi. Kesalahan berulang pengaktifan semula dan, mungkin, arah tekanan pemanjangan serong semasa perselisihan Tertiari, dijana sistem yang kompleks lembangan perselisihan pemanjangan dan transtensional. Ini kerumitan struktur telah dikawal dengan ketara penjanaan, penghijrahan dan pemerangkapan hidrokarbon. Contoh kawalan ini termasuk: (a) struktur penyongsangan terbentuk selepas fasa utama caj minyak hanya akan bergantung kepada yang dipindahkan semula hidrokarbon. (B) condong blok sesar pemanjangan memerlukan meterai sesar sisi dan di bahagian-bahagian dipenggal batu sumber, penghijrahan diarahkan ke dalam takungan overlying dan oleh itu ini adalah satu risiko penerokaan utama (c) sesa mencelup arahan dan lontaran boleh memainkan beberapa peranan dalam sisi penghijrahan hidrokarbon. Tempoh matang haba model untuk Pembentukan Abu Gabra adalah menunjukkan bahawa dalam Abu Gabra Lower penjanaan hidrokarbon mencapai pengusiran di Aptia (> 50% nisbah transformasi) dan terus membentangkan hari dan waktu penjanaan minyak puncak dan pengusiran daripada batu sumber Abu Gabra adalah berlaku selepas kemasukan batuan meterai berkaitan dalam kawasan kajian.

Abstract

Muglad Basin is recognized to be a major part of Sudanese interior rift basins. It's one of the main products of Central African Shear zone. It is characterized by thick non-marine clastic sequences of Late Jurassic /Early Cretaceous to Tertiary age. More than 15 km of sedimentary section have been inferred from seismic data in the main trough. Three major rifting episodes are documented in the basin. The first rifting event is estimated to have occurred in Late Jurassic/Early Cretaceous, the second in Late Cretaceous Coniacian-Santonian times and continued until the end of cretaceous and the third during Tertiary. The structural framework of the basin is controlled by two sets of faults: an approximately north-south trending set of Cretaceous faults and northwest-southeast trending Tertiary faults. The repeated faults re-activation and, possibly, an oblique extensional stress direction during the Tertiary rifting, generated complex system of extensional and transtensional rift basins. This structural complexity had significantly controlled the generation, migration and entrapment of hydrocarbon. Examples of these controls include: (a) Inversion structures formed after the main phase of oil charge would only depend on re-migrated hydrocarbon. (b) Tilted extensional fault blocks require lateral fault seal and in truncated parts of the source rock, migration is directed into the overlying reservoir and therefore this is a key exploration risk (c) faults dipping direction and throw can play some role in the lateral migration of hydrocarbon. The thermal maturity modelling for the Abu Gabra Formation indicates that in the Abu Gabra-Lower the generation of hydrocarbon reached the expulsion in the Aptian (>50% transformation ratio) and continued to present-day and the time of peak oil generation and expulsion from Abu Gabra source rocks accumulate after deposition of related seal rocks within the study area.

Dedication

To Whom I love

Bouchra Boumanqar

Musab, Mohamed, Rayan and Adam

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My sincere thanks and gratitude to my supervisor professors, Dr. Ralph Kugler and Dr. Mustaffa Kamal for their help, friendly assistance, continuous support, encouragement throughout this study, guidance, discussions that made the study interesting and successful.

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CHAPTER ONE

INTRODUCTION

1.1 Background

Mann et al. (2003) noted that the giant oil fields, which contain around 67% of the total world hydrocarbon reserves, group in approximately 30% of the world's land surface. These oil fields can be segregated into six main tectonic depositional configurations: (1) continental passive margins fronting major ocean basins (2) continental rifts and overlying sag or steer's head basins(3) Collisional margins produced by terminal collision between continents (4) collisional margins formed by continental collision linked to terrane accretion, arc collision, and/or shallow subduction (5) strike-slip margins (6) subduction margins not affected by main arc or continental collisions. Of these tectonic regimes, continental passive margins and continental rifts are dominant; the two accounting for over two thirds of the total global hydrocarbon reserves (Perrodon, 1976; Mann et al., 2003).

Such continental rift systems exist in Africa and within which great success in oil and gas exploration is currently being witnessed (Ramberg and Neumann, 1984; Rosendahl, 1987; Morley et al., 1999; Burke et al., 2003; Corti, 2011). In Eastern and Central Africa, these rifts are represented by: 1) the NW-SE trending Central African Rift System (CARS) that formed during the break up and split-up of Africa and South America in the Cretaceous times (Browne et al., 1985; and 2) the N-S trending, tertiary East African Rift System (EARS) (Baker and Wohlenberg, 1971; Baker et al., 1972)

Various workers have studied the development of continental rifts and subsequent basin fills (Bosworth et al., 1986; Lambiase and Bosworth, 1995; Morley, 1995; Morley et al., 1999; Corti, 2011). Continental rifting is generally preceded by crustal down warping where sediments are held in sag-like depressions prior to lithospheric rupture (Baker and Wohlenberg, 1971; Crossley, 1979; Lambiase and Bosworth, 1995) continental rifting is that the deformation style varies progressively along the rift axis during rift propagation. Away from the pole of opening, lithosphere thinning increases and may eventually result in seafloor spreading. The transitional phase from continental rifting to active seafloor spreading can be found in a few places on earth (Van and Blackman, 2004). Continental rupture then gives rise to elongate, 50-100 km long elementary basins (or sub-basins) that are separated along-strike by positive topographic features called 'accommodation zones' (Lambiase and Bosworth, 1995). These sub basins are in many cases asymmetrical with sediment accommodation space being formed closest to the active border faults. As the extension process continues, mechanically inefficient crustal detachments may merge along strike to form larger and more structurally efficient geometries to aid further crustal extension (Lambiase and Bosworth, 1995). This joining of faults results in the merging of sub-basins to form larger basins both in length and in depth, the latter being due to the combined effects of hanging wall subsidence and the isostatic readjustment of the footwall wall (Bosworth, 1985; Lambiase and Bosworth, 1995; Morley, 1995) Figure (1.1)

Muglad Basin is documented as a major part of Sudanese interior rift basins. It's one of the main products of Central African Shear zone, directed northwest-southeast covering an area more than 1200km long and in more than 300km wide. It has elements of a complex structure of linked extensional and transtensional sub-basins. The sub-basins normally have a half graben geometry that was reformed by subsequent reactivation throughout younger rift cycle. Initial half graben asymmetry was reversed in some cases by younger superimposed graben. In addition thin skinned detachments within the syn-tectonic sedimentary fill further complicated the final structural geometries (Mann, 1989).

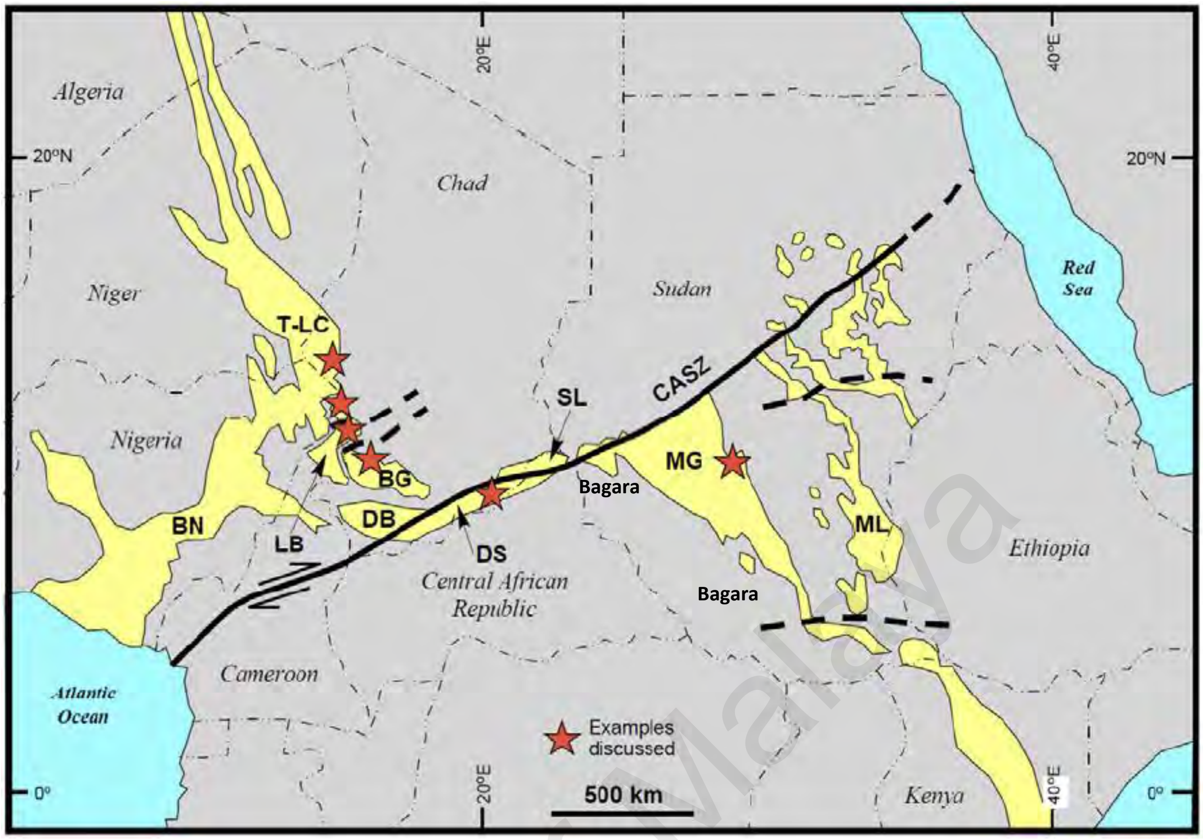


Figure. (1.1)Schematic geological map of Northern Africa and Central Africa. The major fault zones and Mesozoic-Cenozoic rifts are located Modified after Genik 1993 and Manga et al. 2001.

In 1974, the American oil giant, Chevron Overseas Inc. (Chevron) recorded the first exploration success on the north-western extreme of the Central African Shear Zone (CACZ) in Sudan, after drilling the Bashayir-1 and Suakin-1 exploration wells in Block 15, 120 km from Port Sudan (Beydoun and Sikander, 1992). Due to uneconomically discoveries focus was then shifted to the poorly known Muglad Basin located in the Sudanese Central African Rift System (CARS); subsequently, Exploration was continue in the basin by State Petroleum and then lately the consortium of Greater Nile Operating Company(GNPOC). The significant discoveries are catapulting the sub-basins of the Muglad Basin to the category of world-class oil-producing provinces (Schull, 1988) with over 900 million barrels of recoverable reserves (Paul et al., 2003) entrapped in thick non-marine, clastic sequences representing lacustrine, floodplain, fluvial and alluvial environments of Jurassic? - Cretaceous and Tertiary age (Schull, 1988).

1.2 Location

The study area is located in the NNE portion of Muglad basin (Block 4) covers an area around 700 Km^2 (Fig 1.2); Muglad Basin is shared by both Sudan and South Sudan Figure 1.3;it's the largest of the Mid-African rift basins extends over 1,000 km, in a NNW to SSE direction, about equidistant from the borders with Ethiopia and the Central African Republic. Its maximum width reaches 300 km, between basement outcrops, and about 200 km when considering only the area of the basin. The northern part of the Muglad Basin terminates against the metamorphic and igneous complexes of the Darfur Dome, while the north western part ends at the Baggara Basin which is an E–W trending sedimentary basin that formed synchronous with the Muglad Basin and the other Cretaceous sedimentary basins of West and Central Africa.

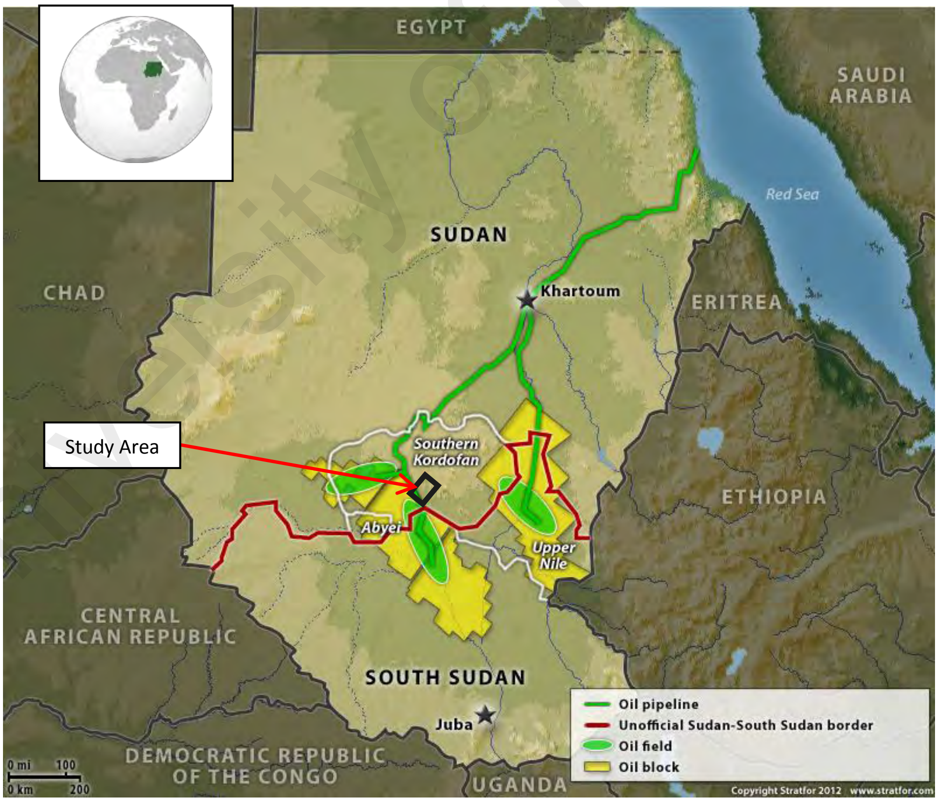


Fig (1.2) Sudan-South Sudan oil fieldshttps://www.stratfor.com/image/sudan-south-sudan-border-and-oil-fields

1.3 Objective and scope of work

This study attempts to provide both qualitative and quantitative structure analysis and related to the hydrocarbon distribution for an extensional trap style.The research will be constrained to wells data (4 wells) and seismic data (531km^2 Seismic 3D and 44 2-D lines extending approximately 1500km), and will provide qualitative models base guidance for the hydrocarbon distribution.

The main goals for the study are outlined below: -

I- To identify the structural style framework for the main structures in the study area.

II- To conduct detail analysis for quantitative seismic interpretation

III- To provide quantitative assessment of fault role in the trapping mechanism in the structures.

IV- To recommend the critical elements that contributes to trap effectiveness for prospective hydrocarbon culmination in the study area.

1.4 Previous work

The tectonic history and resultant structural configuration of the Muglad Basin has been discussed and debated by various authors (McHarqueet. Al, 1992; Schull, 1988; PRSS, 1998; RIPED, 1998; Salama, 1984, 1997). Most authors identified early on the potential links between rifting in the Muglad basin and regional tectonic events elsewhere. Brown and Fairhead (1983) and Berminghamet al (1983) were first to recognize the connection between rifting and shearing across the whole of central Africa. As pointed out by McHargue et al (1992) the Muglad rift is related to spreading centres in the proto-south Atlantic by dextral shearing along the Central African Shear Zone and to the Indian Ocean through Anza rift in Kenya. In terms of the details of structural evolution within the Muglad basin, authors are somewhat at odds with the actual infinitesimal strain mechanisms that result in the recognized finite strains.

Schull (1988) explained the Muglad finite strains as being a result of three phases of extension. Anticlinal features were explained entirely by mechanisms relating to fault plane trajectories. McHargueet et. al (1992) noted that the Sudanese basins formed as a combination of extension and transtension.

1.5 Data Base

The data types available for the study contain the following:

1- Well data sets (well logs, mud log, VSP and End of well reports)

2-3-D and 2D data: -531km^2 Seismic 3D recorded and processed in the 2003 by the Chinese geophysical company, BGP. The data was recorded to 7 seconds and processed to 5.8 seconds; and 44 2-D lines extending approximately 1500km (Fig 1.4)

3- Geochemical reports (TOC, VRO, and bottom whole temperature data).

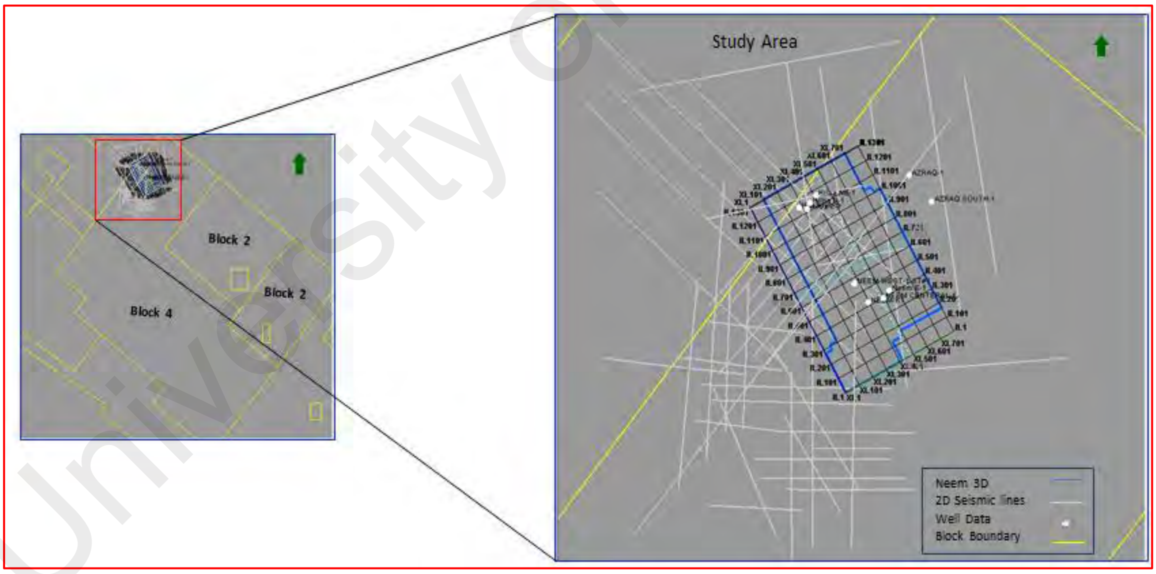


Fig 1.3 Location map of the Study Area

1.6 Methodology

The general plan of this research Fig (1.5) is based on the following:

Assessment of the potential data for structural purposes and detection of structural elements and basin configuration.

Use of well data to identify the sequence boundaries.

Carry out well to seismic tie along seismic sections to map the sequence boundaries through detailed seismic interpretation and seismic attribute if it works.

- Carryout structural restoration for the selected regional lines to delineate the structural styles, extensions, and rifting phases.
- Conduct burial history on the selected wells to study the rifting.
- Integrate all the results to produce the tectono-structural evolution models with reference to NE Africa and Arabia.

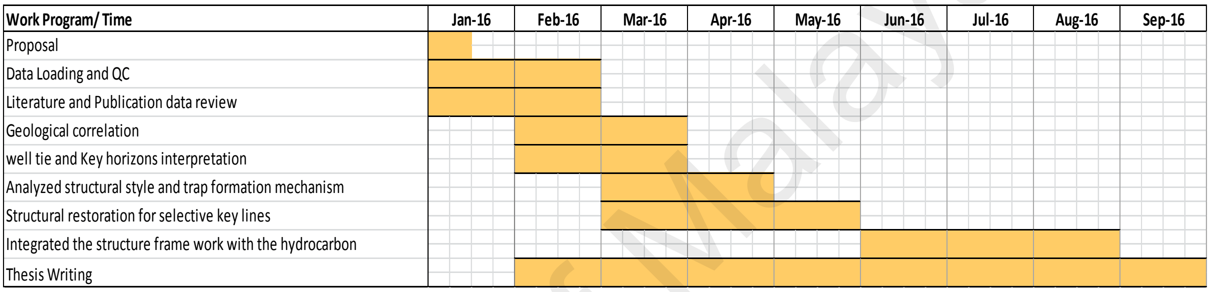


Fig (1.4) General research plan schedule

CHAPTER TWO

REGIONAL GEOLOGY AND TECTONICS

2.1 Plate tectonic evolution

At the start of the Mesozoic, Sudan and Africa lay at the core of Pangea, the super continental plate, which had been assembled by plate collisions throughout the Palaeozoic, culminating in the Hercynian orogeny in the Late Carboniferous.

From Permian times onwards, this large continental plate collapsed by the splitting off of various continental fragments, until by the mid Cretaceous, Africa was surrounded by extensional ocean basins. A major plate reorganisation took place during the Late Cretaceous, when the African and Eurasian plates ceased to separate and started to drift towards each other, resulting in a long lived period of plate convergence and collision which continues in the Mediterranean today.

Pangea fragmented in a clockwise fashion, beginning in North Africa, when a series of continental plate fragments split and drifted northwards in the Permo-Triassic, resulting in the opening of Neo-Tethys in the region of the present day Mediterranean Sea and extending westwards along what is now the Zagros suture zone in Iraq and Iran.

