UNIVERSITY OF NAIROBI

DEPARTMENT OF EARTH AND CLIMATE SCIENCES

SEISMIC STRATIGRAPHY ANALYSIS AND HYDROCARBON GENERATION POTENTIAL OF THE LATE-CRETACEOUS–TERTIARY FORMATIONS FROM THE CORIOLE SUBBASIN (SOMALIA COASTAL BASIN)

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DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree, or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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ABSTRACT

The Coriole basin is the fifth largest sedimentary basin developed on the onshore of Somalia, between larger Mudugh basin in the north-east and Juba-Lamu basin, at the south-west. It also has a relatively thick infill (> 5 km) of sediments belonging to the Mesozoic and Cenozoic which might have created favourable conditions for the development of the Petroleum system elements (source, reservoir, seal, trap and migration). The major purpose of this research was to create a seismostratigraphic framework and determine the structural style of the Coriole basin that controls the hydrocarbon entrapment configuration within the thick Cretaceous to Recent sedimentary infill through the interpretation of 2D seismic data of a total length of 205 km. This kind of research has never been carried out before, and therefore, it has both academic and practical interest. To achieve these objectives, we integrated the interpretations from seven (7) 2D seismic profiles with well top formation data obtained from Afgoi-2 well. This enabled to map the extent of eleven (11) seismic horizons. In order to determine the maturity of the Upper Cretaceous rocks and Tertiary rocks and to evaluate the time of hydrocarbon expulsion-migration-accumulation, a series of Time Temperature Index (TTI) burial history curves were generated and analyzed. TTI results demonstrated that the Jesomma-Auradu Equivalent Formation began to expel some crude oil approximately 9.48 Ma (Tortonian stage Late Miocene), implying that these formations with average TOC (0.5 wt%) values may have possibly generated normal-light oil and wet gas condensate products, and are still in the early oil generating phase (Waples, 1985). The overlying stratigraphic layers are generally immature where the Obbia and Scebeli, and also Somal formations have TTI values ranging from 1.3003 to 3.089. TTI modeling was expanded on other neighboring well sections, including Merca-1, Coriole-1, Afgoi-1 and demonstrated common temporal source rock maturation trends and hydrocarbon expulsion dynamics. The TOC values from Afgoi-2 were used to identify three source rock intervals. These are: the Jesomma-lower Auradu formation interval (9190'-13710') with an average TOC value of 0.86 wt % and Seriole-Auradu transition – lower Somal Sand Member interval (4920'-7330') with an average weight TOC content of 0.90 wt % and Somal formation with an average TOC of 0.39 wt%. According to our TTI calculations, the first two intervals are mature and still capable of producing hydrocarbons (light oil products). Their thicknesses increase towards the Somali Coastal Basin's offshore area. The third source rock (Somal-Scusciuban-Somal Transition Formations) interval is mostly immature and has no HC-producing potential. This integrated study revealed that the Coriole section of the Somalia Coastal basin has three hypothetical (fictional) petroleum systems: a) Jesomma-Auradu Equivalent (Sagahley-Marai Ascia) Petroleum System; b) Scebeli/ Obbia-Auradu Petroleum Systems and c) Somal Petroleum Systems. Among them, the most promising in generating hydrocarbons is the first one, the Jesomma-Auradu-Jesomma Equivalent Petroleum System, consisting of mature source rock intervals and good quality reservoir. The Jesomma and Sagahley Marai Ascia formations offer two types of reservoirs: sandstone and carbonate. The generated isopach and isochore maps enabled us to map the deformations with potential traps and identify the possible primary and secondary hydrocarbon migration pathways. The results demonstrated that the area has been affected by wrench tectonism. This research offers an integrated approach that helps better understand the reasons and explain why the Afgoi-2 well failed to make any commercial hydrocarbon discovery.

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LIST OF ABBREVIATIONS

2D	:	Two-dimensional
3D	:	Three-dimensional
ACAB	:	Amsas Coriole Afgoi Block
BCF	:	Billion Cubic Feet
BGL	:	Below Ground Level
BGR	:	Federal Institute for Geosciences and Natural Resources
BHT	:	Botom Hole Temperature
BP	:	British Petroleum
CGG	:	CGG Robertson
DSDP	:	Deep Sea Drilling Project
DST	:	Drill Stem Test
ENI	:	Italian State Hydrocarbons Oil Company
GDS	:	Geospec Data Services
GSA	:	Geological Time Scale
HC	:	Hydrocarbon(s)
HI	:	Hydrogen Index
HIS	:	Kingdom Suite Seismic Interpretation Software developer
ITCZ	:	Inter-Tropical Convergence Zone
LAS	:	Las well log data format
Ma	:	Million years
MMCF/D	:	Million Cubic Feet per Day
MPMR	:	Ministry of Petroleum and Mineral Resources of Republic of Somalia
PS	:	Petroleum System
RMS	:	Root Mean Square
SMT	:	Seismic Micro Technology
SP	:	Shot Point
ST	:	Surface Temperature
TD	:	Total Depth
TTI	:	Time Temperature Index’s
TWT	:	Two Way Travel Time

CHAPTER 1: INTRODUCTION

1.1 Background Information

The research area is located in the south western region of the Republic of Somalia. The Coriole sub-basin is Somalia's fifth largest (about 25000km^2) sedimentary basin. It is part of the larger Somalia Coastal Basin which stretches from Adelle in the southwest to Ras-Kiyamboni in the northeast, and is divided into three main areas namely: Jubba-Lamu, Coriole, and Mudugh basins (Figure 1.1).

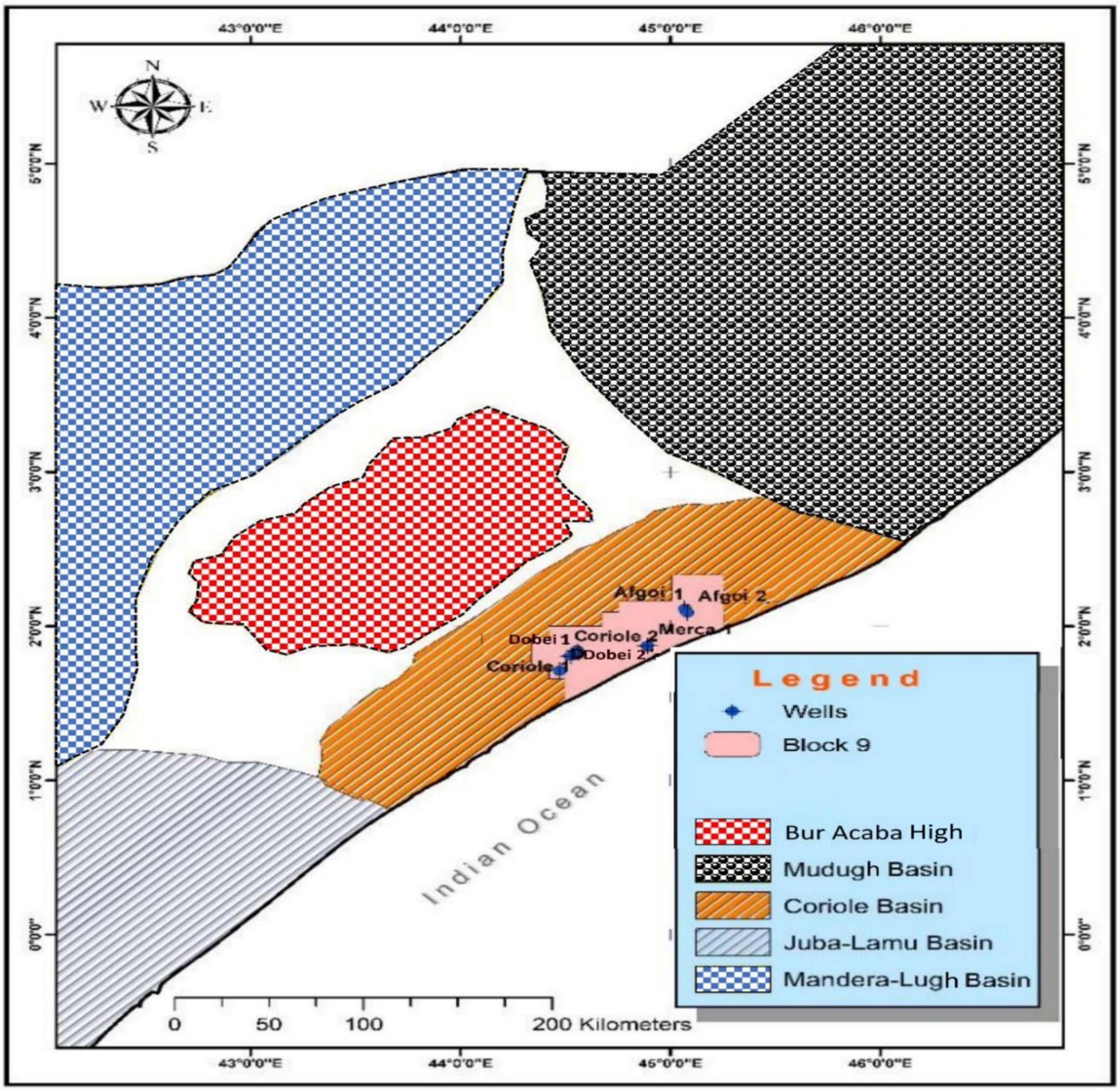


Figure 1.1: The sedimentary basins of south-central Somalia (after Naleye et Harms, 1993).

The history of oil and gas exploration in the Coriole Basin goes back to the mid-20th century when Sinclair drilled its first well in the basin – Merca-1 in 1959, targeting the Upper Cretaceous sediments. However, the first exploration exercises were undertaken by the British explorationists in 1925. This is when Rodger and Sinclair discovered a large seepage of oil in Dhagax Shabel in the north-western region (Abdullahi, 2014). Following this discovery, several wells were drilled by Amoco and Conoco companies in the Coriole Basin where great potential for gas and oil was expected (Abdullahi, 2014). A rapid enhancement in hydrocarbon exploration activities was seen here in the 1950s and 1960s when several wells were drilled across the country. The area of study in the Coriole Basin is estimated to be about 25,000km^2 and, extends further into the offshore Indian Ocean. Abdullahi (2014) opines that despite the fact that most of the exploration activities took place onshore, the potential of offshore Somalia, including the Coriole Basin, seems to be much larger. According to the classification of the pull-apart basins of Klemme (1980), the margin has been subjected to transform fault movements through most of the Late Jurassic to Late Cretaceous times when Madagascar drifted southwards relative to Africa along the Davie Fracture Zone (Amsas Consulting Pty, Ltd, 2013; Abdullahi, 2014). The Coriole-Afgoi exploration Block (ACAB) is about 4700km^2 with the available 2D seismic data that covers only about 854km^2 of the block. A total of 9 wells have been drilled within the block, with two proving to have oil and gas reservoirs (Abdullahi, 2014). Five wells also had oil and gas shows, while the remaining two wells drilled by the Somali government turned out to be dry.

Oil and gas exploration companies, such as Chapman, Petroleum Engineers of Canada, have all estimated that the Amsas Coriole Afgoi Block may be holding up to 51 million barrels of crude oil and 268 BCF of natural gas, all of which is approximately worth $3.75 billion USD (Amsas Consulting Pty Ltd, 2013). As such, the area is deemed to be of great potential. Historically, the Coriole-1 well has been reported to have produced 700 BOPD of light oil at test, while the Afgoi-1 well yielded some 9-15 MMSCFD of natural gas. Since the Amsas Coriole-Afgoi Block occupies a large area, it is highly expected that the prospects of commercially valuable hydrocarbon potential are significant (Abdullahi, 2014).

Historical test well productions of oil were reported from the same Coriole-Block in 1961 when about 700 barrels of oil were produced. Additionally, a gas reservoir with about 200BCF was also discovered at the Afgoi-1 well in the Afgoi region, proving that the oil and gas deposits were present (Abdullahi, 2014). The next stage of exploration activities identified a promising structural flank around the Afgoi-1 well site. All oil and gas exploration activities have been under a state of force majeure since 1991 due to the civil unrest in Somalia. Previous studies have provided data that suggests that the resources have sufficient accumulations of hydrocarbons.

The area has been tested by a total of 11 exploration wells that were drilled here in different years (Abdullahi 2015). Data from the following 11 deep oil exploration wells detail the Coriole basin's subsurface stratigraphy and geology (Table 1.1).

Table 0.1: Wells drilled on the Coriole onshore basin of Somalia (Abdullahi, 2014)

	WELLS	**DATE**	**OPERATOR**	**STATUS**	**TD(m)**	**FORMATION at TD**
1	Brava-1	1962-1963	Sinclair	Dry	3810	Adigrat, Lower Jurassic
2	Merca-1	1958-1959	Sinclair	Dry	3998	Jesomma, U Cretaceous
3	Afgoi-1	1965-1966	MMW	Gas	4163	Jesomma, U Cretaceous
4	Afgoi-2	1984	MMW	Gas shows	4194	Jesomma, U Cretaceous
5	Afgoi-3	1985	MMW	Dry	4359	Jesomma, U Cretaceous
6	Dobei-1	1961	Sinclair	Dry	2131	Coriole Fm – Lower Tertiary
7	Dobei-2	1961	Sinclair	Dry	3829	Gira Fm, U Cretaceous
8	Coriole-1	1960-1961	Sinclair	Gas/Oil Shows	3518	Jesomma, U Cretaceous
9	Coriole-2	1965	Sinclair	Gas shows	4069	Jesomma, U Cretaceous
10	Duddumai-1	1959-1960	Sinclair	Dry	3380	Hamanlei Middle Jurassic
11	Mudun-1	1990	Amoco	Dry	3045	Jesomma, U Cretaceous Santonian

As a result, Table 1.2 shows that the drilling density (Area/Wells) is 2300 km^2 /1 well (Naleye et Harms, 1993). Only four out of the eleven wells drilled in the Coriole basin reported oil and/or gas traces which results with a 33.3 % success rate.

Table 0.2: Sedimentary basins in Somali Coastal basin (after Harms et Naleye, 1993)

No	**Sedimentary basins**	**Area in Km^2**	**Wells drilled**	**Drilling Density=** Area/Wells
1	Lugh-Mandera	70,000	3	23,000
2	Juba-Lamu	45,000	6	7500
3	Coriole	25,000	11	2300
4	Mudugh	150,000	16	9400
5	Daror-Nogal	160,000	14	11,400
6	Guban	35,000	7	5000

The available geology and geophysical data show the development of a thick sedimentary infill (more than 5km). This factor serves as a positive indicator for uncovering oil and gas deposits.

1.2 Problem statement

Despite the fact that the Coriole Basin has brought the attention of Multinational companies, since the early 1950s, the drilling results of most of the wells have ended with disappointing results, with the majority of them either dry or abandoned. The Coriole-1 and Merca-1 wells both confirmed the presence of some natural gas shows from the Lower Eocene formations upon Drill Stem Tests (DST), while the Coriole-2 and Afgoi-1 wells had crude-oil shows from the Upper Cretaceous Jesomma Formation, it is most likely that the unsuccessful exploration and discovery outcomes could be a result of the wrong locating of the well drilling sites. A good example of this is the location of the studied well Afgoi-2, which, according to our interpreted sections, missed the target dome structure by several kilometers due to the wrong 2D seismic survey data interpretations. Furthermore, due to Somalia's political instability, the basin has been inaccessible to researchers and oil firms for nearly three decades. The goal of this study was to use all available datasets (well logs, 2D seismic profiles, reports, and publications, among other) to conduct a comprehensive and integrated study of the geology of the area that could shed light to the sedimentary basin and structural evolution, in order to determine its hydrocarbon potential.

The area is also known to be highly affected by strike-slip (wrench) tectonism, which makes hydrocarbon exploration quite complicated. On one hand, such areas are known for their prolific hydrocarbon deposits, but on the other, their development possesses some severe exploration risks. Some of these were examined and discussed by Biddle (1985). Future planning of 3D seismic survey will enable to understand the complex nature of this area heavily affected by the wrench deformation. Additional structural analysis involving balancing of the seismic profile will estimate the level of layers (formation) shortening, and thus, compression.

The current study tries to give insights on some of the following matters:

- Undertake a Seismic stratigraphy analysis of the Meso-Cenozoic formations developed in the Coriole Basin
- Establish and classify the Petroleum Systems (PS) developed within the Coriole Basin
- Evaluate the source rock potential of the Late Cretaceous-Early Tertiary intervals
- Establish the structural style of the basin and evaluate the extent and intensity of wrench faulting and related hydrocarbon entrapment structures;
- Map the potential structures for future infill drilling based on subsurface geological mapping.

1.3 Aims and objectives

The main objective of this study was to determine the structural and stratigraphic evolution of Coriole Basin, as well, as its hydrocarbon potential through the interpretation of 2D seismic and well log data.

Specific Objectives include.

i. To map the subsurface seismic stratigraphic sequences through the interpretation and integration of well-log and 2D seismic data.

ii. Establish and classify the major petroleum systems types developed within the Coriole basin.

iii. To present a model of the basin evolution and determine / evaluate its hydrocarbon potential through the generation of isochore and isopach thicknesses maps.
iv. Evaluate the source rock potential and maturity through the Time-Temperature Index (TTI) modeling using the Lopatin - Waples technique.
v. To determine and map the kitchen (source rock) and receiving (reservoir) zones and the possible primary and secondary hydrocarbon migration pathway locations.

1.4 Justification

The Coriole subbasin is one the last remaining frontier basins with a high potential in finding significant accumulations of oil and gas. This statement is supported by the presence of oil and gas shows, as well, as production data from some wells in the close vicinity from the study area. Hydrocarbon occurrence within any sedimentary basin is controlled by the distribution of the element components of the Petroleum System.

The study undertook an integrated structural, stratigraphic and geochemical approach in understanding the geological processes and events that led to the occurrence, distribution and preservation of hydrocarbon accumulations within the thick Late Cretaceous-Tertiary infill developed in the Coriole subbasin.

1.5. Significance

Wrench faults are well known for generating, modifying and also destroying sedimentary basins. As such, a detailed structural geology analysis of this type of fault system is necessary to reconstruct its dynamics. Prolonged wrench faulting can affect the preservation of hydrocarbon accumulations and lead to their remigration, thus, creates risks for successful hydrocarbon exploration activities.

Similar wrench tectonic settings are known in other parts of the World (San Joaquin Valley in California, South Sumatra, oil fields in Texas, etc.) where large oil and gas discoveries have been made. Wrench tectonics appears to have occurred in various places of East Africa at a considerably greater extent than previously assumed.

Additional 3D seismic survey acquisition programs are recommended as they will provide a better understanding of the complex nature of wrench faulting not only in Somalia, but in the entire eastern part of Africa.

1.6. Geographic Setting of the Study Area

1.6.1. Location

The Somali Coastal Basin encompasses the coastal strip from the E-W trending Elhumurre strike-slip fault to Ras Kiyamboni on the southern border with Kenya. From north to south, it has three major basins: the Mudugh Basin, the Coriole Basin, and the Juba-Lamu Basins (Figure.1.2). Large scale geological mapping (Abbate et al., 1993) indicates that the Mesozoic and Cenozoic clastic-carbonate marine successions are the dominant rock formations outcropping and covering most of the basin.

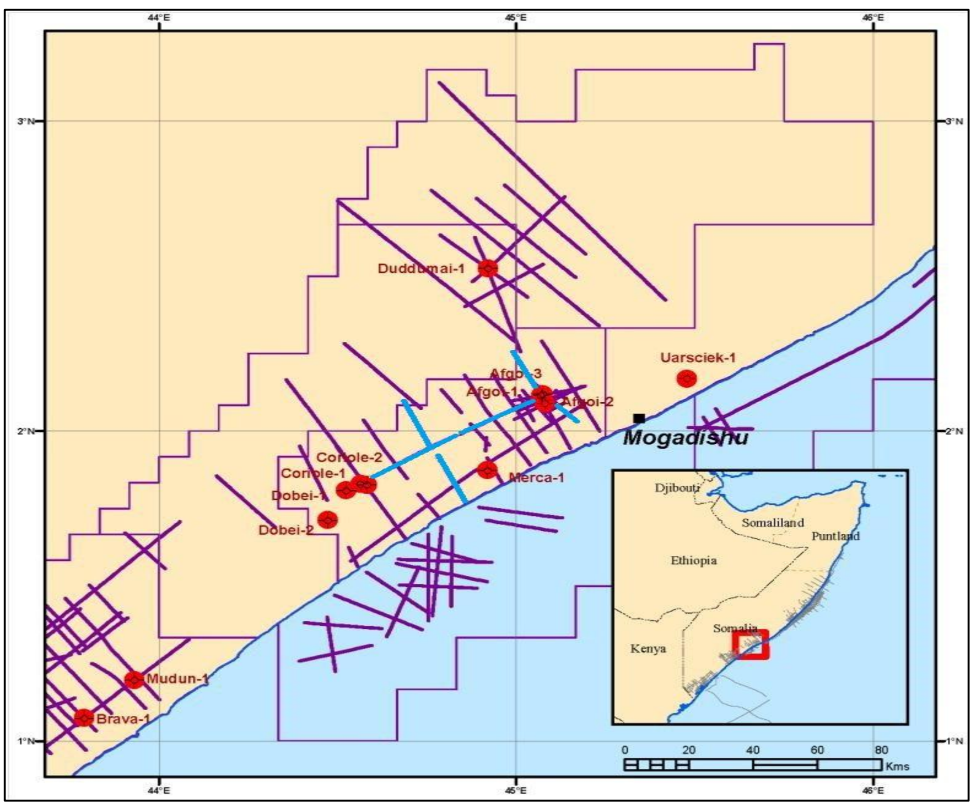


Figure 1.2: Map of the Coriole Basin, exploration blocks and well and seismic survey coverage (after Abdullahi, 2014)

The central part of the coastal basin is termed the Mogadishu basin (Hussein, 1993), and is part of the depression that parallels the Indian coast of Somalia, extending from El-dhere

(250km NE of Mogadishu) to Brava (200km SW of Mogadishu). To the north, the basin borders with the Bur Acaba basement high through a fault system called the Duddumai fault (Carbone et Accordi, 2000). Hussein (1993) mentions that the Mesozoic-Cenozoic formations have been deeply down-faulted, and most of the area is covered by thick alluvial sediments delivered by the Shebelle River, thus concealing most of the subsurface stratigraphy formations (Figure 1.3)

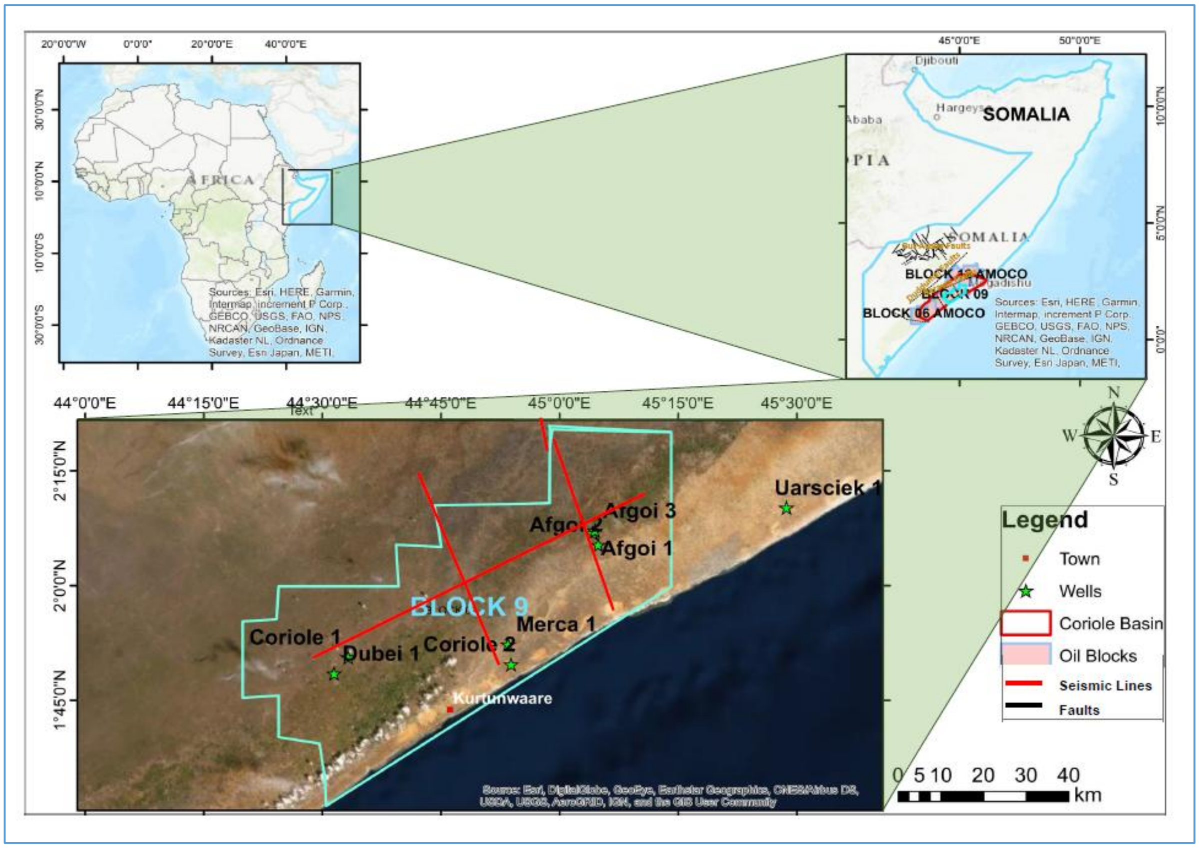


Figure 1.3: The study area position of the Coriole Basin and Location of the Afgoi-2 Well (Amsas, 2013)

1.6.2. Climate

The climate of the vast territory of Somalia is subdivided into two major zones, namely, arid and semi-arid, with five zones diversified by both coastal features and ecosystems (Mahony, 1990). According to UNEP (2005), the south coastal area experiences humid climatic conditions compared to the interior parts of the country which are generally hot and dry (arid) (Figure 1.4). The area is affected by seasonal monsoons, recurring droughts and irregular rainfall patterns (Mahony, 1990).

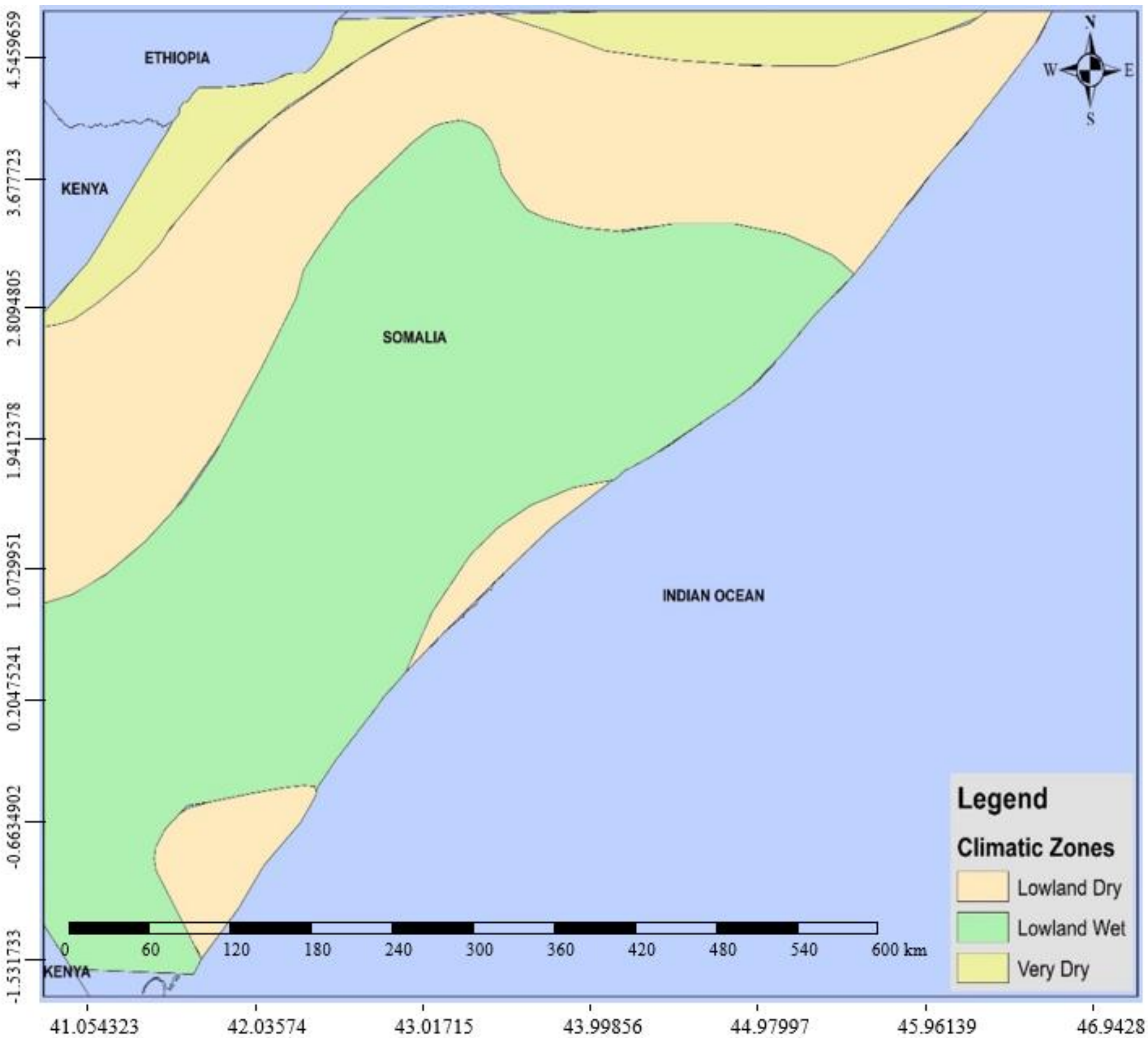


Figure 1.4: Climate zones of Southern Somalia (modified after Mahony, 1990)

There are two rainy seasons, one from April to June, followed by a dry season until September, and the second rainy period is from October to November, followed by the driest season from December to March (Metz, 1992). The research area receives the highest levels of rainfall compared to other parts of the country (Figure 1.5). Here the average annual rainfall ranges from 200 mm in parts bordering the northern side to 600mm in the bay and areas around the lower regions of Juba.

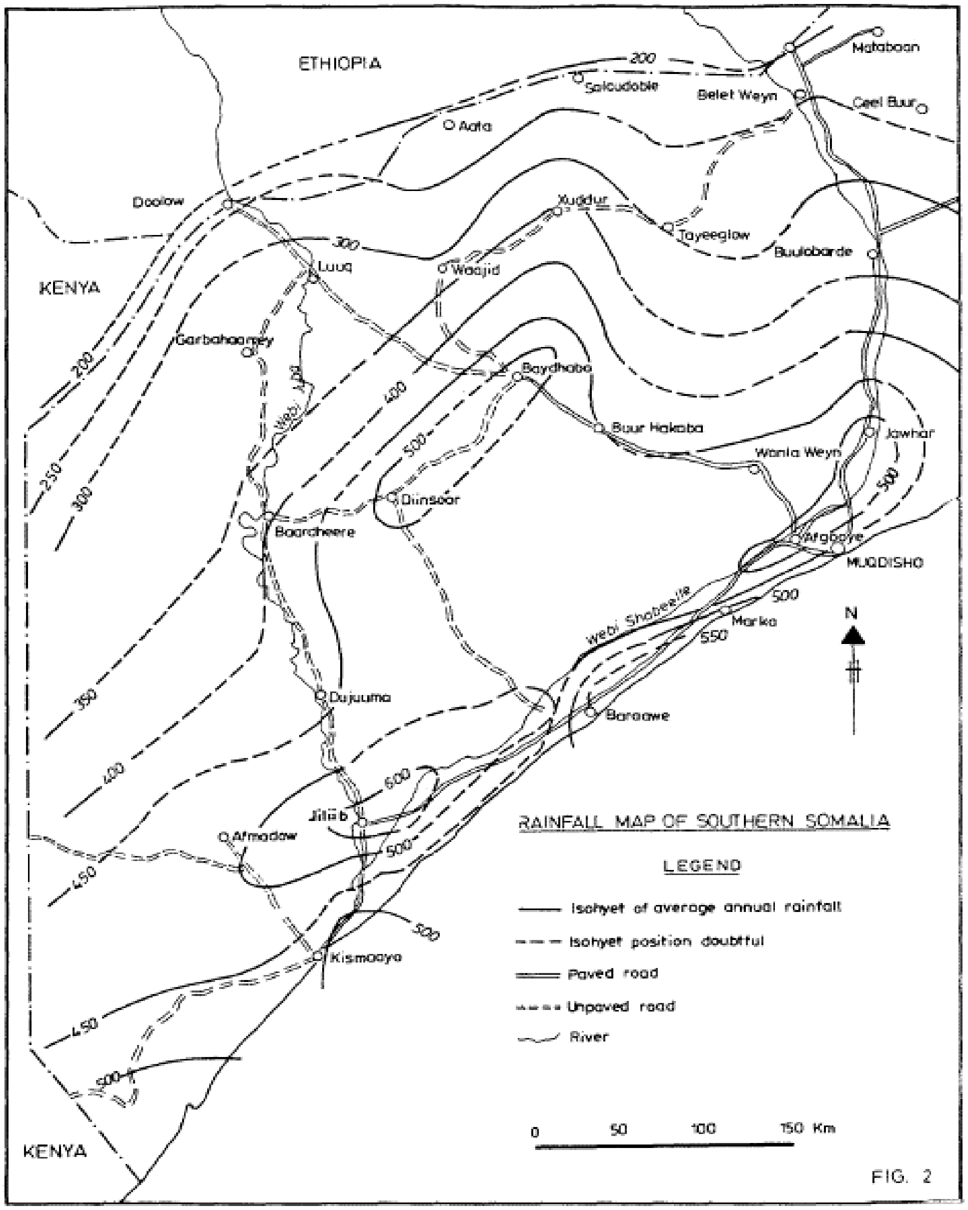


Figure 1.5: Average annual rainfall in the Southern Somalia (modified after Fantoli et al., 1960)

The annual temperatures in the study area vary widely, with the southern parts of the Somalia Federal Republic being about 5-10°C lower compared to those in the inland areas. The lower part of Shabelle is usually hot and dry with temperatures ranging from 26 to 28°C (Figure 1.6).