During the Jurassic the major Indian and Antarctic plus the smaller Madagascar plate drifted from East Africa to open the Indian Ocean. The origins of rifting in the Muglad Basin may lie with this event.

During the Early and mid-Cretaceous, the Americas split from the African plate. The Atlantic opened from south to north. The focus of this extension reached Sudan via the Central African Shear Zone, throughout the Early Cretaceous, which is regarded as the principal rift event in the Muglad Basin.

Rifting has largely continued to the present day in the Sudanese basins. This view is somewhat in conflict with the observation that the northern margin of the African plate has been in convergence with Eurasia since the Late Cretaceous.

2.2 Distribution of West and Central African Rift Systems (WCARS) Basins

The progressive fragmentation of Gondwana super-continent during the Mesozoic has resulted in the development of major sedimentary basins along the present day continental margins of Africa and South America (Binks and Fairhead, 1992).The onset of intra-continental rifling in West and Central Africa was synchronous through gradual breakup of Gondwana (Fig. 2.1), and in specific, with departure of South America from Africa (Guiraud and Bellion, 1995).

The WCARS is a very large scale feature which is distinctive in the sense that it traverses the entire continent. Its complex history involved extension, shearing, and compression over a period extending from the early Cretaceous into the early Tertiary

Basins in the WCARS are organized in two different directions, NE-SW and NW-SE, respectively. The greatest noticeable basin among the NE-SW striking group is the Benue Trough, and the others are spread along the Central African Shear Zone (CASZ), such as, from west to east, Doba, Doseo, Salamat and Bagara basins (Fig. 1.2).

All the basins are interpreted as pull-apart structure in nature as outcome of strike-slip faulting along the CASZ, as evidenced by their basin geometry, intra-basin flower structures, and tectonic situation (Genik, 1992). The group of NW-SE striking basins are widely distributed in West Africa (Guiraud and Maurin, 1992), such as the Tenere rift in East Niger, and Central Africa, such as the Muglad, White Nile, Blue Nile, and Atbara basins which comprise the south Sudanese rift system, and the Anza rift in the North Kenya (Bosworth, 1992). Over-all, basins of the WCARS share much in common in occurrence and evolution because they were developed in a similar tectonic setting, though individuals demonstrate their exceptional histories due to local influences.

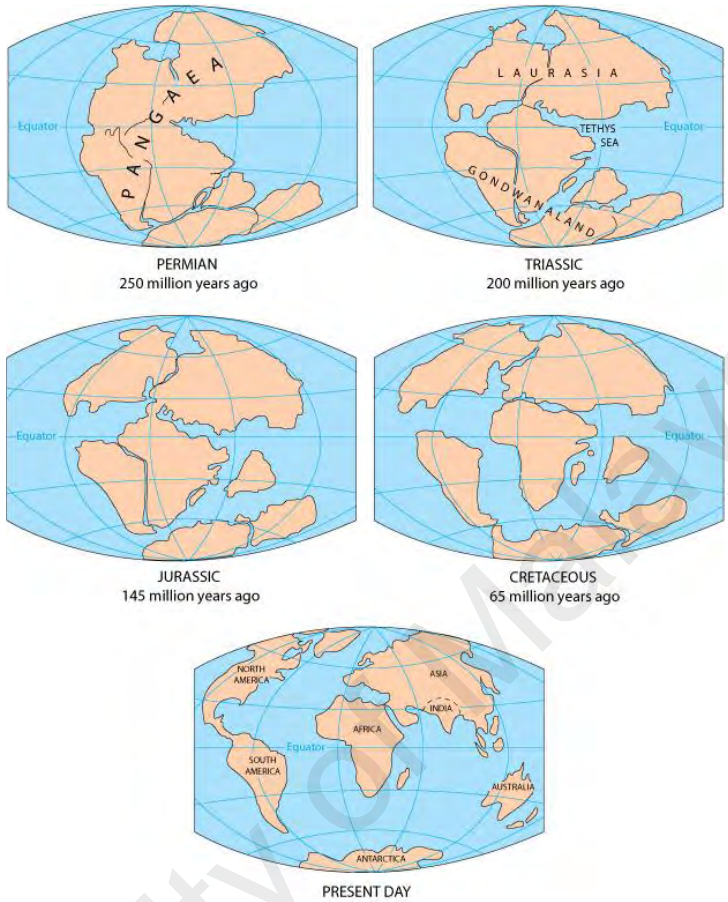


Fig 2.1 The breakup of the Pangaea supercontinent. Credit: U.S. Geological Survey

2.3 Tectonic Framework

The development of the rift basin of southern Sudan is linked to processes that operated not only within central Africa, but also along the western and eastern continental margins of Africa. Three period of rifting creating these basins probably began during the middle Jurassic and continue until upper Miocene.

The initiation of rifting phase had started in the Jurassic to Early Cretaceous period and sustained until near the end of the Albian. (Fairhead and Green 1989). The Indian Ocean has started to open by the middle of the Jurassic, and accordingly Madagascar, India and Antarctica start to drift away from Africa. This breakdown is preceded by a significant phase of intra-continental stresses and sedimentation within Karroo Basin in East and Southern Africa (Bink and Fairhead, 1992).

The second rifting phase began during the Coniacian-Santonian times and continued until the end of cretaceous. Variations in the opening of the south Atlantic account for a late cretaceous period of shear movement on the west and Central African rift system. In Bagara basin, continuation of Central African shear zone strike-slip movement was inferred from compressional features. The strike-slip movement is observed neither in Muglad basin nor further to the Northeast, because this deformation is predominantly expressed on EW faults.

The Third rifting phases recorded in a thick accumulation of sediments. The intensely faulted section of the early Tertiary of southern Sudan basins indicates that this final rifting phase was significant tectonic event. The initiation of this rifting phase is synchronous to the initial phase of opening of the red sea and east African rifting; the Muglad, Melut and Blue Nile basins are sub-parallel to the Red Sea and rifting is response to the African-Arabian extensional forces.

In the late Tertiary, the regional stress regime changed resulting in the termination of the southern Sudan rifting during the middle Miocene.

2.4 Sudan Basins

In Sudan, five NW-SE trending continental rifts are known. They define together an extensional province, which has a wide of 1000 km and a length of at least 800 km parallel to the strike direction (Figure 2.2). From North to South, these rifts are referred to as:

- The Atbara rift.
- The Blue Nile Rift (Khartoum and Khartoum South).

- The White Nile Rift (Melut or Bara and Kosti).
- The Muglad-Abu Gabra Rift (the Muglad-Abu Gabra and Barh el Arab rifts are collectively stated as the Southern Sudan rift). The Muglad is the best known and is the biggest rift basin in Sudan..
- The Bagarra Basin.

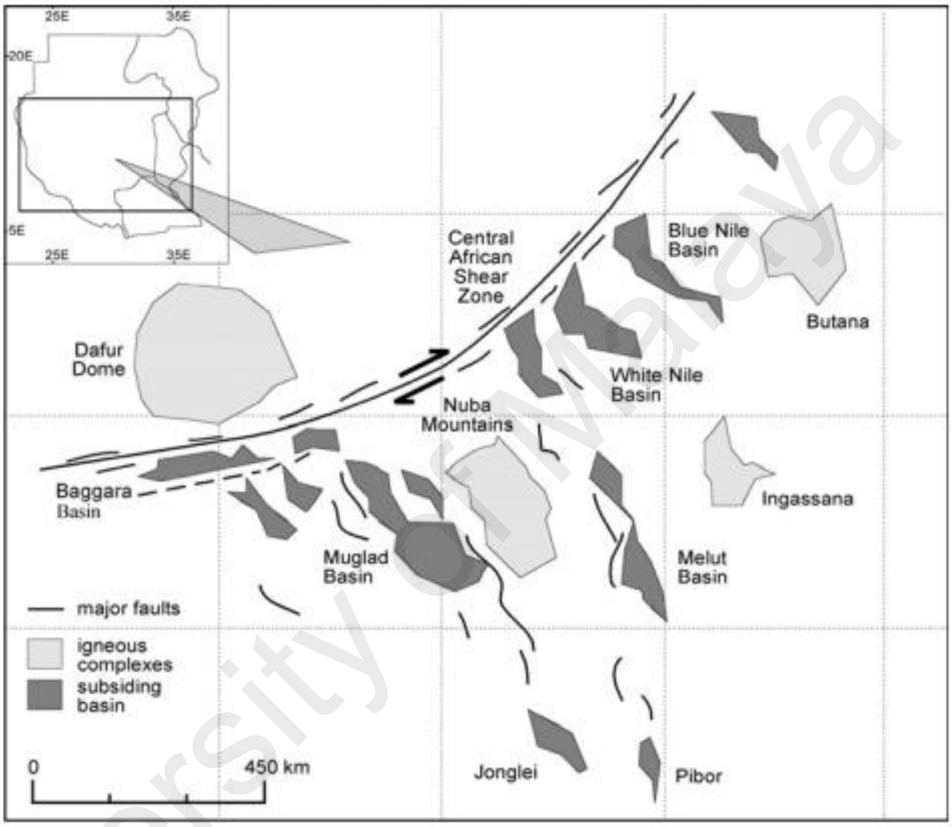


Figure 2.2: Location of Central and Southern Sudan basins (from Robertson Research Int., 1991).

The presence of deep NW-SE orienting Mesozoic-Cenozoic sedimentary basins in southwest Sudan (Muglad, Blue Nile, Melut and Atbara) has been confirmed by Browne and Fairhead (1983), Browne et al., (1985), Schull (1988), Jorgensen and Bosworth (1989), Mann (1989), Bosworth (1992) and Mc Hargue et al., (1992).The Blue Nile, Muglad and Anza Basins experienced substantial inversion in the Early Tertiary, linked to E-W shortening (Bosworth**,** 1992)borders of the basins are recognized by the integration of hydrocarbon exploration and the gravity studies conceded by the main oil exploration companies (Wycisk et al., 1990). The southern Sudan rifts terminate to the

NW contrary to the Central African Shear Zone. At this shear zone, gravity and seismic data shows an occurrence of NE-SW trending structures comprise of numerous small pull-apart basins been linked by likely strike-slip faults (Bosworth, 1992). The major basin on the shear is the Baggara, which encompasses strata as old as Albian-Aptian (Bosworth, 1992), assuming that the CASZ was active since Early Cretaceous.

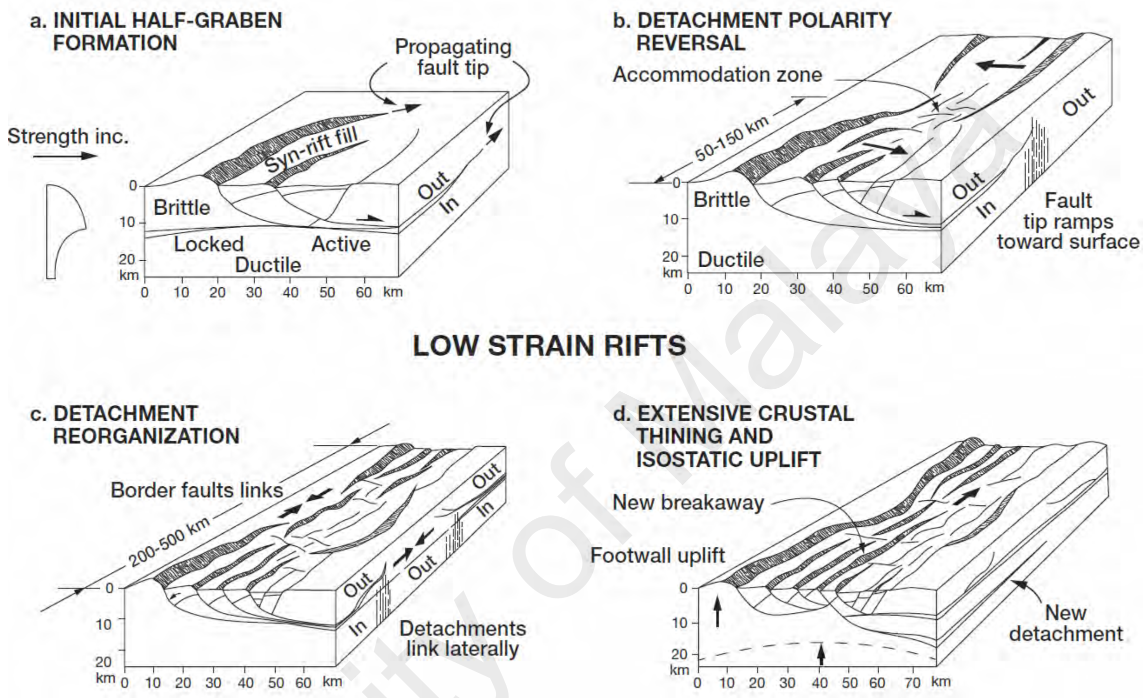


Figure (2.3) Continental rifts are initiated by: (a) Gentle sagging that develops into an asymmetrical half-graben owing to movement along a single detachment in the basement rock; (b) and (c) Additional detachments (which in many cases reflect pre-existing basement structures) develop both vertically and laterally and could coalesce to form a more effective fault system; (d) Crustal thinning leads to isostatic uplift and possible abandonment of existing detachments and creation of new detachment breakaways (modified from Lambiase and Bosworth, 1995).

2.5 Stratigraphy

The Muglad basin received sediments from surrounding uplifted regions, one of which must be the Nuba area located between the Muglad and White Nile basins. The Nuba is composed mostly of rocks of Precambrian age, including gneissic groups, granitoids, meta sedimentary and meta volcanic assemblages, and some mafic and ultramafic associations (ophiolites?). The Nuba seems to be a relatively rigid block sandwiched between shear zones during the Neoproterozoic times. When the adjacent basins (Muglad and White Nile) were subsiding during the Cretaceous, the Nuba began to rise contemporaneously as a result of upward tilting of footwall block, and so served as a provenance for the basins.

The multiphase tectonic history of the Muglad rift comprises three discrete main extension phases: an Early, a Late Cretaceous and an Eocene Oligocene rift phase, resulted in an accumulation of up to 5400 m, 4200 m and 5400 m of sediments, respectively. Each phase consists of a rift-initiation phase, an active rifting phase and a thermal sag phase (McHargue, et al. 1992).

Each rift cycle shows (1) a subtle but regionally correlative angular unconformity, (2) a basal sandstone unit (at least near the rift margins) deposited on the unconformity of the rift initiation phase, followed by (3) an upward coarsening section of lacustrine shale grading (Tim R. McHargue).

The initial rifting cannot be dated precisely. In the case where the basement was penetrated by wells in the north-western Muglad basin, it is overlain by Neocomian- Barremian lacustrine siltstones and claystones attributed to Abu Gabra Formation. Seismic shows that the Abu Gabra is not a monolithic formation, but has a basal member affected by half graben tectonic. This basal member rests unconformably below an upper member, which is usually conformable with the overlying Bentiu Formation. Seismic data indicates also thick sections of older, but undated sediments. Based on widely spaced well information, it is suggested that the rifting begun during the Jurassic (?) or Early Cretaceous. Well control and seismic data indicate that this initial and strongest rift phase lasted until the end of the Aptian. The cessation of the initial rifting is stratigraphically distinct by basin wide deposition of the abundant of Bentiu sandstones which is known as primary reservoirs rocks in Muglad Basin marks the end of the first cycle.

The second rift phase occurred in the coniacian up to Campanian-Maastrichian (Darfour Group, Baraka formation). This phase is seen widespread deposition of lacustrine and floodplain claystone and siltstone (Aradeiba shally formation).

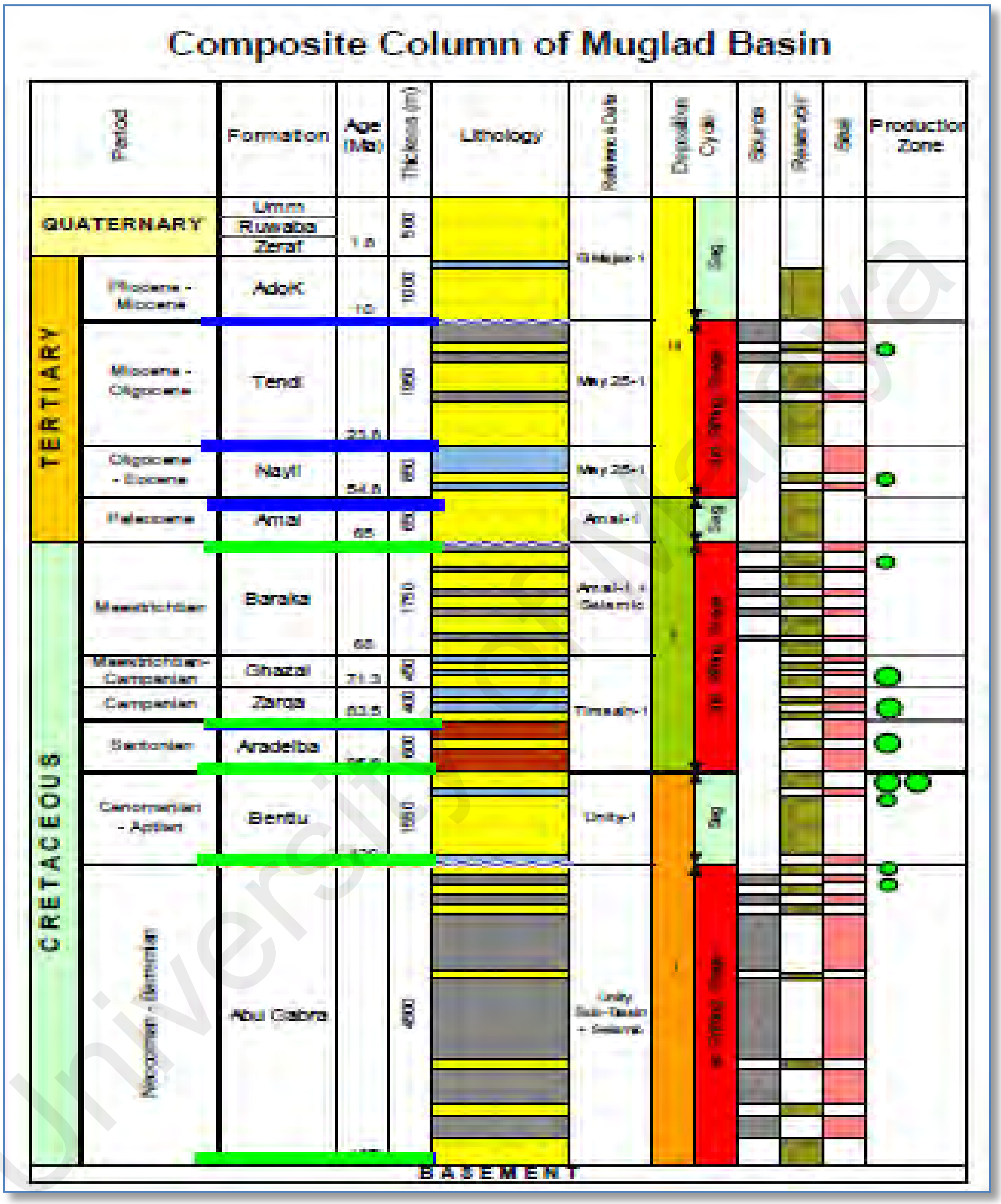


Figure 2.4 Generalized stratigraphic columns for the Muglad Basin, Modified after Mohamed and others (2000) and Dou and others (2007).

This rifting phase was associated with minor volcanism activity is identified in the north western part of the Muglad basin. The end of this phase is distinct by the deposition of an increasingly sand rich sequence that settled with thick Paleocene sandstone of Amal formation.

The third rifting phase began in the late Eocene-Oligocene. This phase is replicated in the sediments by a thick sequence of lacustrine and floodplain claystone and siltstone. After this rift period deposition become more sand rich throughout the late Oligocene-miocene.

2.6 Structure

The Sudanese, West and Central African Rift basins are commonly composed of full grabens and discrete half grabens, some of which exhibit reversed structural polarities (Gibbs, 1984; Bosworth, 1985; Rosendahl et al., 1986; Jorgensen and Bosworth, 1989). The basins are filled by Tertiary-Cretaceous continental and non-marine sediments. The deep sides of the basins are flanked by relays of long normal faults with up to 5000 m of displacement. Some of these faults are listric into the Mantle. Principal fault directions are generally parallel or sub parallel to the basins' long axes'. The general trend direction is NW-SE.

Based on information from seismic interpretation, surface geology and remote sensing, the structural styles in the West African System (Fig 1.2) extensional basins are typically tensional and secondarily contractional (transpressional). It is characterized by rotated synthetic and antithetic fault blocks. The other common extensional structures recognized in the West African System (WAS) are the horsts compactional anticlinal drapes over basement blocks, and the hanging-wall rollovers along normal faults. Several types of these structures are proven hydrocarbons traps. The traps of fault related structures range from a few hundred acres to several thousand acres but commonly about 3000 acres. Other secondary structural styles are manifested by a few contractional anticlines, whose closure areas range from about 1000 to more than 10,000 acres. The West African System (WAS) is also characterized by sinistral transpression structures that originated during the Santonian squeeze such as the structures of Dobo basin (Avbovbo et al., 1986).

The extensional structural style in Dobo Basin in Chad has been modified by strike slip movements which had taken place during the Santonian along the Central African Shear Zone (CASZ). As a result, numerous transpressional anticlines were formed in the Dobo Basin where the anticlines became the best oil-trapping structures.

The extensional basins in Sudan include Muglad, Melut, Blue Nile, Atbara, and Gadarif basin to the east (Fig 2.2). These extensional basins are similar to those of WCARS and are mainly composed of discrete half and full graben.

The deep sides of Muglad Basin is flanked by long normal faults, and some of these listric faults are deep seated into the Mantle.

The size of the structural traps in Muglad basin area ranges from a few hundred square meters to several square kilometres and are commonly about 5 square km. It is worth noting that the horst blocks, anticlinal drapes, and hanging-wall rollovers along normal faults had been proven as hydrocarbon traps in Muglad Basin. The NW-SE trending Sudanese interior rift basins developed in response to an approximate NE-SW crustal extension (McHargue and Livigston 1992). The orthogonal extensional strain in the Southern Sudan (Muglad and Melut Basins) is connected to the sinistral Benue fracture zones by the dextral Central African Shear Zone.

CHAPTER THREE

SEISMIC INTERPRETATION AND STRUCTURAL MAPPING

The seismic interpretation of the Neem area has been carried out based on the formation tops of the wells as derived from the well-log correlations using the available wells data set. There is no detailed sand to sand correlation because it’s beyond the scope of this study Figure 3.1

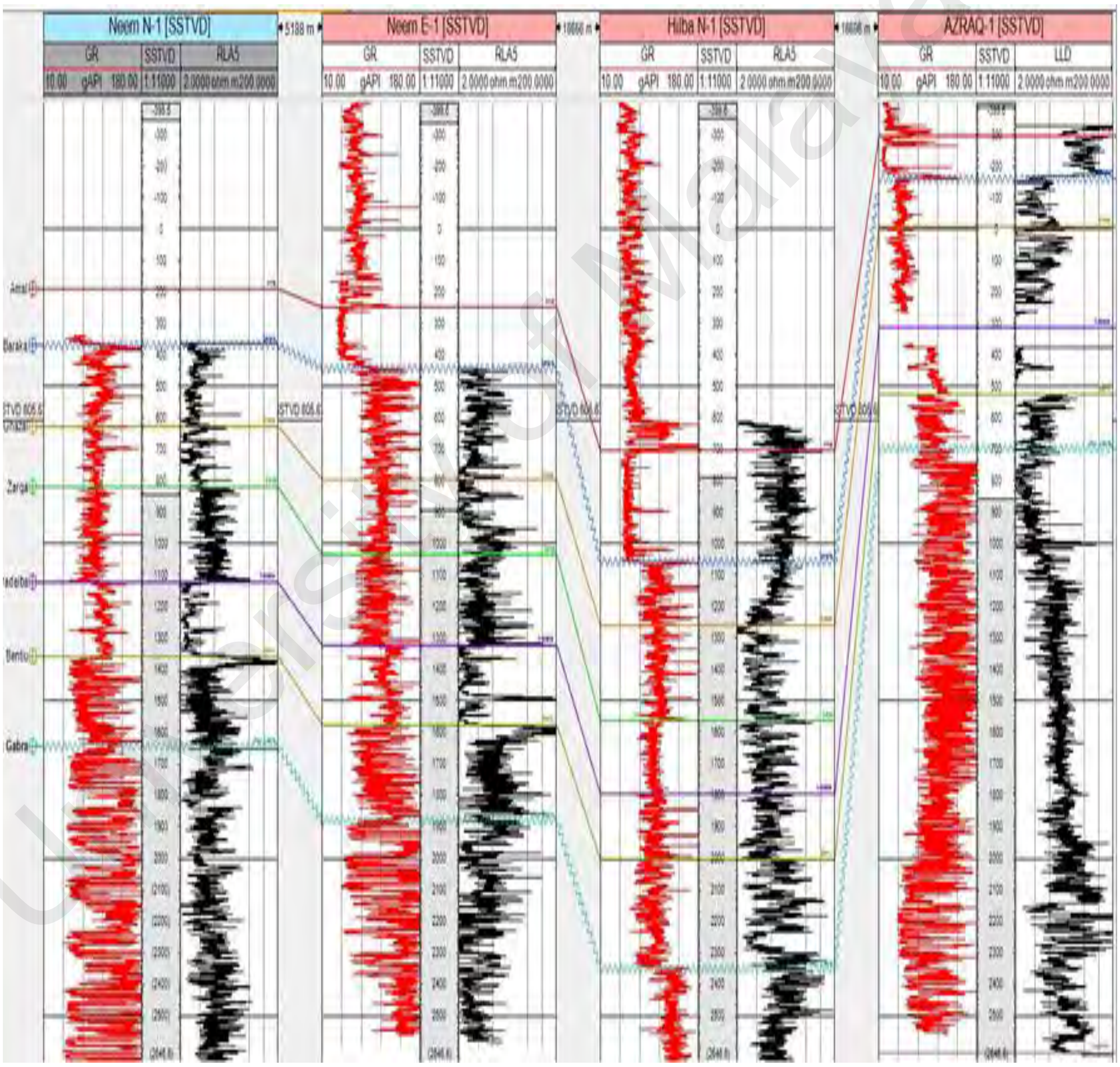


Figure 3.1 Geological correlations through Neem N-1, Neem E-1, Hilba N-1 and Azraq

3.1 Time - Depth Information

The TZ (Time Depth curve) data used for this study were reviewed and analysed by loading the data files into an Excel spreadsheet and plotting the data in a chart as shown on Figure 3.2 the chart of the TZ data of 2 wells shows a common central trend with the curves for Neem N-1diverging from this trend below 550m. This divergence of the curves shows that Neem N-1 has faster velocity towards the well TD (Total Depth).

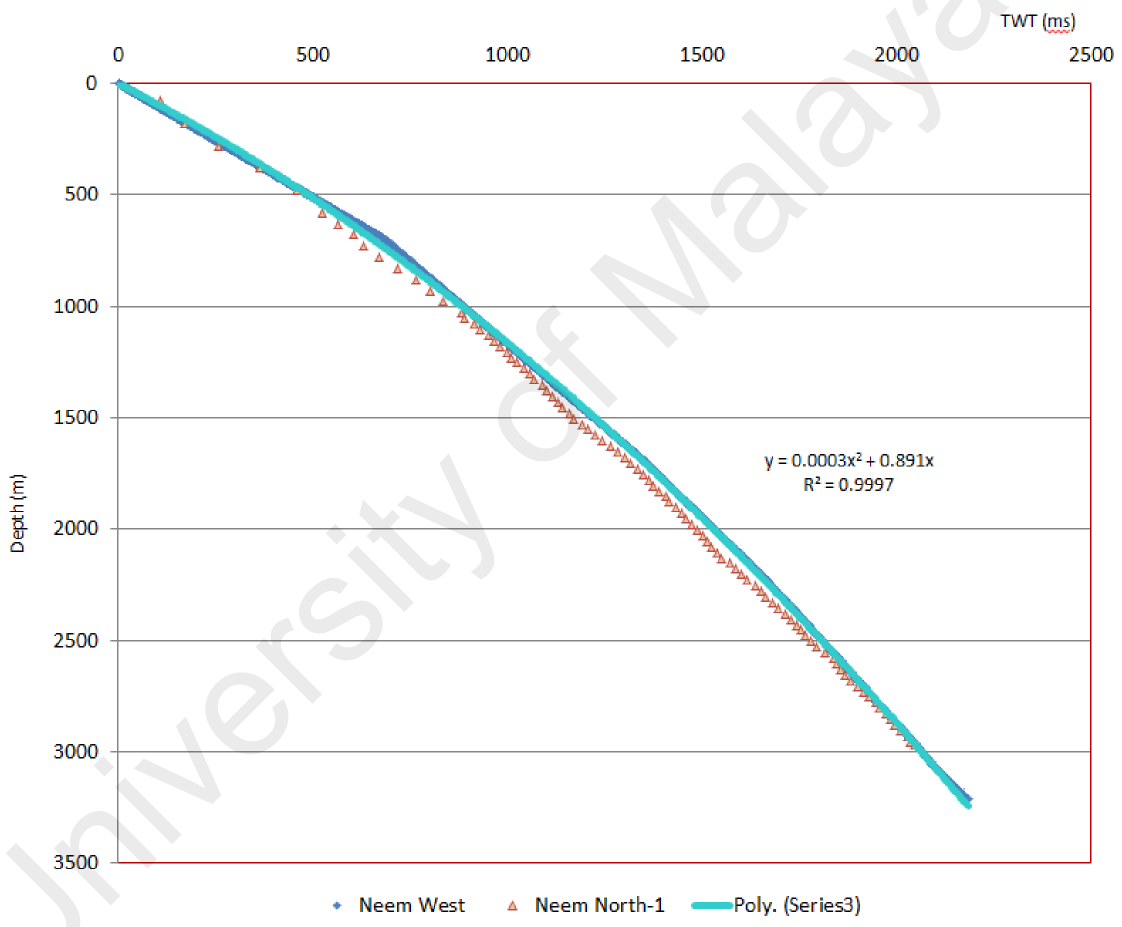


Figure 3.2 TZ curves for Neem W-1 & Neem N-1

3.2 Well to seismic tie

The concept of well to seismic tie is to allow lithology (local stratigraphy) to be placed on the seismic distribution of the sequence (Vail 1978), The synthetic seismogram is a good tool to extrapolate the stratigraphic position of the individual sequence boundary (in depth) from its discrete location at the well into the seismic sections (time). The tying of formation tops to the seismic data is dependent on applying the correct TZ data and the correct correlation of the defined formation tops in the wells however some wells have not got VSP (Vertical seismic profile) data, the VSP data of the neighbouring wells have to be used for the wells. The top of the Amal sand is a good marker horizon defined by a distinct sonic and GR break as it is a sharp boundary between the interlaminated sands of the Nayil sand and the blocky Amal sand. Generally, Amal formation tieis good. The refection features of the key horizons based on the log signature are shown is the (Figure 3.3).

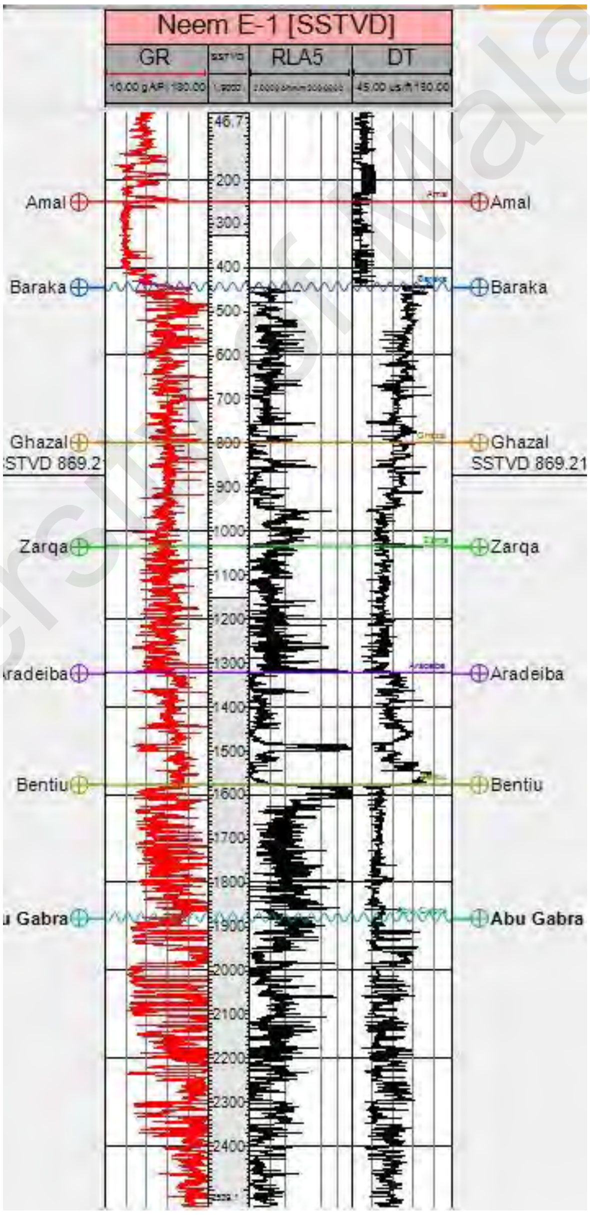


Figure 3.3 Reflection feature from logging signature

The synthetic seismogram was produce to investigate the variation in the seismic character of the 3-D data-set at different locations and to investigate the source wavelet of the 3-D data. Synthetic seismogram provides both time and depth values for accurate reflection events verification. In this case, the seismic data are converted into acoustic impedance (AI) volume that fully integrates the geology. The velocity knowledge is important to calculate the AI volume from velocity and the density log values at a specific layer.

In this study and for the purpose of seismic interpretation, two synthetic seismographs were generated (Figure 3.4). The dominant frequency of the extracted wavelet in the study area is less than 30 Hz (Figure 3.5), which suggests more than 40 meters of vertical resolution for the individual units at a velocity of 3500 m/sec. Also it is realized, the extracted wavelet from seismic is a zero phase wavelet and it provides the best match between synthetic seismograms and seismic data (Figure3.4).

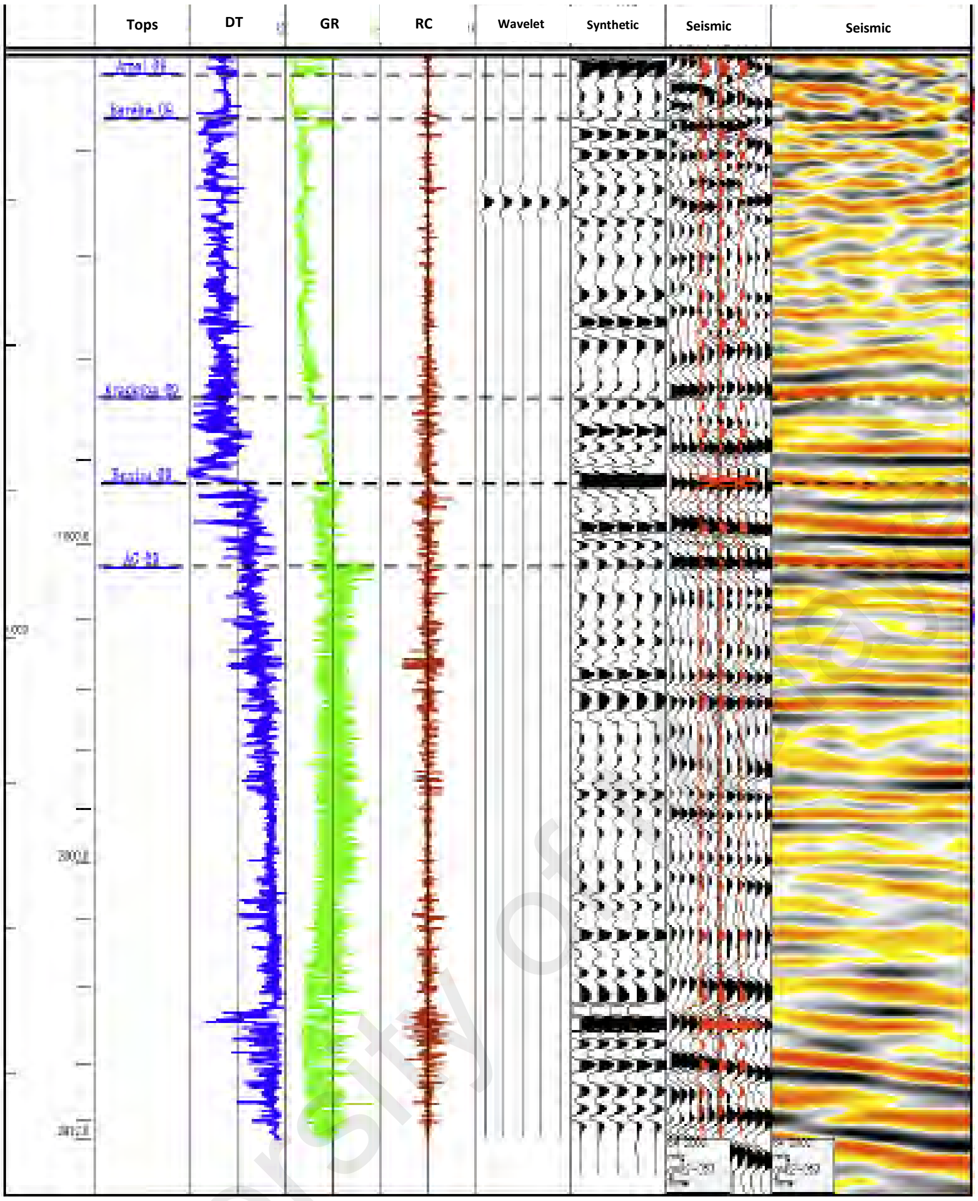


Figure 3.4 Synthetic Seismogram for Azraq-1

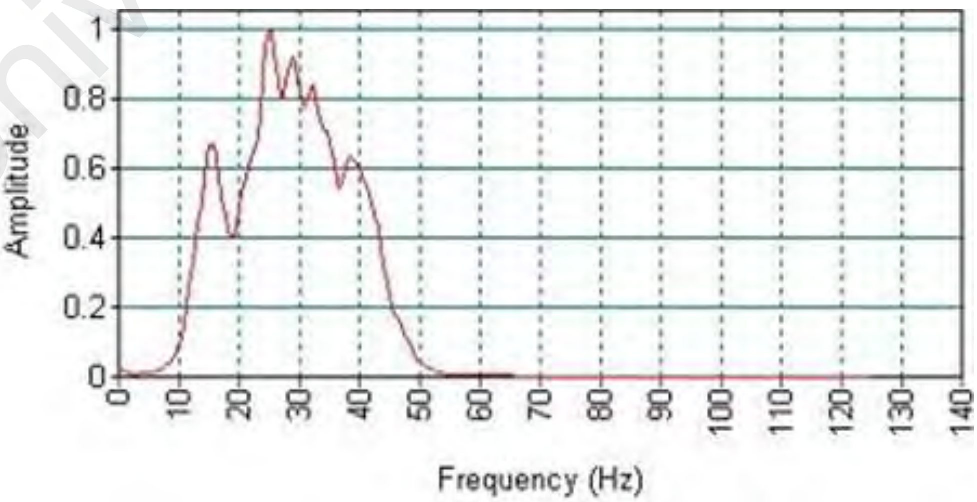


Figure 3.5 Frequency spectrums below 2 sec

3.3 Interpretation Criteria

The type of seismic event interpreted for each horizon according to the synthetic tying is summarised below:

HORIZON NAME	SEISMIC EVENT
Tendi	Variable (unconformity)
Amal	Trough
Baraka	Variable (unconformity)
Aradeiba	Zero crossing +/-
Bentiu	Zero crossing +/-
Abu Gabra	Variable (unconformity)
Basement	Zero crossing +/-

3.4 Interpretation Methodology

From the seismic to well tie interpretation of the 3-D data was carried out on a 16x16 Inline x Crossline grid so that intermediate lines can also be interpreted in more detail, especially to define detailed fault correlations (Appendix A).

Variance cube facilities are used on the 3D seismic data (Neem 3D) to control the fault boundaries locations and their lateral extent. The variance cube is usually performed at the seismic window either as time slice or as horizon (Figure 3.6). The amplitudes is calculates form trace to trace within the selected time window and the output will be displayed on the screen as grey or coloured scale pallet. The variance cube is calculated with respect to a base time (e.g. 850msec) and certain time window (e.g. +10 msec). The incoherent high amplitude areas appear as high contrast while the low amplitude represents low contrast. The lateral fault extends are recognized from the high contrast.

Fault polygon sets were constructed progressively for each horizon as the interpretation progressed.