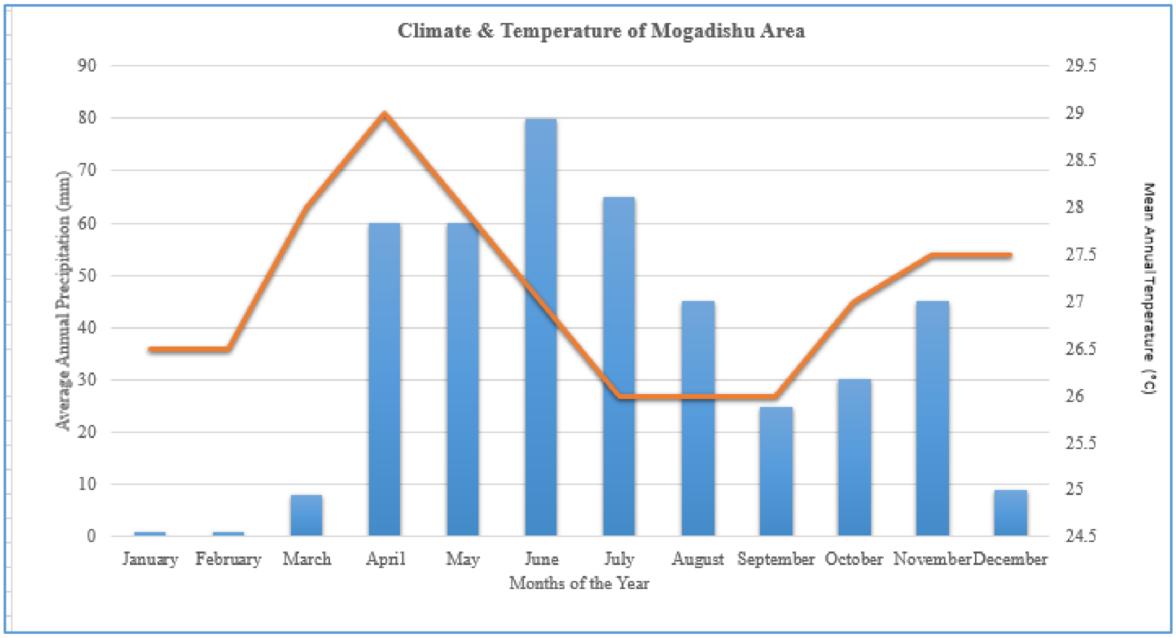


Figure 1.6: The climate and temperature of Mogadishu and its surrounding area (Adopted from: https://en.climate-data.org/africa/somalia/banadir/mogadishu-856/)

The general rainfall distribution across the country is about 280 mm annually (Hughes, 1992). From (Figure.3.4), the highlands to the north bordering Ethiopia receive the most rainfall, receiving about 500 mm of rainfall annually. The rainfall patterns (Figure.3.5) are influenced by the north-south changes in the Inter-Tropical Convergence Zone (ITCZ), causing two major distinctions (Carbone, 2000; Faillace 1986).

1.6.3 Drainage

The drainage of the area is controlled by two major rivers, namely the River Shabelle and the River Juba (Figure.1.7). The Shabelle River originates from the Ethiopian highlands and drains all three coastal basins of Balcad, Afgoi, and Coriole before it discharges its waters into the Indian Ocean in the Gobwain area, near Kismayo. The Juba River, on the other hand, also originates from the Ethiopian highland and flows through the western border of Somalia and Ethiopia through Bardera into the Indian Ocean after combining with the River Shabelle near Kismayo. The two rivers define the drainage pattern of the western and southern parts of the Federal Republic of Somalia.

Figure 1.7: Drainage of the study area and the surrounding area (after Mesenbet et al., 2015)

CHAPTER 2: LITERATURE REVIEW

This chapter highlights the results of previous studies related to the geology of Somalia's Coastal Basin, particularly the Coriole Basin, conducted and published by various authors.

The Coriole sedimentary basin is one of Somalia's onshore basins that has a great potential, however, not much is known about its geological structure. Limited and widely scattered 2D seismic reflection lines, exploratory wells, and potential field data were the only sources of geological information. The data acquired by oil companies was largely kept confidential. The summarizing work undertaken by three researchers, Barnes (1976), Bosellini (1992), and Dualeh (1997) provided an understanding of the geology of Somalia and shed light on the widely underexplored onshore basins. Recent studies obtained from the newly acquired offshore seismic data are mainly focused on the evolution of the offshore extension of the coastal basins (Davidson et al., 2018; Stanca et al., 2016).

2.1 Regional Geology

The geology of the Coriole basin has received relatively little attention. The majority of the research on the subject draws broad conclusions about the regional tectonic context and the evolution of the East African Passive Margin. According to Bosellini (1992), the Indian Ocean Sea floor stretching between Africa and the Madagascar-India Seychelles blocks began during the Jurassic Quiet Magnetic Zone (approximately 180Ma; Toarcian stage). This was followed the disintegration of the Gondwana supercontinent and is reflected by the deposition of the thick Karoo formations succeeded by transgressive and regressive marine formations. The area belongs to the East African continental margin, which through most of its history (Paleozoic–Early Mesozoic times) developed under continental conditions. In the early 1970's, the structure of this area was considered through the concept of large-scaled vertical movements (Kent, 1970). The deposition of these clastic rocks ceased in the Jurassic phase following the break-up of the supercontinent during the Mid-Late Jurassic times. As a result of these reorganizations the marine conditions prevailed from Late Callovian (165Ma) to the Oxfordian (160Ma) times, owing to the disintegration and subsequent phase of regional subsidence. Two distinct deformational episodes are documented by erosional unconformities and siliciclastic sedimentation that took place during the pre-Aptian (Early Cretaceous) and

Late Cretaceous Maastrichtian. The older event was probably the distal intraplate effect of the separation of South America and Africa (Bosellini, 1992), whereas, the Maastrichtian corresponds to the tilting of northern Somalia and is possibly related to a rebound effect of the failed Oman subduction that took place 70 Ma (Bosellini, 1992). The Cretaceous-Tertiary history of the Indian Ocean continental margins is a result of a complex depositional regression that involved the underlying Early and Middle Jurassic rifted margin. To the north, Oligocene-Miocene sediments were deposited during the opening of the Gulf of Aden and accumulated in disconnected structural depressions formed by down faulted rotating blocks bordering the rising Somali plateau.

Reeves et al. (1987) provide geophysical evidence for a failed rift and triple junction at the neighbouring Lamu Embayment of Kenya. The regional geology provides the context to the understanding of the structure of the offshore Somali Basin that can be applied to predict the development and distribution of hydrocarbon accumulations. With no exploration wells drilled deep offshore and only two wells drilled close to the shore, it is necessary to combine as much data as possible from other onshore and DSDP wells, and compare them to analogue basins, such as, the Morondova and Majunga basins in NW Madagascar and the Lamu Basin in SE Kenya.

2.1.1 Plate Tectonics

The plate tectonic history of Gondwanaland and the development of the Indian Ocean are fundamental to the understanding of the regional structural and stratigraphic setting of offshore Somalia. This is best explained in a series of generalized chronological events. According to Bosellini (1986; 1992) and more recently, by, Tuck-Martin et al. (2015), the geological history of the more recently continental margins of Somalia has undergone the following stages:

a) Permo-Triassic (298.9 – 208.5 Ma), when the Gondwana supercontinent's Early Karoo rifting created intracontinental rift basins (Figure 2.1) that deposited thick Karoo sands, organic-rich lacustrine mudstones, and coal. The Permo-Triassic Sakamena Series in Madagascar is a proven source of rocks for the large Bemolanga and Tsimiroro heavy oil fields of northwest of Madagascar. Most of these rifts 'failed' and did not proceed to the drift phase, thus generating a high potential for HC containing Aulacogens (Bosellini, 1992).

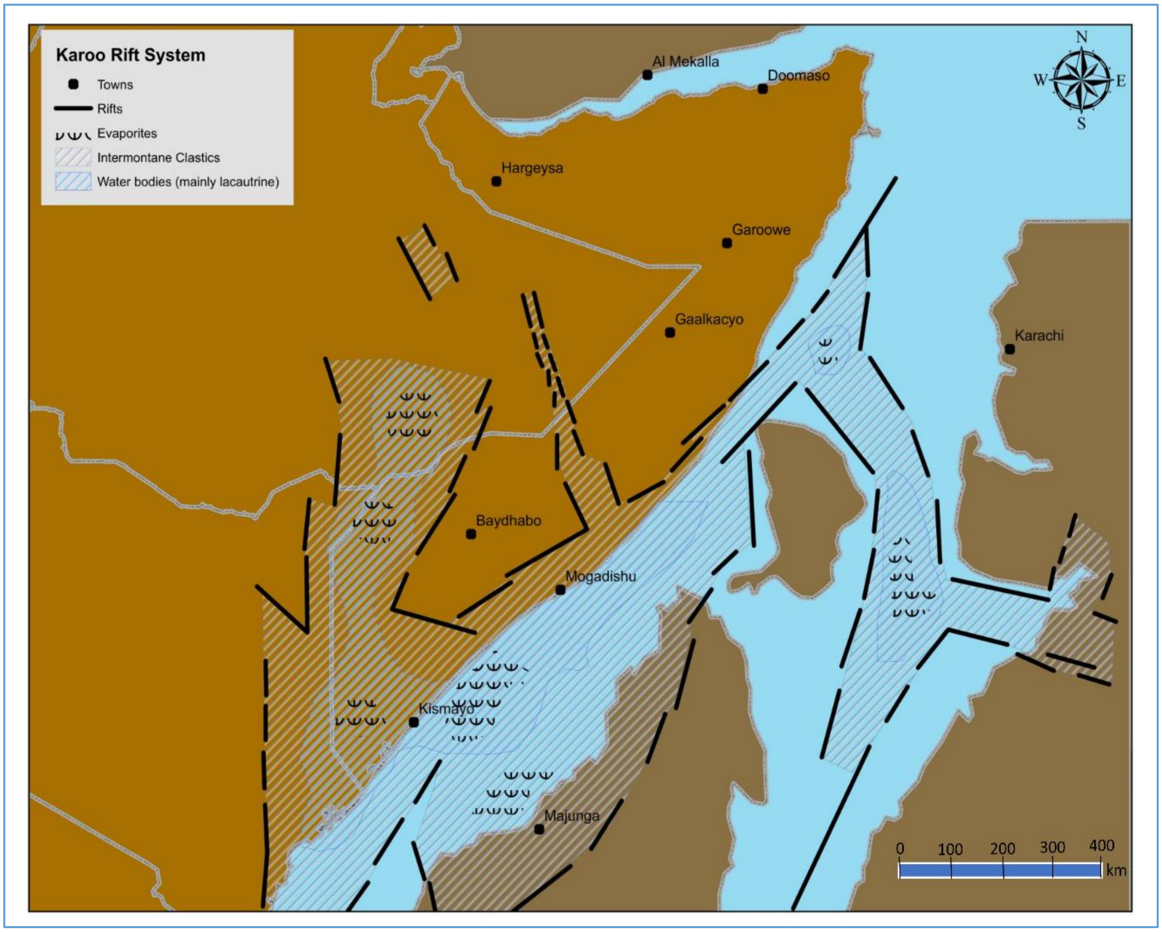


Figure 2.1: Modified Karoo Rift System in East Africa, Madagascar, Socotra, and India (Modified after Bosellini, 1992).

b) The Late Triassic-Early Jurassic period (208.5 – 174.1 Ma) marks the time when East Gondwana separated from the African continent of Gondwana. East Gondwana comprised the Seychelles, Madagascar, India, Antarctica and Australia. The most commonly presented reconstructions (Coffin and Rabinowitz, 1992; Bosellini, 1992) place Madagascar adjacent to the Somali coast, turning both the NW Madagascar and the South Somalia/NE Kenya into conjugate passive rift margins. A restricted marine setting existed in these rifted basins and resulted in the accumulation of marine shales (e.g., Meregh Fm. in Somalia), and evaporites known from Tanzania and NW Madagascar. A triple junction occurred during the Jurassic at the Lamu Embayment (Reeves et al., 1987).

c) The Mid Jurassic-Early Cretaceous period (174.1 – 100.5 M) is distinguished by open marine conditions that existed beginning in the Mid Jurassic. The Davie Fracture Zone was an active right-lateral transform fault from the Mid Jurassic (160 Ma) until the Aptian (120 Ma) through which the East Gondwana moved southward relative to West Gondwana, and since then Madagascar's current position has been static (Bosellini, 1992). During this period, the Somali Basin continued to open and sea-floor spreading produced an oceanic crust between Madagascar and mainland Africa. A major pre-Aptian (125,0 Ma) regional unconformity occurred in Somalia. According to Bosellini (1992), this Neocomian uplift was possibly caused by distal intra-plate stresses resulting from the separation of South America from Africa, and the synchronous development of the West and Central African rift systems.

d) Late Cretaceous-Palaeocene (100.5–66 Ma): In the Mid Cretaceous, Antarctica and Australia separated from the Seychelles and India and drifted south and east, respectively. Later transcurrent rifting separated the Seychelles and India from Madagascar, opening up the Mascarene Basin loacated east of Madagascar. Rifting commenced in the mid Cretaceous (100 Ma) and oceanic crust formation was formed from the Santonian-Campanian (80-85 Ma) as India and the Seychelles drifted north-eastward. Clockwise rotation brought the Seychelles to its current position.

e) Palaeocene (66.0 – 56.0 Ma): India split from the Seychelles, allowing the Arabian Ocean to open. India drifted northwards and collided with the Eurasian Plate to form the Himalayas. A major left-lateral transform fault bounds the south-eastern edge of the Arabian Plate.

f) Oligocene (33.9 – 23.03 Ma): The main rift phase began in the Gulf of Aden and north Somalia at the end of the Early Oligocene (27.82Ma). At this time, much of onshore Somalia was affected by a period of uplift and sub-aerial erosion that resulted in a regional unconformity.

g) Miocene (23.03 – 5.333Ma): The separation and drift phase of Arabia from Africa (the Somali Plate) began in the Gulf of Aden during the Mid Miocene (15.97 – 13.82Ma).

2.1.2 Geology of Coriole Basin

The stratigraphical units developed in the territory of Somalia are geologically subdivided into the northern and southern rock facies (Bosellini, 1992). The northern part is composed of basement rocks which are both crystalline and sedimentary in nature. The southern group, on the other hand, is composed of two Phanerozoic basins that are separated by the elongated crystalline rocks (Bur Complex) from the north (Ali Kassim et al., 2002). The two basins recognized in southern Somalia are the NE-SW trending Mesozoic-Tertiary Somali Coastal Basin, which the Coriole Basin is part of, and the NNE-SSW trending Luuq-Mandera Basin in the Southwest. The primary geological formations developed and dominating much of the Somali land are presented by Mesozoic and Tertiary marine sedimentary successions (Figure 2.2).

The Bur Region, which separates the two sedimentary basins, consists of the Crystalline Basement System formations which were formed during the Proterozoic and are exposed to the surface as small hills. The outcrops of these units are few and faulted. The Somali Coastal Basin is infilled with thick clastic and carbonate sediments. HC is among the largest basins in the region with an infill of about five kilometers of sedimentary deposits in thickness. These basins were formed due to plate tectonic evolution of the E and W Gondwana and are products of the movement of India and East Africa and the opening of the Indian Ocean as described in Hadden (2007).

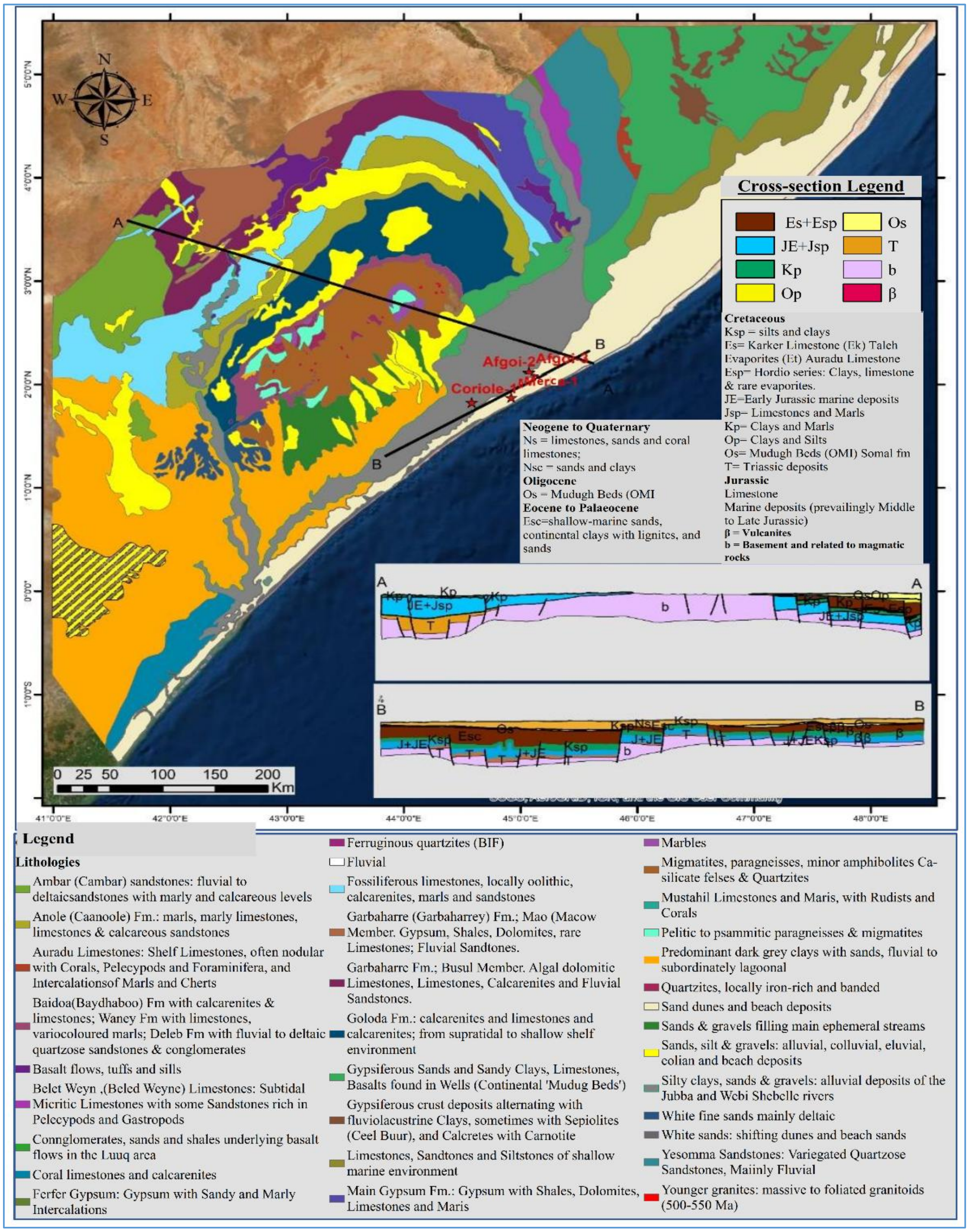


Figure 2.2: Geological sketch map of Southern Somalia (modified after Abbate et al., 1993).

2.1.3 Geological Structures

The thick sedimentary units in both the Coastal basin and Juba-Lamu embayment are commonly fault-controlled (Bosellini, 1989; Carbone and According 2000). Piccoli (1988) notes that the ridge is massive and projected to house 16m of producible sand with 200 BCF of gas. As such, the gas sands are believed to have a potential of 5MMCFD per well.

The Bur Acaba High, (Figures 2.3 and 2.4), is the most prominent feature and consists of outcropped basement rock formations. The Duddumai fault system bounds the southern limit of the basement high with the Upper Cretaceous-Tertiary Coriole basin. It is confined to the south west by the Brava fault. Normal faults which have shallower dips with depth and typically found in extensional regimes) and rotated fault blocks dominate the Coriole and Mogadishu sub-basins, but there are some localized structural inversion structures in the Tertiary, as shown in well Merca-1 (Figure. 2.4) which has a Late Eocene unconformity. In well Brava-1, there are other significant erosional surfaces related to the Oligocene-Upper Eocene unconformity, but it is unclear whether this is related to the Tertiary structural activity in the Coriole Basin or due to the tectonic reactivation along the Brava Fault (Abbate et al., 1993).

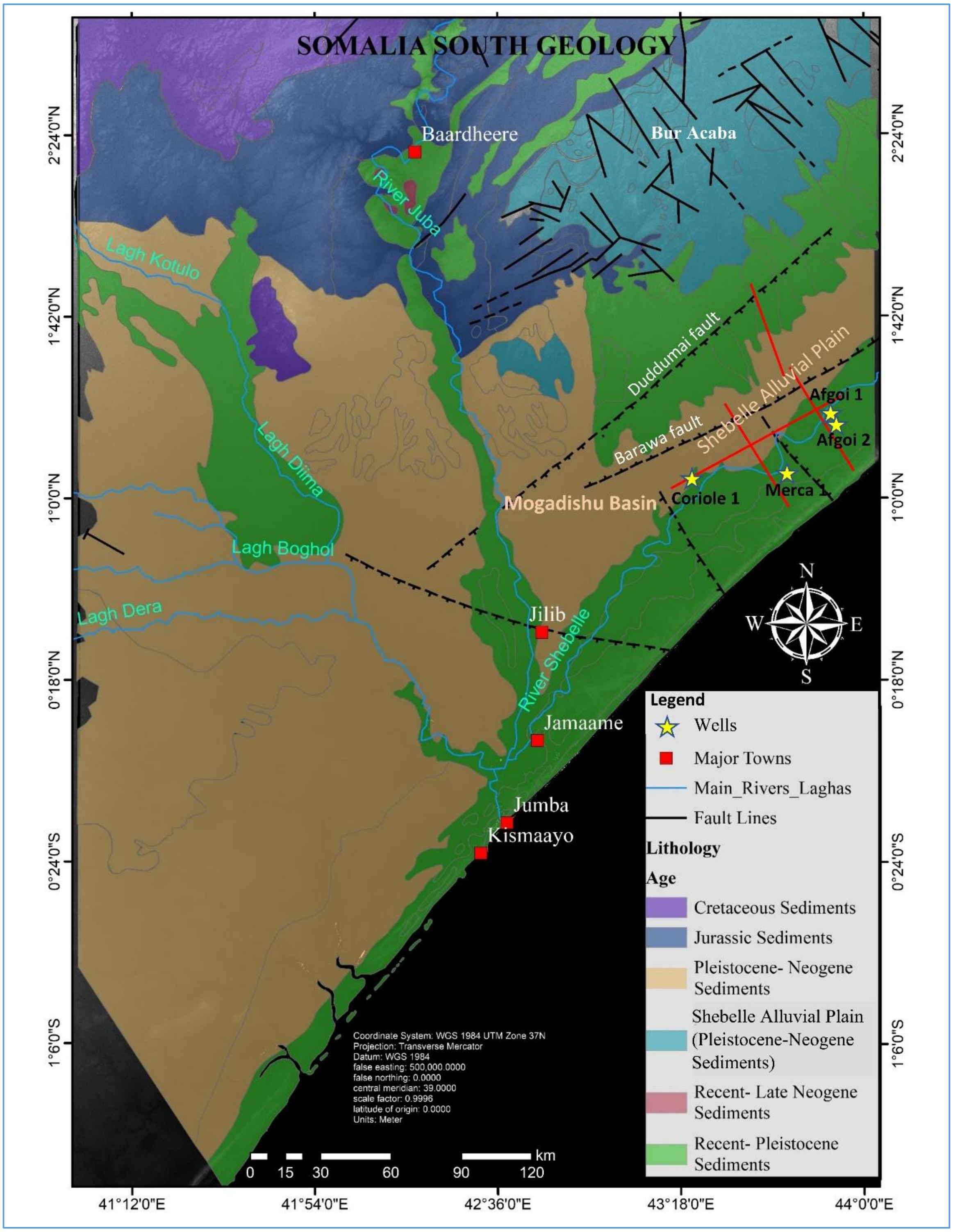


Figure 2.3: Geology and structural features of the Southern edge of the Somalia Coastal basin (after Abbate et al., 1993) and Carbone et Accordi, 2000).

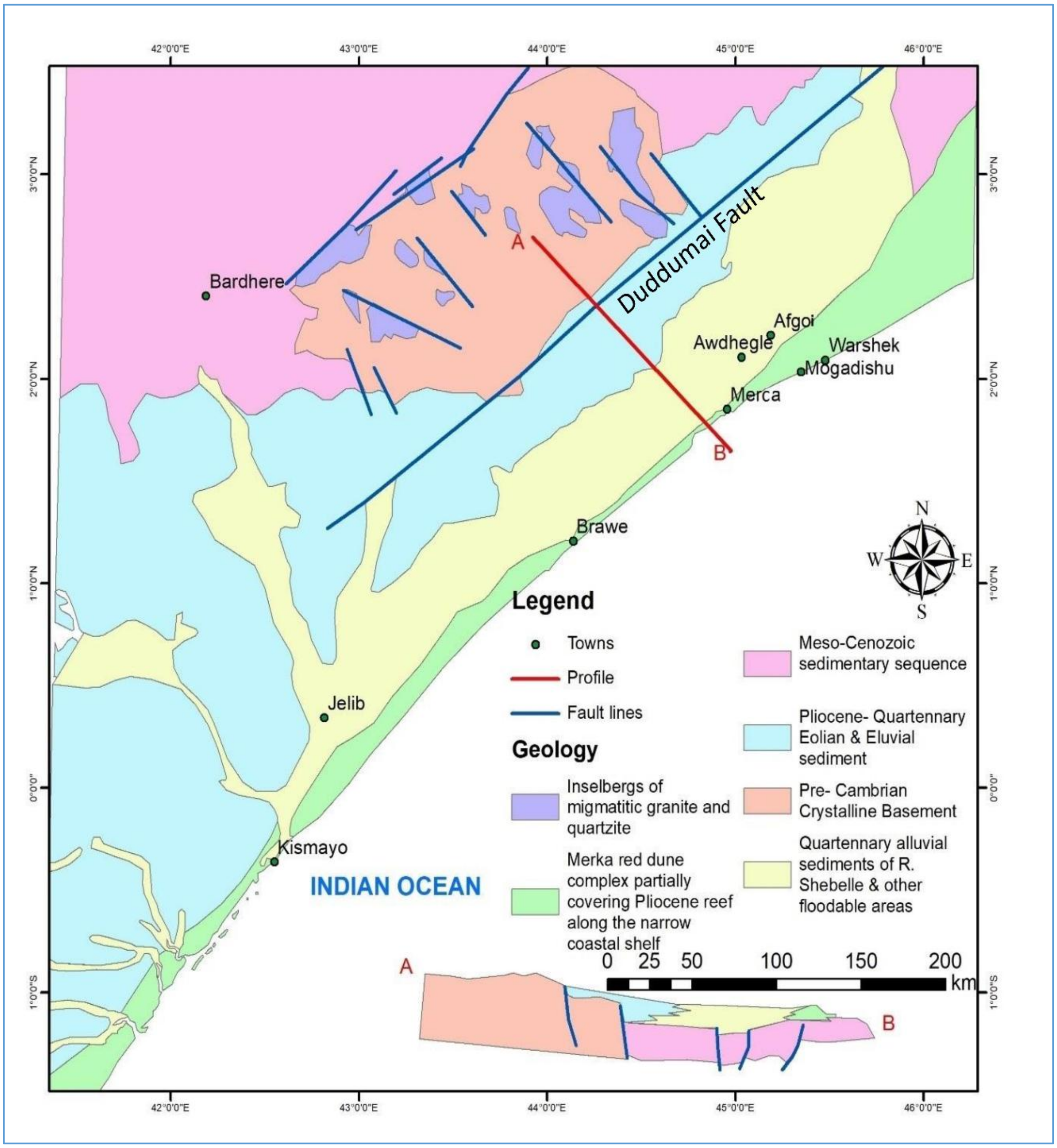


Figure 2.4: Schematic geological map of the Southern Somali coastal belt (modified after Carbone et Accordi, 2000)

2.2 General Stratigraphy of Somalia Coastal Basin (Coriole Basin Sector)

The coastal sub-basin, consists of a thick sediment belonging to the Lower Jurassic to Quaternary ages (Beltrandi & Pyre, 1973).

2.2.1 The Basal Clastics (Adigrat Formation)

According to Bruni & Fazzuoli (1977), the term Adigrat Sandstone is the name given in Ethiopia and Somalia. Stratigraphical equivalents of this formation have a common appearance in other neighbouring sedimentary basins. These are the widely developed Kohlan Formation in the southern Arabian Peninsula, the Lathi Formation in western India (Rajasthan), the Mansa Guda Formation in north-eastern Kenya, the Isalo Group (Upper Karroo) in Madagascar, the Mazeras Formation in coastal southern Kenya (Mombasa-Malindi area), and the Ngerengere Beds in Tanzania. The basal clastic sediments are generally well exposed in northern Somalia along the escarpment of the Somali plateau. The best sedimentological description of the Adigrat Sandstone so far available comes from the Bihendula section near Berbera (N. Somalia).

The peneplained Precambrian-early Palaeozoic basement of the Gondwana sector is generally overlain by terrigenous sediments of variable thickness. Bosellini (1992) describes that the depositional environment of the basal clastics is mainly alluvial. This section's sedimentary characteristics include primarily coarse-grained clastics at the base, while shale units near the top. They lack aquatic fossils but happen to contain scattered plant detritus.

The basal clastics are thought to be Triassic-Early Jurassic in age, although fossil evidence remains scarce. In other places, such as, Tanzania, Madagascar, Eastern Kenya, southern coastal Somalia (Brava well), northern Ethiopia (Tigray and Danakil), and western Yemen, the Adigrat equivalents have recorded thicknesses of over 700 m.

In Southern Somalia, there are no reports of pre-Jurassic rocks since none of the well sections have intersected them or the basement (Figure 2.5). The oldest rocks penetrated are Triassic to Early Jurassic in age, and were discovered in the coastal basin's Brava-1 well. In this well, almost 2000m of mainly greenish shale was penetrated, interbedded with limestone bands that contained Middle Jurassic to Early Cretaceous ammonites (Mbede & Duale, 1997).

2.2.2 Jurassic Formations

The small limestone outcrops, dated as Lower Jurassic, are developed near Yaaq Braawe on the south-western side of the Buur Area, and these are the oldest sedimentary rocks overlying the Basement Complex. Of greater importance are the Upper Jurassic formations which are divided into units: the Baydhabo and Canoole formations (Bosellini, 1992), (Figure 2.5).

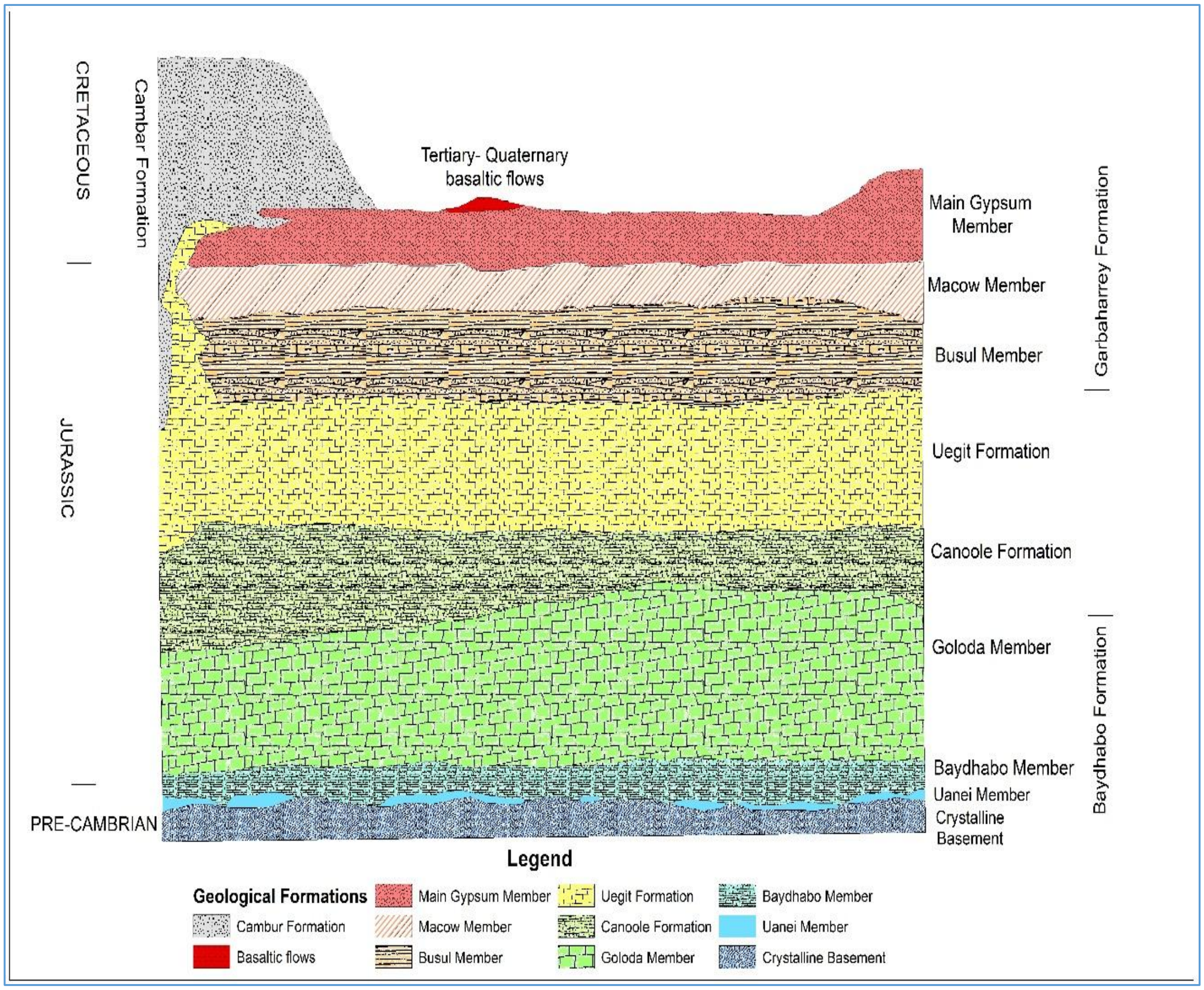


Figure 2.5: Stratigraphic relationship of the geological formations in the Southern Somalia (modified after Piccoli, 1988)

2.2.2.1 Hamanlei Formation (Baydhabo) or (Meregh Formation)

The Hamanlei depositional sequence is the Early-Middle Jurassic basal sediment package that overlaps the East African craton. The Hamanlei Formation (also called the Iscia Baidoa Formation) in Bosellini (1992) is a dominantly carbonate unit that abruptly overlies the

Adigrat clastics and ranges in age from the Pliensbachian to the Callovian (183–164Ma). In the Hol-1 well, this is a 1031 m thick layer that overlies 1050 m thick anhydrite and dolomites and 1500 m of black argillaceous mudstones. The Hamanlei Formation is developed along the Oddur Arch (1200-1500 m thick) in the Ogaden and in the entire shallow water shelf of northern Somalia (Bosellini, 1989).

In the Coriole Basin, the Duddumai-1 was drilled to a total depth of 3,380 m (11,090 ft.). The well reached the Middle Jurassic, Hamanlei Formation. The Jurassic section below >1,554m (5,100ft) is dominated by tight limestones, with porosities below 10%. It is overlaid by Upper Jurassic-Cretaceous limestones, shales and clays. (Bosellini, 1992).

The Meregh Formation is named after the Meregh-1 well drilled some 300km NE from Afgoi-2 and its thickness exceeds 2500 m. The Meregh Formation, which is confined to the Mudugh and Mandera-Lugh basins and to the Indian Ocean continental margin, is generally composed of black, pyritic micrites and dolomites. Thick oolite intervals (Obbia-1, Marai Ascia-1, El Cabobe-1), many of which are porous occur in the upper part of the succession. The stratigraphic setting suggests that they were gravity displaced and deposited by turbidity currents and accumulated in the deeper parts of the basin. The adjacent shelf's shallow water succession contains well-documented Pliensbachian (Domerian) foraminifera, implying a Sinemurian (199 – 191 Ma) age for the basal Meregh Formation (Bosellini, 1992).