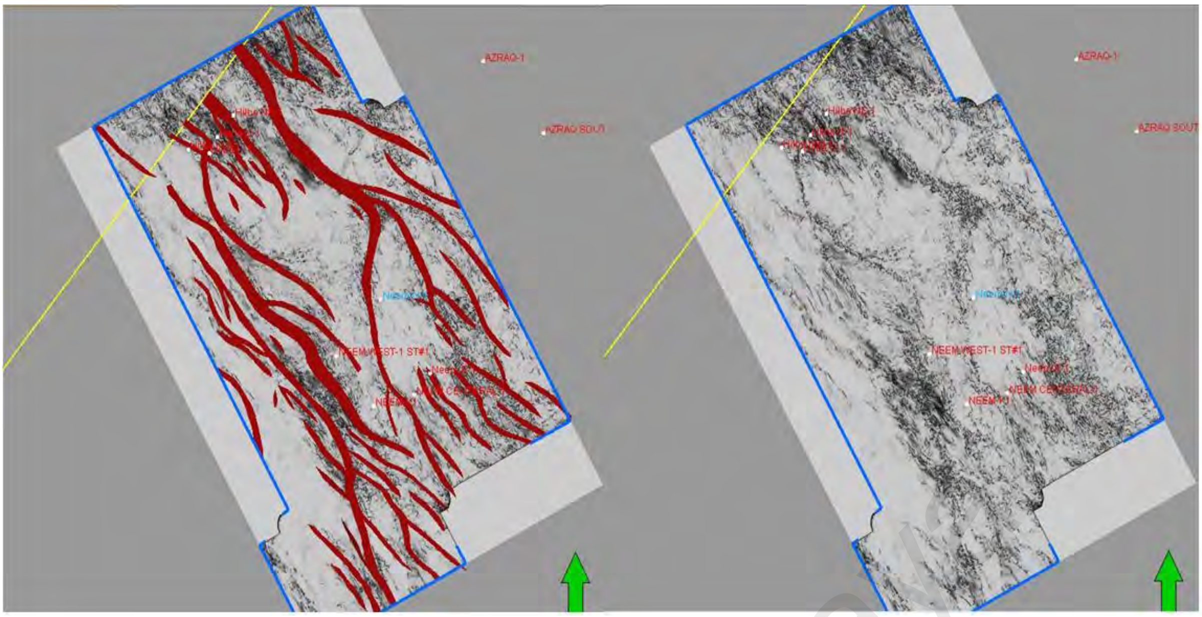
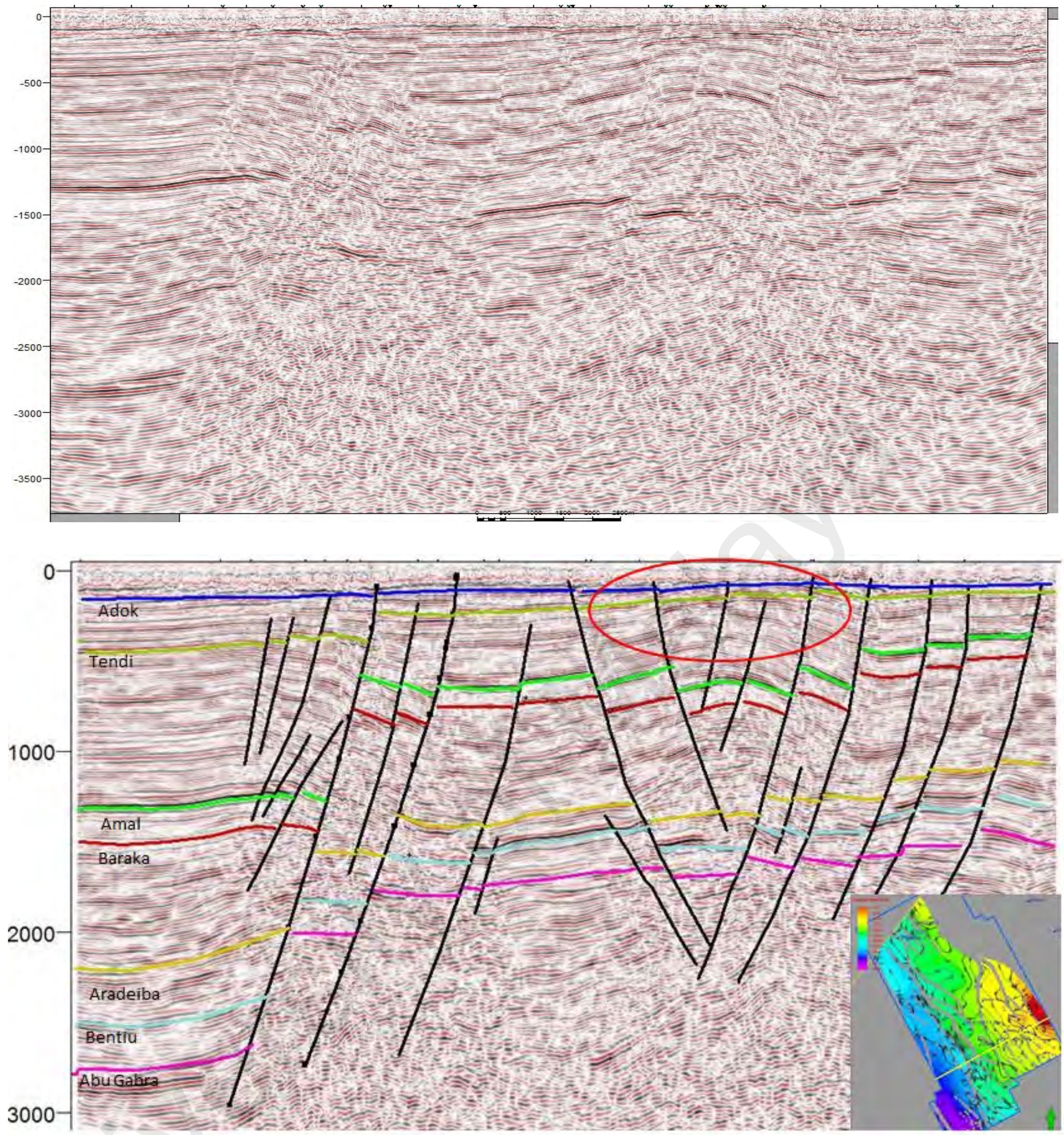


Figure 3.6 Variance cube slices at 850ms based on Neem 3D surveys can *visualize* the spatial distribution of faults.

3.4.1 Top Adok and Top Tendi horizons

The Adok horizon was commonly characterized by a broad trough in a majority of wells, where the Adok and Tendi horizons are well defined in the area of the study area. The Top Tendi horizon is the shallowest major unconformity in the area. It does not always show significant erosional subcrops, but only subtle dip changes in the underlying section.

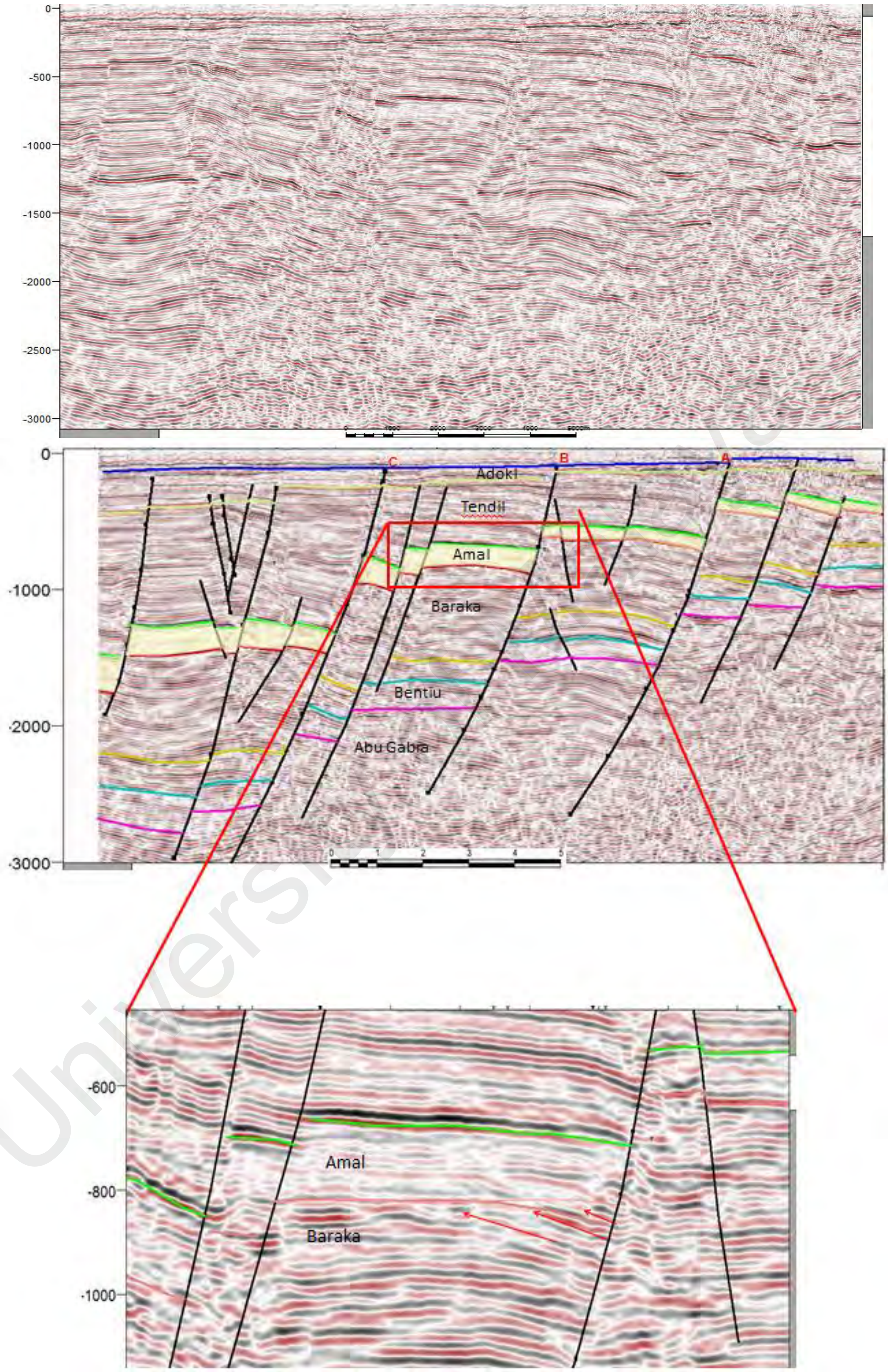
The erosional truncation of the Tendi Formation is distinctly shown in some of the compressional structures in the northern and SE part of the 3-D data area Figure 3.7.



Figures 3.7Subcrop below Tendi horizon, truncation of compressional structure.

3.4.2 Top Amal and Top Baraka horizons

Generally, in the area of the 3-D data-set there is no major structural tilting and erosion at this level. The only well-defined unconformity surface is in the northern part of the 3-D. In the central part of the 3-D area, the Top Baraka horizon is generally conformable to the internal structural dip of the formation, though there are some subtle unconformity indications as shown in the figure3.8. The fault block to the west of fault B shows some erosional truncation below the Baraka horizon. The thickness of the overlying Amal sand is controlled by 3 faults (A, B and C) and there are only minor thickness variations within individual fault blocks. The Amal horizon was interpreted as a potential separate exploration target.



Figures 3.8 Baraka unconformity – minor erosion, little thickness variation within fault blocks

3.4.3 Top Aradeiba and Top Bentiu horizons

The Aradeiba and Bentiu Formations are generally locally conformable to the top of the Abu Gabra since the basin was a simple sag basin during the period from the Barremian to the Mid-Maastrichtian structural event related to the Baraka unconformity. Bentiu is dominated by predominantly high amplitude discontinuous reflection to moderate continuous amplitude reflection. The reflection free amplitudes also exist in the study area.

3.4.4 Abu Gabra horizon

The deepest formation is top of the Abu Gabra. The erosional truncation on structural highs created at the time of this major structural event is clearly visible on the 3-D data. The log character of the Abu Gabra section is also distinctive as it is composed of interbedded sands and organic-rich shales Series of high-angle reverse faults splay off the main fault SW are a response to some transpressional movement along the fault (Figures 3.9).

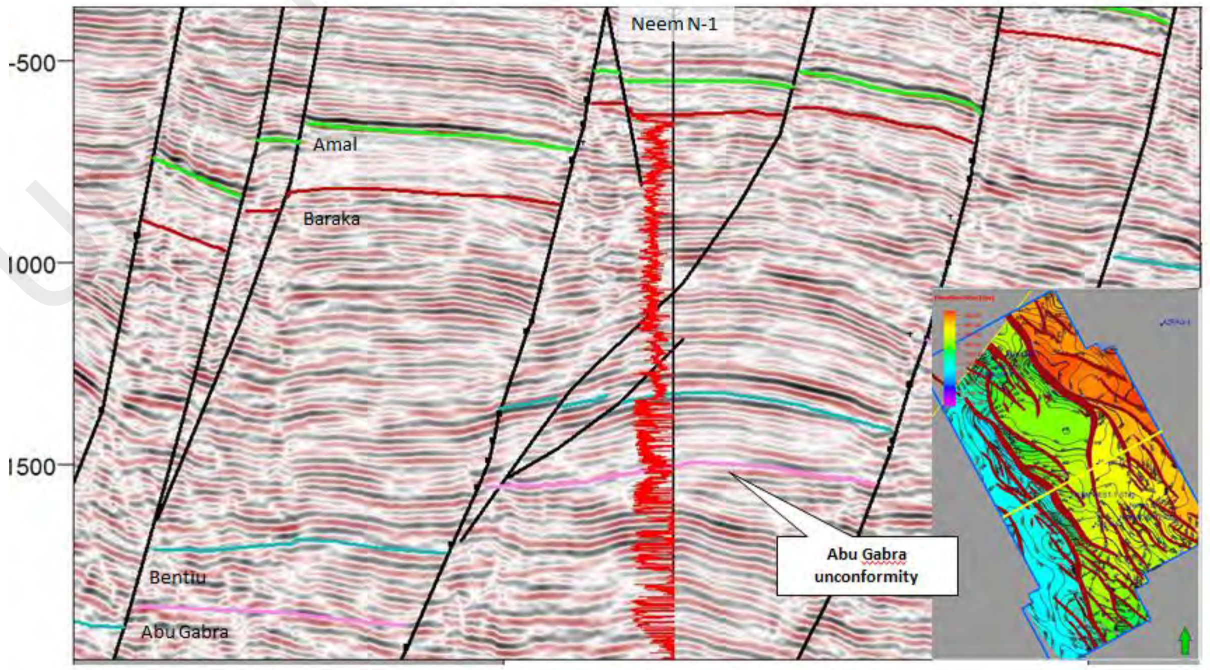


Figure 3.9 Neem North-1 – GR/DT logs, Abu Gabra unconformity

3.5 Mapping

Interpreted time horizons were gridded in PETREL using a grid spacing of 50 metres. The gridding algorithm applied was the default algorithm which is a ‘convergent interpolation’ algorithm which will detect automatically all the input geometry from the input data with option for the user defined input data. For the time gridding low smoothing was applied. Two Way Travel Time structure maps for (Tend, Amal, Baraka, Aradeiba, Bentiu and Abu Gabra) are shown as contour maps with colour-fill in figures 3.10

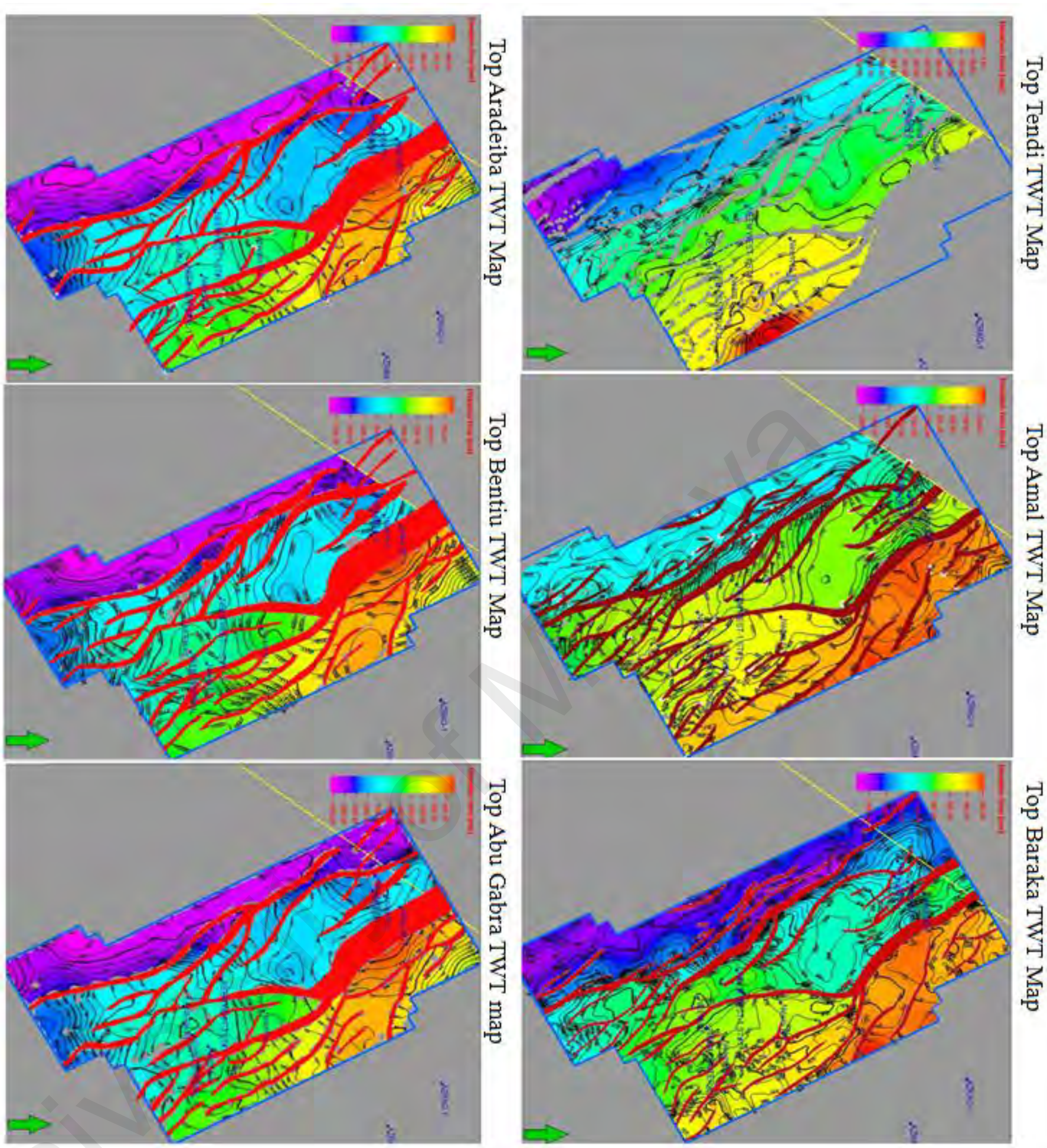


Figure 3.10 TWT maps for the interpreted horizons

3.5.1 Velocity Mapping

The fault complexity of the study area would be difficult to depth convert as the sum of a series of isopach maps because the fault planes progressively mask the deepest horizons would have only small areas of depth grids. Hence, simple average velocity depth conversion was used to produce the depth maps.

The average velocities at the wells were calculated from the times and depths of the formation tops. A compilation of the formation tops, and the calculated average and interval velocities is presented in Table 5.1. For each well, the formation tops are given as measured depth (MD), vertical depth above sea-level (TVDSS) and vertical depth relative to the seismic reference datum (TVD SRD). Formation tops which are faulted contacts were not used in the calculation. The time is based on the active TZ curve for each well.

Average velocity contour maps were digitised from these well values either by hand digitising on the screen or editing of contours generated by gridding the velocity values input as control point files. The contour maps were initially gridded using the same algorithm (Figure 3.11).