2.2.2.2 Uarandab Formation (Canoole) and Equivalent Units

Over most of East Africa, a large transgression appears to be associated to the drifting period, culminating in shale deposition over the Hamanlei depositional sequence. The Uarandab Formation, the Canoole Formation, and the Gahodleh Shale are all shale units that were deposited in deeper water (Bosellini, 1992). The Uarandab Formation is mostly shaly or marly, however there are a few thin layers of carbonate or siltstone in the top section. In the Hol-1 well, the formation is roughly 180 meters thick, although it is said to be about 400 meters thick in the Bur Canoole area (Barbieri, 1968).

The Uarandab Formation is widely distributed and is present in Ogaden along the northern extension of the Mandera-Lugh basin and across the Oddur arch, where thicknesses average about 150 m. Along the Indian Ocean continental margin, the Uarandab sequence consists of greenish-grey and black fissile shale and micrite (Bosellini 1992). The maximum thickness occurs in the Brava-1 well (844 m) and in the centre of the Mudugh basin (1050 m in El Dibirre-1). Thinner sections occur along the coast, to the north of the Mudugh basin, where the interval has been partly eroded by post-Jurassic uplift at Galcaio-2, El Hamurre-1, and northeastern Ogaden.

In the Bihendule section of northern Somalia, the Gahodleh/Gawan succession is exactly equivalent to the Uarandab/Gabredarre sequence of central Somalia. The shaly part of the succession corresponds to the Uarandab Shale, while the overlying Gawan correlates with the shallowing-up carbonates of the Gabredarre/Uegit formations (Bosellini, 1992).

The Gabredarre, or Uegit, is mainly a well-bedded limestone sequence composed of bioclastic calcarenites, cross-stratified oolitic grainstones, and oncolitic micrites with thin shaly or marly intercalations. According to Bruni and Fazzuoli (in Ali Kassim et al., 1987), the age is late Oxfordian and Kimmeridgian (157-152Ma) to early Tithonian (Portlandian) 150Ma.

2.2.3 Cretaceous Formations

2.3.3.1 Gumburo Group Formations

The sea's transgression in East Africa began in late Aptian times (125-100.5Ma), and a shallow water carbonate shelf became established over most of central and northern Somalia. In central Somalia (Hiraan region) along the wide Scebeli Valley, continuous outcrops of Cretaceous limestone occur from the town of Bulo Burti to as far as Ogaden. The succession consists of three units known from bottom to top as the Mustahil, Ferfer, and Belet Uen formations. The Brava Formation (201Ma) is unconformably overlain by the Gumburo Group (Upper Cretaceous). Over 1000 m of light grey shales, sandstones, and siltstones with rare limestone interbeds were deposited in an inner middle neritic environment with a strong deltaic influence (Bosellini, 1992).

a) Mustaxiil Formation: The Mustaxiil Formation is a very fossiliferous marlstone-limestone unit with rudist and coral build-ups. Thicknesses vary from 130 to about 200 m, and the age is late Aptian-Albian (125-100.5Ma). A 50-m-thick member of marl and shale, rich in Aptian ammonites, occurs at the base directly overlying the Main Gypsum (Barbieri et al., 1979). In central southern Somalia (Mogadishu and Juba- Lamu basins), the middle-Upper Cretaceous succession indicates relatively deep-water, basinal conditions. The beginning of substantial terrigenous supply, probably related to the fully exposed Bur Acaba and Mandera-Lugh areas, is registered only at the very end of the Cretaceous.

b) The Mustaxiil Formation outcrops along a belt extending from Belet Weyne as far as beyond Buulobarde, the right bank of the Shebelle River. It overlies the on Main Gypsum Formation and is constituted by fossiliferous marly limestone. Basal grey marls are followed by marls and limestone; the uppermost part is constituted mainly of limestone. The thickness of the Mustaxiil Formation is about 200 m nearly the complete sequence outcrops west of Belet Weyne.

c) Fer-Fer Formation: The Fer-Fer Formation overlies the Mustaxiil Formation. It consists mainly of limestone, marly limestone, marls, sandstone, sandy limestone, and gypsum, deposited in a small evaporitic sub-basin. It outcrops in a belt on the left bank of the river, extending from Fer-Fer to halfway between Belet Weyne and Buulobarde maximum thickness of this formation is estimated at about 60m.

d) Belet Weyne Formation: The majority of this formation is made up of fossiliferous sandy limestone. It abuts the Shebelle River on the left bank in a 20-25 km broad strip that stretches for roughly 200 km north to south. It has a thickness of around 200 meters.

2.2.3.2 Jesomma (Yesomma) Formation

The type section is located near Jesomma village, east of the Shebelle valley, in southern Somalia, north of Mogadishu. It is mainly composed of reddish-brown-yellow to coarse-grained sandstone with some localized gypsiferous beds at the base (Barnes, 1976). Bosellini (1992) reported that the type section locality of this formation is located near Bula-Burte, and is represented by thick units (350 up to 400m) composed of reddish-yellowish cross bedded sandstones, with minor conglomerates, siltstones, and shale beds.

Barnes (1976) additionally stated that the formation is cross-bedded. According to Arush and Basu (1993), the Yesomma (Jesomma) Formation attains a thickness as great as 1700 m in the north, near Guban. However, it thins out towards the south to approximately 80 m near

Jesomma village (Alticheri et al, 1982, Arush et Basu, 1993). In Ethiopia, this formation has been encountered by the well section XF-5 in the Eastern Ogaden Basin (Hunegnaw et al., 1998) with a thickness of 1410' (430m). In general, the Jesomma has sedimentological characteristics consistent with the lower coastal plain depositional environment (Arush et Basu, 1993). Although Alticheri et al. (1982) preferred a fluvial origin for this formation.

Jesomma (Yesomma) sandstone correlates with the Tawilah group of Saudi Arabia, the Ambar Aradam sandstone of Ethiopia and the Nubian sandstone (Arush et Basu, 1993). Based on stratigraphic positioning in the south, the formation's age is poorly constrained and diachronous; a Coniacian-Campanian (86.3 – 75.5Ma) age for the basal units and a Palaeocene age for the top were suggested (Alticheri et al., 1982 and Arush et Basu, 1993) for the southern sections; and Late Cretaceous for the sections near the Guban area, where the Jesomma overlies the Upper Jurassic (Guwan) limestone (Arush et Basu, 1993, Bosellini,1992). Bosellini (1992) recognizes four general facies of the Yesomma (Jesomma) depositional sequence. These are: (1) fluviatile facies, the Yesomma Sandstone proper; (2) a marginal, shallow marine belt of shale, sandstone, and carbonate; (3) a zone of shallow water carbonate; and (4) a block-faulted basinal area where deep-water claystone and shale (Sagahley Formation) accumulated in the down faulted blocks.

The Yesomma Formation has been intensively investigated for two reasons: (a) scholarly interest in connection to the reconstruction of the Gondwana supercontinent breakup; and, (b) hydrocarbon reservoir features (sandstone composition). Northern Somalia is home to the majority of the outcropping portions of the Jesomma (Yesomma) formation (Arush et al., Basu, 1993).

A major unconformity with the underlying Upper Jurassic Gawan limestone is observed in northern Somalia sections. Here it has a broad occurrence of about 120km, ranging N-S from Hargeisa to Bulo-Burte and Jalalagsi (Alticheri et al., 1982). The basal part of the formation in the studied Jesomma section consists of an alteration of siltstone and fine-grained to medium-grained sandstones with conglomerate lenses. The section ends with coarser grain, hardly cemented quartz, and conglomerates (Alticheri et al., 1982).

Thin section studies of over 50 samples of the Jesomma formation from different localities in Somalia indicate that the principal mineral component of the formation is mature quartz (Arush et Basu, 1993). Thus, qualifying this sandstone type as a product a potential Quartzite reservoir. Feldspar and lithic components accounted for less than 10%. The feldspar is potassic (K-Feldspar) with some alterations to kaolinite and illite. The microcline is absent in the southern sections. Based on modal analysis of types, the Jesomma sandstone had two (2) distinct claystone areas of provenance: (a) granite or gneissic source and (b) low grade metamorphic. The transgression of Somalia occurred from both the east and south as Madagascar drifted towards the south via the Davie fault in the Lower Jurassic – Middle Cretaceous times. This confirms the initial conclusions stating that transgression come from the north (Arkell, 1957).

2.2.4 Tertiary Formations

The top portion of the Jesomma Sandstone, as well as the Palaeocene and Eocene Auradu, Taleh, and Karkar Formations all constitute the Tertiary successions developed in Somalia and eastern Ethiopia. The Jesomma Sandstone is a diachronous Cretaceous and Palaeocene sandstone that is extensively spread in eastern Ethiopia and central Somalia (Kamen-Kaye and Barnes, 1979). The Palaeocene and Early Eocene Auradu are represented by a 500-meter-thick marine fossiliferous limestone unit that is 1,600 ft (487.8m) thick.

Northern Somalia is devoid of post-Eocene sedimentary rocks, although they may be found along the coast in east-central and southeast Somalia, where they are represented by 1,000 m (3,300 ft.) or more of marine sandstone, shale, and limestone in the Lamu embayment. Post-Eocene uplift and erosion on the Somalia-Ethiopia shelf may have destroyed a significant portion of the Lower Tertiary section, leaving intact portions of Tertiary rocks only along the Somalia coast, in the Lamu embayment, and in the offshore regions of the Somali Basin (Faillace & Faillice, 1986).

2.2.4.1 Eocene - Lower Palaeocene

i) Auradu Formation and Equivalent Units

This is a composite succession consisting of Auradu limestone, Taleh Formation, Karkar Formation, Obbia Formation, etc.) that records both structural and eustatic movements.

a) Auradu Formation

A Late Palaeocene or Early Eocene marine transgression terminated the terrestrial conditions that previously existed over much of eastern Africa and southern Arabia. The first Eocene calcareous deposits called Auradu Limestone, are rich in corals, molluscs, and foraminifera remains and overlie Middle Cretaceous carbonates at Socotra (Beydoun & Bichan, 1970), littoral sandstones and carbonates in northeast Somalia, and alluvial sandstones and the crystalline basement in central and western parts of northern Somalia. The base of the Auradu is time transgressive, being older to the east and progressively younger westward. In middle Eocene times, the sea started to withdraw, and finally, in the Early Oligocene, all of Somalia was practically sub aerially exposed. The Auradu Limestone, represented by a thick, shallow water limestone unit (mainly mudstone/ wackestone) is massive or thick bedded in the lower part. The thickness of the entire Auradu succession is on the order of 400 to 450 m. The Auradu is generally assigned to the Early Eocene (Macfadyen, 1933; SOEC, 1954; Altichieri et al., 1981).

b) Taleh Formation

The massive limestones of the Auradu series are overlain by the Taleh Formation consisting of almost pure deposit of anhydrite, averaging 300 to 350 m thick. It consists of dense, massive to banded or laminated anhydrite.

c) Karkar Formation

The Karkar Formation, the youngest unit of the Eocene depositional mega sequence consisting of marly, nodular, fossiliferous limestones, and other molluscs, corals. The reduced depositional area of the Karkar suggests that much of the region was being uplifted about this time. Near the basin centre (Darin-1) in the Darror-Nogal Basin, the Karkar is about 360 m thick but thins out to the south and west. In the offshore wells of the Gulf of Aden, the Karkar is either missing (Bandar Harshau-1 well) or it is replaced by a terrestrial succession (Dab Qua-1 section). Eastward, the Karkar Formation reaches the Indian Ocean from Cape Guardafui to as far south as Garad Mare-1. Guardafui-1 shows the transition from platform to basinal conditions (Abbate et al., 1987, 1988).

d) Obbia and Seriole Formation

The Obbia Formation is used to denote deep-water Eocene facies. It consists mostly of clay and shale, rich in Globorotalia and Globigerina foraminifera species, and was encountered in many coastal wells (Guardafui-l, Ras Binnah-1, Hordio-1, Hafun Terrestre, and Garad Mare1). The Obbia and Seriole Formations are defined by deep marine plankton-rich Oligocene-Upper Eocene silty shales 1524-1838m (5000 ft.–6030ft thick) and Upper–Middle Eocene interbedded siltstones, sandstones, and silty shales 1838-2118m (6030ft–6950ft thick) in Afgoi-2 well section.

2.2.4.2 Upper Oligocene-Miocene Formations

a) Merca/Somal Formations: The majority of the Somal Formation's characteristics are derived from lithological descriptions of oil wells drilled in the Jubba and Shebelle valleys. This formation consists of marly limestone shales and occasional sandstone interbedded beds. In well Brava-1, the formation is about 3000 feet (914.4m) thick and overlies unconformably the Lower Cretaceous shales. The age has been established to range from the Lower to Upper Miocene. The "Merca Formation" is predominantly of carbonate composition and overlays unconformably the Obbia Formation on the eastern margin of the Coastal Basin. It probably outcrops to the north of Wallan Wayne and has been found in various water wells such as those in Duddumai, Kuunyo Hober, and Yaaq Bari Weyne in the Wanla Weyn districts. It was deposited during the sea incursion which penetrated deeply into the Shebelle Basin.

Most of Tertiary Somalia was peneplained by the end of the Early Oligocene, exposed to subaerial conditions as a result of major tectonic uplift and deformation. This is documented by the angular unconformity at the Merca/Somal sequences interboundary and by the widespread basaltic flows of the Mudugh region. Along the Indian Ocean continental margin, the Late Oligocene-Miocene were dominated first by a general marine transgression (Somal Formation, base of the Eil sequence), followed by a Miocene depositional regression all during the highstand phase of the cycle (Merca Formation, upper part of the Eil sequence). The Gulf of Aden coast of Somalia represents a typical passive margin, where geological history can be described in three phases: pre-rift phase, rift phase, and drift phase (Abbate et al, 1988). By the end of the Oligocene, the main rifting stage was over, and was followed by the drift phase that started during Middle-Late Miocene times. These sediments at the top

Afgoi-2 well section ranging between 80ft and 2050ft depth and consist mainly of sands, interbedded with minor siltstones, shales, and limestone.

b) Scusciuban-Somal transition: A sand interval (2050ft—2670ft) within the Afgoi-2 deposited during Middle Miocene times appears to be transitional in character between the overlying Scusciuban sands and limestones and the underlying Somal carbonates.

c) Scusciuban formation: This is a lagoonal facies equivalent of the Miocene marine rocks. The unit consists of marl, marly sandstone, and subordinate limestone, limestone conglomerate, and gypsum. The rocks are Early and possibly Middle Miocene age (Merla et al., 1979; Osman et al., 1976).

The sediments at the top of the well section of Afgoi-2 between 80ft and 2050ft consist mainly of sands interbedded with minor siltstones, shales and limestones. They represent regression conditions from shallow inner shelf/marginal marine (2050ft---1510ft) to marginal marine/supratidal (1510ft---80ft) environments, which were recorded in the Sinclair Merca-1 well and mapped in Northern Somalia as the Scusciuban formation by Agip Geologists (Merla et al., 1979; Osman et al., 1976).

In the Afgoi-2 well section, the Yesomma (Jesomma) Formation was encountered in the lowermost intervals of 13470' – 13747'; 4106.7-4191.2m. According to the geological report, the lithology of the overlying strata from depth 12588' (3837.8m) is represented by interbedded sand fine to medium–grained, angular to sub angular, shale grey to black platy with occasional thin limestone stringers and basalt flows becoming thicker towards the basal part of the section (Durkee, 1982).

The micropaleontology of this section was identified based on the palynology and foraminifera biostratigraphy of *Heterohelix sp*. The sample from 13350-13560' (4070 – 4143m) depth interval with sporadically diverse foraminifera assembleges was assigned a Cretaceous age based on the presence of *Rotalia spp* (13470' – 13530'; 4106.7-4125m), *Lenticulina spp* (4106.7m - 4125m), *Teaplophracymaides spp* (13530' – 13700'), *Gavaliralla spp* (13700' – 13747'), *Heterohelix sp* (4125m – 4176.8m) and sparce *Rugoglobigerina rugosa* (4176.8m – 4191m) TD. This microfossil assemblages indicate marginal marine to shallow inner shaly depositional environments for the upper part of the section. While deeper on marine eruditions were recognized for the 13700-13747’ TD (4176-4191m) section (Attewell et al., 1985).

2.3 Wrench Tectonics and Hydrocarbon Potential of Related Sedimentary Basins

For over a century, wrench (strike-slip or transcurrent) tectonics has caught the attention of geologists. Since the early 1970s, its study has largely been possible through the improvement in seismic data acquisition and quality. Interpretations of such data have demonstrated that wrench (transcurrent) faults are developed on a much wider scale than earlier believed.

In structural geology, strike-slip (wrench) faults are those that are vertical in the upper part of the crust and have generally horizontal (lateral) movement directions. They are classified into two major groups depending on the direction of the motion. These are:

a) Sinistral (left lateral)
b) Dextral (right lateral)

Wrench tectonism can generate, modify, and even destroy sedimentary basins (Biddle, 1985). As a result, hydrocarbons can be generated, be migrated, become trapped and dispersed through the tectonism of the basin. This leads to hydrocarbon "productive and “lean" wrench fault systems.

Each strike-slip (wrench) fault movement involves an oblique component of displacement. This enables a sedimentary basin to develop as a result of either localized extension or shortening. Sedimentary basins generated due to wrench tectonics have various dimensions, but are much smaller than those related to rifting or regional shortening. The limited dimensions of the basins lead to a significant heat loss through lateral conduction.

An ordinary wrench fault consists of a principal displacement zone (PDZ) with a fault trace and a complicated arrangement of smaller associated, or en echelon faults and fractures. The last two are shorter and parallel to one another. They are also oblique to the major linear zone. As such, five (5) sets of these structures have been recognized through laboratory experiments and models (Figure 2.9):

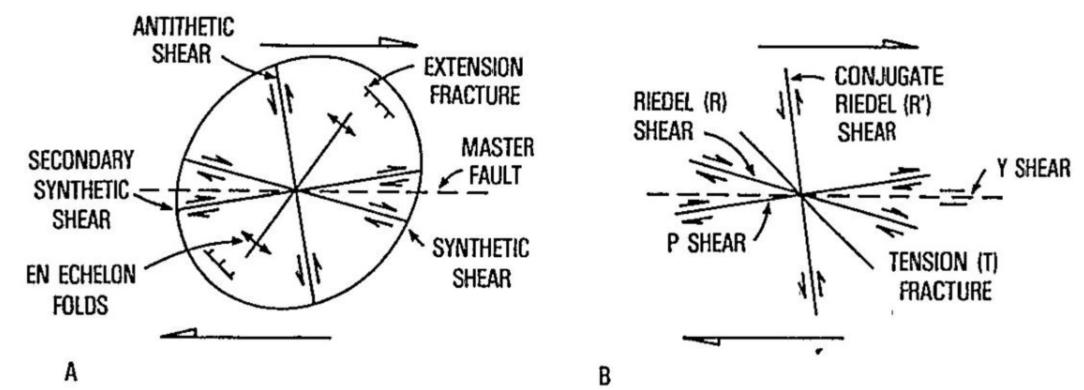
I. Synthetic strike-slip faults or conjugate Riedel (R) Shears = R_1

II. Antithetic strike-slip faults or conjugate Riedel (R) shears = R_2

III. Secondary strike-slip faults or P shears

IV. Extension or tension fractures/faults

V. Y shears or faults parallel to the principal displacement zone (PDZ). The interaction of these structures forms most potential traps in the principal displacement zone (PDZ).



Structures formed by simple shear: (A) strain ellipse terminology of Wilcox *et al.* (1973) and (B) Riedel shear terminology used by Tchalenko and Ambrayses (1970).

Figure 2.6: Strain ellipse in wrench tectonics (after Biddle, 1985)

According to the Anderson's dynamic classification, in wrench or strike-slip faults the principal stress is vertical, while and are horizontal. This means that the fault planes are vertical and the movement direction will be horizontal or strike-slip (McClay, 1991). Large-scale strike-slip movements occur along the tectonic plate boundaries. These movements will be either horizontal or sub-horizontal.

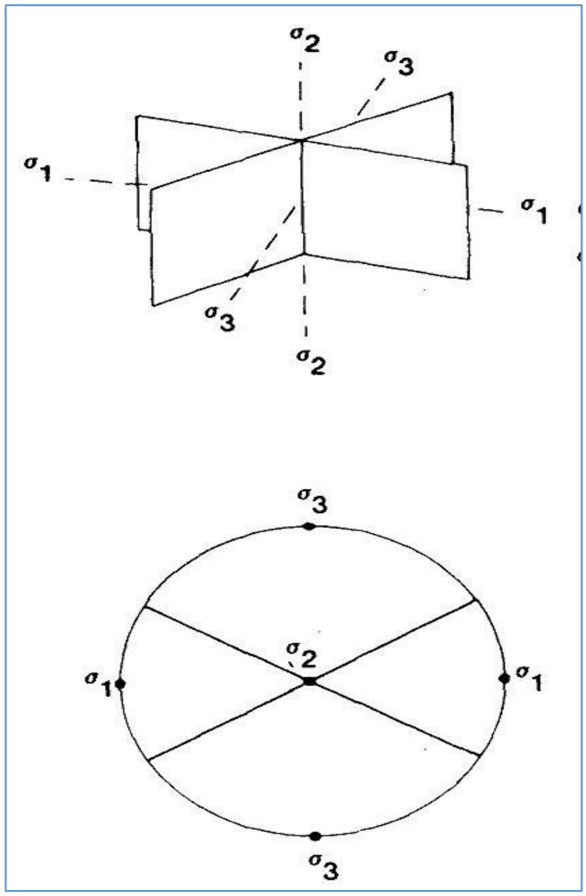


Figure 2.7: Anderson's dynamic classification of strike-slip (wrench) faults (from Mcclay, 1991)

Zalan (1987) lists the main criteria that are used in identifying strike-slip (wrench) faults in seismic sections. These are:

a) Flower structures
b) Change in magnitude, or even reversal of fault throws with depth
c) Abrupt changes in thickness of seismic facies across the fault
d) Abrupt changes in nature of seismic facies across the fault
e) Abrupt change in style and/or intensities of deformation across the fault
f) Complex geometries of the fault plane
g) Change from normal to reverse separation fault, and vice versa
h) Upthrown block switching side along the subvertical fault plane
i) Change in the magnitude and/or direction of dip of fault plane

From these criteria, only the first one – the presence of flower structures – is firmly identified within the coriole subbasin sector of the Somalia coastal basin. Zalan (1987) mentions that although the flower structures are the most reliable indicators of the strike-slip movements, the other criteria should be employed collectively.

Zalan (1987) further provides criteria that can be used during seismic interpretation to identify strike-slip faults. He classified them into 2 major groups: a) characteristics seen in a single seismic section, and b) characteristics seen in several successive seismic sections. Below we briefly consider the first group.

a) Characteristics of strike-slip faults in single seismic sections

I. Flower structures: This is the most important and frequently recognized characteristic of a strike-slip fault in seismic sections. These consists of a subvertical fault resembling a stem from which a series of other subsidiary faults branch from and open upwards.

II. A positive flower structure will occur when the central parts are dominated by reverse faults and are elevated with respect to the margins. This is an indication of transpression deformation along the fault (Zalan, 1987). Transpression is the compression associated with movement along a curved strike-slip fault (Kearey, 2001).

The opposite, negative flower structures have their central parts dominated by normal faults, and thus, they become depressed relative to the margins. This condition indicates transtension deformation along the fault (Zalan, 1987). Transtension is the tension associated with movement along a curved strike-slip fault (Kearey, 2001). These two characteristics have been identified within the interpreted seven (7) 2D seismic profiles from the coriole subbasin. The remaining characteristics listed by Zalan (1987) should be employed collectively and with a certain level of precaution.

In order to assure the correct seismic interpretation, at least 2, 3 or even 4 of these criteria should be displayed on the section. These include:

III. Abrupt changes of thickness of seismic facies across the fault

IV. Abrupt changes in nature of seismic facies across the fault depending on the magnitude of lateral movement.

V. Abrupt change in styles and/or intensities of deformation across the fault.

VI. Irregular and complex geometries of the fault plan.

As mentioned earlier, of all these characteristics, the presence of flower structures is a definite indicator of strike-slip faults.

Folds and fault blocks that parallel the fault near (at) the Principal Displacement Zone (PDZ) tend to occur in areas where there is either a component of extension or shortening across the zone, near the restraining or/and releasing bends developed along the strike-slip fault. (Figure below)

A restraining bend is a curve in a strike-slip fault across which there is compression parallel to the straight parts of the fault, while a releasing bend is a curve in a strike-slip fault across which there is extension parallel to the straight parts of the fault (Kearey, 2001).

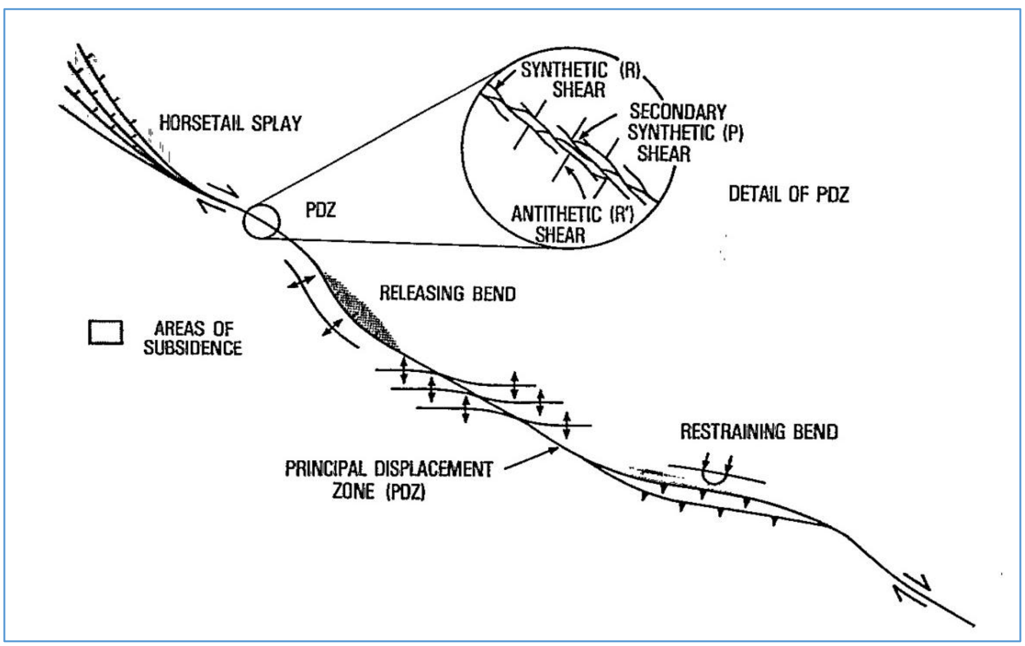


Figure 2.8: Map view of an idealized right-lateral wrench Fault (Biddle, 1985)

Biddle (1985) recognizes two types of wrench fault systems: a) convergent and b) divergent.

a) Convergent wrench fault systems are characterized by enhanced en echelon folds, more developed and dominating positive flower structures within the fault zone, and common reverse-separation faults. Its normal separation faults are also present but at a lesser extent.

b) Divergent wrench fault systems compared to the previous type do not possess en echelon folds, but instead have en echelon faults. This fault zone may be characterized by normal fault separations. Folds developed here are commonly drape and forced folds that were formed due to vertical movements, and as such, they will occur parallel to the edges of the underlying fault blocks.

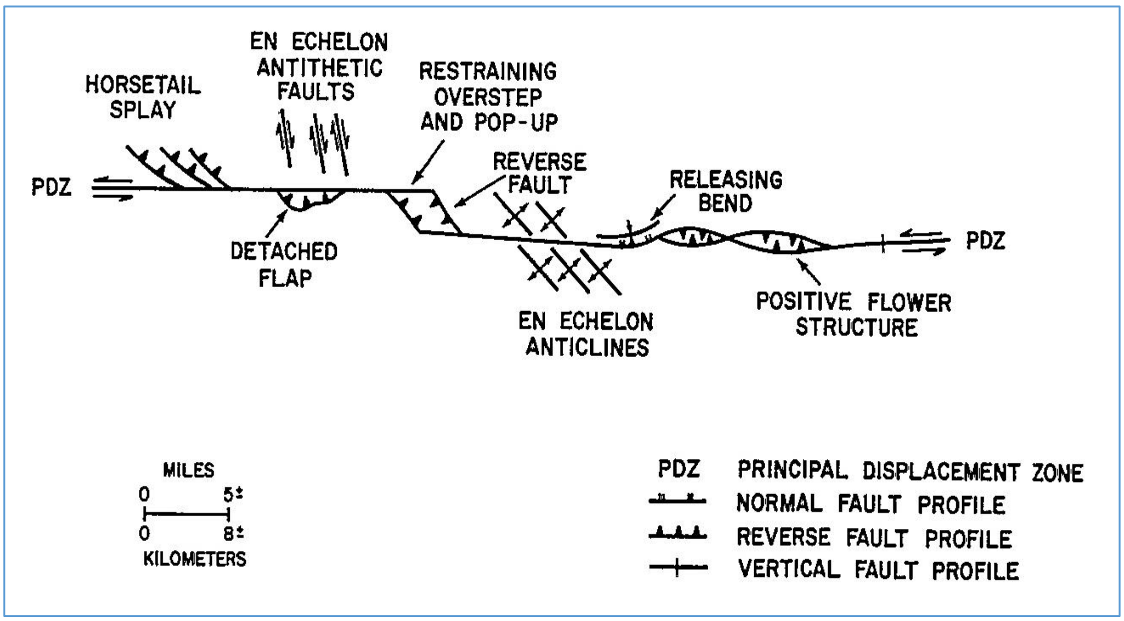


Figure 2.9: Structural patterns along a schematic divergent wrench-fault system (Biddle, 1985)

Both convergent and divergent wrench fault systems are capable of generating potential structural traps for hydrocarbons. The best traps in convergent systems occur in the flanking en echelon folds and antiforms associated with positive flower structures. Additionally, the fault block traps could have some potential.

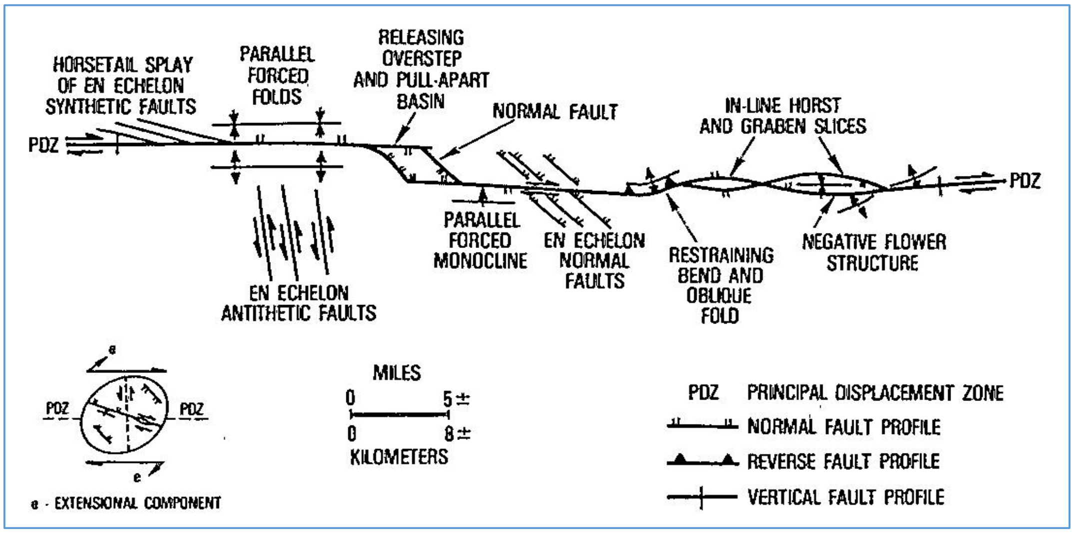


Figure 2.10: Structural patterns along a schematic divergent wrench-fault system (Biddle, 1985)

In divergent wrench-fault systems, the most promising tectonic traps occur in folds located above extensional fault blocks and fault block closures. According to our seismic interpretation of seven (7) profiles, the Coriole-subbasin is characterized by a convergent wrench fault system. This is testified by the presence of positive flower structures seen on profiles running along and across the sedimentary basin.

Thurston et Theiss (1991) referred to one of Harding's publications where some of the criteria seen both on profile and map indicate the presence of wrench faults. These are:

a) Individual fault bands of the wrench zone are generally narrow-ranging between 10 to 16km (6 to 10 miles), straight, through going and are over 160km in length.
b) Shallow splay faults converge at depth into steep fault zone that displaces the basement;
c) Abrupt thickness changes in correlative seimostratigraphic units occur across faults at different structural levels.

All abovementioned criteria's have been encountered at a different level in the studied seven (7) 2D seismic profiles.