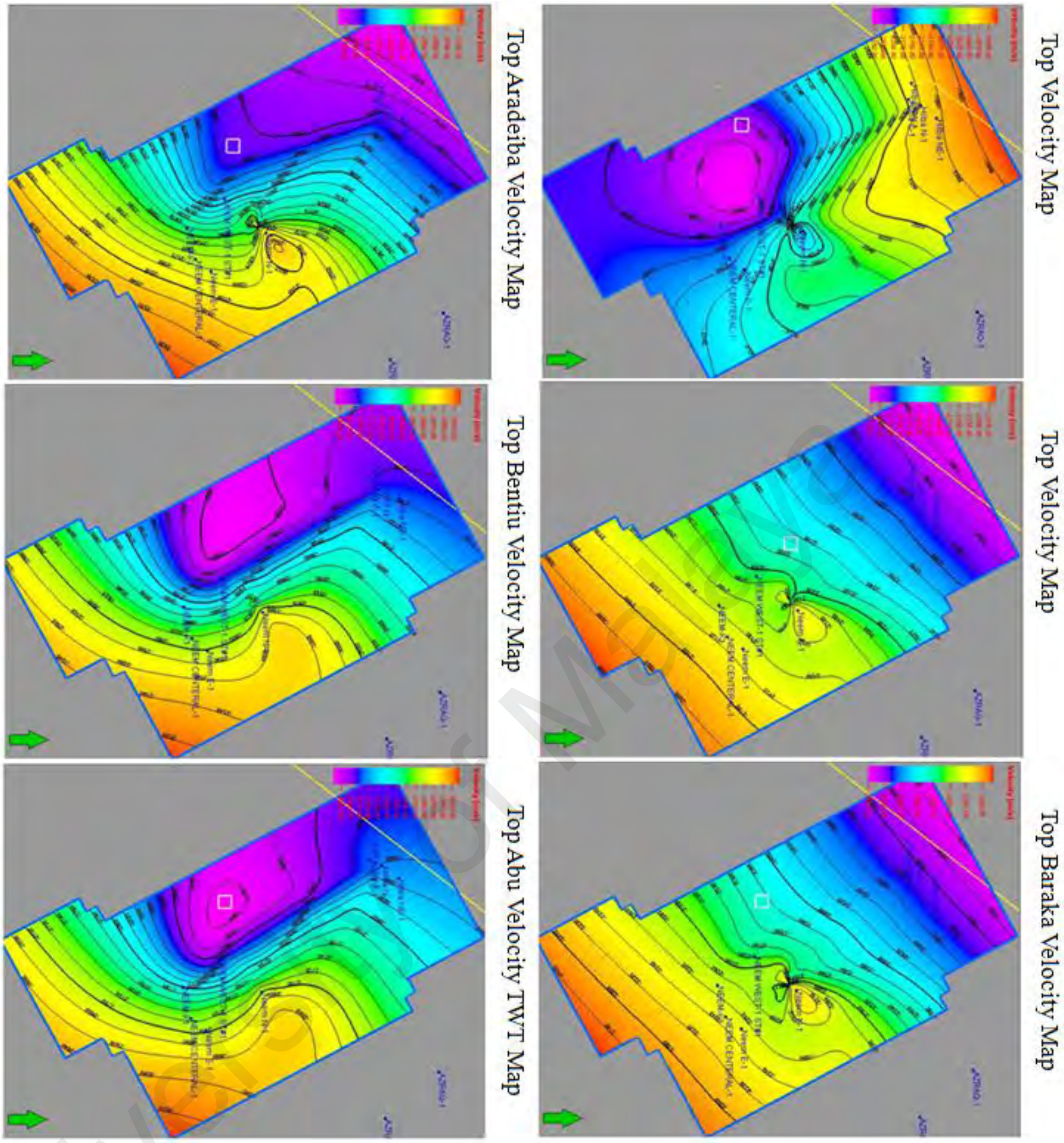


Figure 3.11 Velocity maps for the interpreted horizons

Table 3.1 Compilation of tops and calculated average velocities-Neem E-1, Hilba N-1, Neem W-1 and Neem N-1

		Neem E-1	Hilba N-1	Neem W-1	Neem N-1
	KB	522	518	499	520
Tendi	MD	257.00	342.00	375.00	284.00
	TVD SS	265.00	176.00	124.00	236.38
	TVD SRD	134.00	224.00	275.00	163.62
	Time (TWT)	0.13	0.23	0.26	0.15
	Va SRD	2142.00	1979.00	2231.00	2142.00
Amal	MD	747.00	1197.00	879.50	679.50
	TVD SS	-224.60	-697.00	-389.00	-159.12
	TVD SRD	624.00	1079.00	789.00	559.12
	Time (TWT)	0.59	0.92	0.72	0.52
	Va SRD	2130.00	2334.00	2190.00	2133.20
Baraka	MD	914.00	1546.00	1088.00	817.00
	TVD SS	-392.00	-1028.00	-606.00	-297.00
	TVD SRD	792.00	1428.00	1006.00	697.00
	Time (TWT)	0.70	1.14	0.87	0.62
	Va SRD	2251.00	2499.00	2323.00	2234.00
Aradeiba	MD	1816.00	2298.00	2110.00	1609.00
	TVD SS	-1293.00	-1780.00	-1610.00	-1088.00
	TVD SRD	1693.62	2180.00	2010.00	1488.60
	Time (TWT)	1.32	1.61	1.51	1.16
	Va SRD	2568.00	2705.00	2657.00	2558.00
Bentiu	MD	1816.00	2493.00	2466.00	1858.00
	TVD SS	-1293.00	-1975.00	-1966.00	-1337.60
	TVD SRD	1962.60	2375.00	2366.00	1737.00
	Time (TWT)	1.51	1.72	1.72	1.34
	Va SRD	2598.80	2752.00	2758.00	2590.00
Abu Gabra	MD	2377.50	2873.00	2900.00	2163.00
	TVD SS	-1856.12	-2319.00	-2400.00	-1643.00
	TVD SRD	2255.12	2719.00	2800.00	2043.00
	Time (TWT)	1.67	1.90	1.94	1.51
	Va SRD	2703.30	2858.00	2886.00	2703.00

3.5.2 Depth Mapping

The depth conversion of each horizon was calculated by dividing the time grid by 2 and multiplying by the average velocity grid. The detailed depth mapping for the main horizons interpreted are shown in (Figure 3.12).

From the depth maps there are number of Prospects and Leads has been identified for all the levels interpreted

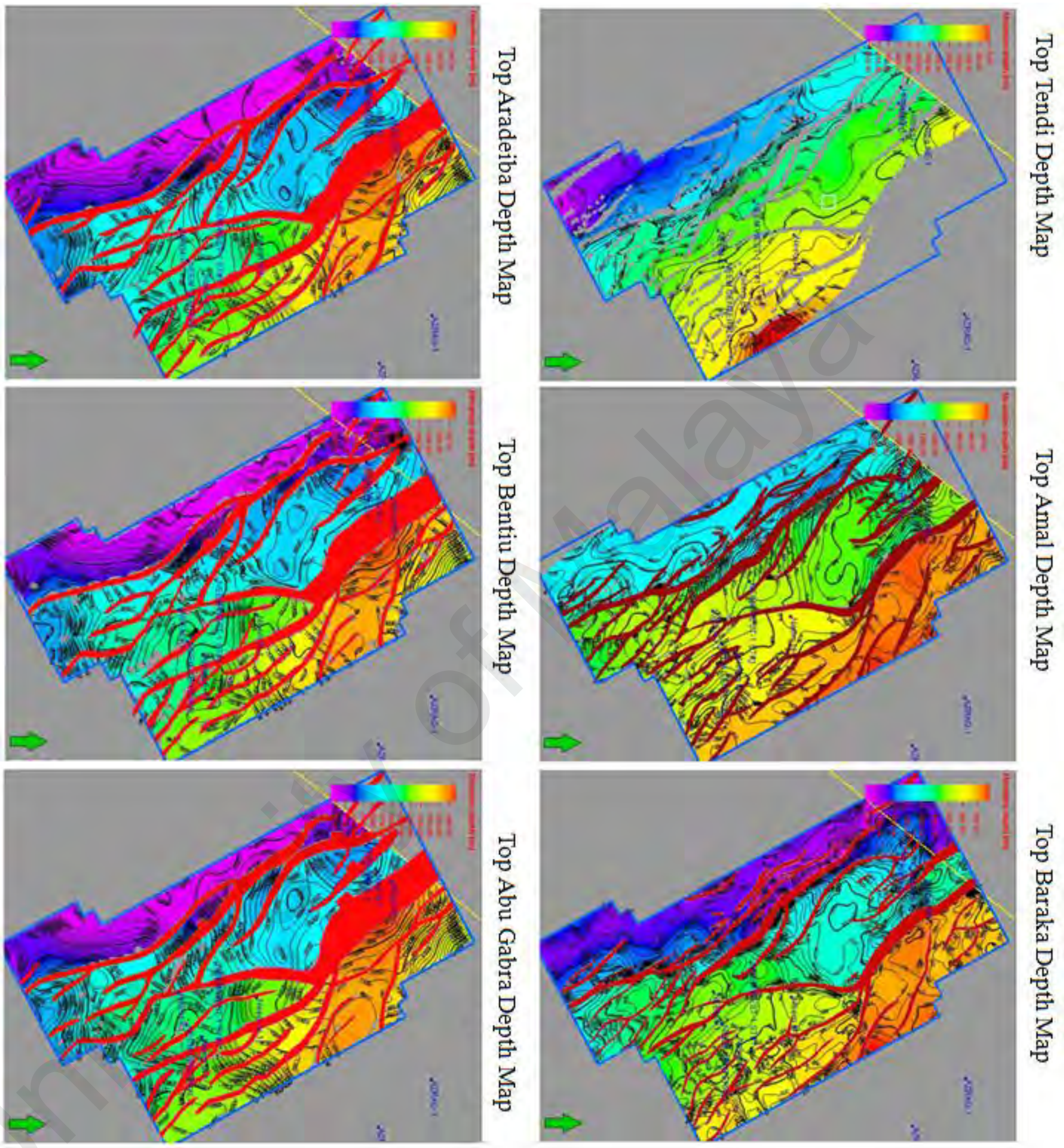


Figure 3.12 Depth maps for the interpreted horizons

3.6 Attribute analysis

In dominant exploration, development and reservoir seismic surveys, the core purposes are, first, to appropriate image the geological structure in time and depth domain and, second, to properly illustrate the amplitudes of the reflections. Assuming that the amplitudes are exactly rendered, a host of extra features can be derivative and used in interpretation. These features are stated to as seismic attributes.

The basic attribute, and the most commonly used, is seismic amplitude, and it is usually described as the maximum (positive or negative) amplitude value at each sample along a horizon picked from a 3D volume. It is privileged that, in many cases, the amplitude of reflection resembles directly to the porosity or to the saturation of the underlying formation; due to data quality all the attributes are hard to infer or interprets with related to facies, fluid or other rock properties.

CHAPTER FOUR

STRUCTURE ANALYSIS OF THE STUDY AREA

4.1 General structure characteristic

Muglad basin are characterized by extension and/or transtensional structure style and inverted structure formed due to structure inversion during the late sagging stages, Major structures in the basin result from faulting undertakings during Early cretaceous Abu Gabra stage and early tertiary Nayil and Tendi stages, and structure inversion during late of Darfur stage. The relatively weak faulting of early Darfur stage might either cause some new structures or cause reactivation and enhancement of the old structures. Categories of the structures mainly include rotated (tilted) fault block, un-rotated fault block, fault rollovers, drag fold, trap door fault blocks, highly faulted block, faulted anticlines, drape anticlines, or differential compaction structures and inverted structure figure 4.1.

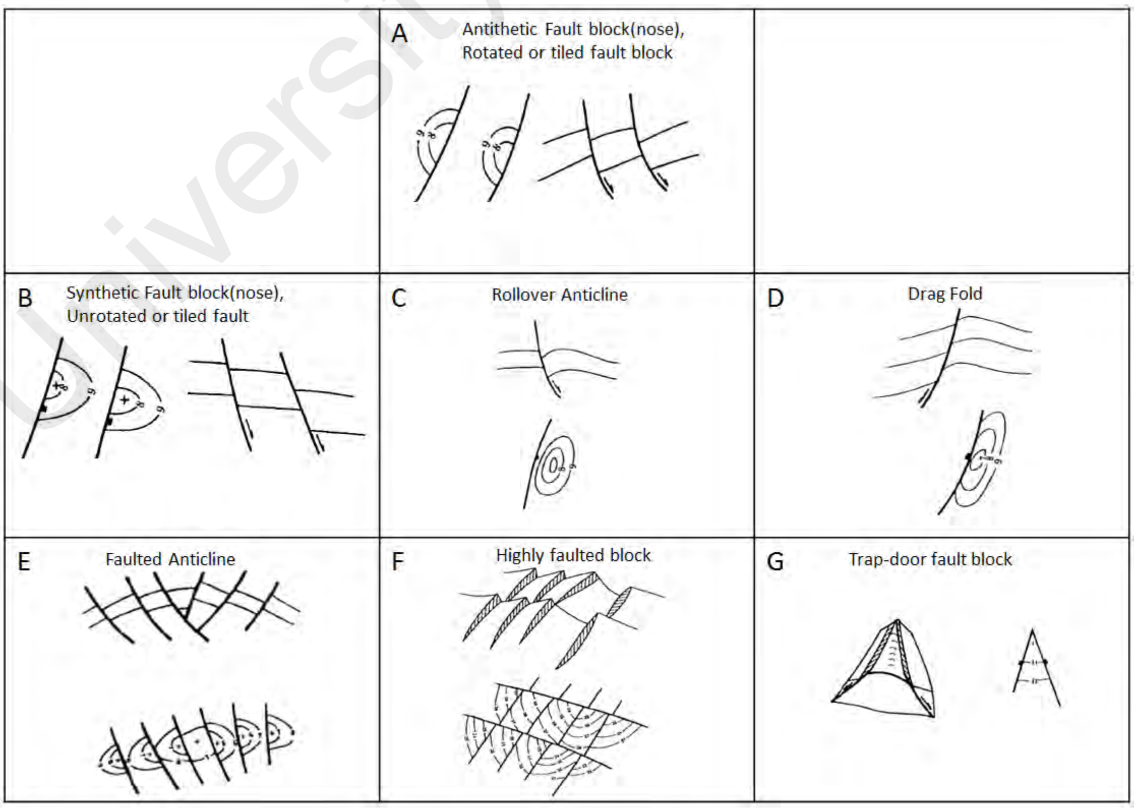


Figure 4.1 Fault style analysis (RRI) (1990)

4.1.1 Rotated (tilted) fault blocks (noses)

The downthrown block of the listric fault occurred rotation or tilting when falling down along the fault, forming a rotated or tilted fault block or nose. Since the fault dipping direction is opposite to that of the stratigraphic beds, we also call the structures antithetic fault blocks or noses. This type of structures is often three-way dip closed and one-way fault closed (Figure 4.1A).

4.1.2 Unrotated fault blocks (noses)

The planar (or domino-style) fault-bounded blocks, which did not occur rotation when slipping downdip, are termed unrotated fault blocks (noses), or synthetic fault blocks (noses), also one-way fault closed and three-way dip closed figure (Figure 4.1B).

4.1.3 Fault rollovers

Fault rollovers occur mainly in the downthrown blocks of the main boundary growth faults, with the axes parallel to the fault (Figure 4.1C).

4.1.4 Drag folds

Drag folds occur along the edge of the upthrown wall of some large growth faults due to dragging of frictional force arising from the downdip movement of the downthrown wall. Examples can be observed in the marginal side of the upthrown wall of some large faults (Figure 4.1D).

4.1.5 Trap-door fault blocks

Two or three faults merged together or intersected, forming two or three-way fault closed and one-way dip closed structures, termed trap-door fault. Examples of the trap-door fault blocks are commonly seen in the fault step zones (Figure 4.1G).

4.1.6 Faulted anticlines

The former anticlines, such as basement hill related anticlines, were cut subsequently by faults, which were termed faulted anticlines. Examples of the structures can be observed in the fault step zone (Figure 4.1E).

4.1.7 Highly faulted blocks

Some blocks were cut by multidirectional faults into fragments, which we termed as highly faulted blocks (Figure 4.1F).

4.1.8 Drape or differential compaction anticlines

Drape anticlines, formed over basement highs and/or faulted horsts, can be commonly seen in the upper of the faulting cycle sedimentary sequences and in the sagging sequences. In the work area, some relatively complete anticlines, although cut by faults into fragments (Figure 4.2).

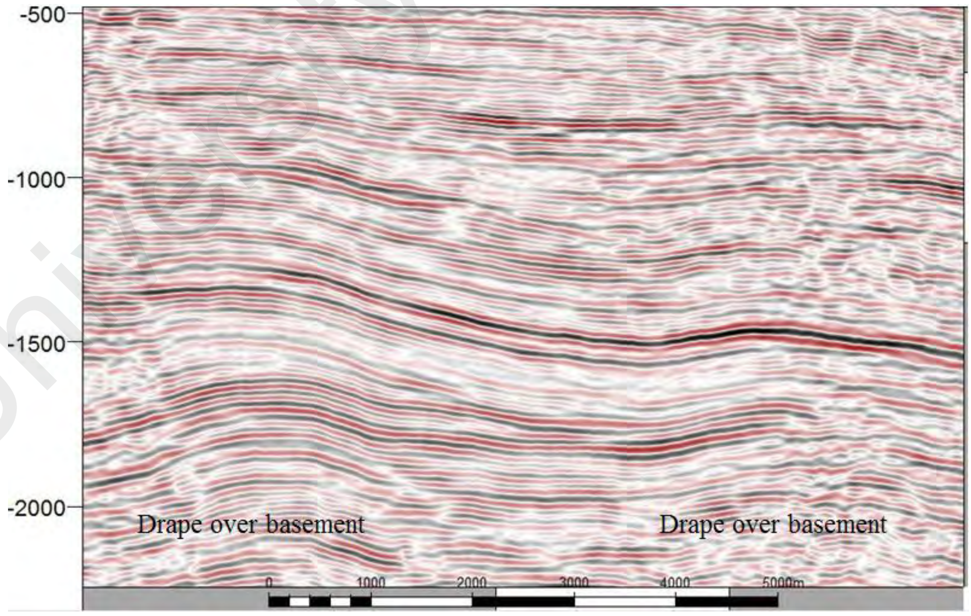


Figure 4.2 Xline 527 drape over basement less affected by the Tertiary tectonics

4.1.9 Inverted structures

Some faulted anticlines might also be regarded as originally being compressional folds formed during the structural inversion of late of Darfur stage. The folds are very favourable for forming of the original oil pools and also favourable for the secondary oil pools in the faulted blocks on the background of the folds (Figure 4.5).

4.2 Faults on the 3-D seismic data set

In the southern part of the 3-D coverage, most lines show evidence for two different fault styles. At the SW end of the inlines, there is usually a non-rotational fault with a significant throw. Non-rotational faults are usually transcurrent, and it may be significant that such faults usually trend north-south in the 3-D area (Figure 4.3).

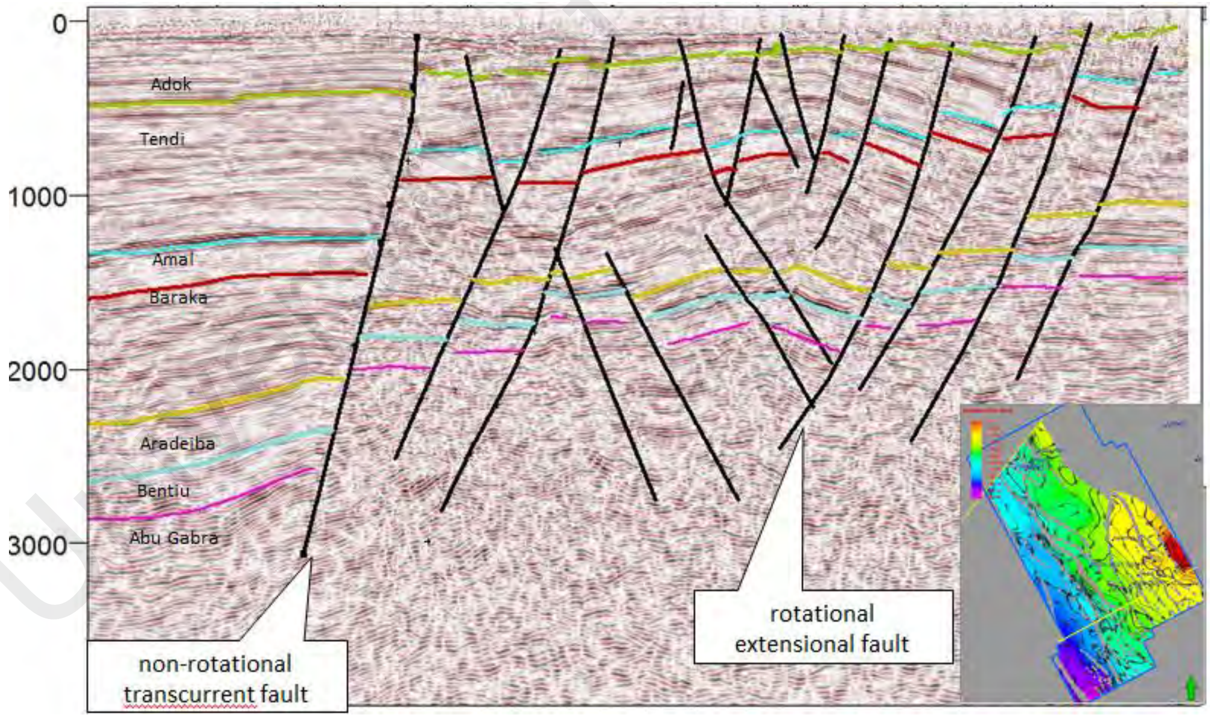
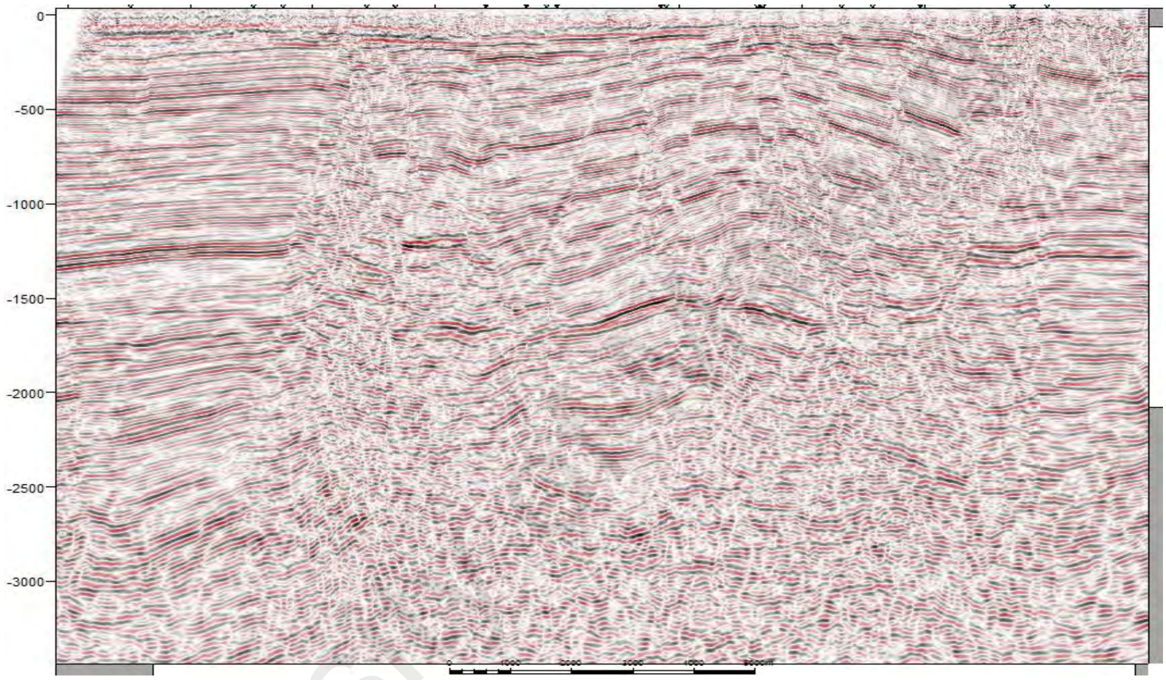


Figure 4.3 Rotational and non-rotational faults

The same non-rotational and rotational faults are imaged on a line 279 (Figure 4.4). There is a gentle fold structure and the Top Baraka and other. This line demonstrates that horizons on the hanging wall of the main rotational fault are all low to regional, which implies that the fold has formed as the result of extension, rather than inversion. It is likely that the controlling fault is sinuous in shape with a gently inclined section beneath the crest of the anticlinal fold. The age of the faulting must lie within missing section beneath the Top Tendi horizon, and is probably Early Miocene. Consequently, the anticlinal structure is young and may have formed after the main period of hydrocarbon charge.