CHAPTER 3: MATERIALS AND METHODS

3.1. Procedures

To undertake this research, the following multistep workflow procedures were adopted (Figure 3.1):

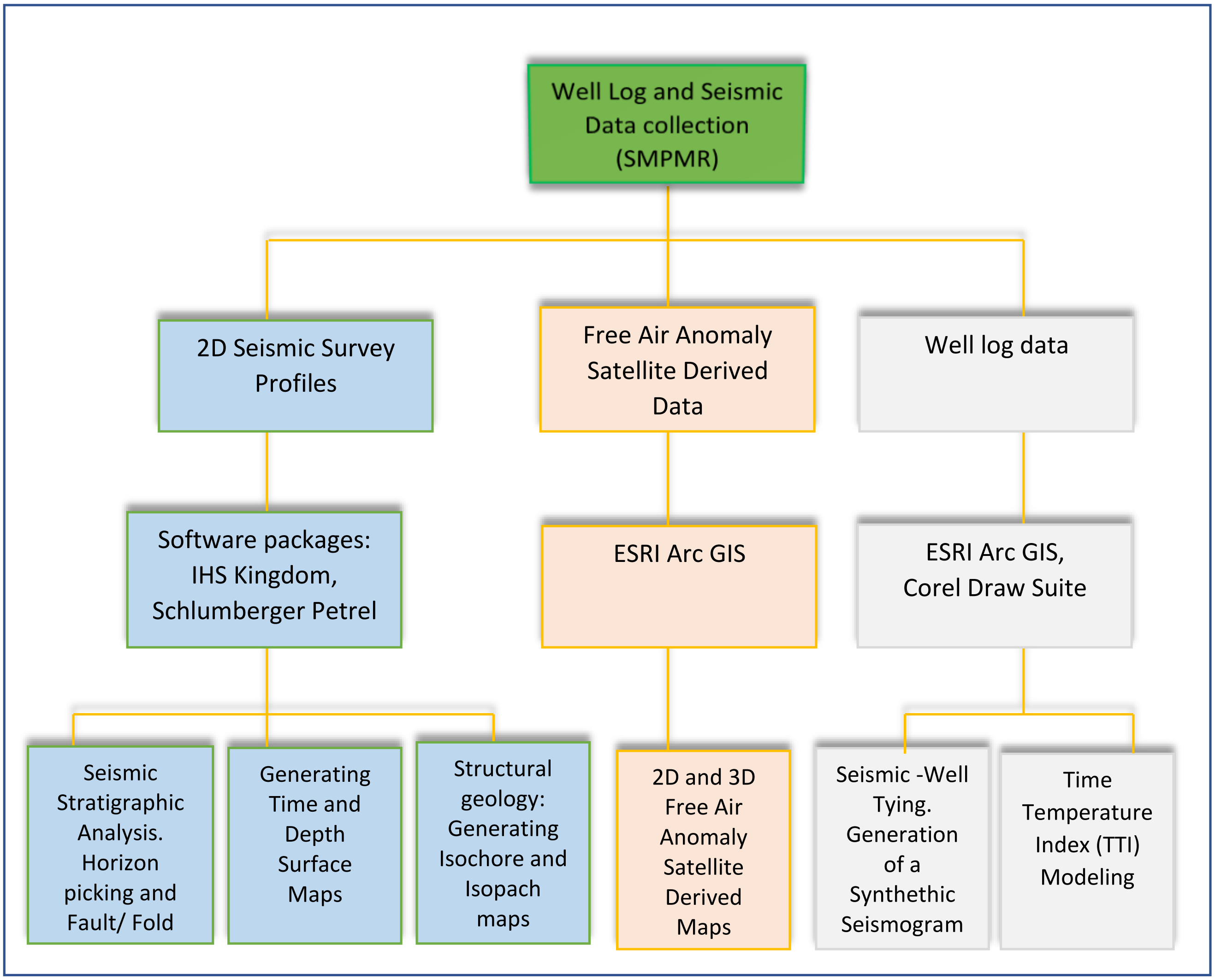


Figure 3.1: The Multistep workflow of the study(Ga'al 2021)

3.2 Data Collection

A total of seven (7) 2D seismic profiles and well log data of Afgoi-2 well located in the Coriole subbasin were used for this study.

The 2D seismic survey data was provided by CGG Robertson who is the custodian of all geological data and manages it on the behalf of the Somalia Ministry of Petroleum and Mineral Resources (Mogadishu). This data was supported by a number of Industrial reports and laboratory results.

3.2.1 Software tools and Data Sources

The software's used for data analysis included IHS Kingdom Suite Software 2015 – 2019 versions, Schlumberger Petrel 2017, ESRI ArcGIS Software version 10.5 and Corel Draw Suite 2020.

Table 3.1: Summary of the data and software used in this study

Task	**Output**	**Software**
Desk Study	Digitized Geological map Digitized Drainage map Satellite Gravity map	ESRI Arc GIS 10.5 ESRI Arc GIS 10.5 ESRI Arc GIS 10.5 Microsoft Excel
Structural Interpretation	Seismic sections	IHS Kingdom Suite 2017/2019; Schlumberger Petrel 2016/2017
	Depth structure map	Schlumberger Petrel 2016/2017
Stratigraphic Interpretation	Seismic facies sections	IHS Kingdom Suite 2017/2019
	Stratigraphic chart Digitized Stratigraphic chart	Corel Draw 2020 ESRI Arc GIS
Time-Temperature Index (TTI)	TTI Curve TTI Comparison chart	Corel Draw 2020 Corel Draw 2020
Free Air Gravity Anomaly Interpretations	Free Air Gravity Anomaly Map	ESRI Arc GIS

3.2.2 Seismic 2D data

All examined seven (7) 2D seismic profile (205 km) are SEG – Y format. The location of the studied 2D seismic profiles with in the Coriole Basin is given in (Figure 3.2).

These seven (7) seismic lines (Figures 3.2 and 3.3) intersect one another and are supported by well logs from Afgoi-2 well. These seismic lines were shot in the late 1950s while Afgoi-2 well was drilled between December 1984 and March 1985 to a total depth of 4194m (13761 ft.). This well is located approximately 3.1 km to the south of the Afgoi-1 well.

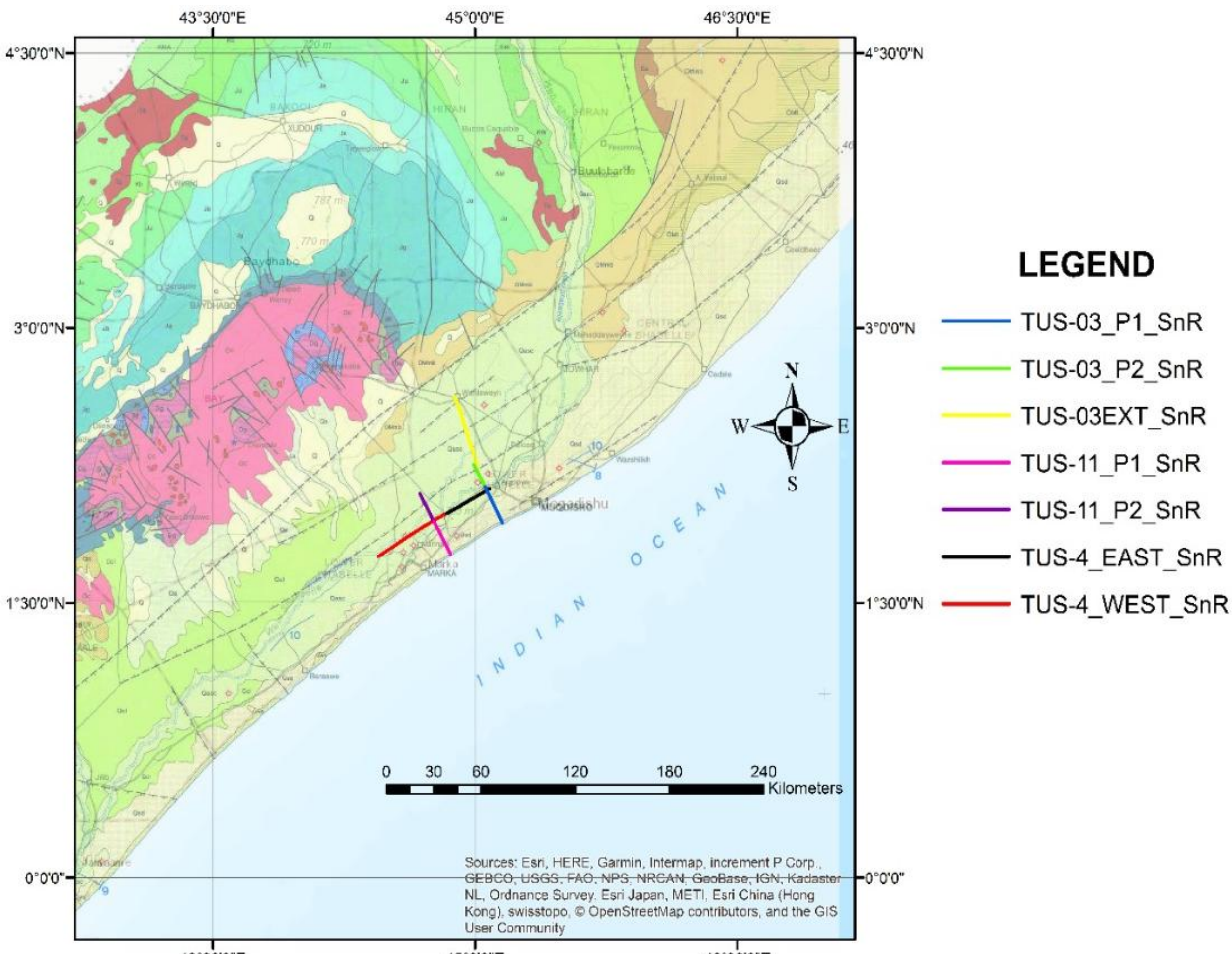


Figure 3.2: Geological map of the Somalia Coastal Basin and the 2D seismic survey area (modified after Abbate et al., 1993)

All data was easily loaded and interpreted in IHS Kingdom Suite 2015 software (Figure 3.3).

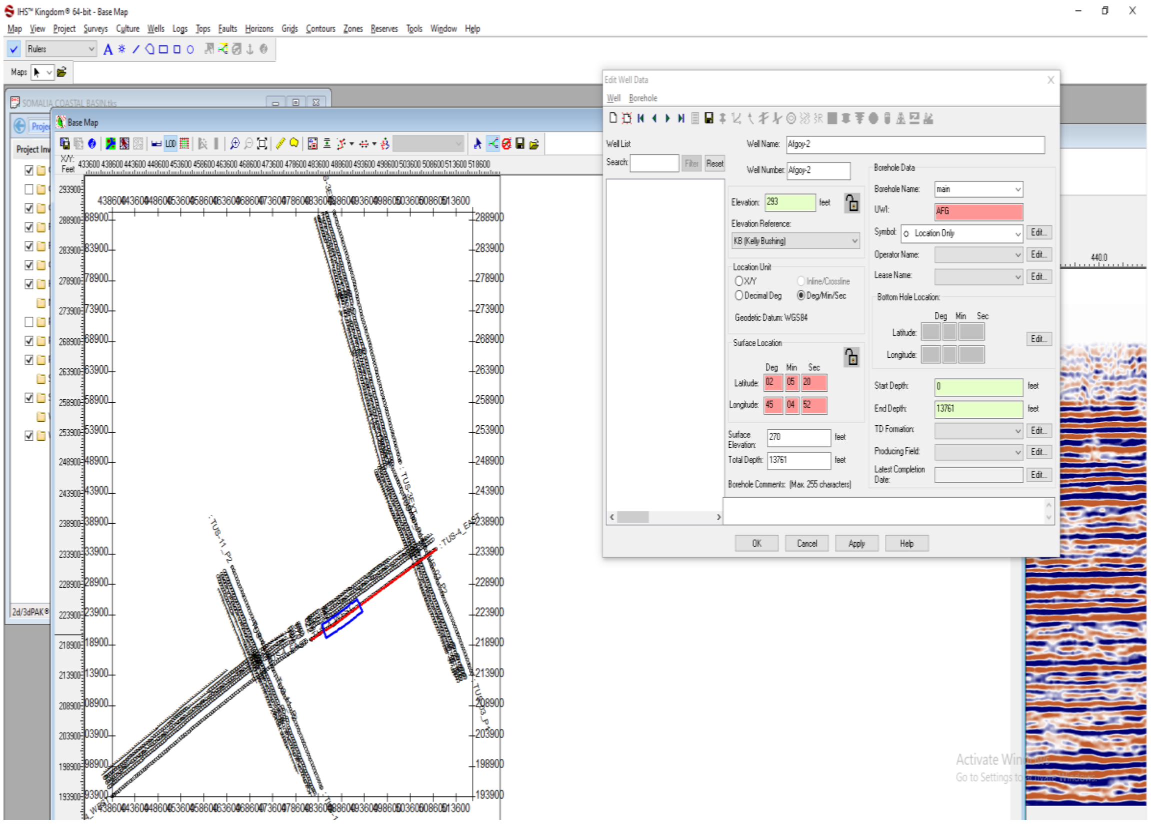


Figure 3.3: Orientation of the seismic lines on the IHS Kingdom Suite 2015 Base Map

Seven 2D seismic lines were analyzed (Table 3.2). The seismic profile lines extend over most of the Afgoi structure. However, the chosen lines are a good representative of the subsurface structure of the basin. In this study, seismic digital SEG-Y data containing dip lines and strike lines was used for interpretation. The seismic data lines parameters include the seismic line name, its orientation, SP, Migration Type, and Line Length (total of 205 Km) for each seismic line are given in Table 3.2.

Table 3.2: Seismic Data Lines Parameters

Line name	First SP	Last SP	Length (km)	Survey type
TUS-03_P1	100	580	24.1	Scanned and reconstructed SEG-Y migration
TUS-03_P2	663	999	15.3	Scanned and reconstructed SEG-Y migration
TUS-03EXT	1003	1875	43.8	Scanned and reconstructed SEG-Y migration
TUS-11_P1	5	447	22.3	Scanned and reconstructed SEG-Y migration
TUS-11_P2	968	1350	19.0	Scanned and reconstructed SEG-Y migration
TUS-4_EAST	4	622	31.0	Scanned and reconstructed SEG-Y migration
TUS-4_WEST	641	1630	49.5	Scanned and reconstructed SEG-Y migration
Total (km)			**205**	

3.2.3 Well Data

The Afgoi-2 well is located in the Coriole basin, specifically Block 9, with the following coordinates: 02º 05 20 "N 45º 04´ 52’’ E. It is within 200m of the intersection of lines TUS-10 and TUS-03-P1, a fair distance that provides a good seismic-well tying exercise. The target of the well was strata of the Paleocene (Sagaleh Formation). The well data was provided in a (Las format) and included a wide array of logging measurements, including, Caliper, Gamma Ray, Spectral Gamma Ray, Density, Spontaneous Potential and Resistivity logs (Table 3.2). Additionally, the formation tops from Afgoi-2 well were used to analyse the Time-Temperature Index (TTI) modelling to evaluate the source rock potential.

Table 3.3: Well Information and Las Files of Afgoi-2

Well name	Las curves
Afgoi-2	CALI-CGR-DRHO-DT-DTL-GR-PNL-POTA-RHOB-RILD-RILM-RSFL-SGR-SP-THOR-URAN

A display of some of the well log data in IHS Kingdom Suite 2015 version is given in Figure 3.4.

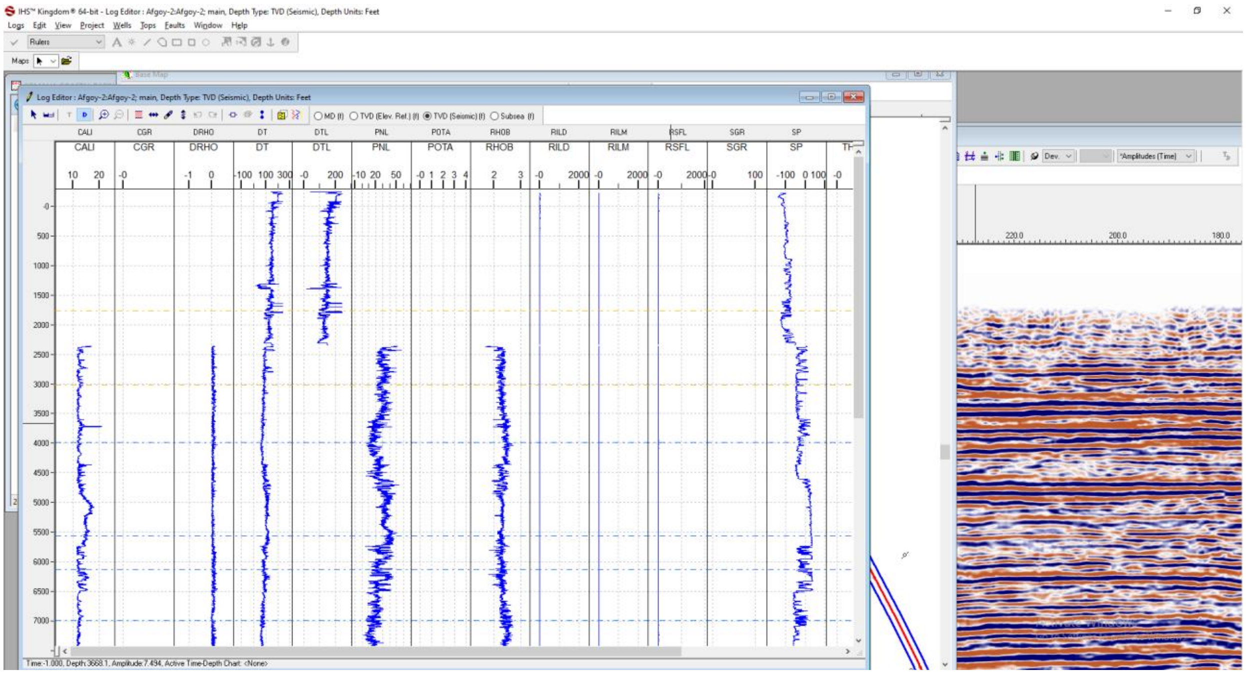


Figure 3.4: Examples of well logs from Afgoi-2 visualized with the help of IHS Kingdom Suite version 2015

3.2.4 Gravity Data

Gravity data was acquired from an open-source online site (Http://Topex.Ucsd.Edu/Cgi-Bin/Get_Data.Cgi). The data which tabulates the gravity values against the coordinates, was exported in Excel file. Using one of the ArcGIS Geostatistical Analyst Tools (*Interpolation*), the data was interpolated into a raster depicting spatial distribution and variation of gravity in colour codes.

3.3 Structural Analysis

The 2D seismic data was used to reconstruct the structural geometry of the basin. The data was interpreted using IHS Kingdom Suite Software 2015 – 2017 and Schlumberger Petrel 2017 versions. In using the software, the following methods were employed.

a) Seismic line and well tie
b) Horizon picking

c) Fault picking

A careful analysis using latest state-of-art seismic interpretation software packages enabled to map the stratigraphic and structural units, and generate a series of time and depth, and also, isopach and isochore structural maps.

3.3.1 Interpretation of the Seismic Data

The procedures in the 2D seismic interpretation included the following steps: (1) Importing seismic data in SEGY format for 7 seismic profile lines, as well as, logs for seismic – well tie for visualization, stratigraphic and structural analysis. This includes:

i. Horizon correlations (seismic stratigraphy analysis)
ii. Fault picking and folds mapping;
iii. Generation of Time and Depth Surface Maps;
iv. Generation of structural (isochore and isopach) maps

3.3.2 Seismostratigraphy and Faults Interpretations

Horizon interpretation seeks to identify correlatable surfaces bounding the major stratigraphic packages, such as unconformities, flooding surfaces, or sequence boundaries visible on a seismic line's vertical display. This procedure involves the identification of observable horizons or groups of horizons with similar attributes. This was followed by the picking of faults of interest and mapping them. Peaks in the seismic data that correspond to these surfaces were traced along the available seismic transects and data (Figure 3.5).

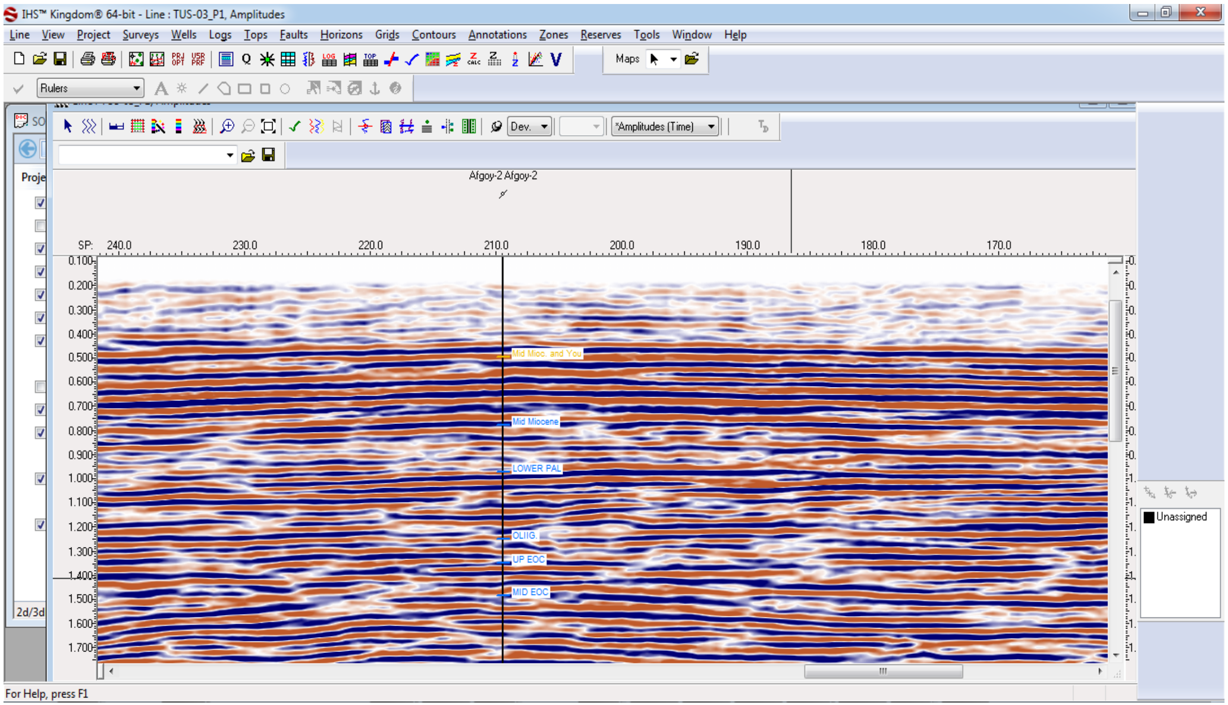


Figure 3.5: Seismic Line TUS-03_P1 and Afgoi-2 well tie with formation tops displayed in IHS Kingdom Suite 2015 version

3.3.3 Depth and Structural Maps

Geologists heavily rely in their interpretations on maps that represent the geological structure of both the surface and subsurface. Apart from mapping the fold and fault structures, seismic interpretation provides crucial information on the behaviour (attitude) of selected surfaces of interest. In our case, the available data allowed us to compile a series of depth and structural maps that depict the complex nature of the subsurface and the distribution of the elements of the petroleum system, within the Coriole basin.

Depth and structural maps were generated for the specific surfaces of interest, in particular, formation boundaries, the source rock, reservoir, seal, and also, possible migration pathways. This involved the mapping of formation thicknesses through isochore and isopach maps. All this obtained data enables us to understand the sedimentary basin's hydrocarbon potential, including the distribution of the main petroleum system components.

3.4 Source Rock and Maturation

The source rock maturity and hydrocarbon generating potential were evaluated by using the Lopatin-Waples method through the manual construction of a series (families) of burial history curves and Time Temperature Indexes. This approach was first introduced by Lopatin (1971) and later advanced by Waples (1985) and it offers a quick estimation of the source rock potential in areas of frontier exploration. As of lately, this technique has been successfully applied within the Anza Basin in Northern Kenya (Waga & Mwachoni, 2019; Angengo, 2020). The additional advantage of this technique is that it can be applied to any geological model, irrespective of its complexity (Waples, 1980).

3.5 Time-Temperature Index (TTI) Modelling and Analysis

Burial history analysis aims at reconstructing the vertical movement of sediments in a basin. It quantitatively describes the geologic history of a basin (van, Hinte, 1978). This study adopts the Lopatin-Waples method, which involves the construction of burial history graphs, and the calculation of TTI values that estimate the onset of petroleum generation. TTI analysis provides information on the timing of petroleum generation and the type of hydrocarbon produced. These results are later incorporated (integrated) with the 2D seismic interpretations that enable one to deduce the possible migration pathways of the expelled hydrocarbons.

Data required for TTI analysis include:

- Bottom-hole temperatures obtained publications or industry reports
- Well formation tops
- Sediment thickness from paleontological / stratigraphy analysis
- Sediment age
- Sedimentation rates

Corel Draw version 2020 and ESRI ArcGIS version 10.5 were used for image digitization and modeling of the Petroleum System (PS). Both burial history and sedimentation rate curves are manually generated using graph paper, and later, scanned and digitized with the help of Corel Draw Software. The depths and thicknesses used in the TTI modelling for the Afgoi-2 well are given in Table 3.4.

Table 3.4: Formation tops and thicknesses encountered in Afgoi-2 well section

Top and base Depth (ft.)	Top and base Boundary	Thickness (ft)	Age
80 - 2,050	Confident	1970	Middle Miocene and younger
2,050 – 3,310	Confident	1,260	Middle Miocene
3,310 – 4,280	Confident	970	Lower Miocene
4,280 – 5,860	Confident	1580	Oligocene
5,860 – 6,420	Unconformable	560	Upper Eocene (Pribonian)
6,420 – 7,290	Confident	870	Middle Eocene
7,290 – 9,580	Confident	2,290	Lower Eocene
9,580 – 12,000	Confident	2420	Upper Palaeocene
12,000 – 13,290	Confident	1,290	Upper - Lower? Palaeocene
13,290 13,470	Confident	180	Lower? Palaeocene - Upper Cretaceous
13,470-13,747	Confident	277	Maastrichtian

Time and temperature both influence the rate of source rock maturation. The Lopatin method establishes the time of the onset of petroleum generation. It assumes that for each 10ºC increase in temperature, the rate of the chemical-kinematic reaction doubles. The relationship between the chemical rate and temperature is expressed by applying the Arrhenius equation

$$\boldsymbol{K = koe^{-E\propto/RT}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (Equation\ 3.1)$$

Where **K** – reaction rate constant, **koe** — rate constant (also expressed as **Aexp**); **E** – activation energy, kcal/mol (also given as **Ex**), **R** – universal gas constant, **T** – -absolute temperature (Lopatin, 1971; Waples, 1985; North, 1985). A list of temperature factors for every 10° C interval increase is given in Table 3.5.

Table 3.5: Temperature factors for every 10°C used in the Lopatin method after (Waples, 1985).

Temperature interval	N	r^n
20-30°C	-8	$^1/_{256}$
30 – 40°C	-7	$^1/_{128}$
40 – 50°C	-6	$^1/_{64}$
50 – 60°C	-5	$^1/_{32}$
60 – 70°C	-4	$^1/_{16}$
70 – 80°C	-3	$^1/_{8}$
80 – 90°C	-2	$^1/_{4}$
90 – 100°C	-1	$^1/_{2}$
100 – 110°C	0	1
110- 120°C	1	2
120 – 130°C	2	4
130 – 140°C	3	8

The total maturity is the sum of the individual maturity indexes calculated for each 10°C interval. The steps: involved during the Lopatin-Waples modelling include:

Step I: Construction of age-depth plot graphs and sedimentation rates curves based on the micropaleontology results. This provides information on the sedimentation and the presence of erosional events and related unconformities, plus their durations.

Step II: construction of burial graphs. These are depth versus age profiles of the sedimentary layers. The effects of sediment compaction or water loading are ignored.

Step III: Creation of a temperature grid for each 10°C interval increment assume that the geothermal gradient and bottom hole temperatures (BHT) remains constant through time.

Waples (1980, 1985) gave a general relationship of TTI values with other maturity indicators and their relation to petroleum maturation as described in Table 3.6

Table 0.6: TTI –Vitrinite Reflectance Correlation and Hydrocarbon Type after (Waples, 1985)

TTI	Ro	Hydrocarbon type (80% probability)
50	0.90	Normal oil
75	1.00	Normal light oil
180	1.35	Condensate – wet gas
500	1.75	Wet gas
900	2	Dry gas

Uplifts and associated erosional processes decrease the temperature factor. The TTI values are always positive because maturity increases regardless of burial or uplift processes. However, the rate of maturation decreases of the uplift and cooling lasts for a long period of time (Waples, 1985).

3.6 "Interpretation of Free Air Gravity Anomalies".

The gravity map (Figure 3-3) was plotted using the open-source satellite gravity data available from the website: www.topex.ucsd.edu. The map was generated with the help of ESRI ArcGIS software. It shows the depth of the basement high value of 38.70-26.25mGal and thus, identify the thickness of the sedimentary cover. Gravity measurements are important in oil and gas exploration in identifying sedimentary structures composed of various crustal rocks that differ through their densities. Figure 3-4 demonstrates that the offshore shelf part of the Indian Ocean has gravity lows and negative values measured in the range of 4-60m Gal to 31mGal. These values increase towards the coastline. Within Coriole Basin (from Adalle to Barava), the values range between -11 to +8.82 mGal. There are delineated areas within the basin that have greater values in the range between positive 8.82 mGal and 38 mGal values.

The high gravity values (green) suggest the development of basement ridges or highs within the basin. The Coriole and Afgoi structures are completely or partially concealed under the thick sedimentary cover. These structures are key in oil and gas exploration because they might have been responsible for generating hydrocarbon traps within the overlying thick sedimentary column. The lower gravity values (coloured yellow-red and blue) indicate the presence of either less denser materials or deeper locations of the basement, and hence, thicker sedimentary infill.

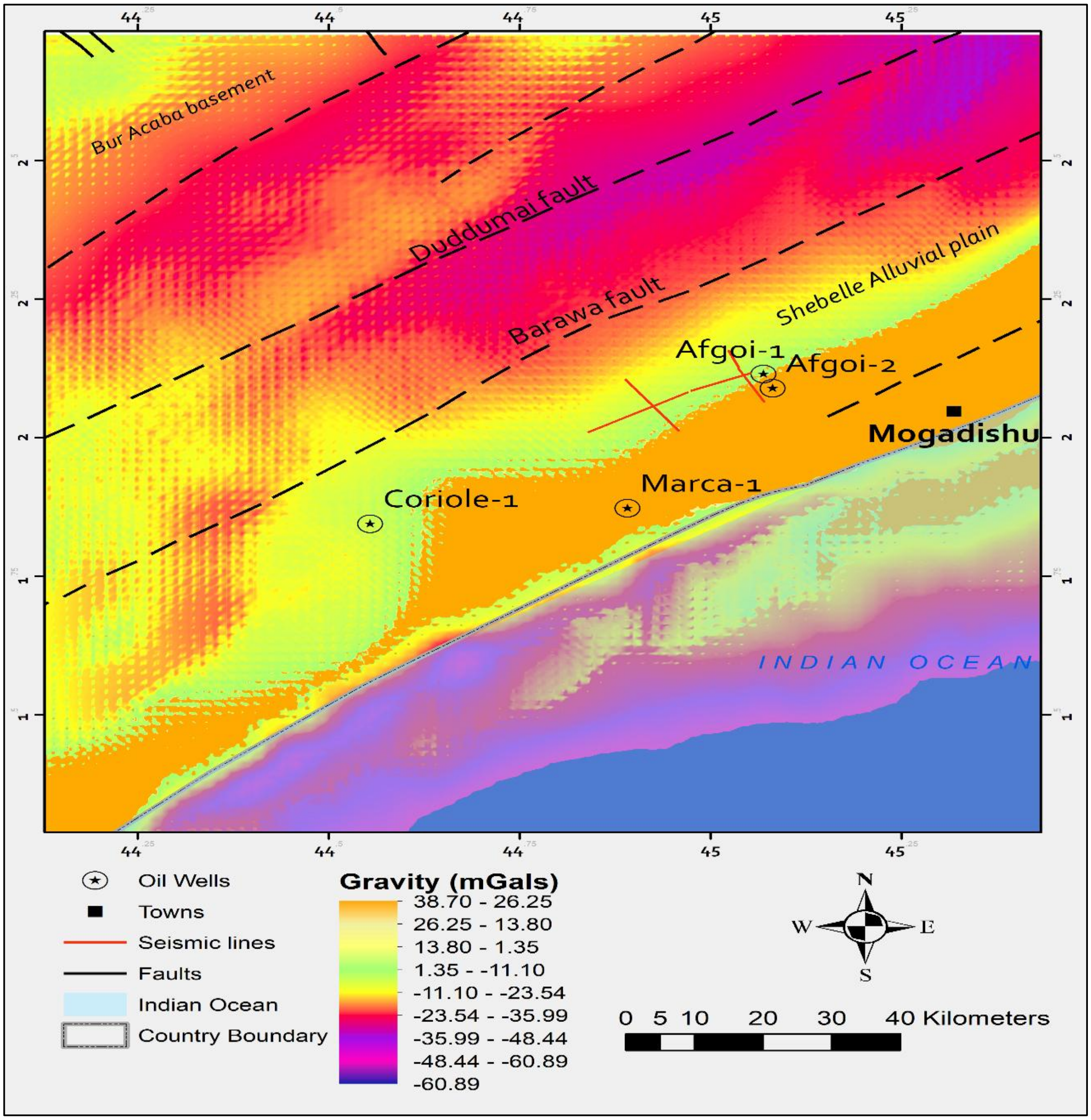


Figure 3.6: 2D Satellite-Derived Free Air Gravity Map for the Coriole Basin. Interpretation Free Air Gravity Anomaly Data Adopted From Http://Topex.Ucsd.Edu/Cgi-Bin/Get_Data.Cgi

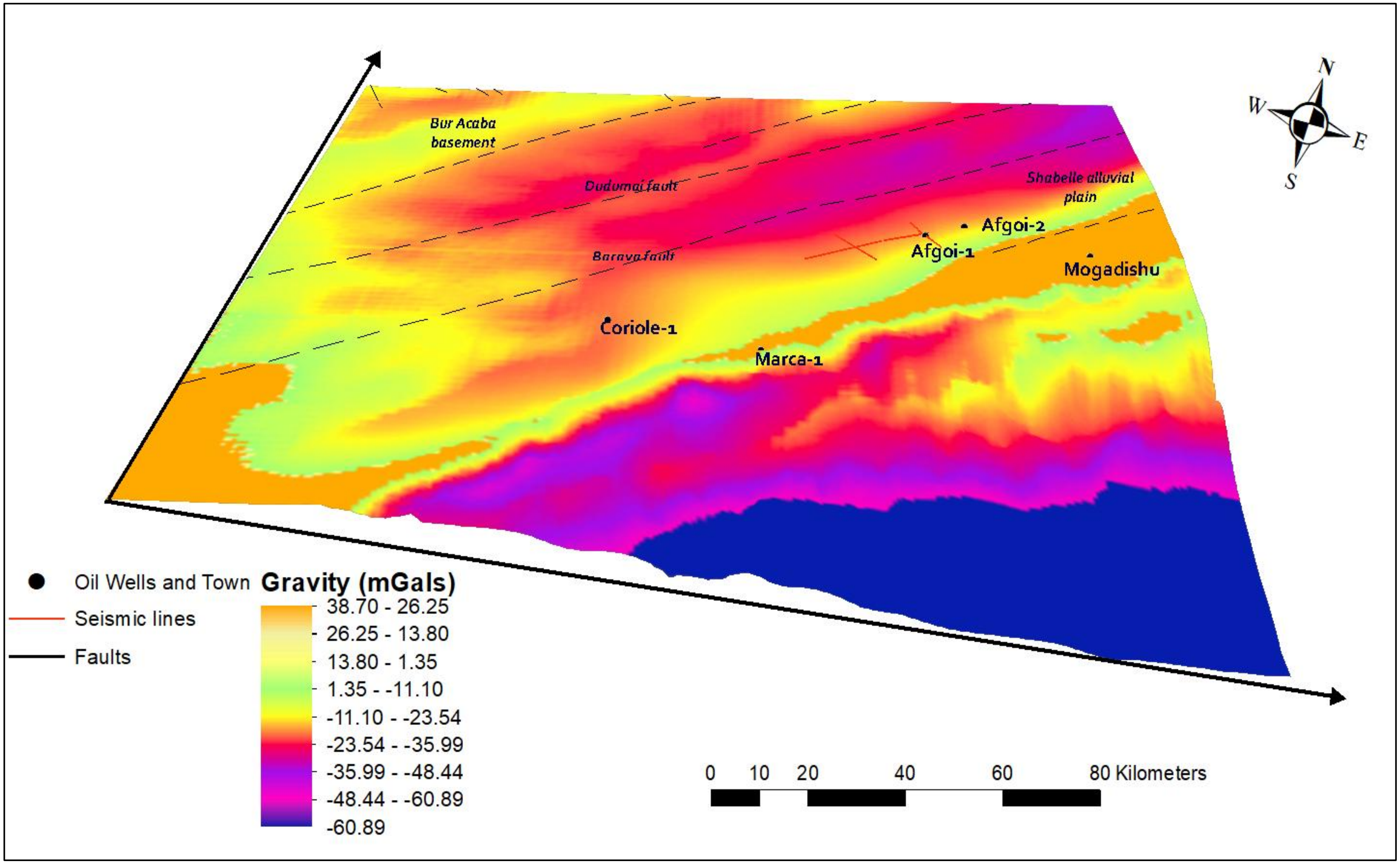


Figure 3.7: 3D Satellite-Derived Free Air Gravity Map for the Coriole Basin. Interpreation Free Air Gravyit Anomaly Data Adopted From Http://Topex.Ucsd.Edu/Cgi-Bin/Get_Data.Cgi

3.7 Correlation of Formations

The Afgoi-Coriole cross section (Figure 3-5) spans from the Afgoi structure (Afgoi 1, 2 wells) towards Merca, 35 km in the south-western direction, deviating eastwards 38 km towards the Coriole-1 well (See Figure 3-6). The stratigraphy of the Afgoi-Coriole structures was best understood through the construction of a regional cross-section.

The Coriole Basin has a variety of sedimentary facies developed in it, which is evident from the logs of the four wells. Compressed sediments dominate the deeper parts of the section of the wells within the basin, while alluvial sediments that resulted from the periodic flooding by Shebelle River and its tributaries dominate among the shallow and younger layers.

Afgoi-1 well encountered 6 different sedimentary formations. The oldest, the Jesomma formation, lies at a depth of 13,658’ (4164m) and defrags to Upper Cretaceous (121-66.1 Ma) has an average thickness of 1,070 ft (326m). A similar layer can be found between 12,582 feet (3836 meters). Younger formations corresponding the Oligocene and Pliocene, the Somal 2745 ft (837m) and Scusciuban formations (35 ft (11m) occur (developed) at different depths.

Afgoi-2 well has about 12 formations. The Maastrichtian (Jesomma Fm) is the oldest, measuring between 13476 and 13747 feet (4109 – 4191 meters). The Jesomma transition, the Auradu equivalent, ranges between 13290 and 13470 ft (4052 – 4107m). Auradu formation and 7290 to 13290 ft (2223 – 4052m). Quaternary sediments and Scusciuban are the youngest layers, ranging in depth between 0-80 ft bgl and 80-2050 ft (24–625).

Merca-1 well has encountered seven formation tops. The Jesomma formation of the Upper Cretaceous (72.1 Ma) occurs at the depth of approximately 13,118 ft (3,999m). The Auradu formation of the Upper Palaeocene (57.6 Ma) lies at a depth of 11918 ft (3049m). Younger formations are represented by the Scusciuban and Somal formations of the Pliocene (5.33 Ma) and Miocene (23.03 Ma) ages. The depth range of the shallow layers is 35 ft and 2745 ft (837m), respectively.

The Coriole-1 well section encountered eight layers. The Jesomma/Sagehhey formation of the Middle Cretaceous (60.5 Ma) lies at a depth of about 11,543 ft (3519m) and has a thickness of 1,543 ft (470m). Marai Ascia formation (59.2 Ma) occurs at depths of about 10,000 ft (3049m) and has a thickness of about 1000 ft (305m). The younger alluvial sediments belong to Merca formation (11.6 Ma) and extend up to a depth of about 1,700 ft while the Somal formation (16.4 Ma) was encountered at a depth of about 4570 ft (1393m) and has a thickness of 2670 ft (814m).

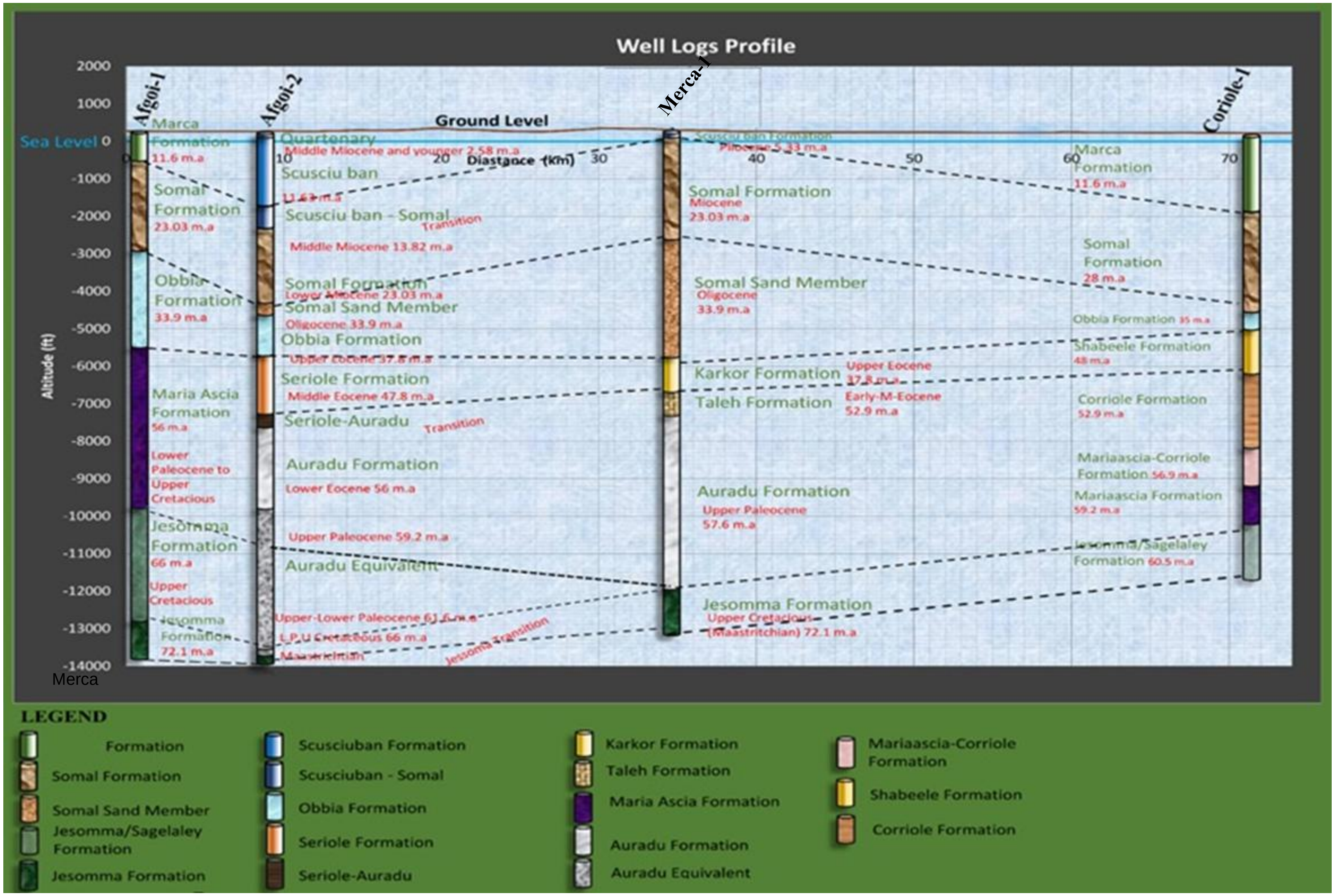


Figure 3.8: Correlation of formations (Well Logs Profiles) in the Afgoi-Coriole Cross-Section

Figure 3.9: The location of the correlated wells along Afgoi-Coriole Cross-Section (Google Earth Extract, 2021)

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Stratigraphy and Petroleum system Elements of the Afgoi Structure of Coriole Basin

4.1.1 Lithology and Biostratigraphy of the Mesozoic-Cenozoic Sediments of Afgoi-2 well

The stratigraphy of Afgoi-2 well is composed of Upper Cretaceous, Tertiary and Recent sediments. The well was drilled to a total depth of 4191m (13761') into the Upper Cretaceous, Jesomma Formation. The total thickness of the Upper Cretaceous on an outcrop north of the Scebeli River is more than l, 000 ft. (304 m) and is overlain by Auradu limestone of Palaeocene-Early Eocene age (Hughes, 1985).

The stratigraphy, palaeontology and lithology data of the Afgoi-2 well were all adapted from industrial reports and are briefly summarized below. The descriptions are provided starting from the oldest to the youngest.

a) Upper Cretaceous (Maastrichtian) Jesomma (Yesomma) Formation (13470' to 13747'**) (4106 – 4191m)**

In the range from 13470' to 13747' (4106-4191 m), the interval belongs to the Upper Cretaceous, Maastrichtian (Jesomma formation). It is mainly comprised of the shales and sandstones. Their age is defined based on the palynomorph and microfossil (planktonic foraminifera, calcareous nannofossil) biostratigraphy from the (13530'-13747'; 4125 – 4191m) interval. The shales are interbedded with sandstones and siltstones between 13747' (4191m) T.D. and 13420' (4091m). The Maastrichtian, as well as the succeeding Lower Paleocene interval, were deposited under inner shelf and periodically shallow inner to marginal marine conditions near to a coastal mangrove environment. The Lower Palaeocene interval was deposited under inner shelf and periodically shallow inner shelf marine conditions near to a coastal mangrove environment. Between 13700 '(4176m) and 13747 '(4191m), sparse microfaunal content is characterised by *Gavelinella spp*. and the planktonic foraminifera *Rugoglobigerina rugosa* and Hetero helix sp., which indicate normal marine conditions of deposition.

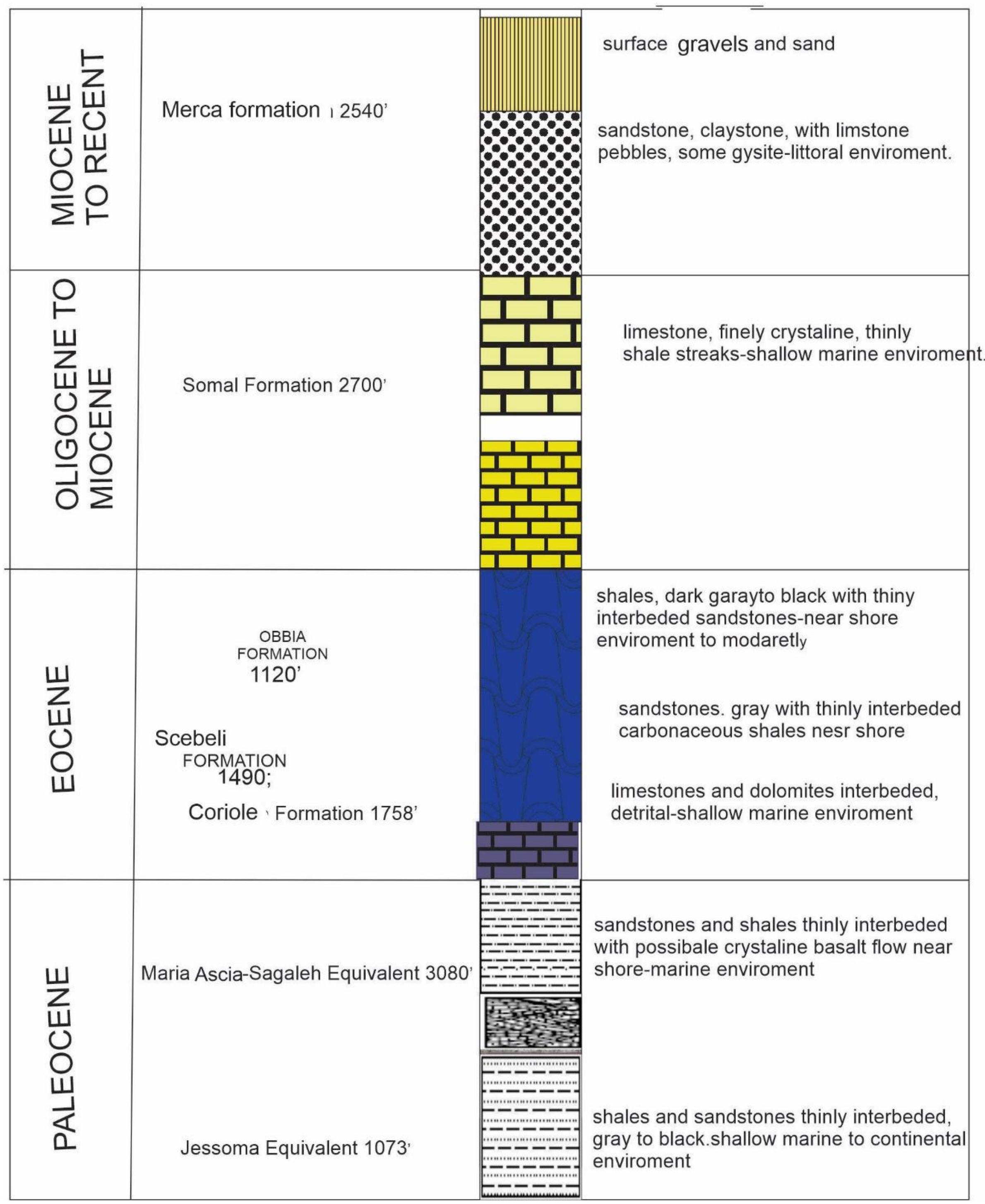


Figure 4.1: Digitized stratigraphic section for Afgoi-2 Well (modified after Durkee, 1982)

The shales and sandstones recorded below 13470' (4106m) down to 13747' (4191m) T.D., are of Cretaceous age and are characterized exclusively marine conditions than the overlying lithological units, and can be assigned to the Jessoma Formation. Lithologies within this interval include sandstones, siltstones and shales with minor igneous rocks. The Jesomma Formation was influenced by the Oman Collision event that led to the uplift of North-Central Somali due to inversion during the Late Cretaceous.

b) Lower Palaeocene – Upper Cretaceous (61.6-66Ma) Auradu equivalent—Jesomma transition 13290'—13470' 4051 – 4106m depth interval

Between 13290ft and 13470ft (4051m and 4106m), shales and minor sandstones contain no age index biostratigraphic markers capable of distinguishing the Lower Palaeocene from the Late Cretaceous Maastrichtian, and the sediment appears to be transitional between the Auradu equivalent and the Jessoma the formation.

c) Lower Eocene – Palaeocene (47.8-61.6Ma) Auradu Formation and Auradu Equivalent (7290' to 13290') 2222 – 4051m depth interval

Limestones, dolomites and sandstones with interbedded shales between 7290' and 13290' contain impoverished assemblages of mainly very shallow marine foraminifera similar to those recorded from the Auradu Formation. None of the medium depth foraminifera reported from the Marai Ascia Formation were recovered. The upper part of this interval (7290'-9490') is hence comparable to the Auradu Formation. However, the lower part (9490'-13470') contains shallow marine to marginal marine sands and probably represents Auradu equivalent sediments which have been subjected to massive clastic sediment influx from a nearby coastal mangrove environment.

d) Middle Eocene (37.8-47.8Ma) Seriole-Auradu transition (6950'-7290'; (2119 – 2223m)

The interval 6950'-7290', comprising marine shelf silty shales, sandstones and larger foraminifera-bearing limestones appears to be transitional between the Seriole Formation and the underlying Auradu Formation.

e) Upper Eocene (33.9-37.8Ma) Seriole Formation (6030'-6950'1838 – 2119m)

Relatively deep marine sandstones, siltstones and silty shales recorded between 6030' and 6950' (2118m) also yield planktonic foraminifera ranging in age Upper Eocene (Bartonian

38Ma). The sediments of the Seriole Formation are overlain by Oligocene sediments, and they range in depth from 5840' to 6030' (1780–1838m) and have similarities to the previous studies.

f) Oligocene (23.03-33.9Ma) Somali sand member and Obbia Formation (4650’-6030’) 1418 – 1838m)

The mainly sandy unit from 4650' to 5000' is of Oligocene age and has been assigned to the Somal sand member Formation. Plankton rich, deep marine silty shales and minor siltstones between 5000’ and 6030' range in age from Oligocene to Upper Eocene are assigned to the Obbia Formation by Keplinger geologists.

g) Lower Miocene (13.8-23.03Ma) Somal Formation (2670’-4650’) (814 – 1417m)

The layer extends from 2670’ to 4280' (814-1305m). According to the results of samples analysed in previous studies on the upper parts of the layer, the formation is composed of carbonate rich with little organic matter. On the other hand, the lower parts comprise clastic material. The main source rock is the Scusciuban-Somali Transition to Somali formation that extends to a depth of 4560’ (1390m). The traps are the stratigraphic unconformities, while the area lacks seal rock due to the absence of evaporites as seen in the Mandera-Lugh and Ogaden Basins.

h) Middle Miocene (11.6-13.8Ma) Scusciuban-Somal transition (2050’-2670; 625-814m)

The mainly sandy interval between 2050’ and 2670' comprises shallow marine microfaunas and appears to be transitional between the Scusciuban Formation and the underlying Oligocene-Miocene carbonates. The transition zone is made up of clastic and carbonate-rich sediments, which ranges from 2050' to 3520’ (625-1072m) and do not show any potential for oil and gas, hence are organically lean.

i) Middle Miocene and/or Younger (2.6-11.6Ma) Scusciuban Formation (80’-2050’; 24-625m)

This formation is composed of clastic sediments with average cumulative thickness of 1970’ (600.6m) 80’ to 2050’ (24.4-625m). They are organically lean and, therefore, do not have any oil and gas potential. The formation is known as Scusciuban, and due to its increased sand content, the formation has a high risk of top sealing even if it qualifies as a source rock has potential for oil and gas.

4.2 Petroleum Systems of Coriole Basin

The term Petroleum System (PS) was first introduced by Magoon et Dow (1994) and is defined as a pod of active source rock and all related oil and gas essential elements/processes needed for oil and gas accumulations to exist. It obtains its name from the source rock and the major of the reservoir rock. Based on the data available, we identified the presence of at least three (3) Petroleum Systems (PS) in the Coastal region of Somalia.

4.2.1 Petroleum Systems in Somalia Coastal Basins

The presence of a thick sedimentary infill is the major prerequisite of finding hydrocarbon accumulations which are products of the interaction and development of 5 ingredients of the Petroleum System (PS) – source rock, reservoir rock, seal rock, trap and migration. All of these components are present within the Coriole basin to some extent. A brief discussion of each component is provided below.

4.2.2 Source Rocks

Despite the absence of solid geochemical evidence on source rock quality, there are some hydrocarbon indications, lithological mineral composition of some units, and the presence of large oil seepages (Barnes, 1976; Kamen-Kaye and Barnes, 1979). In addition, Mesozoic marine grey shale and argillaceous limestone found in Somalia and Eastern Ethiopia could be considered as potential source rocks. However, inadequate maturity and burial depth are likely to be the major factors impacting source-rock quality. The Tertiary sections of the Mandera-Lugh Basin, the Lamu embayment, and coastal basins have all demonstrated a good/fair potential for finding oil and gas deposits (accumulations)

4.2.3 Reservoirs

In Somalia's coastal and offshore areas, the porous limestone and dolomite beds and the Cretaceous-Tertiary sandstone layers and Miocene carbonate beds situated to the south of the Bur Acaba uplift are the main reservoir rocks (Whiteman, 1981).

4.2.4 Seals

Widespread Jurassic, Cretaceous, and Tertiary shale and evaporite layers offer adequate regional and local seals (Whiteman, 1981).

4.2.5 Traps

Normal faults, anticlinal traping over buried and rejuvenated basement blocks, and igneous intrusives are all the most frequent regional and local features developed in the Somali Coastal Basin. Most structures are linked with acute slip faults and compressional folding. There are few studies on the levels of porosity of fossiliferous-reefal carbonate facies and deltaic sandstone layers and this warrants further research (Whiteman, 1981; Kamen-Kaye and Barnes, 1979; Barnes, 1976).

Total Organic Carbon (TOC) analyses of several selected enriched intervals with organic carbon have enabled the selection of potential source rocks. These are:

a) Jesomma-Auradu Equivalent (Sagaleh-Marai Ascia) (!)PS

The Jesomma formation encountered elevated TOC values ranging between 0.78-1.61 (wt%). Similar TOC values are seen within the entire extent of the Aurada Equivalent (Sagaleh-Marai Ascia formations). According to the classification of Peters (1986) and McCarthy et al. (2015), this source rock has a fair quality. The total thickness of this source rock interval is 4520' (1378m).

The reservoir rock interval is presented by two types. The sandstone reservoir unit has been the major target of almost all exploration activities in the coastal basins of Somalia. In the Coriole-1 well, the Upper Cretaceous Jesomma sandstone tested gas which, after 14 hours, turned into oil with a flow of 100b/d and a gas-to-oil ratio (GOR) of 14000. The oil also contained an increased number of aromatics and low sulfur content (Kamen-Kaye et Barnes, 1979).

Abdullahi (2015) provides a table according to which the Coriole-1 tested 2MMcf/d (million cubic feet per day) of gas and condensate from Upper Cretaceous volcanics at the depth of 11500 (3505.2m). Davidson et Steal (2017), who also refer to Abdullahi (2015) and Somali oil reports, further mention that 100 barrels of 36-47^{o} API oil were recovered from Paleogene reservoirs.

The second type of reservoir unit occurs within the Upper Auradau Equivalent (top Sagaleh-Marai Ascia formations), which may contain a possibly mixed carbonate (limestone) and sandstone composition. This section is probably corresponding to carrier beds that are important in hydrocarbon migration. Well, Merca-1 reported a flow of gas and salt water at the depths of 7858 -7870ft (2395-2397m) of the Middle Eocene Marai Ascia Formation (Barnes, 1976).

b) Seriole (Scebeli) – Obbia-Auradu(!) PS

TOC values for the Scabeli-Obbia formation vary between 0.8-1wt%, which also qualifies them as source rocks of fair quality (Peters et al., 1985; McCarthy et al., 2015). The total thickness of this organically enriched strata is 2410 (734.5m).

The reservoir element of this PS is the Auradu formation, which is commonly represented by a dolomitized section, thus classifying it as a carbonate type. This is a highly potential reservoir. From the Eocene dolomite at a depth of 6,500 ft. Coriole-1 produced 700b/d of salt water and 12b/d of greenish-brown, 44API, paraffin-base oil from the Eocene dolomite (Kamen-Kaye et Barnes, 1979; Abdullahi, 2015). This Eocene interval in Afgoi-2 well is presented by the Coriole formation (Figure 4.2).

c) Somal (!) PS

TOC values for the Somal and Scusciuban-Somal transition formations are much lower than for the previous interval. In Afgoi-2 well they range between 0.15-086wt%. These values correspond to a poor to fair quality source rock (Peters et, 1986; McCarthy et al., 2015).

The most promising reservoir unit occurs at the base of the Somal formation between 4560-4650’ (1389.9-1917.3m) and is represented by dolotomized carbonates. Kamen-Kaye et Barnes (1979) refer to the Dagah Shabel oil seep age in northern Somalia where one well seemingly tested oil from the Nubian or Miocene sandstones. The term "Nubian" should be applied with caution for it is commonly used for sandstones developed further to the north in Egypt and Israel, and is known to have an age ranging from the Paleozoic to the Mesozoic

(Shukri, 1945). It is also one of the most important acquifers of North Africa (Thorweihe et Heinl, 2002). Abdullahi (2015) provides an Upper Cretaceous and Jurassic age for the sandstones and fractured limestones developed at Dagah Shabei oil seepage.

According to Magoon et Dow (1994), the selected Petroleum Systems are Hypothetical or Fictional (!) for the geochemical information has identified only source rock intervals, but has no geochemical match between the source rock and oil/gas accumulations yet identified.

Our Temperature-Time Index (TTI) modelling has indicated that the Somal PS is immature with the exception of the thin dolomitic limestone will unlikely produce any hydrocarbons.

Both Jesomma –Auradu Equivalent (Sagaleh-Marai Ascia) and Seriole (Scebeli) – Obbia – Auradu Petroleum Systems provides evidence of their capacity and encouraging positive results for future exploration activities within the entire Coastal region of Somalia.

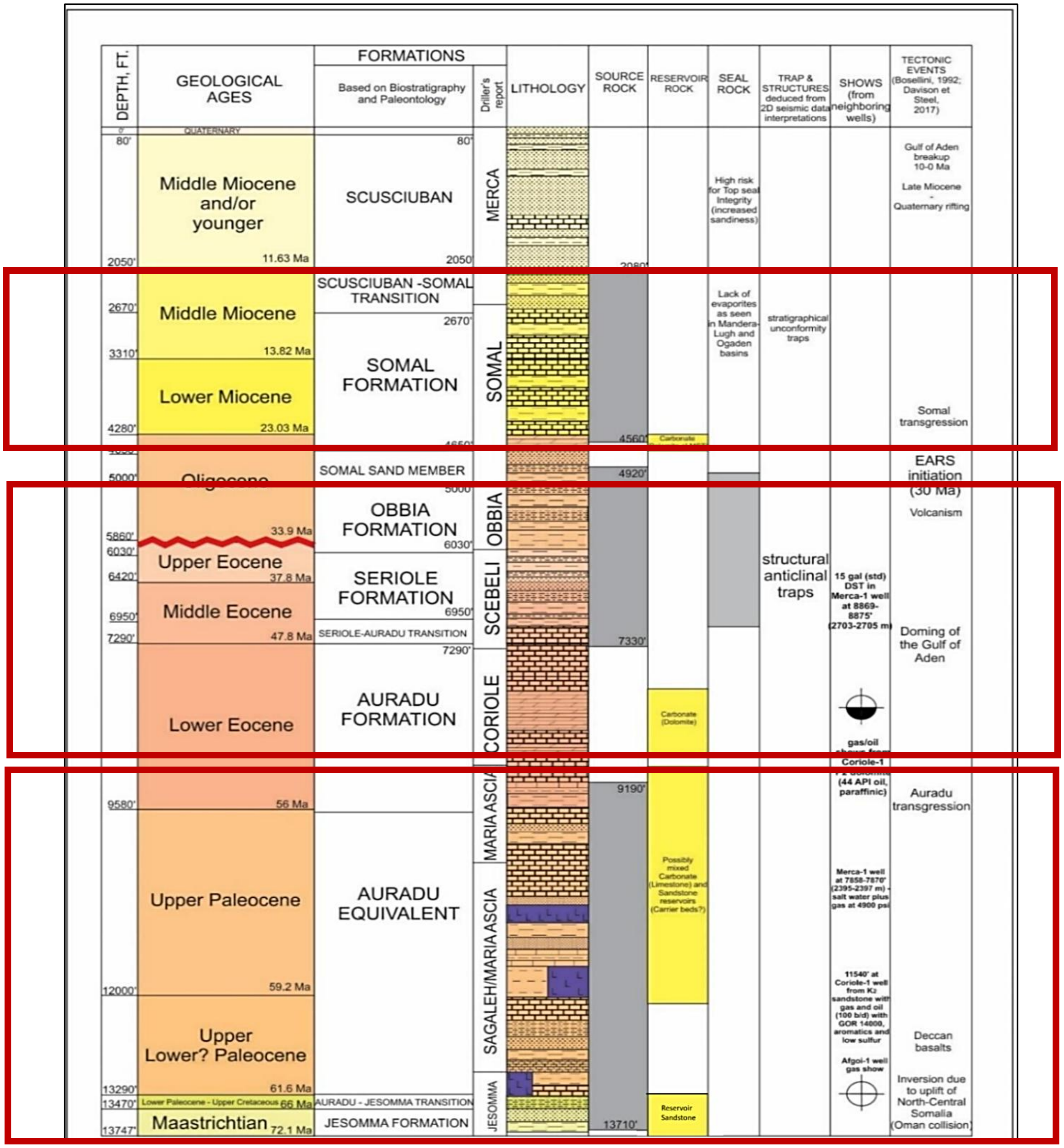


Figure 4.2: A generalized petroleum system chart for the Afgoi-2 well site area (Coriole/Somalia Coastal basin) with hydrocarbon occurrences, tectonic events and the three Fictional Petroleum Systems (Ga'al, 2021)

4.3 Seismic Stratigraphy Analysis and Interpretations

Seismic Stratigraphy is defined as a study of the stratigraphy and distinct, genetically related, depositional units from seismic reflection data by the analysis of non-structural information on seismograms (Kearey, 2001).

Alternative definition for Seismic stratigraphy was given by Cross et Lessenger (1988). According to them, this is the science of interpreting or modelling stratigraphy, sedimentary facies, and geologic history from seismic reflection data.

This chapter provides detailed discussions of the results of 2D seismic stratigraphic analyses and interpretations done on seven (7) profiles from the Coriole basin. The location maps and illustrations of both uninterpeted and interpreted seismic profiles are all presented here. All profiles were tied to the only well section available (Afgoi-2). As a result, eleven (11) well tops were selected and mapped throughout the survey area. From bottom to top these are:

a) Maastrichtian: Jesomma Formation

b) Lower? Paleocene – Upper Crateceous: Auradu-Jessoma transition

c) Upper Lower? Paleocene- /Auradu Equivalent

d) Upper Paleocene Auradu Equivalent Formation

e) Lower Eocene: Aurada Formation

f) Middle Eocene: Seriole-Aurada transition and lower Seriole formation

g) Upper Eocene (Oruabibuca): top-Somal –bottom Obbia formation

h) Oligocene: Obbia (mid-top) – Somal-sand member – bottom Somal formations

i) Lower Miocene: mid Somal formation

j) Middle Miocene: top Somal formation – Scusciuban – Somal transition

k) Middle Miocene and younger: Scusciuban formation

4.3.1 Seismic Profile TUS03_P1_SnR

TUS03_P1 (Figure 4.3) trends along a length of 24.1km in a NW-SE direction which is perpendicular to the axis of the Coriole basin. The well was drilled at the crest of a broad anticlinal structure. The observed wrench faults on the geological maps were also interpreted on the seismic profiles. All stratigraphic sequences were easily detected and mapped throughout the 2D seismic survey area.

As seen from Figure 4.6, all eleven (11) well tops selected in Afgoi-2 well have been mapped along the entire seismic profile TUS03-P1-SnR. All mapped formation thicknesses are preserved along the profile, but seem to increase towards the SE.

The strata are layered almost horizontally without significant deformations; only near trace line 322-87 a broad anticline related to the positive south-eastern flower structure can be observed. The top of the Lower Paleocene-Upper Cretaceous (Auradu-Jesomma transition) tapers out near trace 87 (Figure 4.3). Besides this, the interpreted section demonstrates strong fault development of flower structures that are associated with strike-slip (wrench) tectonics.

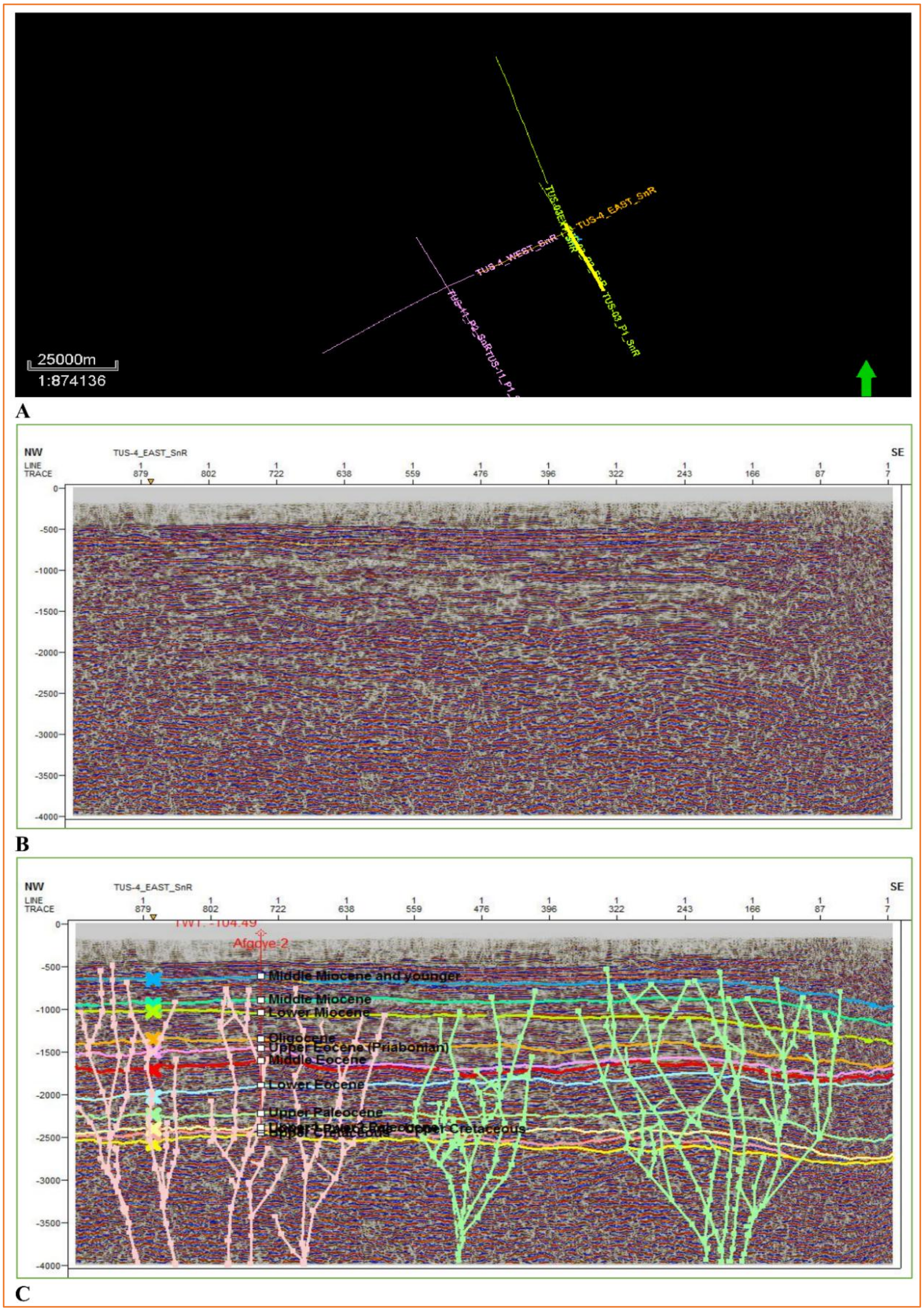


Figure 4.3: (a) Location of the seismic line, (b) un-interpreted seismic profile Tus03_P1 Snr, and (c) interpreted faults and horizons

4.3.2 Seismic Profile Tus03_P2_SnR

TUS03_P2 (Figure 4.4) is a seismic profile trending in a NW-SE direction, perpendicular to the axis of the Coriole basin. It is the north-western extension of the previous seismic profile in comparison with which it has no significant registered deformations except for some almost vertical faults (Figure 4.4). The formations sustain their thicknesses throughout the profile and are horizontally-laid. A minor positive flower structure can be seen from the centre of the section. The main stratigraphy of the section is dominated by marine sands and shales with prominent carbonate intervals in the lower Eocene (Coriole formation) and lower Miocene (Somal formation). Basaltic intrusion was observed below the upper Paleocene. A gentle anticlinal structure can be observed in the NW part of the section.