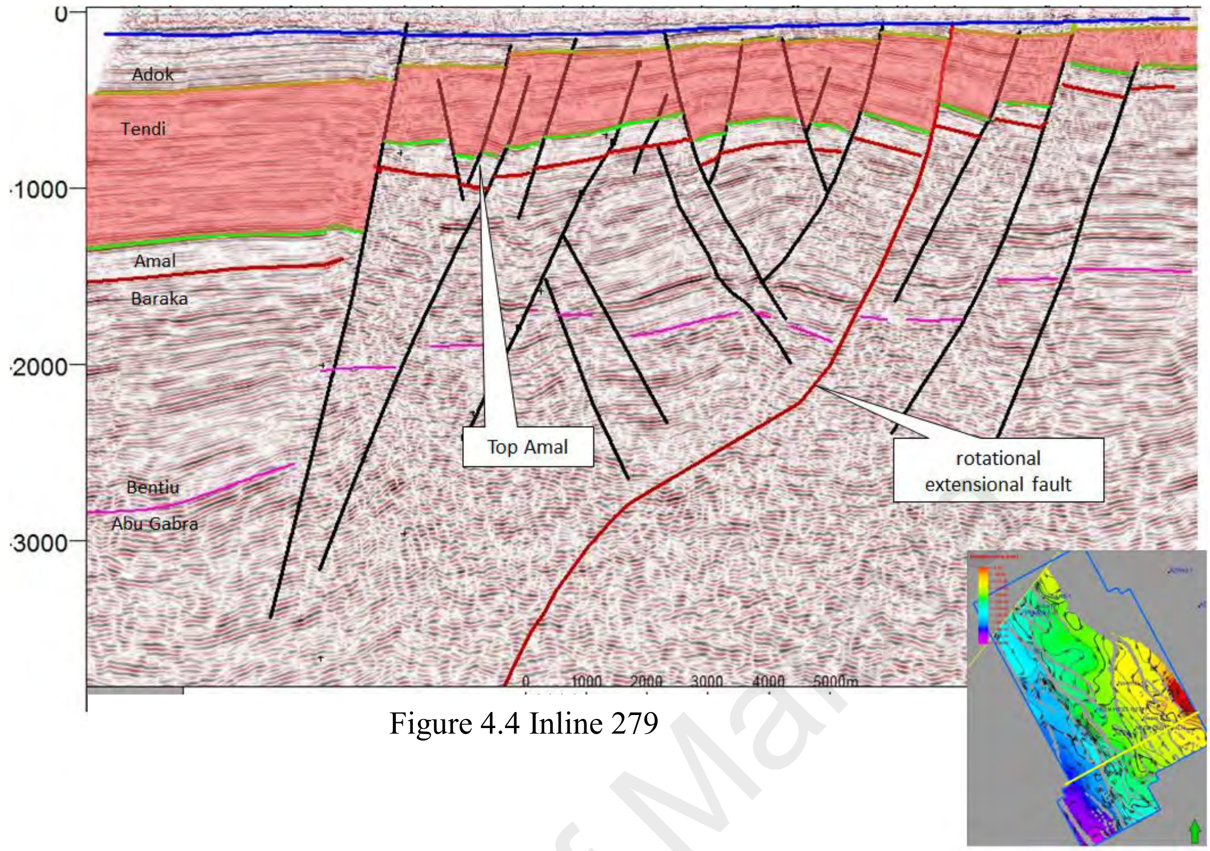


Figure 4.4 Inline 279

4.3 Contractional structures

Candidates for contractional structures were not clearly observed on the study area; the regional African Santonian inversion event was published Unity Field shows that all the structures to be truncated by the unconformity at the top of the Tendi sequence. However, there is also a deeper synclinal fold which appears to be truncated at the top of the Baraka Formation (Figure 4.5).

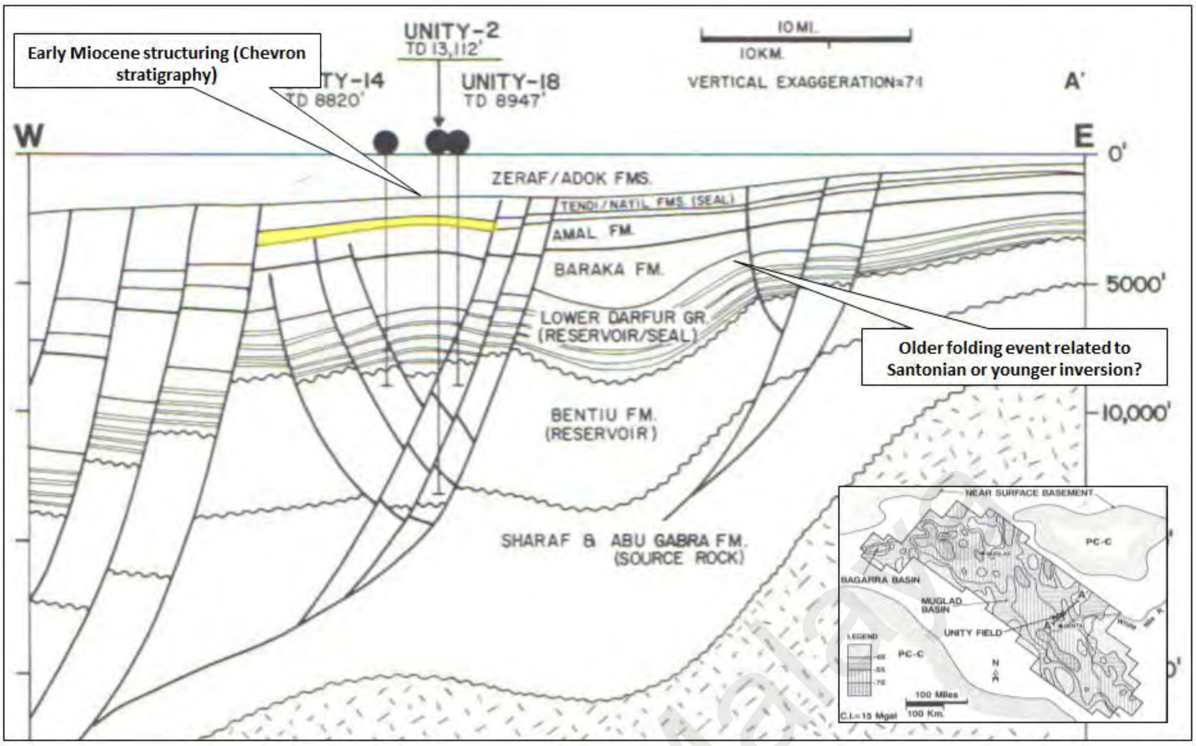


Figure 4.5 Inversion at Unity Field

Guiraud (1997) has illustrated an example of a Santonian inversion structure from the Khartoum Basin in Sudan (Figure 4.6). He noted that in the Muglad Basin, where well control is most extensive, Late Cretaceous rifting is thought to last from the Turonian to the Late Senonian (Schull, 1988). For this reason, Bosworth (1992) interpreted the age of the Khartoum Basin inversion, to be Early Cenozoic.

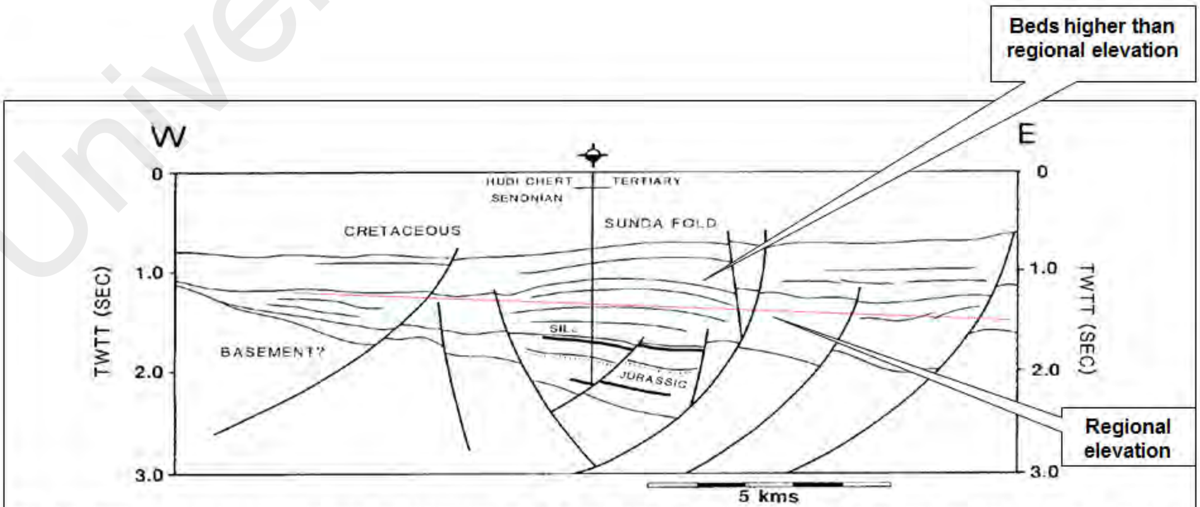


Fig. 19. Structural cross section through the Khartoum basin of the Blue Nile rift (Sudan), after seismic interpretation by Bosworth (1992). The name of the oil well is Al Democratia-1.

Figure 4.6 Evidence for Santonian inversion (Guiraud, 1997)

Basin inversion is the progression of shortening an extensional sedimentary basin whereby the basin fill is uplifted and partially extruded and pre-existing faults are re-used (Cooper et al). It is characterised by uplift of the basin fill, folding of syn- and post-rift sediments and (partial) reactivation of normal faults.

Inversion geometries have been commonly modelled as involving complete reactivation of the basin forming extensional faults such that extensional sedimentary wedge is pushed up – (inverted) above the pre-extensional regional elevation figure 4.7

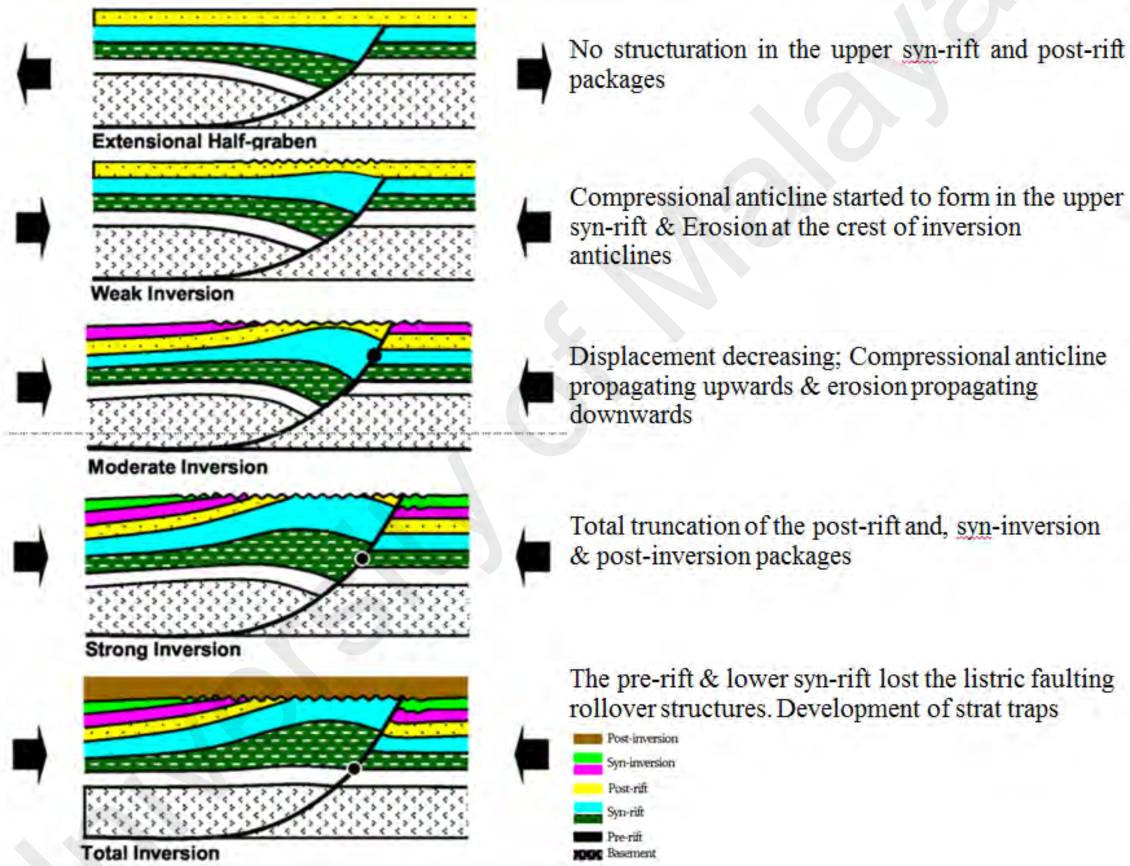


Figure 4.7 Conceptual inversion model (modified from Cooper et al. 1989)

4.4 Compactional folds

Differential compaction may have also played a significant part in the formation of the folds in the Block 4 study area. A simple synclinal plunge closure is imaged at northern side of crossline 468 and is visible on the timeslice at 0.7 seconds TWT (Figure 4.8).

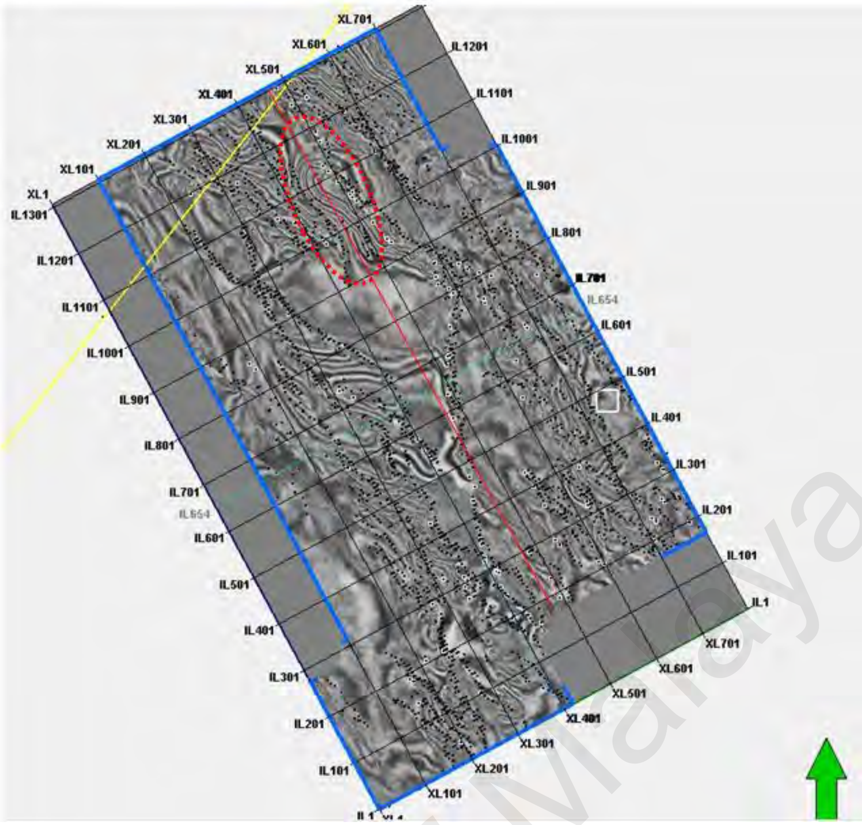


Figure 4.8Timeslice 0.700 msec

The structure is most pronounced at the level of Top Baraka and Top Amal horizons, but dies out upwards. It has minimum amplitude at the Top Tendi level and even a slight anticlinal form at Top Adok level (Figure 4.9).

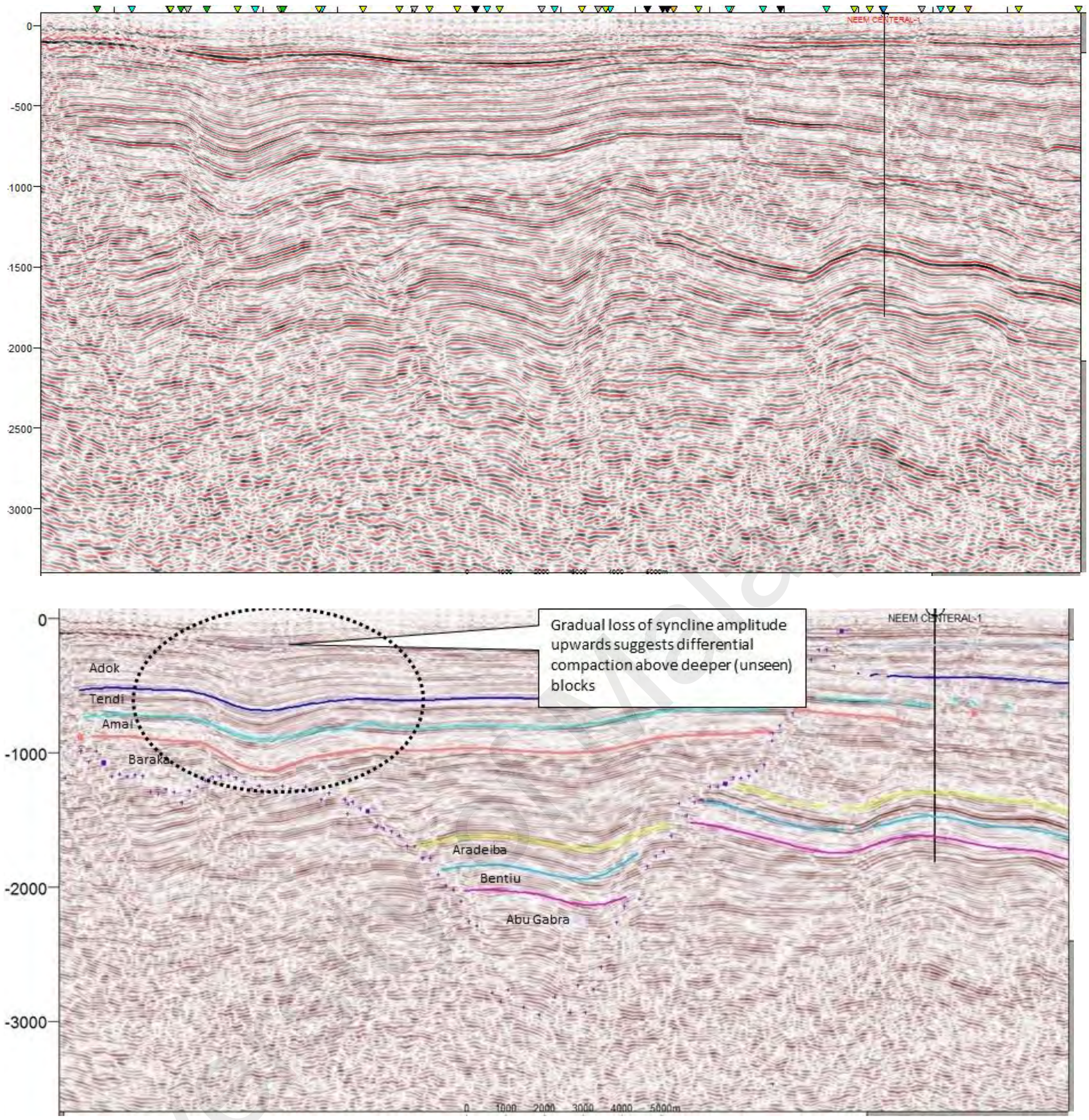


Figure 4.9 Syncline formed by differential compaction (Crossline 468)

The fold has grown gradually through the Cenozoic. Such folding is usually associated with differential compaction above deeper highs and basins, rather than discrete extensional or compressional events. It is possible that much of the Cenozoic faulting and associated folding are fundamentally compactional effects above deeper, more significant fault sequences in the Early Cretaceous section. These fault sequences lie beneath the base of the seismic data set in Study area.