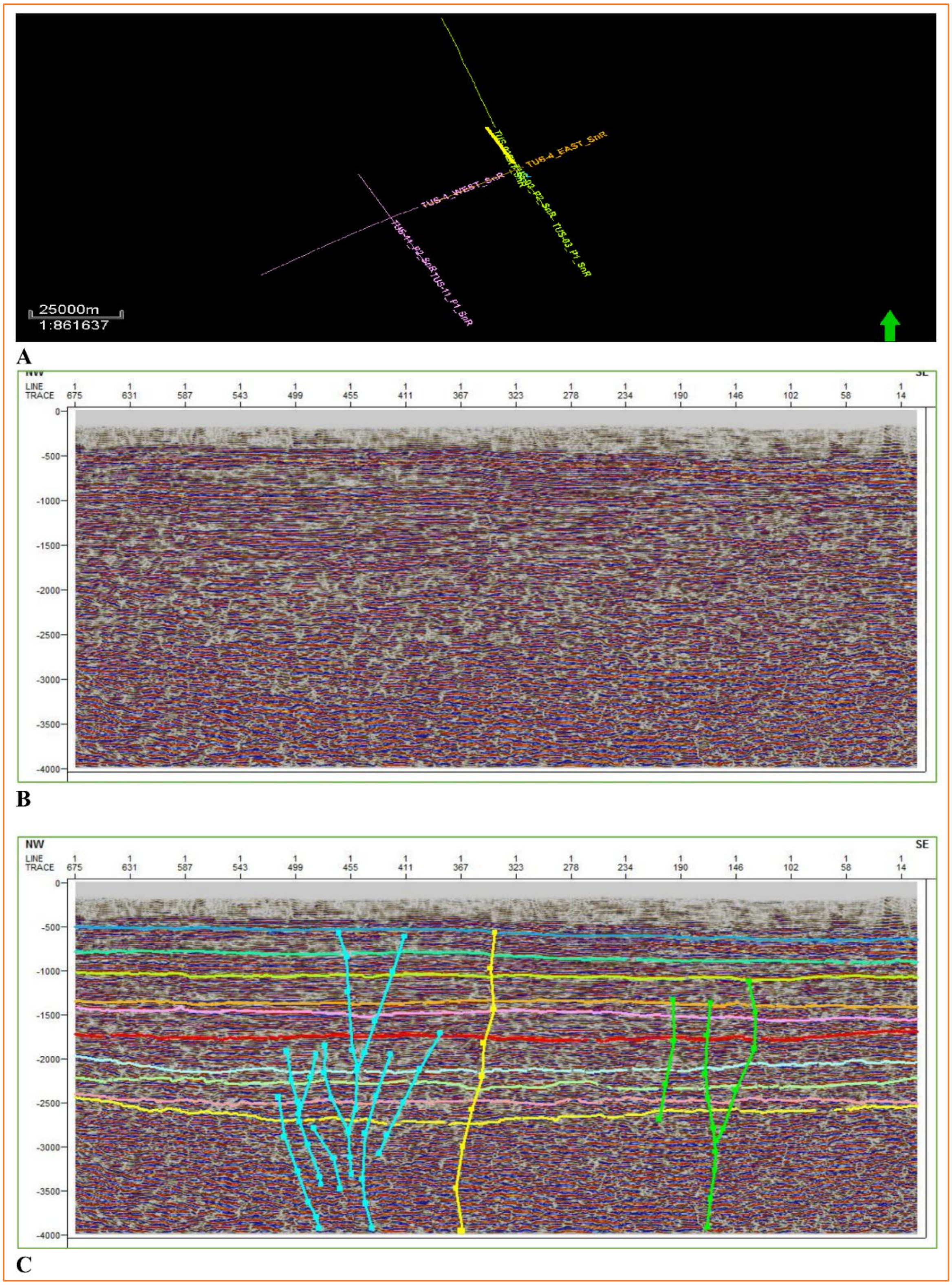


Figure 4.4: (A) Location of the seismic line, (B) Un-Interpreted Seismic Profile Tus03_P2_Snr, And (C) interpreted faults and horizons.

4.3.3 Seismic Profile Tus-03_Ext_SnR

Line TUS-03_Ext_SnR is the northernmost seismic profile of the survey, and it has an almost (N-S) longitudinal trend for a length of 43.8km, again perpendicular to the axis of the Coriole basin. The interpreted section (Figure 4.5) demonstrates a complex geological structure of the subsurface with the involvement of structures (folds, faults) and the stratigraphy. The mapped formations are deformed on the northern edge of the profile into a fold whose exact nature could be due to a longitudinal compressional event. From a simple stratigraphic analysis, we conclude that the compression and succeeding uplift took place during the Upper Eocene (Priabonian) time. The base of the Upper Eocene is highlighted in black (Figure 4.5), marking an angular uncomformity. Note that the Oligocene-Miocene and younger successions are laid almost horizontally with a slight tilt southward. The profile also reveals the significance of wrench (strike-slip) faulting and related flower structures (Figure 4.5).

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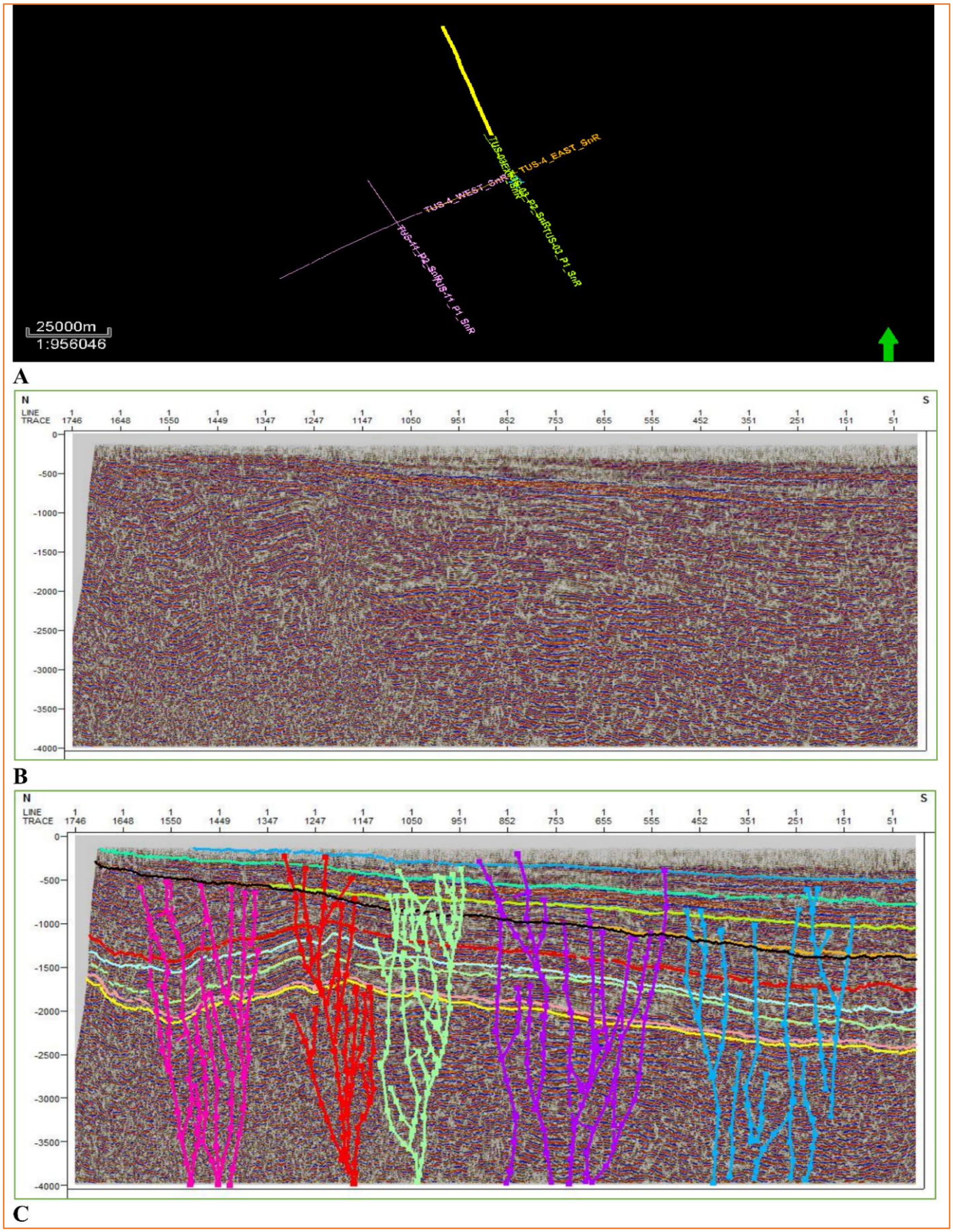

Figure 4.5: (A) The location of the seismic line, (B) un interpreted seismic profile Tus-03_Ext_Snr, and (C) interpreted faults and horizons

4.3.4 Seismic Profile Tus_4_East-SnR

Line TUS_4_EAST trends in a NE_SW direction at a distance of 31km which is parallel to the axis of the Coriole basin (Figure 4.6). The mapped formations seem to retain their thicknesses throughout the extent of the seismic profile.

Fault flower structures are well developed here. Most of these splaying faults converge into a steep fault zone at deeper levels (beyond 4000ms; Figure 4.6). They also do not seem to lead to any significant deformations of the strata.

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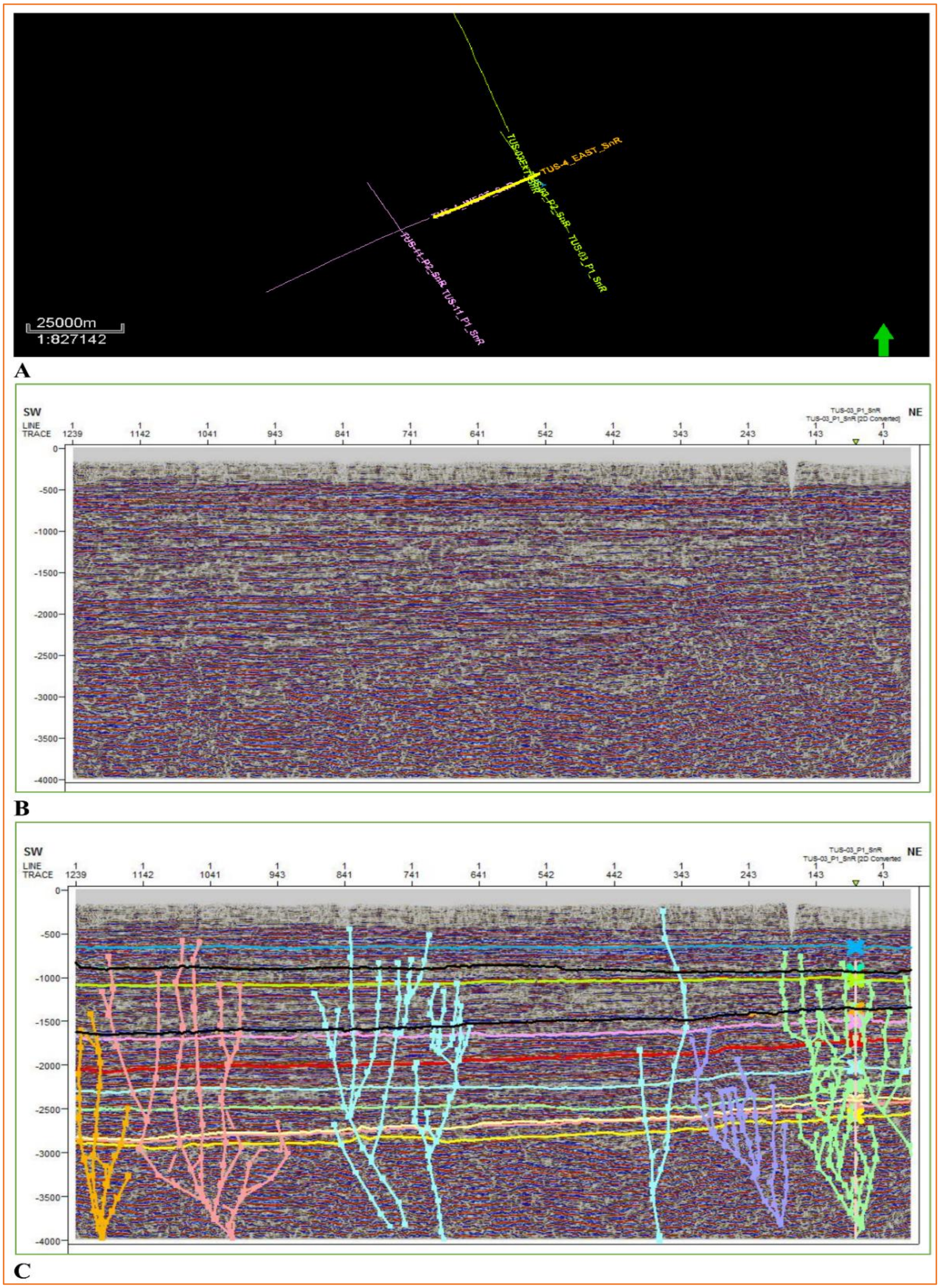


Figure 4.6: (A) The location of the seismic line, (B) un interpreted seismic profile Tus_4_East_Snr, and (C) interpreted faults and horizons.

4.3.5 Seismic Profile Tus-4_West_Snr

Line TUS_4_WEST (Figure 4.7) is a south-western extension of the previous seismic profile for a distance of 49.5km. It runs parallel to the axis of the Coriole basin. This profile resembles that of TUS_03 EXT discussed earlier in pages 83-84. Here, a structured high occurs at the south-western edge of the profile. An asymmetrical fold can be observed here with one limb dipping towards the NE. Its core is cut by a positive splayed flower structure fault. This potential hydrocarbon trap will be discussed in detail in the next sub-chapter. This structural high (on uplift anticlinal fold) was tested with two wells (Coriole-1 and Coriole-2). As mentioned earlier, Coriole-1 gave results from two reservoirs: a) Upper Crateceous (Jesomma) sandstone tested both by gas and aromatic oil; and b) Eocene dolomite gave 700b/d of salt water cuttings and 12b/d of paraffin oil (Karmen-Kaye et Barnes, 1979, p.37).

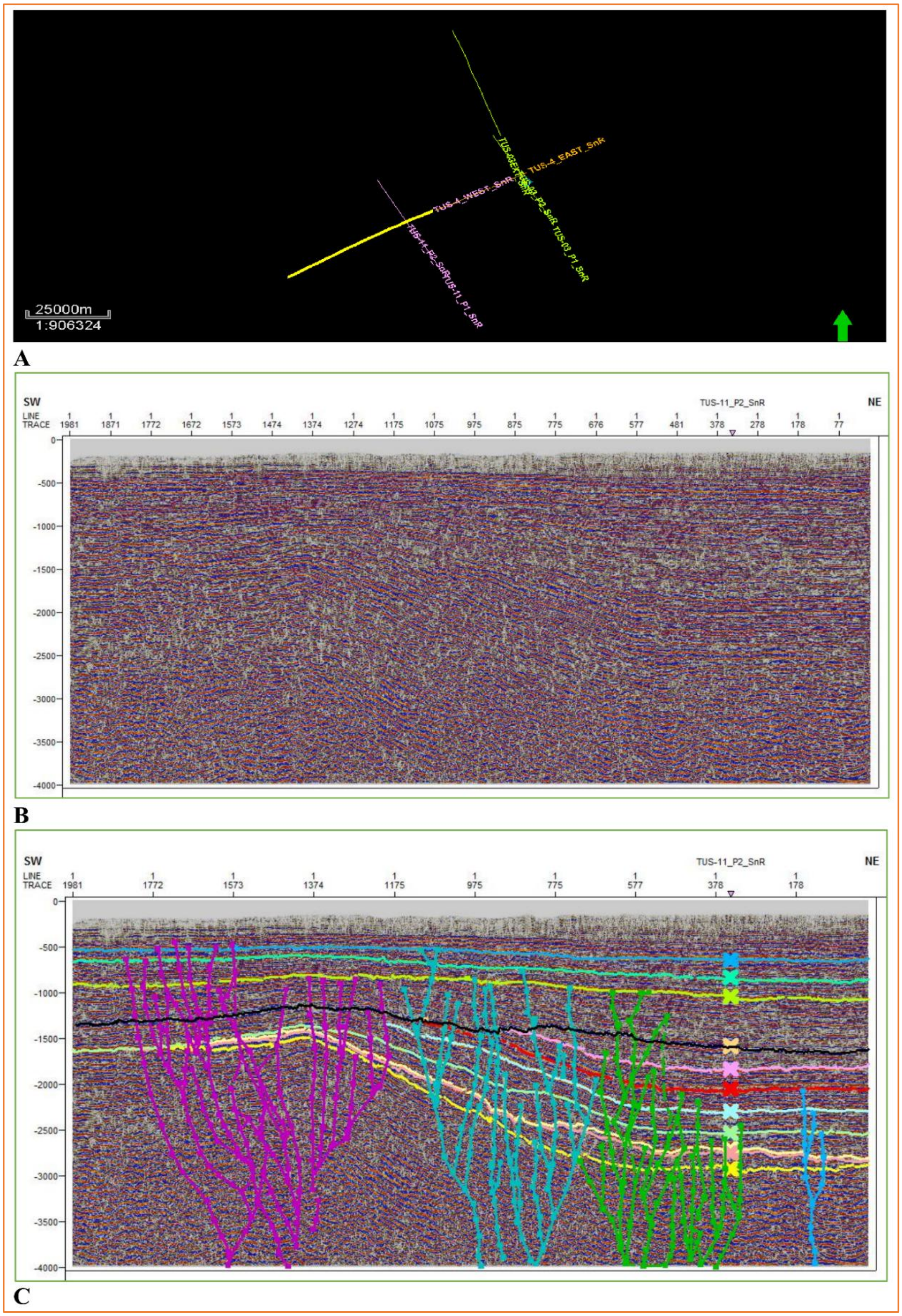


Figure 4.7: (a) The location of the seismic line, (b) un interpreted seismic profile Tus_4 West_Snr, and (c) interpreted faults and horizon

4.3.6 Seismic Profile Tus-11_P2_SnR

Seismic profile TUS_11_P2_SnR trends along a distance of 19km in a NW-SE direction, perpendicular to the strike of the Coriole basin (Figure 4.8). The interpreted seismic profile shows that all formations are horizontal but seem to thin out towards the NW (Figure 4.8). The entire length of the profile is cut across by the strike of wrench faults whose top splays are well seen. It is most likely that they all converge into singular vertical dipping faults at much deeper levels.

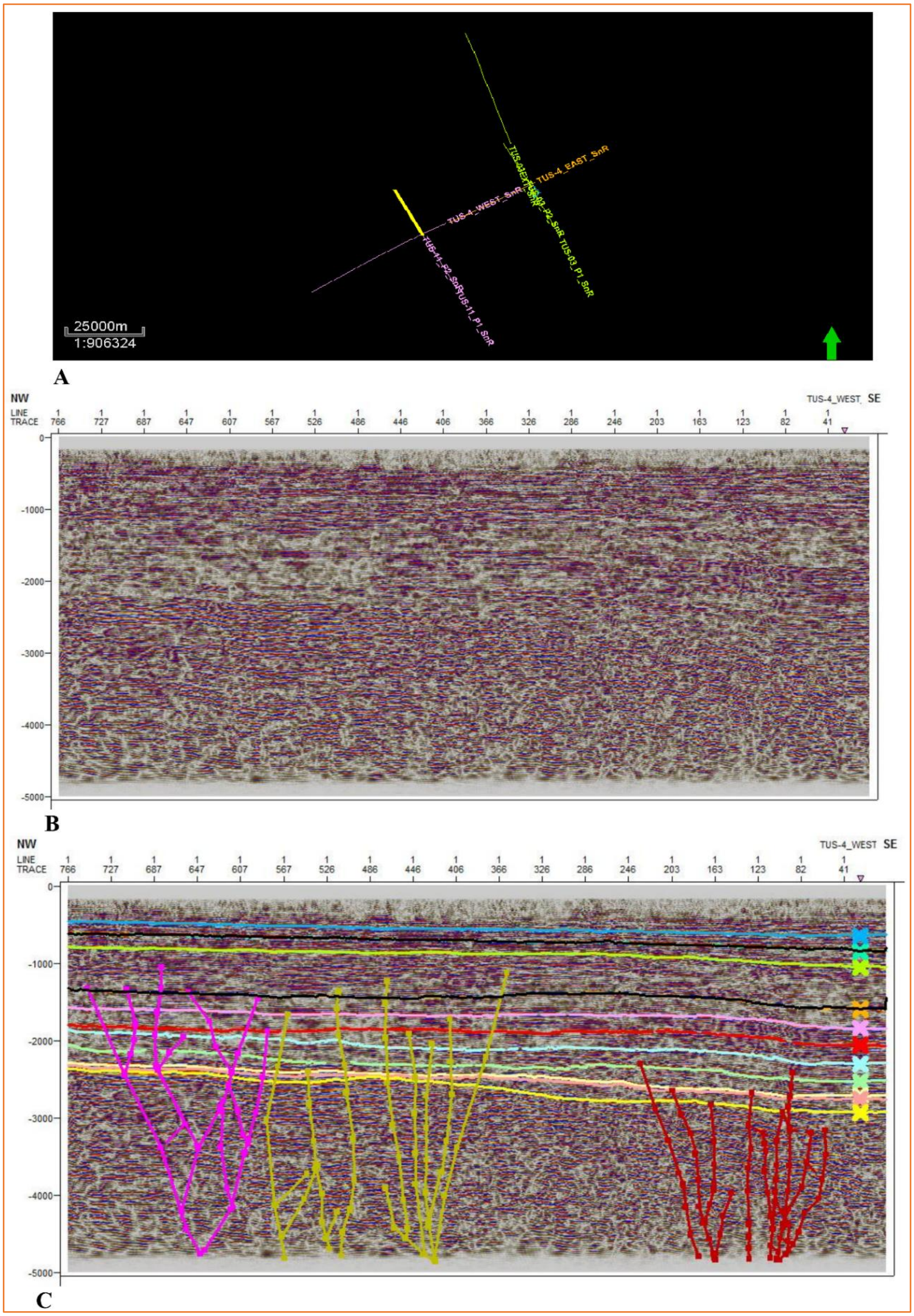


Figure 4.8: (a) The location of the seismic line, (b) Un interpreted seismic profile Tus 11_P2_Snr, and. (c) Interpreted faults and horizons.

4.3.7 Seismic Profile Tus-11_P1_SnR

TUS_11_P1_SnR seismic line of southeastern continuation in the previous profile. It has a length of 22.3km and a NW-SE trend which is about perpendicular to the axis of the Coriole basin. The SE edge of the profile has some slight deformation involved, resulting in a broad anticlinal structure extensively cut by a splay of the positive flower structure wrench fault. All f9aults tend to converge into steeply dipping faults at deeper levels (Figure 4.9).

From this data, we are now able to deduce the age of the wrench fault. The topmost tips of the splays seem to terminate at the basal part of the Scusiuban formation. This suggests that the latest active phase of faulting took place during the Middle Miocene (11.63 Ma; Tortonian stage).

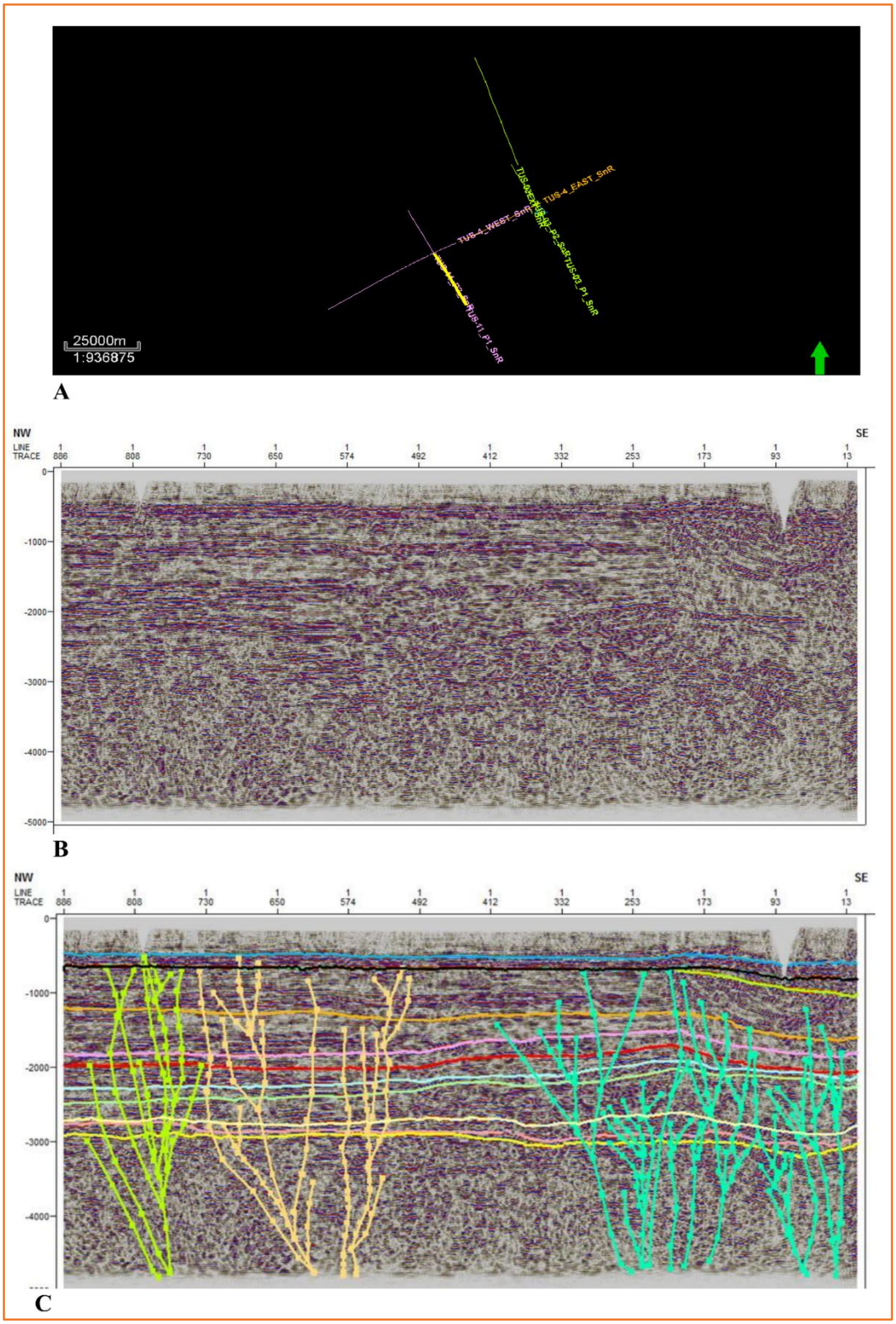


Figure 4.9: (a) the location of the seismic line, (b) un interpreted seismic profile Tus-11_P1_Snr, and (c) interpreted faults and horizons.

4.4. Subsurface Geological Maps

The seismic interpretation results discussed in the previous subchapter enabled to generate a series of time and depth geological maps that reveal the complex structure of the subsurface. The set includes the Elevation Time (in ms) structures maps and depth maps (Figures 4.10 – 4.25).

Schlumberger Petrel version 2017 software was used to generate surface maps (time and depth) maps of the top (surfaces) of interest. Note that all surfaces correspond to the base boundaries of the formation.

4.4.1 Maastrichtian Jesomma Formation Base Map

Both time and depth maps reveal the complicated nature of this surface. Two (2) highs or elevated areas of the base surface are mapped in the area's SW and NE (Figures 4.10 – 4.11). Figures 4.12 and 4.13 provide a 3D view of the generated surface for better visualization.

The depositional centre was located at the drilling site of well Merca-1 (Figures 4.10-4.13). The structural high in the southwest is known as the Coriole structure, while the one in the northeast, is known as, the Duddumai structure.

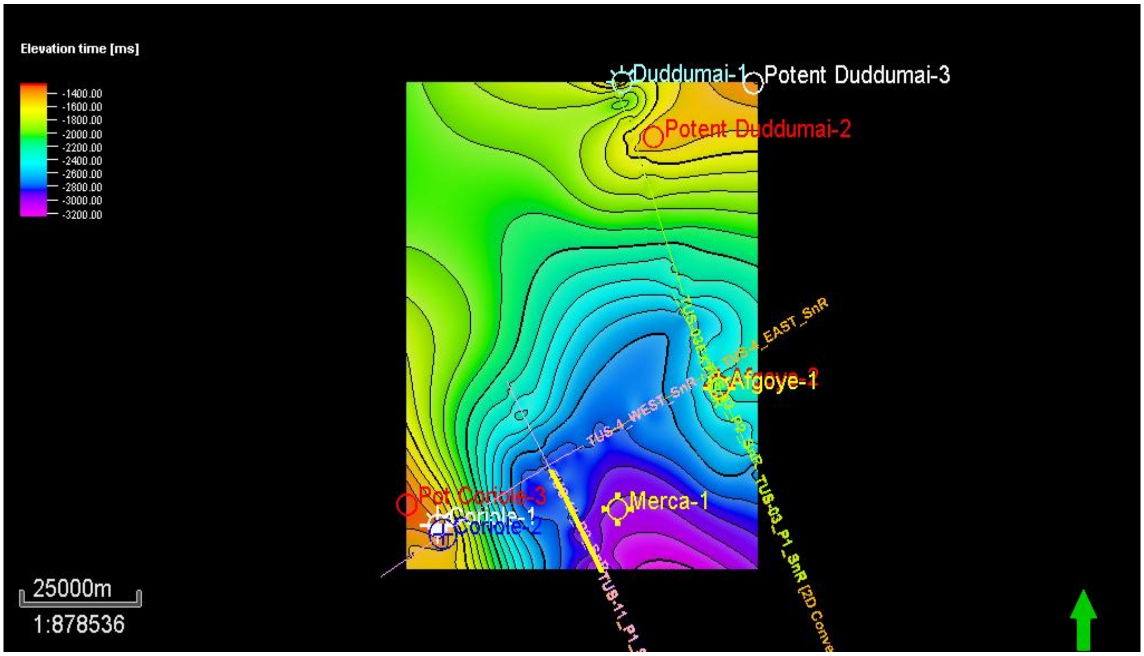


Figure 4.10: 2D Upper Cretaceous (Jesomma Formation) Elevation Time (m) Map with wells locations.

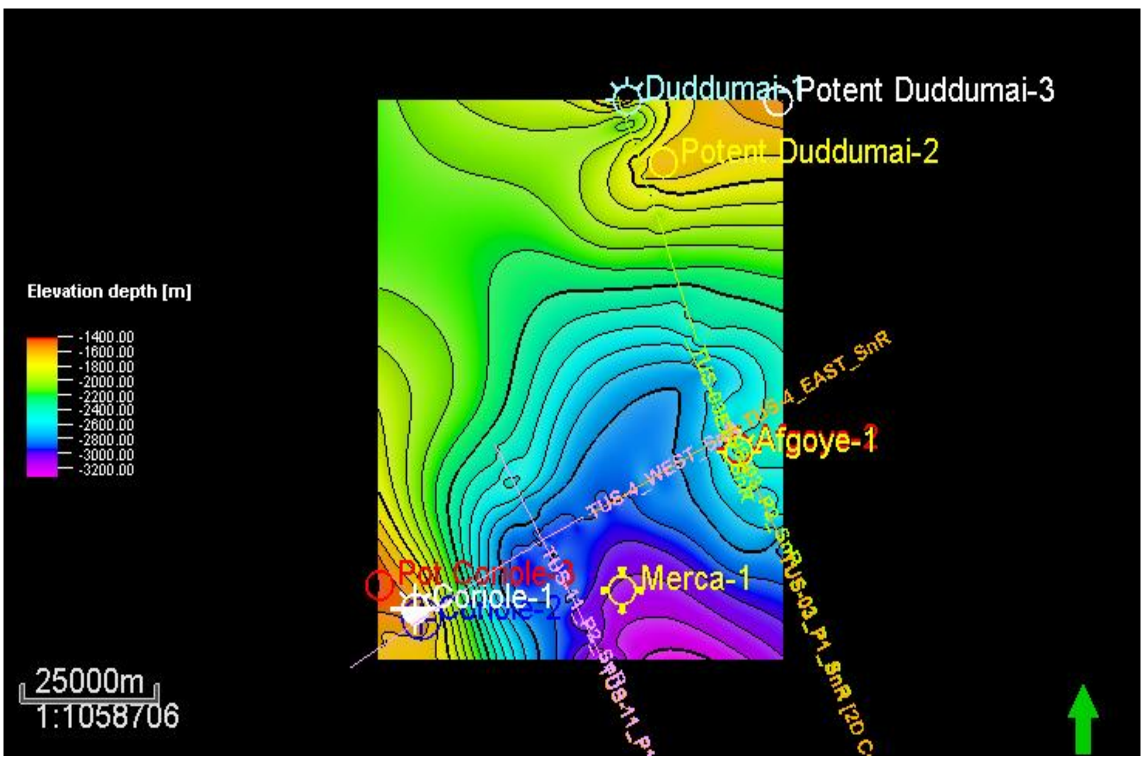


Figure 4.11: 2D Upper Cretaceous (Jesomma Formation) Depth (m) Map with well's locations

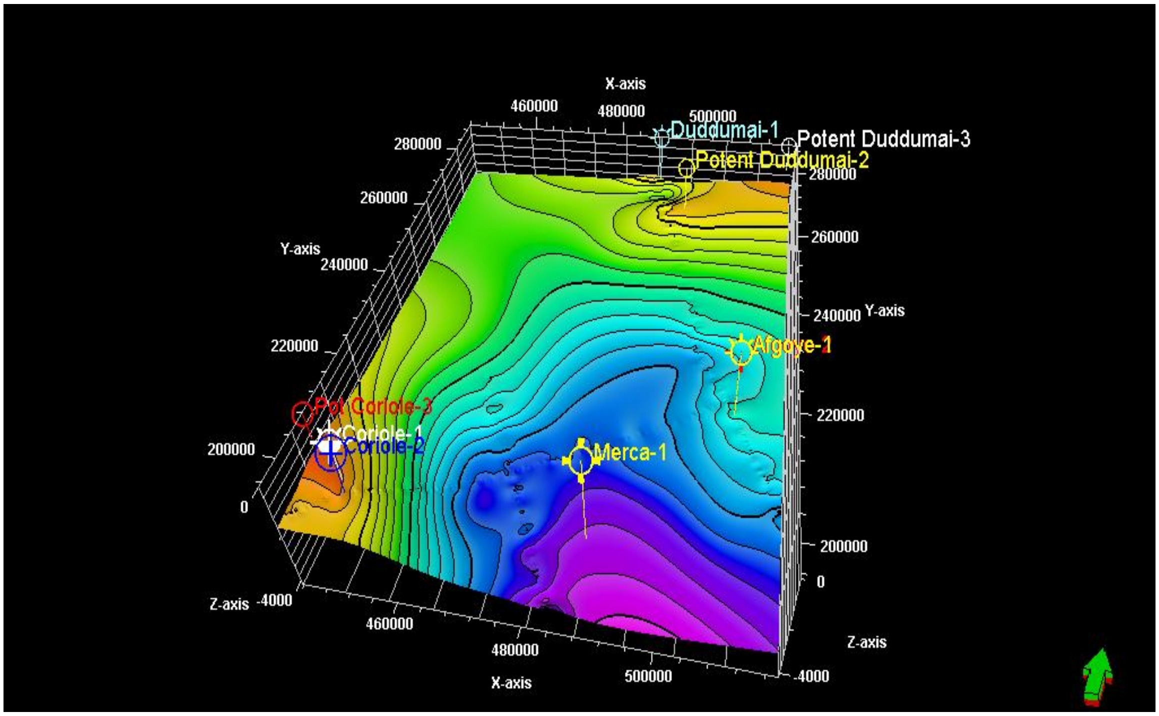


Figure 4.12: 3D Upper Crateceous (Jesomma foundation) depth (m) map with well locations

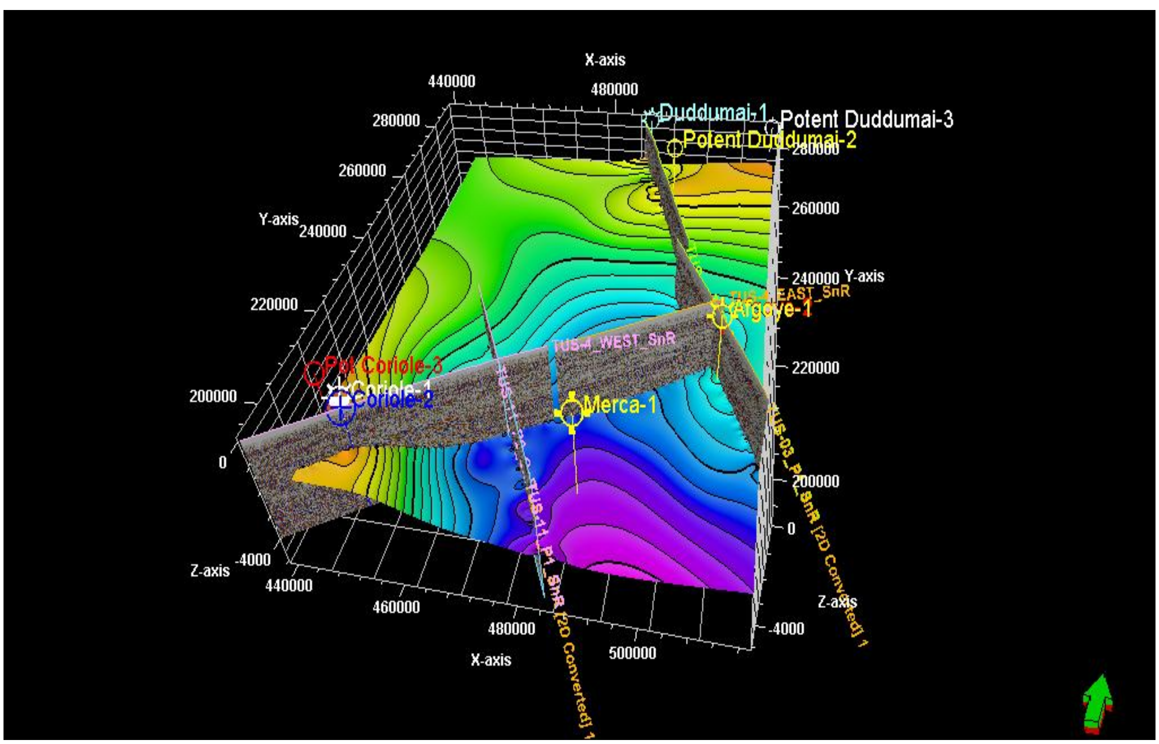


Figure 4.13: 3D Upper Cretaceous (Jessoma formation) depth (M) with well locations and 2D seismic profiles

4.4.2 Lower Palaeocene -Upper Cretaceous (Auradu-Jesomma Transition) base surface map

This surface map shows similar structure of the surface with two (2) structural highs at the SW and NE corners and a depocenter located at the southern edge of the survey area (Figures 4.14 and 4.15) beneath drill site of Merca-1 well.

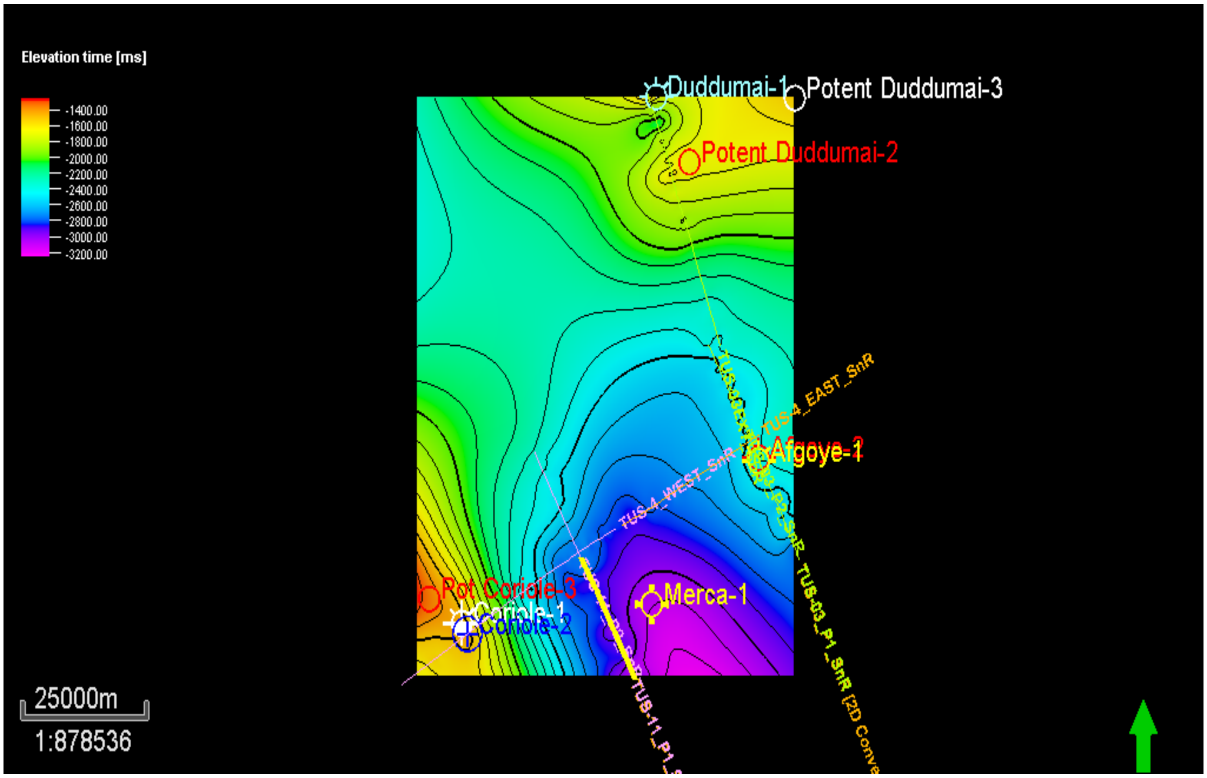


Figure 4.14: 2D Lower Paleocene-Upper Cretaceous elevation time (m) map with exploration wells locations

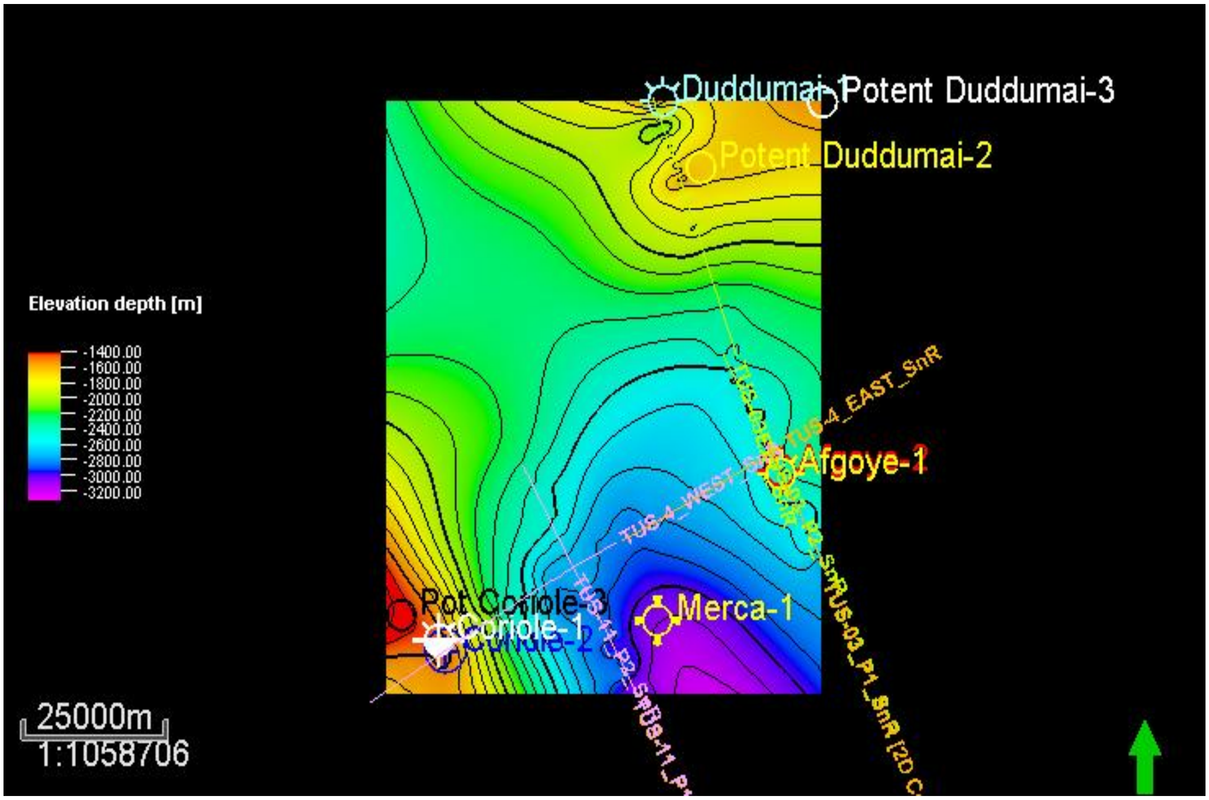


Figure 4.15: 2D Lower Paleocene-Upper Cretaceous elevation depth (m) map with exploration wells locations

4.4.3 Upper Lower Paleocene (Bottom Auradu Equivalent – Sagaleh Formation):

The depth contour map for the base of the Upper Lower Paleocene is given in Figure 4.16. This map reveals that the Auradu Equivalent-Sagaleh Formation is suitable for hydrocarbon entrapment in the SE part of the survey area. The formation thickness increases towards the southeast corner of the map where it creates a depocenter (Figures 4.16 – 4.18). The subsurface maps demonstrate a smaller extent of this formation compared to the previous surface. It was not mapped in the NE corner of the survey area, which suggests the presence of an (?) unconformity or truncation of the entire formation at this location of the Duddumai 1 and Duddumai-2 well sections. The Coriole structural high at the SW of the survey area is well defined (Figures 4.16-4.17). The depocenter continued to develop in the south-eastern area.

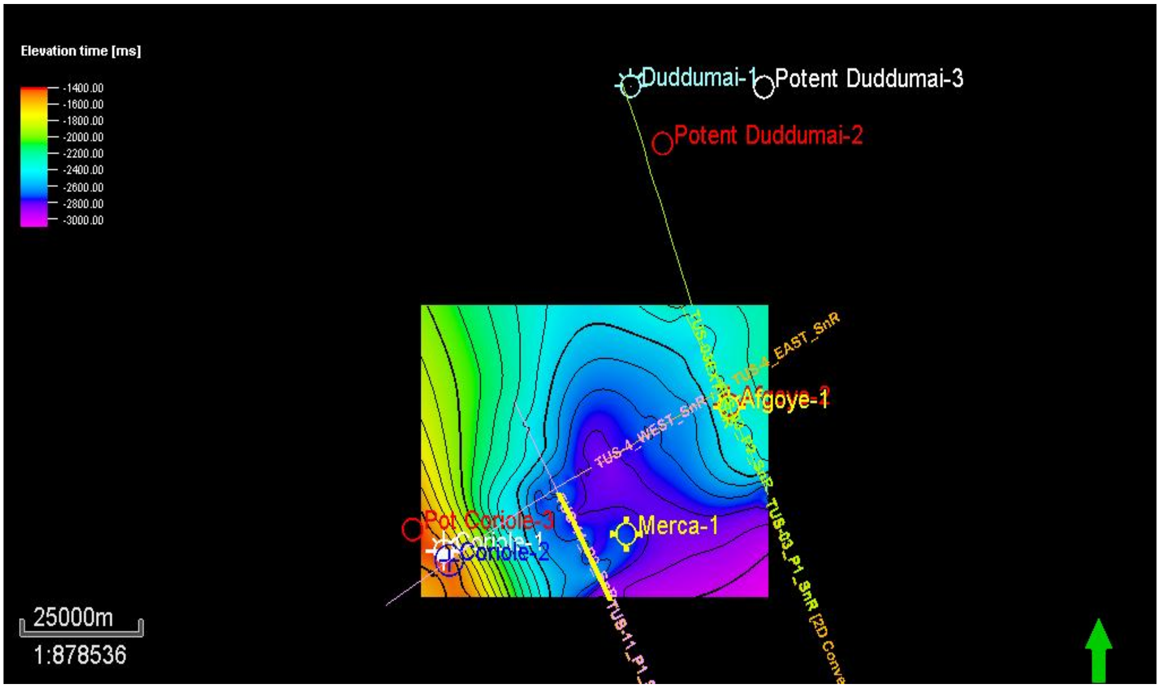


Figure 4.16: 2D Upper Lower ? Paleocene Flower Auradu Equivalent (Sagaleh formation) elevation time (ms) map with well locations map

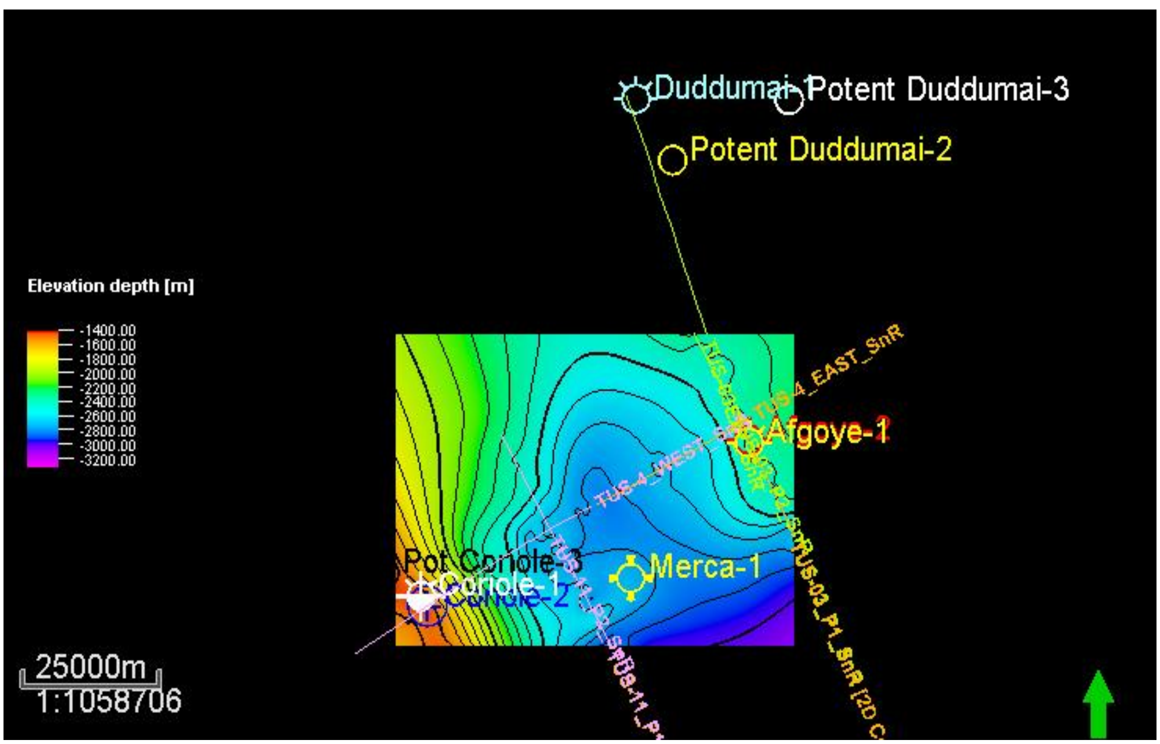


Figure 4.17: 2D Upper Lower? Paleocene (Lower Auradu) Equivalent (Sagaleh Formation) Elevation Depth (m) Map with wells seismic line locations

4.4.4 Upper Paleocene (Top Auradu Equivalent – Sagaleh/Marai Ascia Formations) Base Map

The Upper Paleocene map replicates the surface attitude seen for the Upper Cretaceous and Lower – Paleocene – Upper Cretaceous subsurface maps (Figures 4.14 – 4.15). Both uplifted structures are prominent once again at the SW and NE parts of the survey area. The only difference now is that the depocenter has been subdivided into two sub-basins by a saddle visible at some distance from well Merca-1 (Figure 4.17). Furthermore, the depocenter's axis position (trend) appears to have shifted from a NW-SE direction for the Upper Cretaceous – Lower Paleocene surfaces (Figures 4.14–4.15) to a NE-SW trend for the Upper Paleocene (Figure 4.18).

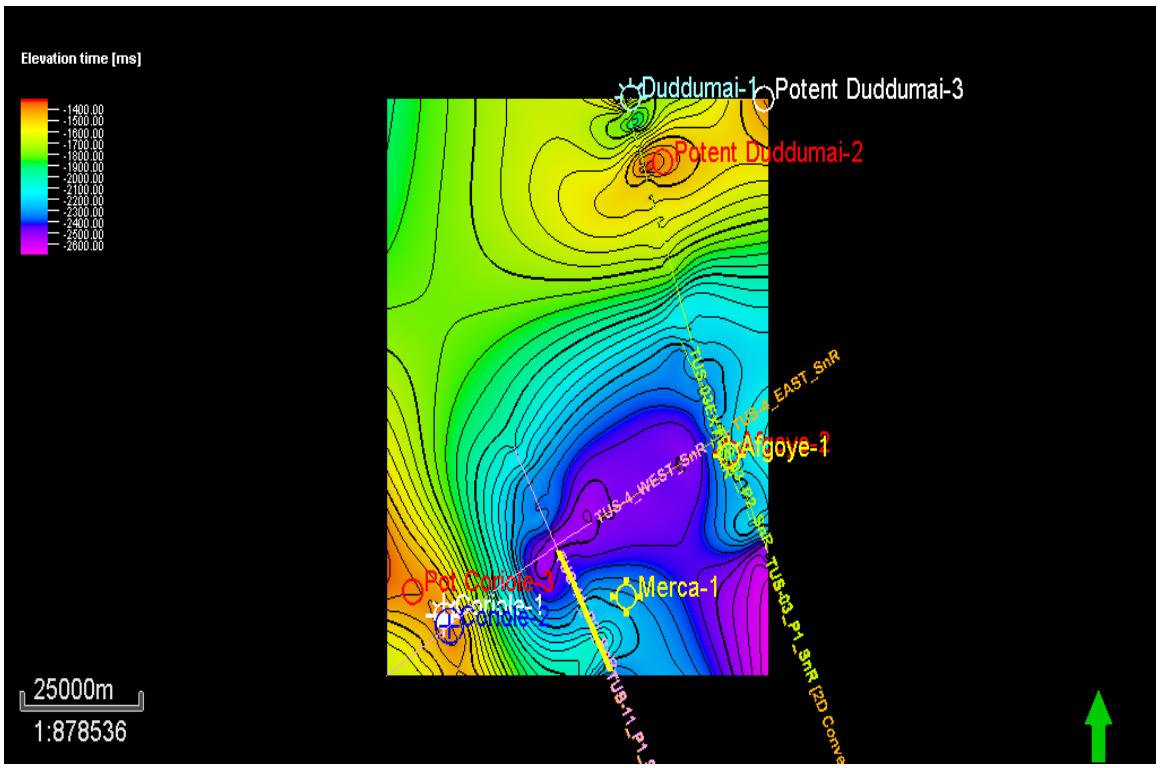


Figure 4.18: 2D Upper Palaeocene (Auradu Equivalent – Marai Ascia Formation) Elevation Time (ms) map with well and seismic profile locations.

4.4.5 Lower Eocene (Auradu Formation) Base Surface Map

Compared to the previous subsurface maps (Figure 4.14-4.17), the depocenter has expanded further north to the central part of the survey data. This suggests deepening and subsidence of most of the area during the Early Eocene. The depocenter retains the general NE-SW trend. The Auradu

Formation consists of a mixture of carbonate and clastic sediments. Subsidence clastic processes affected the eastern and north-eastern flank of the Coriole structure at the SW corner of the survey area (Figure 4.19). On the other hand, the northern area remained uplifted.

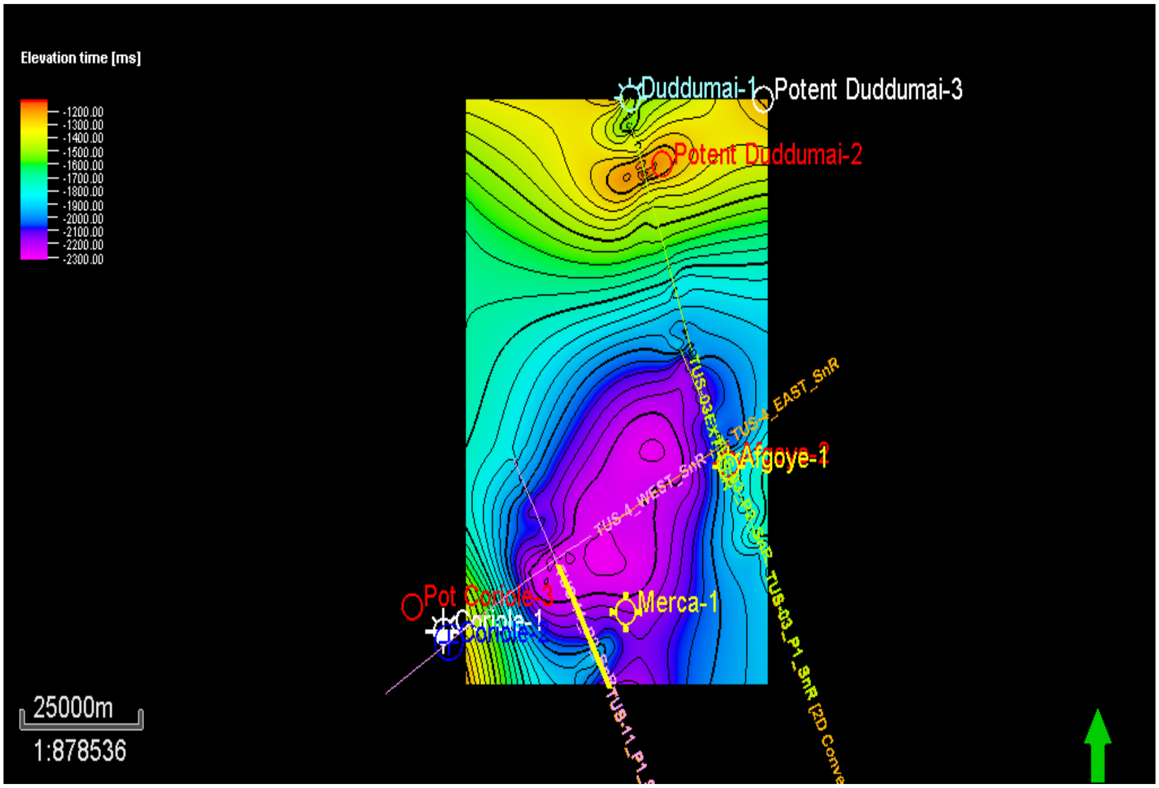


Figure 4.19: 2D Lower Eocene (Auradu Formation) Base Elevation time (ms) Map with well and seismic profile locations

4.4.6 Middle Eocene (Seriole-Auradu Transition/Seriole Formation) Base Surface Map

The attitude of the Middle Eocene subsurface map (Figure 4.20) is almost identical to that of the Lower Eocene (Figure 4.19). However, the axis of the depocenter seems to have changed its trend to a NW-SE direction? (Figure 4.20). The uplifted areas remain at the SW and NE. These were the areas that supplied clastic material to more depressed areas of the basin (central and southern parts of the study area. These resulted in the accumulation of clastics – mainly siltstones.

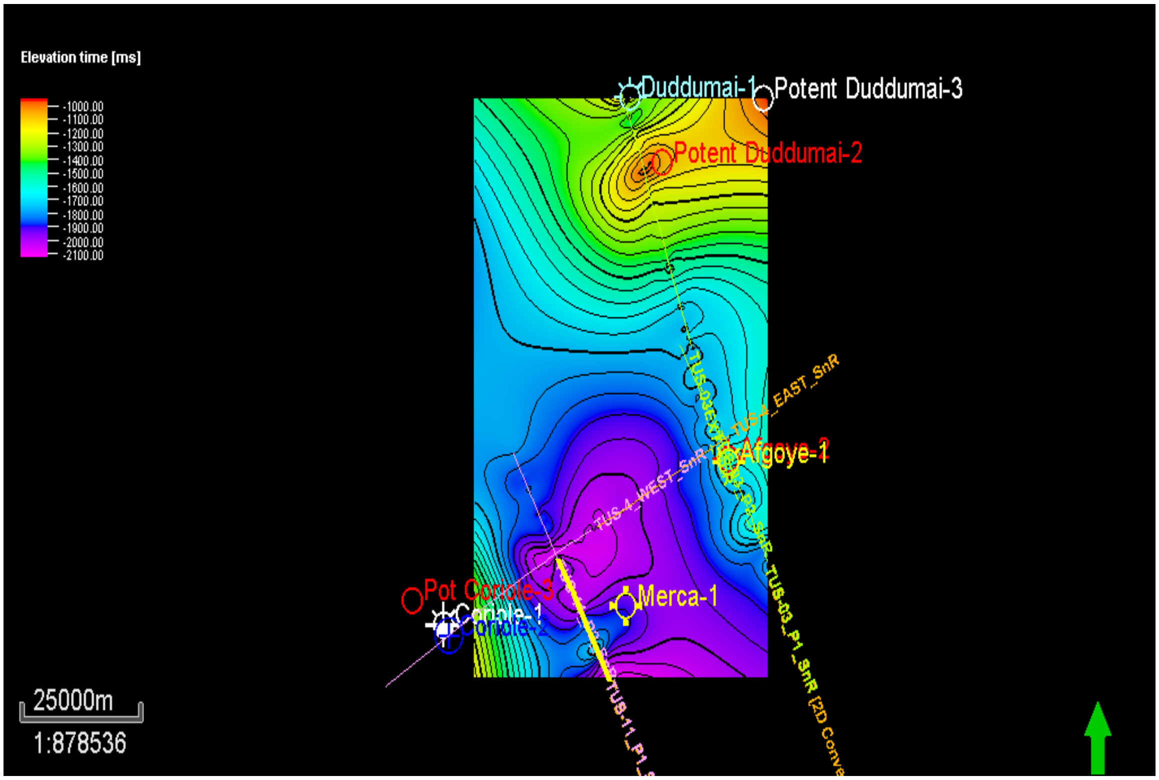


Figure 4.20: 2D Middle Eocene (Seriole-Auradu Transition/Seriole Formation) Base Elevation Time (ms) Map with well and seismic profile locations

4.4.7 Upper Eocene (Priabonian) – Top Seriole Formation Base Surface Map

The Top Seriole formation base surface map in Figure 4.21 demonstrates the change of the depositional environment, and probably, tectonic regime during the Late Eocene. The trends of both the uplifted areas and depocenters have a strict latitudunal (E-W) direction. The uplifted areas continue to provide clastic material to the depocenters located to the south (Figure 4.21).

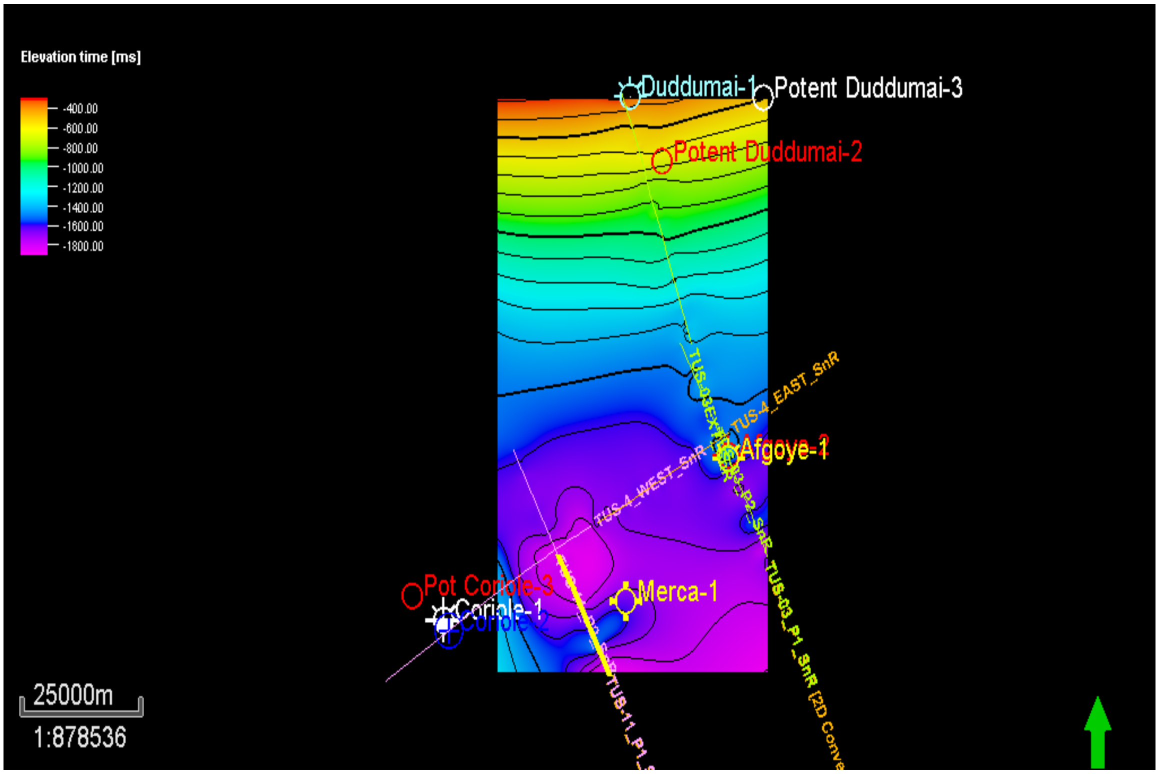


Figure 4.21: 2D Upper Eocene/ Priabonian (Top Seriole Formation) Elevation Time (ms) surface map with well and seismic profiles locations

4.4.8 Oligocene (Obbia – Somal and Member Formations) Base

The 2D Oligocene (Obbia-Somal sand Member formation elevation) depth contour map is given in Figure 4.22. This map structure displays two high regions, one at the northeast and the other at the southwest. There might be some hydrocarbon trapping mechanisms related to these elevated areas developed at the north and southwest beginning (Obbia-Somal sand member). The depocenter retreats towards the southeast and the North West is a continuous uplift, and likely supplied material to the deeper basins located in the South-east (?). In the Afgoi-2 area, the Oligocene consists of clastic sediments with average organic matter content.

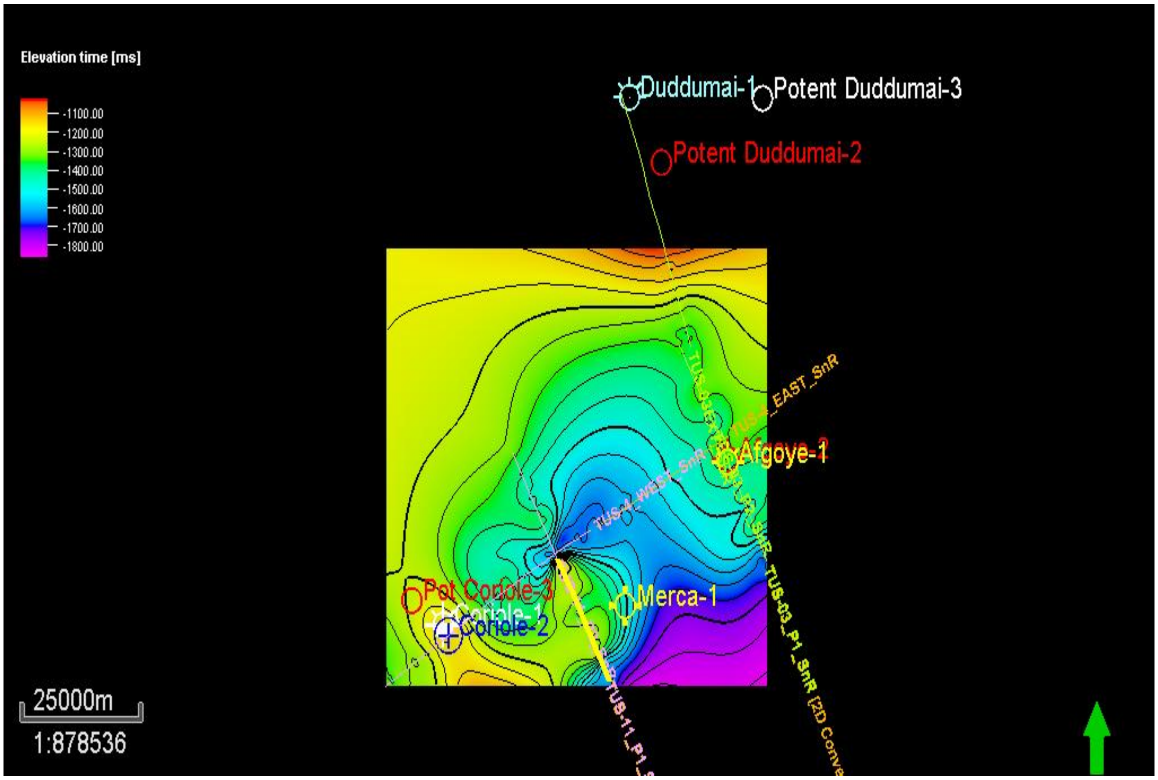


Figure 4.22: 2D Oligocene (Obbia and Somal Sand Member Formation) Elevation time (ms) Map with well and seismic profile locations

4.4.9 Lower Miocene (Somal Formation) Base Surface Map

As illustrated in Figure 4.23, the Lower Miocene (Somal formation) base elevation surface map demonstrates that most of the central western and northern areas of the survey area were uplifted, while the depocenter completely retreated to the SE corner (Figure 4.23). This probably reflects the rapid regressional events that occurred in the Somalia coastal basins during the Early Miocene, and in particular in the Afgoi-2 area. The Somal formation consists of carbonate and clastic sediments.