CHAPTER FIVE

PETROLEUM SYSTEM ELEMENTS

Since each rift cycle has the potential to provide all the necessary elements for a full petroleum system, there could be as many as three petroleum systems in the general area. So far, however, there is only one proven regional petroleum system related to the excellent Early Cretaceous lacustrine source rock section of the first rift cycle.

5.1 Reservoir

Considering the high proportion of sands in the sedimentary section of the Muglad basin, it would appear that finding reservoirs for petroleum accumulations should not be a serious problem.The proven reservoir rocks in the study area are the continental fluvial sandstone where marketable oil flows have been confirmed. The reservoirs in Muglad Basin consist of stacked braided stream to meander fluvial channel beds, lacustro-deltaic layers of Cretaceous, Palaeocene and Eocene (Schull, 1988; Giedt, 1990). The thicker sandstone bodies occur in the late rift or post-rift sag phases of each of the three rift cycles: the Bentiu, Amal and Adok formations. These thick sandstone bodies have also excellent reservoir properties. The Abu Gabra is known as reservoirs in limited areas. The average porosities in the main reservoirs are 20-35% that decreases linearly with depth at 3000-3900 m (Mohammed et al., 1999). Reservoir quality decreases with depth due to compaction in the study area.

5.2 Source

The dark grey lacustrine claystones and shales of the early rift phase(Neocomian-Aptian/Abu Gabra- Lower Bentiu) are moderately rich oil-prone source rocks. The gross source interval more than 2000 m but normally consists of hundreds aggregate meters or less of thin-bedded organic-rich shales, as indicated from direct sampling (Meyer and Nederiof, 1984; Passey et al.,1990).The average Total Organic Carbon (TOC) in Muglad Basin (Evoy et al., 1999) is more than 4 wt. %. However, the average TOC in Block 4 at the study area(Azrag and in Neem areas) rages from 2 to4 wt. (Table 5.1). Additional shales are found in the Maastrichtian (Ghazal to Lower Baraka) and late Eocene-Oligocene (Nayil-Tendi) intervals with limited source potential. The depositional environment of the thickest oil-prone source rocks was within large lakes distal from the primary clastic influx. The Kerogen type are mixed organic matter of Type II and III and were mainly terrestrial derived. The transition from oil-prone to gas-prone source material often occurs quickly both vertically and horizontally within a formation, reflecting the rapid changing environments of lacustrine depositional system.

Table 5.1 Neem N-1 TOC and Rock Eyal.

Depht (m)	Formation	S_1 (mgCO2/g rock)	S_2 (mgCO2/g rock)	S_3 (mgCO2/g rock)	S_1+S_2 (mgHC/g)	TOC (%)	Tmax (^oC)	HI	OI	TPI S1/S1+S2
2300	Abu Gabra	0.12	9.53	0.73	9.65	1.58	447	605	46	0.01
2310	Abu Gabra	0.42	22.66	0.80	23.08	3.06	448	740	26	0.02
2320	Abu Gabra	0.43	21.67	0.87	22.10	3.08	446	703	28	0.02
2330	Abu Gabra	0.47	27.16	0.84	27.63	3.64	447	746	23	0.02
2340	Abu Gabra	0.24	17.56	0.60	17.80	2.45	451	716	25	0.01
2360	Abu Gabra	0.31	17.17	0.59	17.48	2.53	448	680	23	0.02
2370	Abu Gabra	0.48	21.82	0.73	22.30	3.07	448	710	24	0.02
2380	Abu Gabra	0.55	21.29	0.94	21.84	3.27	447	651	29	0.03
2405	Abu Gabra	0.31	11.84	0.74	12.15	1.91	445	621	39	0.03
2410	Abu Gabra	0.31	12.48	0.88	12.79	2.23	446	559	39	0.02
2435	Abu Gabra	0.48	31.19	0.90	31.67	4.10	449	760	22	0.02
2480	Abu Gabra	0.90	25.64	0.62	26.54	3.42	448	750	18	0.03
2490	Abu Gabra	0.95	28.77	0.65	29.72	3.73	449	771	17	0.03
2500	Abu Gabra	0.37	17.03	0.66	17.40	2.56	449	665	26	0.02
2510	Abu Gabra	0.57	28.38	0.65	28.95	3.73	450	761	17	0.02
2525	Abu Gabra	0.84	29.66	0.62	30.50	3.87	449	766	16	0.03
2540	Abu Gabra	0.29	2.23	0.70	2.52	0.53	444	424	133	0.11
2565	Abu Gabra	0.31	14.43	0.74	14.74	2.21	449	654	34	0.02
2595	Abu Gabra	0.65	17.97	0.35	18.62	2.71	449	663	13	0.04
2610	Abu Gabra	0.47	23.67	0.41	24.14	3.25	452	729	13	0.02
2625	Abu Gabra	0.73	22.57	0.49	23.3	1.99	449	1136	25	0.03
2635	Abu Gabra	0.88	22.59	0.72	23.47	3.33	449	679	22	0.04
2645	Abu Gabra	0.58	9.56	1.15	10.14	1.61	449	595	71	0.06
2650	Abu Gabra	0.85	13.93	0.96	14.78	2.35	449	592	41	0.06
2685	Abu Gabra	0.52	7.39	0.85	7.91	1.47	450	502	58	0.07
2700	Abu Gabra	0.85	17.59	0.1	18.44	1.56	451	1128	6	0.05
2710	Abu Gabra	0.6	12.83	0.91	13.43	2.43	450	528	38	0.04
2720	Abu Gabra	0.94	17.63	0.93	18.57	3.36	449	524	28	0.05
2730	Abu Gabra	1.44	16.52	0.97	17.96	3.64	449	454	27	0.08
2740	Abu Gabra	1.06	21.25	0.76	22.31	3.54	451	600	21	0.05
2750	Abu Gabra	0.42	6.8	0.92	7.22	1.43	451	476	64	0.06
2760	Abu Gabra	0.39	19.51	0.92	19.9	3.51	451	555	26	0.02
2790	Abu Gabra	0.51	15.15	0.91	15.66	2.67	449	567	34	0.03
2810	Abu Gabra	0.89	14.37	1.12	15.26	2.76	451	521	41	0.06
2825	Abu Gabra	0.12	3.05	1	3.17	0.85	448	358	117	0.04
2840	Abu Gabra	0.45	16.28	1.13	16.73	3.01	452	542	38	0.03
2855	Abu Gabra	0.08	0.74	0.87	0.82	0.4	448	184	217	0.10
2860	Abu Gabra	0.62	15.03	1.16	15.65	3.19	451	471	36	0.04
2870	Abu Gabra	0.15	1.67	1.29	1.82	0.78	447	215	166	0.08
2880	Abu Gabra	0.51	14.99	0.87	15.5	3.08	451	486	28	0.03
2890	Abu Gabra	0.63	10.79	1.13	11.42	2.54	450	424	44	0.06
2900	Abu Gabra	0.73	15.05	1.03	15.78	3.23	451	467	32	0.05
2935	Abu Gabra	0.99	16.25	0.95	17.24	3.47	452	468	27	0.06
2980	Abu Gabra	0.76	8.08	0.9	8.84	1.85	451	436	48	0.09
3000	Abu Gabra	1.09	10.2	0.8	11.29	2.28	450	447	35	0.10
3010	Abu Gabra	0.91	13.67	0.65	14.58	2.95	450	463	22	0.06
3020	Abu Gabra	1.22	9.8	0.92	11.02	2.35	451	418	39	0.11
3045	Abu Gabra	0.82	7.62	0.9	8.44	1.89	451	403	48	0.10
3090	Abu Gabra	0.82	6.31	0.95	7.13	1.77	451	357	54	0.12
3125	Abu Gabra	0.86	8.36	0.77	9.22	2.1	450	398	37	0.09
3135	Abu Gabra	0.73	5.79	0.76	6.52	1.67	451	347	46	0.11
3155	Abu Gabra	0.86	6.5	0.78	7.36	1.69	451	385	46	0.12
3185	Abu Gabra	0.82	6.44	0.88	7.26	2	450	322	44	0.11
3200	Abu Gabra	0.61	5.85	0.87	6.46	1.81	450	323	48	0.09

5.3 Seal

Efficient sealing is the most critical factor for the preservation of hydrocarbons in a severely faulted basin as the Muglad basin because of the complication of the geology, together structurally and stratigraphicaly, and the sandy content of the whole section have formed a very leaky system. Vertical migration, particularly along fault planes, isobserved as an important aspect of many accumulations. Numerous shale intervals act as seal over the sandy reservoir. The main shaly covers involved in the Petroleum System are localized in Abu Gabra Formation, Aradeiba Formation, Nayil and Tendi Formations.

Lateral seal drive on the thickness and the lithology of the Aradeiba shale and the fault throw. The Aradeiba Formation has difference thickness and variable sand/shale ratio. More than 1000m of Aradeiba Formation was in the central part of the basin, decreasing to less than 20 m along the basin edges (Kamil M. Idris and Su Yongdi). Most of the excellent lateral seals are because of direct juxtaposition of Bentiu sandstone against Aradeiba shale. Examples of this condition are shown in Figure. 5.1 In some situation clay smear and shale gouge ratio play an important role in lateral seal integrity.

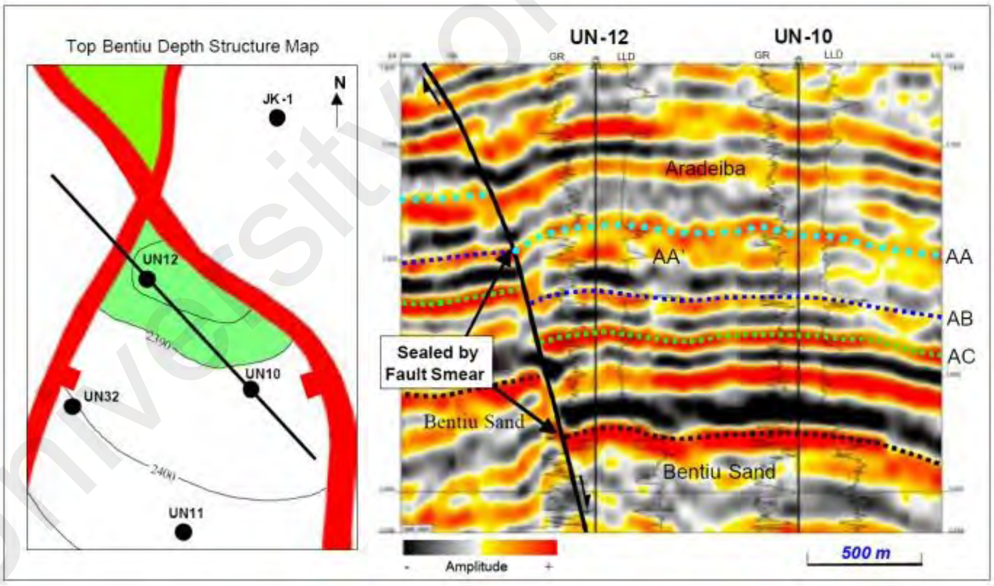


Figure5.1.juxtaposition against Aradeiba intraformational shale across the fault provide good lateral seal. (Kamil M. Idris and Su Yongdi 2004).

5.4 Traps

The productive and catchment structures resulting from this complex extensional basin have been categorised as rotated fault block, drape folds, and reverse drag folds:

- Rotated fault block are made by simple block rotation along a normal fault plan. These structures are important producing traps, but the entrapment depends on a seal at or across fault closure.
- Drape folds are formed in the sediments overlying the upthrown side of deeper normal faults. This type of closure has been found in areas where faults formed during early rifting phase we not rejuvenated.
- Downthrown rollover anticlines have resulted from rotation into listric faults. These listric faults are often accompanied by antithetic faults sub-parallel to the primary fault trend.

In Muglad basin the extension tectonic created four major structural traps styles; upthrown fault block (horst and tilted fault block), faulted anticline, rollover anticline and downthrown fault block. The major limiting control on trap size is cross-fault seal (Figure 5.2). Stratigraphic trap linked to fluvial sands distribution and flooding shale are also expected.

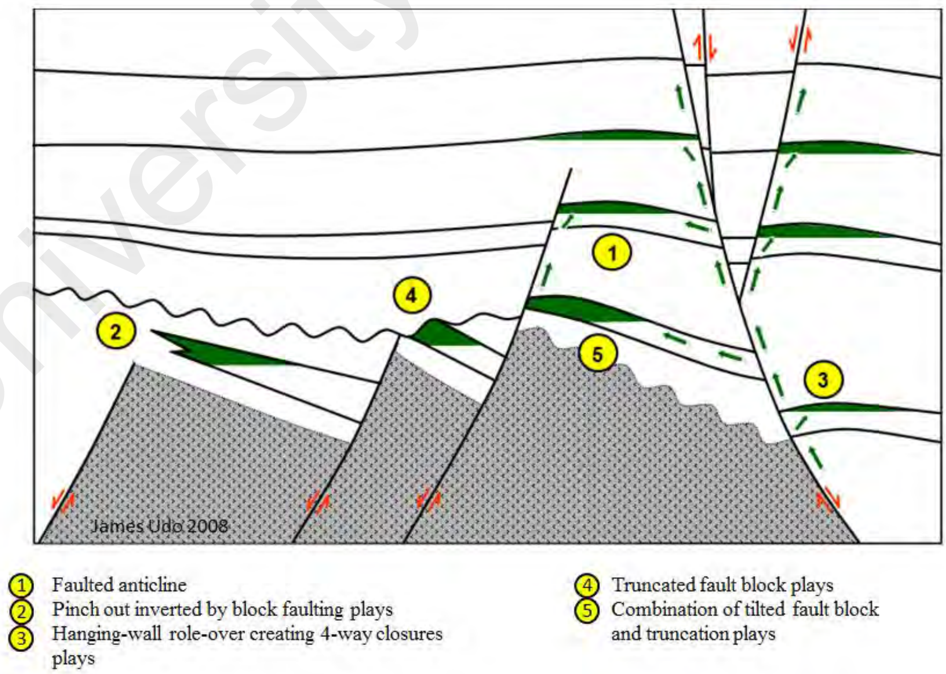


Figure 5.2 major structural traps styles

5.5 Modelling petroleum generation in the study area

A petroleum system is a geologic system that includes the hydrocarbon source rocks and all associated oil and gas and which comprises all of the geologic elements and processes that are crucial if a hydrocarbon accumulation is to exist (Magoon and Dow, 1994). A petroleum systems model is a numerical data model of a petroleum system in which the interconnected procedures and their results can be simulated for understand and predict them (Hantschel and Kauerauf, 2009). Basin modelling is dynamic modelling of geological processes in sedimentary basins over geological time spans (Hantschel and Kauerauf, 2009). The geological processes calculated and rationalised at each step include deposition, erosion, compaction, heat flow analysis, expulsion, phase dissolution, hydrocarbon generation, accumulation and migration. These processes are simulated in a dynamic petroleum systems model in the assessments of exploration risks, migration scenarios and drainage areas.

Basin modelling is conducted usingcomputer based simulation software PetroMod 2012for the 1D & 2D modelling along selected cross-section to identify the thermal history for the source rock Abu Gabra Formation. Neem N-1 was selected as key well to replicate the expulsion, petroleum generation, model the maturity of the source rocks and the timing of hydrocarbon generation in the study area. The well is situated in the central of the study area and penetrated all the strata with deep penetration of the source rock, all the geochemical analysis result data is available as part of the data base (TOC%) , (HI) values, (Ro) which is use for calibrating maturation models. Formation tops and it's associated ages were taken from the end of well report and publish data from Mohamed et al. (1999) Table 5.2 shown ages, lithology, and formation tops and thickness of each modelled rock unit.

Table 5.2 Input data for modelling of depositional for Neem N-1

Formation	Lithology	Deposition Age		Formation		
		From (ma)	To (ma)	Top (m)	Bottom (m)	Thickness (m)
Zeraf	Shale (organic lean, typical)	1.8	0	0	175	175
Adok	Shale (organic lean, typical)	3	1.8	175	280	105
Tendi	Shale (organic lean, typical)	11.2	3	280	470	190
Nayil	Shale (organic lean, typical)	28	11.2	470	680	210
Amal	Sandstone (typical)	58	28	680	820	140
Baraka	Shale (typical)	66	58	820	1120	300
Ghazal	Sandstone (clay rich)	69.5	66	1120	1330	210
Zaraga	Shale (organic lean, typical)	78.8	69.5	1330	1620	290
Aradeiba	Shale (typical)	84	78.8	1620	1870	250
Bentiu	Sandstone (typical)	93.5	84	1870	2170	300
Abu Gabra	Shale (organic rich, 3% TOC)	120	94	2170	2791	621
Middle Abu Gbara	Sandstone (clay rich)	127	120	2791	3000	209
Lower Abu Gbara	Shale (organic rich, 3% TOC)	140	127	3000	4700	1700
Basement	Granite (150 Ma old)	150	140	4700		

The re-evaluation of the heat flow with PetroMod software was done in order to integrate a rift model responding to the extensional processes of the Muglad basin. During rifting, the crust and upper mantel are supposed to be thinned; consequently the thermal structure of the basement is modified according to the rifting event. The bottom sediment heat flow is directly influenced by this basement thermal structure.

Heat flow was mainly used throughout the modelling process to obtain a good calibration of the maturity and subsidence history (Figure 5.3). Excellent fitting curve between measured and calculated % Ro values would need a reflection of erosion thickness and/or heat flow. Mohamed et al. (2002)'s heat flow values and erosion thickness base prior to adjusted to have well calibration with model in the study area.

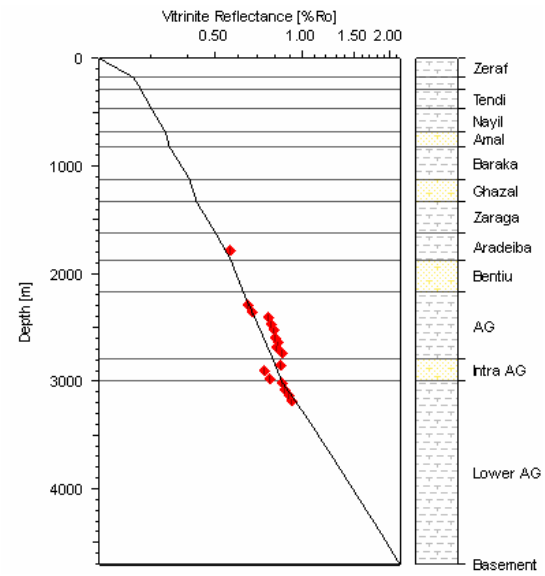


Figure 5.3 measured and calculated % Ro values correlation

5.5.1 Source rocks characteristics

Generally the examined Abu Gabra plot in the mature region of Types I and II kerogen grading to mixed Type II-III kerogens. Nevertheless, the Py-GC analyses recommend that the source rocks are mostly oil prone Type I kerogen (Fig. 5.4).

Consequently, hydrocarbon generation and expulsion phases were calculated postulating Type I kerogen and using reaction kinetics data based on Pepper and Corvi (1995).

The data indicates that the shales/claystones of the Abu Gabra Formation proved to be excellent source rocks for hydrocarbon generation (mainly oil-prone) in the study area.

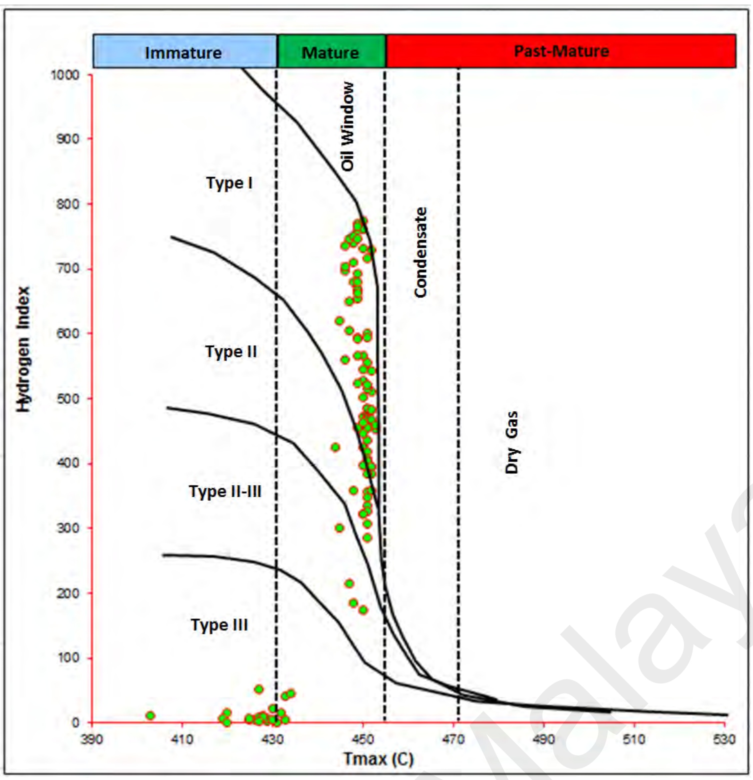


Figure 5.4 Plot of hydrogen index (HI) versus pyrolysis Tmax

The burial history plot, thermal history assessment and timing of hydrocarbon generation were built for Neem North-1 which is shown in Figure 5.5and Figure 5.6.The burial history indicates that the highest subsidence and sedimentation rate and syn-rift sediments progressive during the first rift phase (Neocomian – Barremian).

Fast burial and subsidence that started during late Early Cretaceous (140-100 Ma) where by Abu Gabra Formation the organic-rich shales were deposited.

The thermal history restorations and hydrocarbon generation of the study area were control by the heat flow tectonic events of the Muglad Basin. The modelling results shows differences in source rock maturity and hydrocarbon generation histories due to the variation in thermal and burial histories (Figure 5.3).

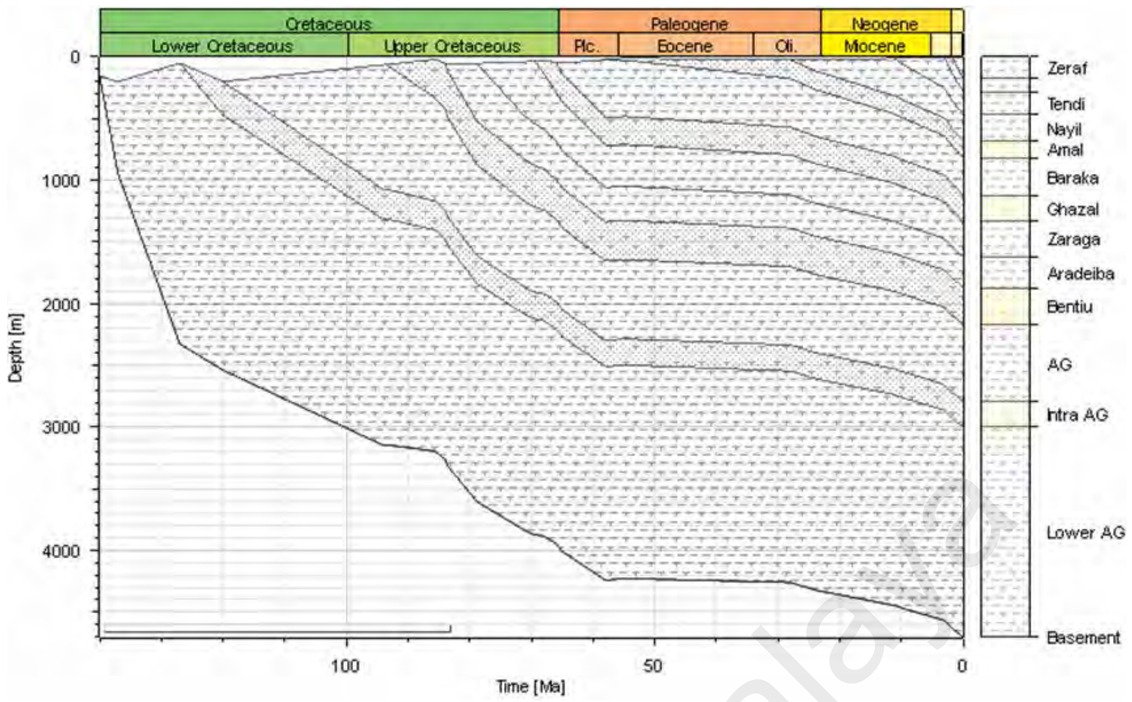


Figure 5.5 Burial history curves for Neem-N1

From the burial/thermal history model of the Neem N-1, the calculated vitrinite reflectance values are 0.55-1.3% Ro (>50% TR, Figure 5.4), specifying that the formation has approach the oil window (Figure 5.6(e.g. Sweeney et al., 1987). Oil generation of the Abu Gabra Formation (Abu Gabra-lower) in this well started from about 95Ma with the calculated vitrinite reflectance (VR) value of 0.55% Ro, at the depth of about 1500m(Figure 5.6) and transformation ratio 1-10%.

The maturity of the Abu Gabra-lower reached 0.70% Ro at 77 Ma at the depth of 2000 m (Fig. 5.6), however the oil generation of the Abu Gabra-Upper began at about 70Ma with VR values of 0.55% Ro (1-10% TR), at the depth of about 1320m, and the maturity reached 0.70% Ro at 67 Ma at a depth of 1800m.

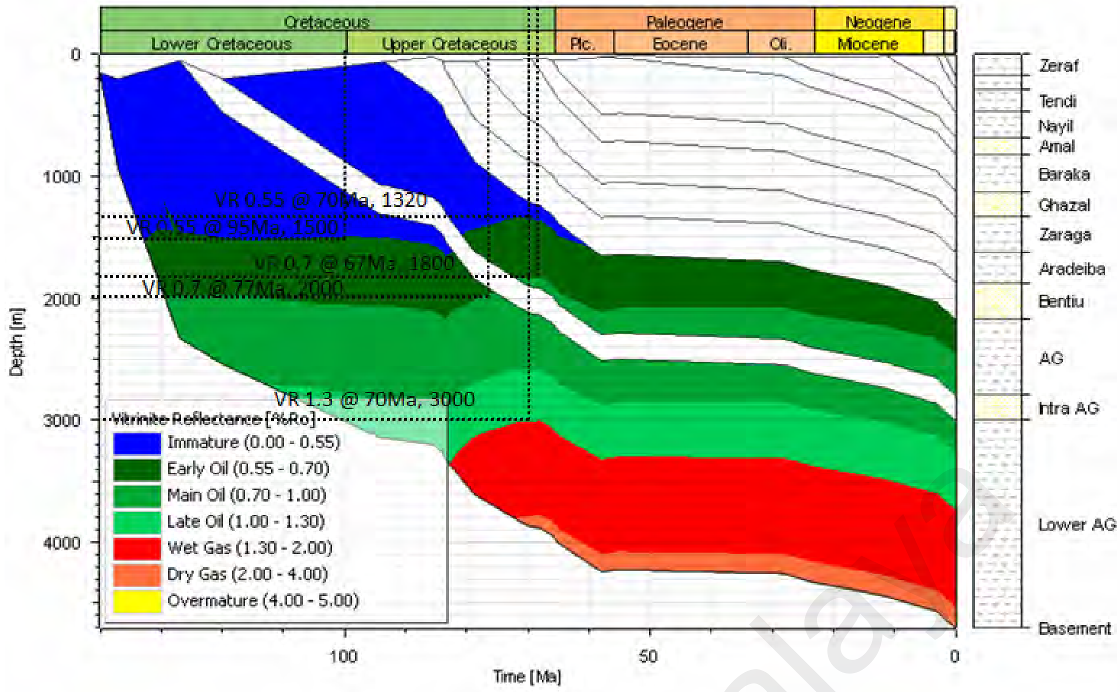


Figure 5.6 Burial and thermal maturity historiesmodels for Neem N-1

5.5.2 Hydrocarbon generation and expulsion

Petroleum generation and expulsion (mg HC/g TOC) time of Abu Gabra Formation modelled. Oil generation is identified in this study by transformation ratios between 10% and 50%. The immature source rocks transformation ratio is less than 10% which mean there is no generation. Peak oil generation occur at a transformation ratio of 50% when the oil generation phase is reached. The modelled petroleum generation and expulsion of the selected well shows that the Abu Gabra Formation source rocks generated only oil and wet gas as the main product.

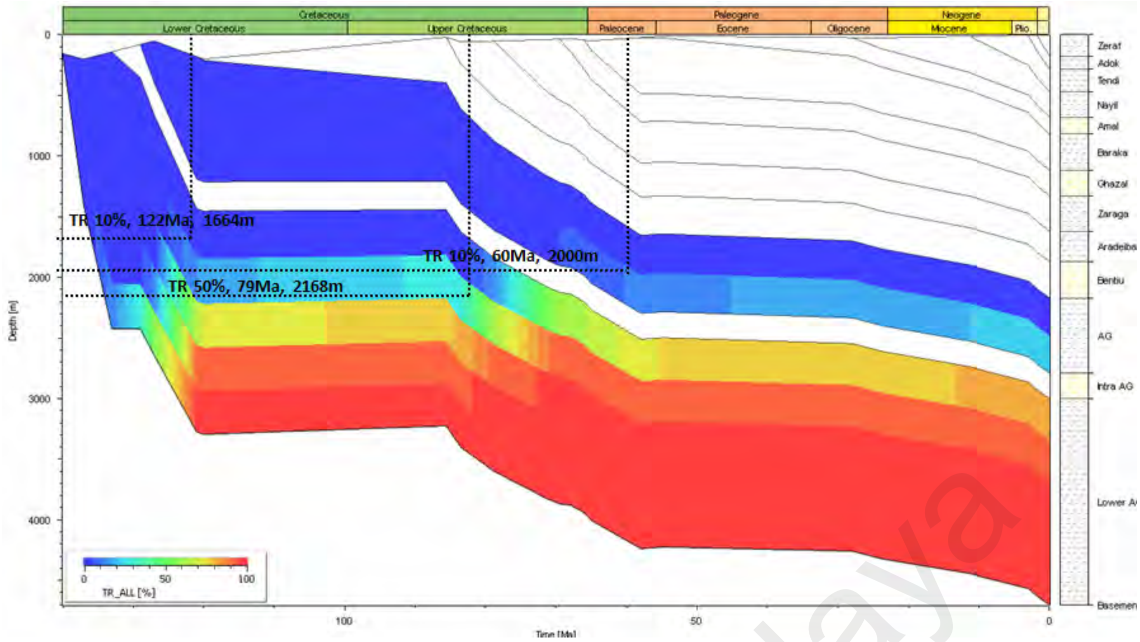


Figure 5.7 Starting and peak of oil generation is represented by transformation ratios of 10% and 50%.

The event chart of the Cretaceous to Tertiary petroleum system recaps the chronological connection among the fundamentals and processes of the petroleum system. It demonstrates the hydrocarbons originated from the organic-rich shale of the Abu Gabra Formation and migrated into the middle Abu Gabra sandstones (reservoir), Bentiu and Darfur Group sandstones. The Abu Gabra and Darfur Group claystones are the most essential regional seal rock within the Sub-basin. The overburden rock that overlies the Abu Gabra source rock includes the Bentiu, Darfur Group, Amal, Kordofan Group, and Zeraf formations. Most of the structural traps formed during the rifting phases during the Early Cretaceous, Late Cretaceous, and early Tertiary. The events chart also shows that generation, migration and accumulation started in the Upper Cretaceous (79 Ma) and continue till today. Furthermore an important concept in process timing of the hydrocarbons generation, migration and accumulation in a petroleum system is the "critical moment." The critical moment occurs when the source

rock is at 50% generation (50% transformation ratio) and all the elements of the petroleum are in place, which is the relative conversion of organic matter to hydrocarbons. The critical moment of the petroleum system in this study is considered to be at the early Maastrich.

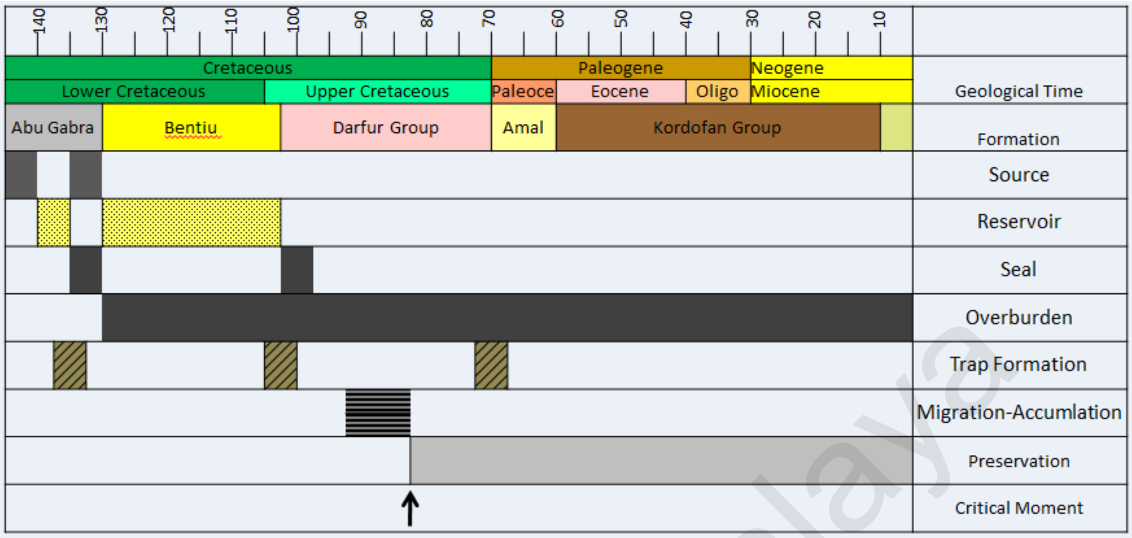


Figure 5.8 Event chart

5.6 2D Basin Modeling

2D basin modelling fully integrates seismic, stratigraphic and geological interpretations with multi-dimensional simulations of thermal, fluid flow and hydrocarbons migration throughout geological time in the basin (Hantschel and Kauerauf, 2009). In this study, the 2D modelling was performed along a 14 km long and 6 km deep. The selected 2D seismic dip line passes through the known oil/gas discoveries that have been made at Neem N-1 which is enabled calibration of both maturity and hydrocarbon accumulations.

Suitable facies, source rocks and faults are needed to be defined as well as their properties must be assigned to the modelling grid. In general, similar source rock properties and input parameters that were used in the 1D models are adopted here because the ID model was carried out in Neem N-1 which is located along the 2D seismic line.

There are some uncertainties associated with 2D model due to velocity model limitation for the seismic time to depth conversion which resulted shallower formation than the reality due to low velocity used in the velocity model.

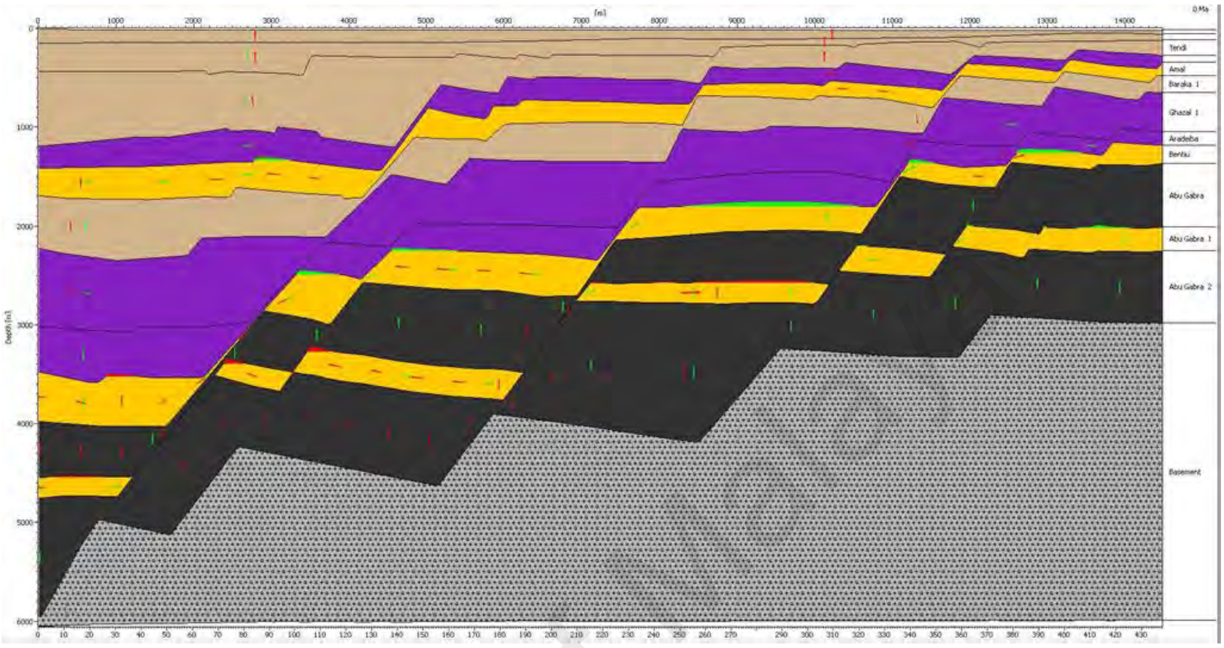


Figure 5.9 2D model along Neem N-1

Modeling results have shown multiple phases of generation; expulsion from organic-rich Abu Gabra lower and upper sources. The migration efficiency able to reach the reservoir which it has been defined from the 2D model result (Figure 5.9).

CHAPTER SIX

CONCLUSION

The most recently published tectonostratigraphic scheme for the Muglad Basin identified 3 specific periods of rifting (Idris et al., 2004):

- Neocomian – Barremian Abu Gabra rift
- Santonian – Maastrichtian Bentiu – Baraka rift
- Eocene – Mid Miocene Amal – Tendi rift

However, in the study area, abrupt thickness changes across faults have also been identified in the Miocene-Pliocene (Adok) and Palaeocene (Amal sequences).

Folds, truncated by erosional unconformities have been observed at various levels in the Cretaceous and Cenozoic sequences. It is frequently unclear whether the folds have formed during phases of extension or contraction. Some folds, which lose amplitude towards the surface, are probably the result of differential compaction above deeper rift sequences, which lie beneath the base of the seismic data.

The current model for the study area base on the available seismic resolution is as follows:

- Primary rifting event Neocomian – Barremian with NW-SE grain, poorly imaged on 3-D seismic data
- Aptian – Palaeocene thermal subsidence with local active faulting, mainly due to differential compaction above deeper fault blocks (note no Aptian penetrated in the Study Area)
- Eocene – mid Miocene faulting involving extension along NW-SE faults and wrenching along N-S fault segments, probably associated with East African rift activity

- Mid Miocene – Recent thermal subsidence with local active faulting due to differential compaction above deeper fault blocks

Possible phases of structural inversion have been identified in the Maastrichtian (pre-Baraka), pre-mid Miocene (pre-Tendi) and post-Pliocene (post-Adok) which was not clear in the study area however it was reported in Unity field in southern part of Muglad basin and in Khartoum basin. The origin of these unconformities is uncertain and they could also potentially have formed by the erosion of folds (formed during extension or by differential compaction).

This seismic interpretation has been heavily data-constrained. Fault-definition on the 3-D data still proved to be highly problematic. This is partly a function of very complex faulting geometries. Well information (log, check-shot and VSP) is not adequate for this study and the available data also required extensive editing and was not easy to integrate with the seismic data.

The study of the petroleum system of the study area has demonstrated the attractiveness of the basin as petroleum province. Timing of petroleum generation/expulsion and thermal histories has been modelled for Abu Gabra source rock, using (1D) and (2D) basin modelling. The lower Abu Gabra reached the early stage of maturity (0.55% Ro) about 122 Ma to 60 Ma with a depth of 1664-2000 m and enters the oil window (0.70-0.1% Ro) at about 70 Ma with a depth of 1320 m while lower Abu Gabra reach oil window at 95Ma and depth of 1500m.

From the thermal maturity modelling for the Abu Gabra which is conducted, it designate that in Abu Gabra-Lower, the generation of hydrocarbon reached the expulsion in the Aptian (>50%transformation ratio) and sustained to present-day while gas started generation at 70 Ma. There is no expulsion has happened from the Abu Gabra-Upper source rock. Most of the oil generated in the area is possibly from the deeper parts of the Sub-basin. Timing of peak oil generation and expulsion from Abu

Gabra source rocks took place after the deposition of related seal rocks within the study area.

The study of the Petroleum System of the study area has demonstrated the attractiveness of this basin as a petroleum province.

Implications for Prospectivity

- Inversion structures formed after the main phase of oil charge would only depend on re-migrated hydrocarbon.
- Most of the extensional geometry was already in place relative to initial maturation of source rocks and peak migration.
- Tilted extensional fault blocks require lateral fault seal and therefore this is a key exploration risk.
- Inversion anticlines may post-date initial migration from source rocks, introducing some charge risk.

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