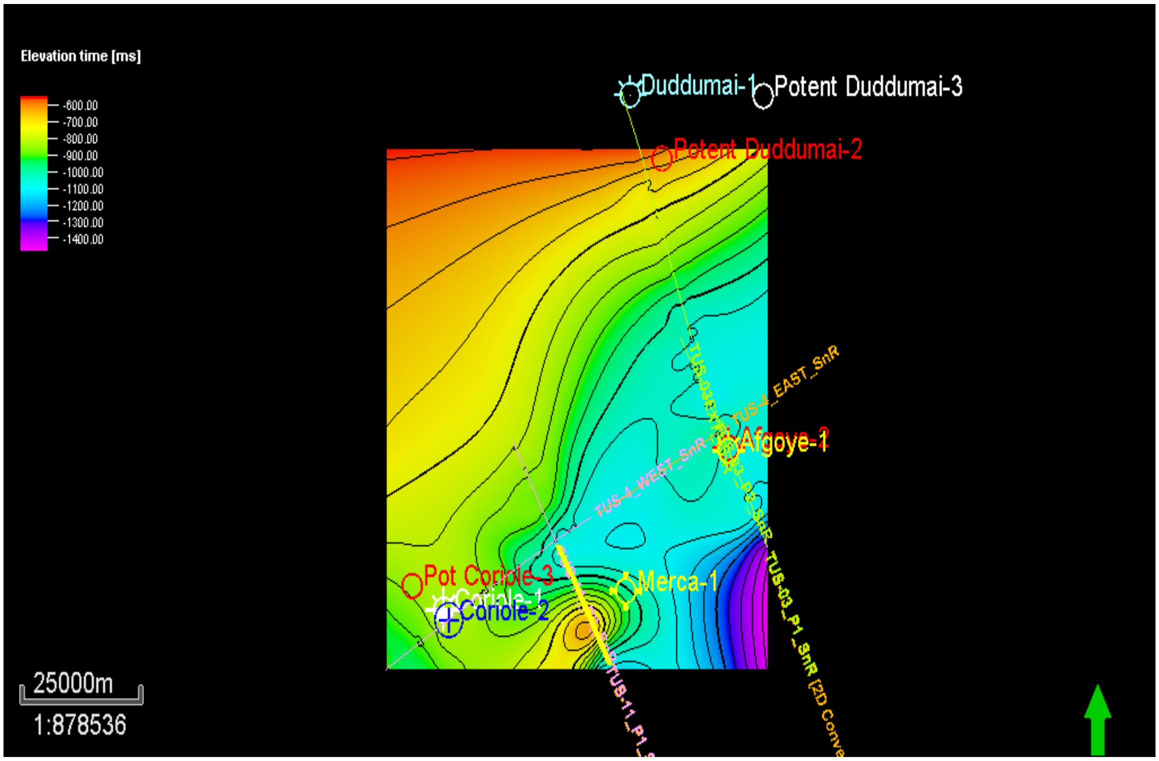


Figure 4.23: 2D Lower Miocene (mid Somal Formation) Base Elevation time (ms) Map with Well and 2D Seismic Profiles Locations

4.4.10 Middle Miocene (Scusciuban-Somal Transition)

The Middle Miocene (Scusciuban-Somal transition) elevation base map demonstrates a transgression and deepening of the central and eastern parts of the survey area. This deepening probably corresponds to a short-term transgressional phase the area experienced in the Middle-Miocene. The depocenter has a roughly NE-SW trend. The Afgoi-2 well site area was the deepest location at that time. The lithologies of the Scusciuban–Somal transition formations are represented by carbonates (limestones) and clastics with average and poor TOC content.

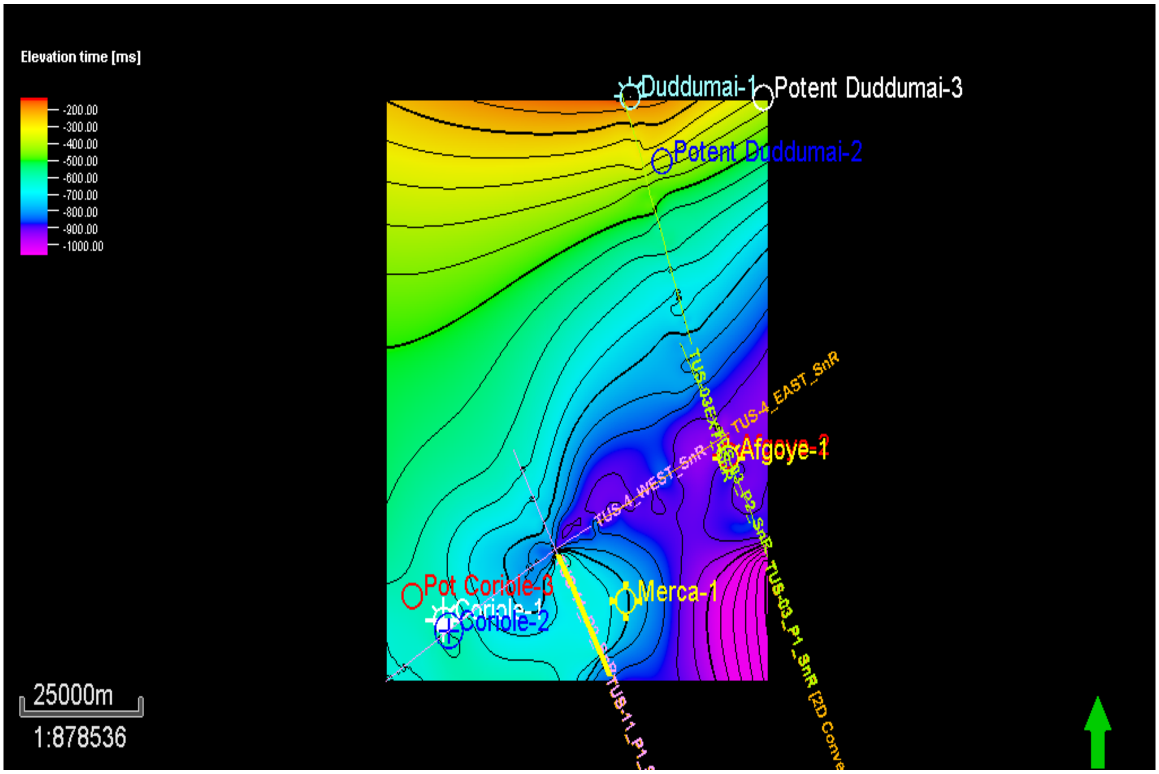


Figure 4.24: 2D Middle Miocene (Scusciuban-Somal Transition and Top Somal Formations) base surface elevation time (ms) map with well and seismic profile locations

4.4.11 Middle Miocene and Younger (Scusciuban Formation)

The Scusciuban Formation base surface map (Figure 4.25) shows a similar attitude to that observed in the Middle Miocene. However, the depocenter retreats again to the east-southeast, suggesting another regressional phase during the late Middle Miocene. More shallower conditions possibly prevailed at the Afgoi-2 well site area. An increased sand content is seen in the Scusciuban formation. The northern and central parts of the survey area remained elevated.

As such, we conclude that almost all mapped formations indicate the presence of two prominent uplifted areas: one located in the south-western part of the survey area, and the other in the north-eastern corner. The major depositional center (depocenter) was constantly progressing in the southern area (Late Cretaceous to Upper Eocene Priabonian times).

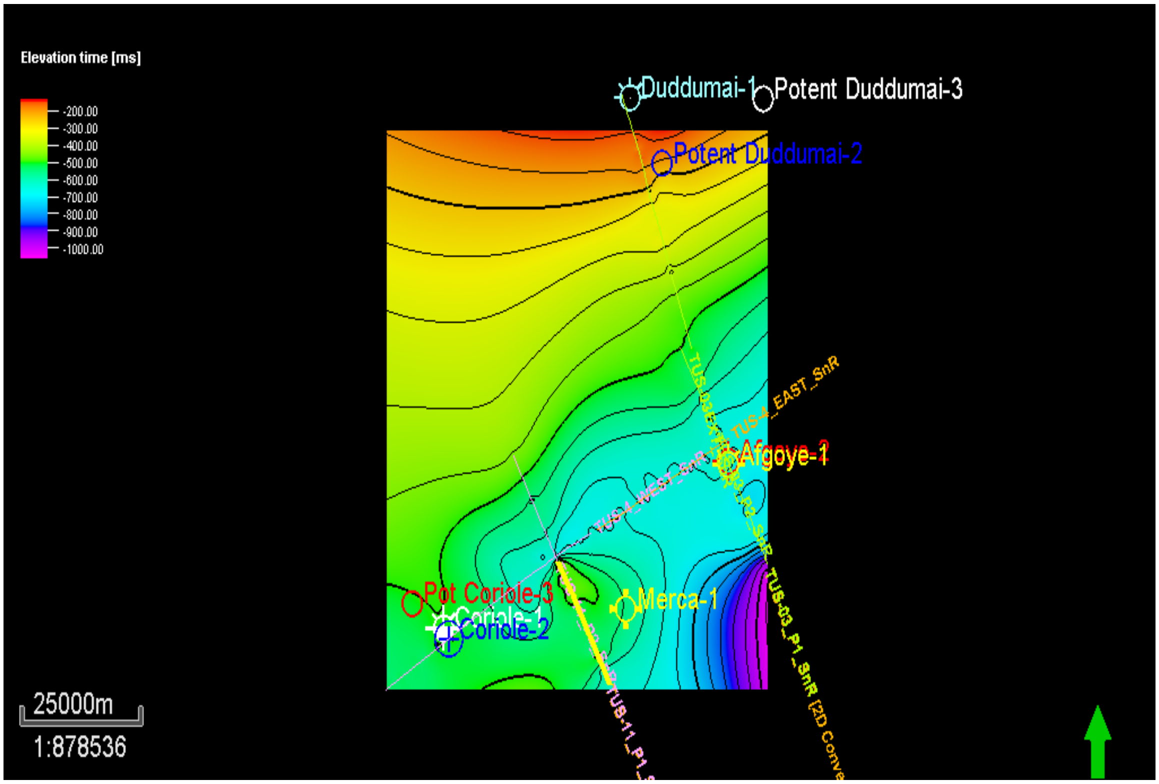


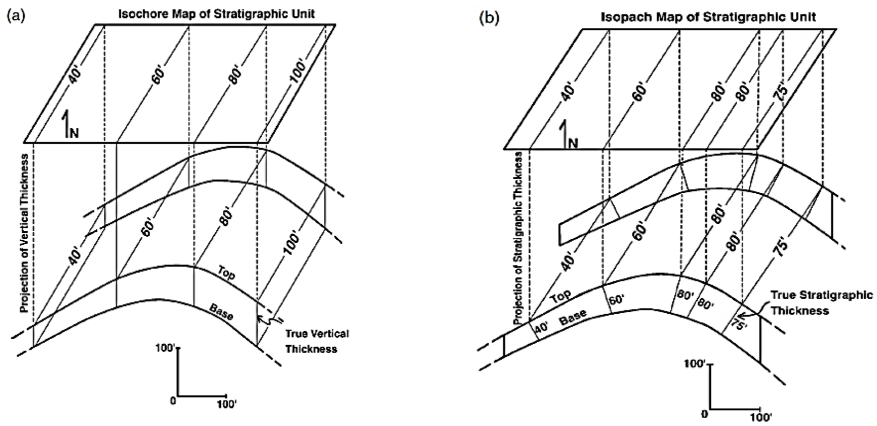
Figure 4.25: 2D Middle Miocene and Younger **(**Scusciuban Formation**)** base surface Elevation Time (ms) map with well and seismic profile locations

4.5 Thicknesses (Isochore And Isopach) Maps

4.5.1 Thickness Maps

The two most common subsurface geological features used in oil and gas exploration practice are: ***isopach*** and ***isochore maps***. For a long time, there had been common confusion among the geological community on what each one of them stands for. The difference between these two thicknesses is provided below (Teapork & Bischke, 2002).

> "An ***isochore map*** *delineates the* ***true vertical thickness*** *of a stratigraphic interval, whereas an* ***isopach map*** *illustrates the* ***true stratigraphic thickness*** *of a stratigraphic interval"*. (Figure 4.26)



c)

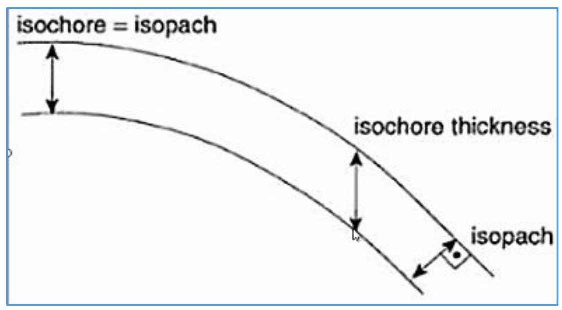


Figure 4.26: The principal difference between an (a) Isochore, (b) Isopach maps and their comparisons.

According to the web dictionary (https://en.wiktionary.org/wiki), the word "Isopach" comes from the Ancient Greek word (páchos; plural or) for thickness, corpulence, or fatness. In geology, a line on a map joining parts of a stratigraphic unit that have the same stratigraphic thickness is termed as an ***isopachous line***.

The word isochore derives from the words iso-+ Ancient Greek χώρα (*khṓra*, "place"; *plural* isochores. In geology, a contour line showing points of equal vertical thickness of strata is called an ***isochore line***.

Isochores will be equal to an ***isopach***s if the strata are horizontal (Figure 4.26).

Isopach maps are the most important because they provide the correct (stratigraphic) thicknesses, and hence, the depth of the formations of interest. Until the late 1940s, the full application of these maps was not well realized or employed in daily subsurface interpretations. However, even at that time, they were used for predetermining drilling depths to a specific horizon of interest, for locating buried structures in areas where formations would become thinner over the crestal parts of such structures, and for estimating the elevation of a datum bed below the drill bit that had encountered another known stratigraphic horizon or datum layer (Low, 1949).

4.6 2D Seismic Data Petroleum System Analysis

4.6.1 Source Rock Thickness Maps

Three (3) source rock intervals have been selected from the obtained Afgoi-2 TOC values. These are: a) Jesomma-lower Auradu formation interval (9190-13710') with an average TOC value of 0.86 wt.%; b) Seriole-Auradu transition – lower Somal Sand Member interval (4920-7330') with an average 0.90 wt.% TOC content; and c) Somal-Scusciuba-Somal transition with an average TOC value of 0.34 wt.% TOC content.

Among them, the TTI calculations discussed later have demonstrated that the first two intervals are mature and have/or are still potentially generated (-ing) hydrocarbons mainly light oil products. Their thicknesses increase towards the offshore part of the Somali Coastal basin. The third topmost source rock interval (Somal-scusciuban-Somal transition) is largely immature and has no hydrocarbon generating potential.

The following isochore thickness maps were generated for each of the selected source rock intervals:

a) Jesomma-lower Auradu formation interval (9190-13710') source rock isochore (true vertical) thickness map;
b) Seriole-Auradu transition – lower Somal Sand Member interval (4920-7330') source rock isochore (true vertical) thickness map;
c) Somal-Scusciuban – Somal transition interval (2080-4560) source rock isochore (true vertical) thickness map.

a) Jesomma-lower Auradu Formation Interval (9190-13710') Source Rock

The thickness of the Late Cretaceous-Early Paleogene source rock interval increases from the south to the north. In the north-east and west of the survey area, the source rock interval creates two depositional centres or kitchen zones where the temperature and pressures probably induced its increased maturation levels (Figures 4.27 and 4.28).

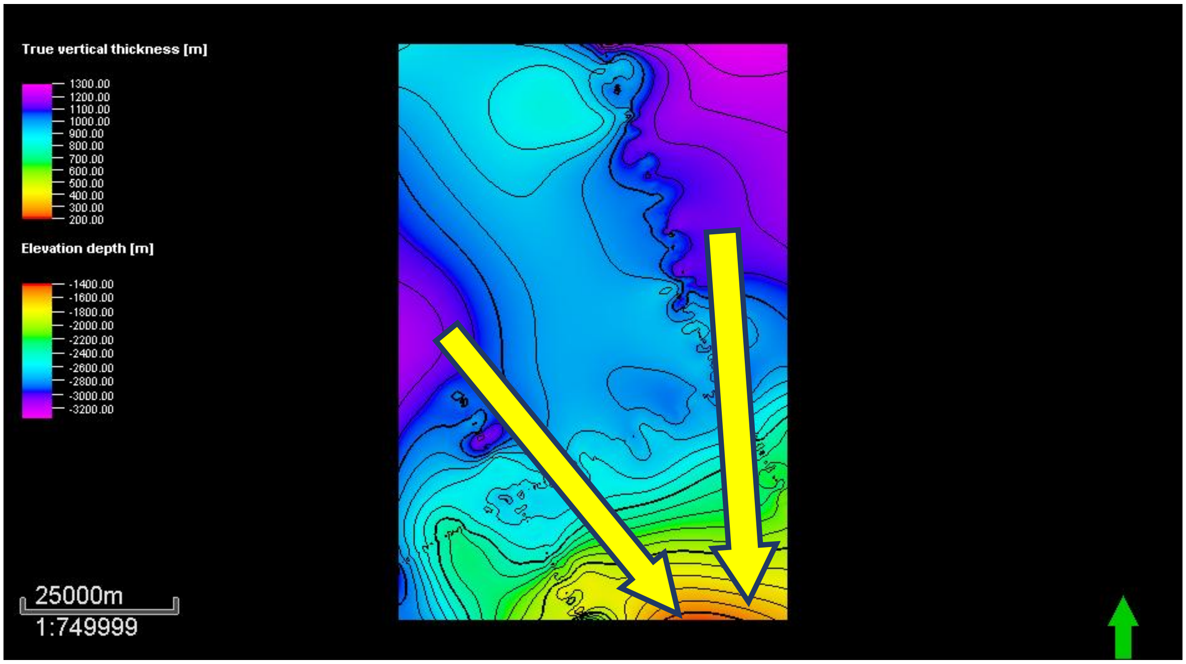


Figure 4.27: 2D Jesomma-Lower Auradu Formation Interval (9190-13710') Source Rock Isochore (True Vertical) Thickness Map with Arrows are Indicating Possible Primary Migration Pathways.

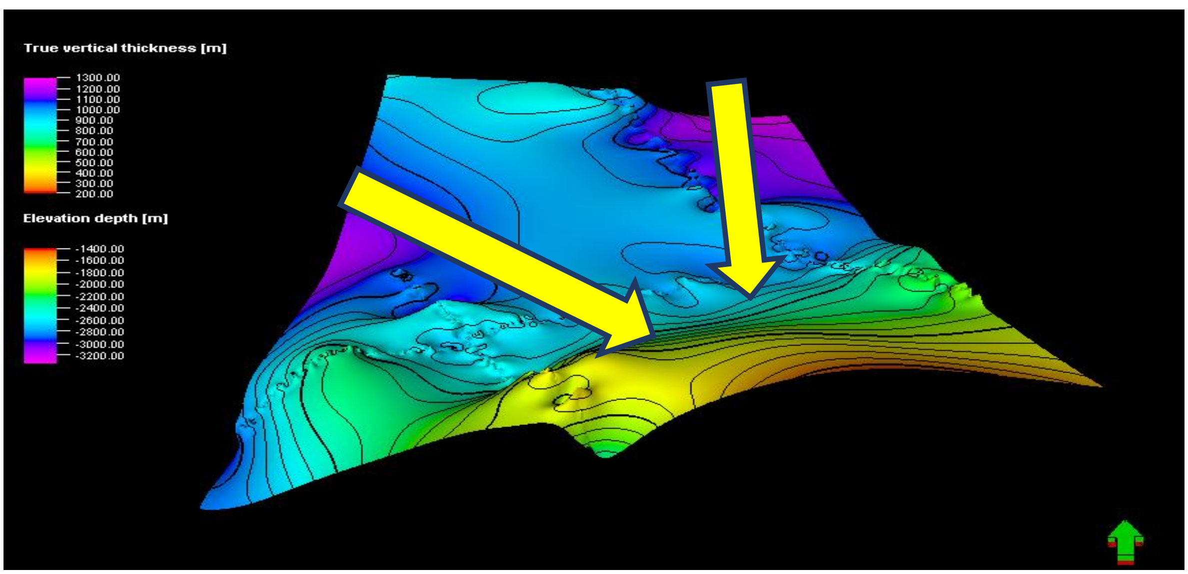


Figure 4.28: 3D Jesomma-Lower Auradu Formation Interval (9190-13710') Source Rock Isochore (True Vertical) thickness map with arrows are indicating possible Primary Migration Pathways.

The expelled hydrocarbons probably primarily migrated towards the south. TTI modelling suggests that the expulsion of protopetroleum from the Jesomma-lower Auradu formation interval (9190-13710’) source rock interval began around 25Ma age (time?)

b) Seriole-Auradu Transition – Lower Somal Sand Member Interval (4920-7330’) Source Rock

This source rock interval has a similar average value of TOC of around 0.9 wt. %. It corresponds to the Middle Eocene-Oligocene time. This source rock interval has depositional centres (kitchen zones) located in the north, east, and south-west of the survey area (Figures 4.29 and 4.30).

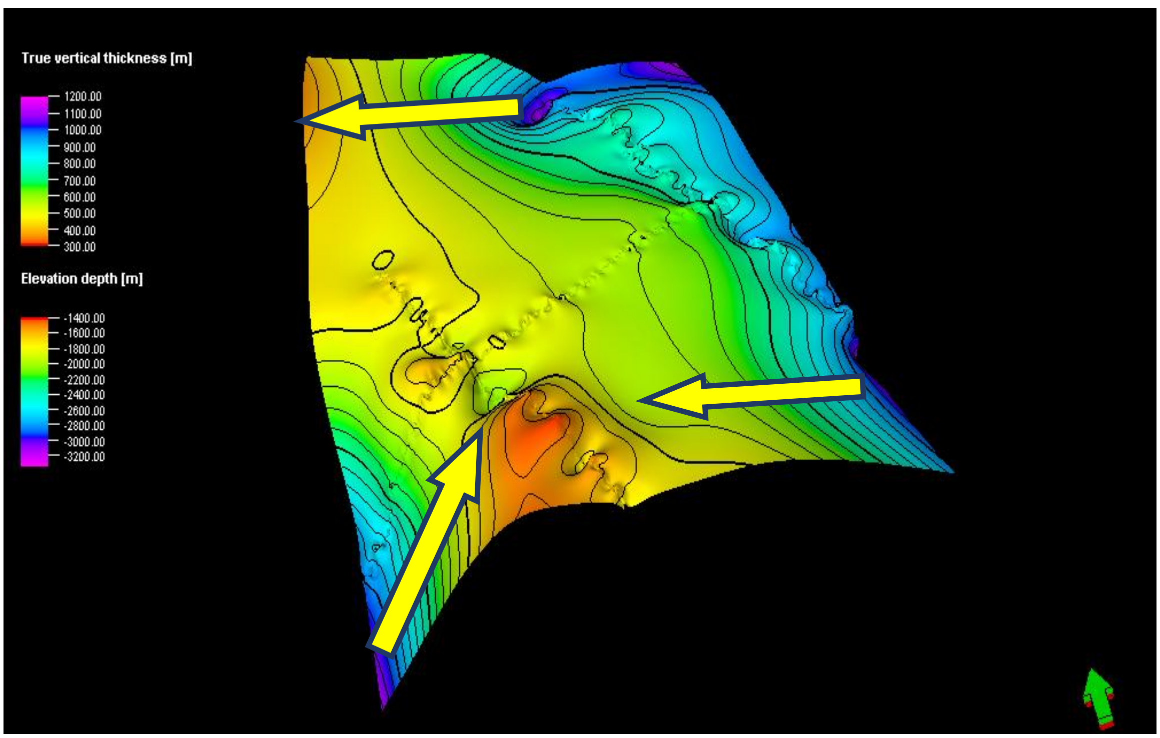


Figure 4.29: 3D View of the Seriole-Auradu Transition – Lower Somal Sand Member Interval (4920-7330’) Source Rock Isochore (True Vertical) Thickness Map.

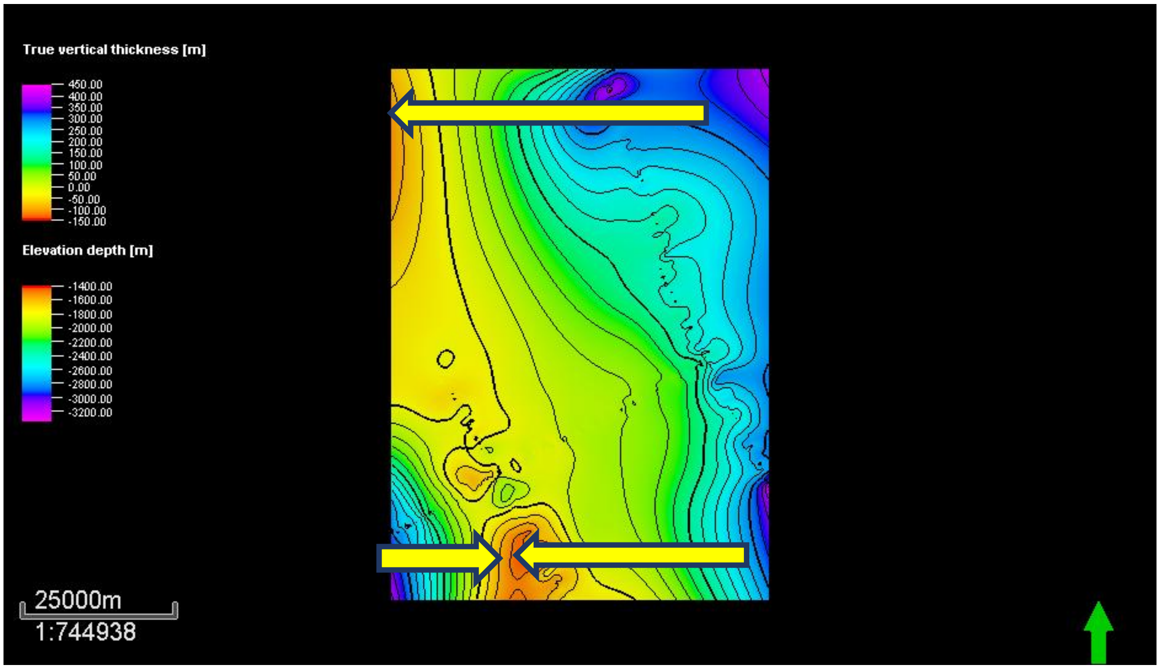


Figure 4.30: 2D view of the Seriole-Auradu Transition – Lower Somal Sand Member Interval (4920-7330') source rock Isochore (true vertical) thickness map. The arrows are indicating possible primary migration pathways.

The migration of the expelled hydrocarbons from this source interval was different compared to the one observed for the Late Cretaceous-Early Palaeocene intervals. The increased thickness of the source rock in the south-west and east of the area suggests east-west (latitudinal) migration to the more deformed and elevated central area. The primary migration that occurred within this map indicates that generated oil migrated through the conduit faults located in the south and west.

TTI modelling for this section from well Afgoi-2 indicates that the source rock has currently (at present) entered the oil window, with a TTI value of 10.

c) Somal – Scusciuban – Somal Transition (2080-4560') Source Rock Interval

The true vertical thickness for this source rock interval illustrates a general decrease in thickness distributions compared to the former two intervals. They do not exceed 500 meters, commonly between 100-350m. The surface creates two (2) highs and one (1) depocenter with NE-SW and E-W trends. This interval is immature and has low average TOC values of 0.34wt%, and this is very unlikely that it will generate any hydrocarbons (immature) TTI values for this internal measure 0.3 and 0.06.

4.6.2 Reservoir Rock Thickness Maps

Three reservoir elements are recognized within the Coastal basin. These are:

a) A combined Jesomma and Auradu-Jesomma transition zone reservoirs of the Upper Cretaceous-Lower Paleogene.
b) Auradu Equivalent reservoir the Sagaleh/Marai Ascia and lower part of Marai Ascia Formations the Upper Lower Palaeocene to Late Palaeocene.
c) Auradu formation (top Marai Ascia-Coriole formations) of the Lower Eocene.
d) Lower Somal formation of the Lower Miocene

Here we provide a detail description of the results of the structural seismic mapping of these selected formation surfaces and structures involved.

a) Combined Jesomma and Aurada-Jesomma transition one formation of the Late Cretaceous-Early Paleogene Reservoirs

Most of the hydrocarbon discoveries made in the Coastal Basin are related to the Jesomma Formation (Afgoi-1 and Coriole-1 wells). In the Afgoi-2 well site area, the Jesomma formation ranges between 13470 and 13747 feet and is followed by a thin Auradu-Jesomma transition zone (13290-13470’). Lithologically, this section represents a mixture of sandstones and carbonates with minor volcanics. The reservoir generates two distinctive zones (probably folded structures) with good vertical closures in the south part of the survey area, and also in the north (near the Duddumai well site), in the proximity of the Bur Acaba high (Figures 4.31-4.32).

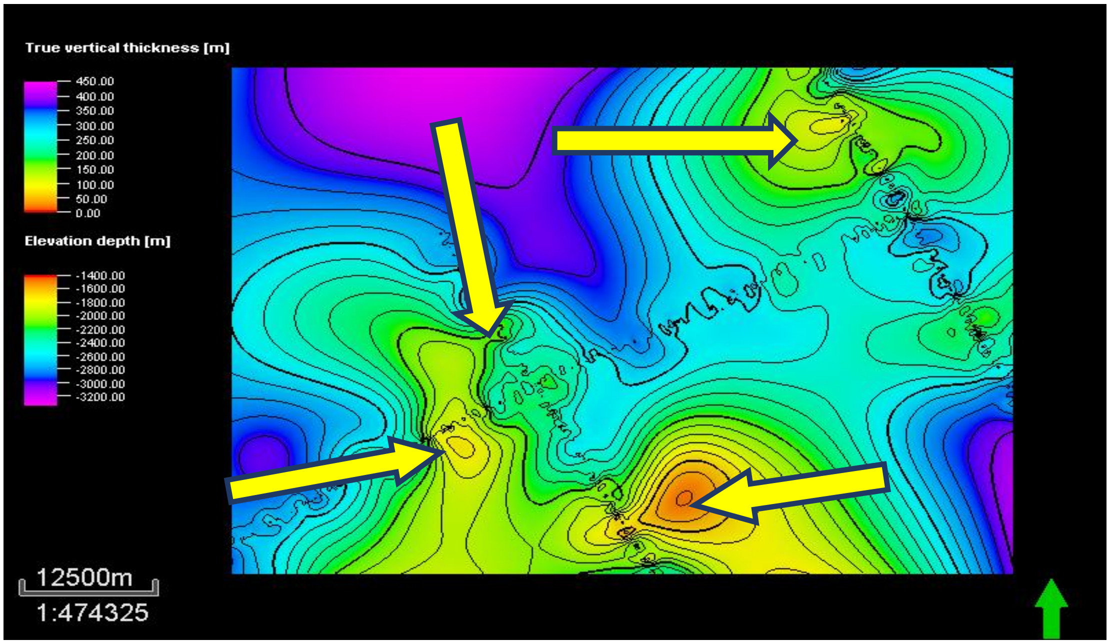


Figure 4.31: 2D Isochore (True Vertical) Thickness Map between Maastrichtian and Upper Lower Palaeocene (Jesomma and Auradu-Jesomma Transition Base Formation) Surfaces (13710-9190') With Arrows indicating Secondary Migration Pathways.

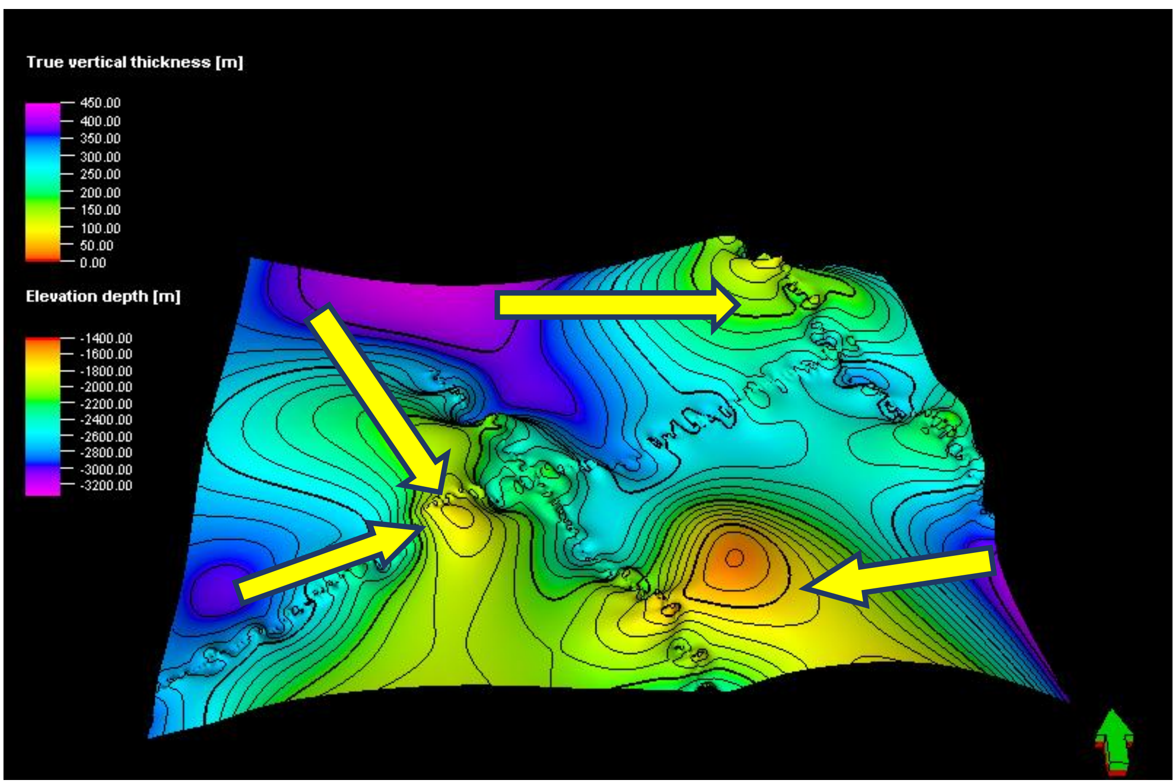


Figure 4.32: 3D Isochore (True Vertical) Thickness Map between Maastrichtian and Upper Lower Palaeocene (Jesomma and Auradu-Jesomma Transition Base Formation) Surfaces (13710-9190')

The produced thickness maps demonstrate that the Upper Cretaceous-Lower Palaeocene strata were intensively deformed with structures having NW-SE and E-W strikes.

These reservoir rock units demonstrate increased thickness in the NW, W and SE sectors of the survey area. Figures 4.31 and 4.32 depict the possible pathways of the secondary hydrocarbon migration. The hydrocarbon migration direction illustrated by yellow arrows occurred from the deeper reservoir horizons to the shallower (elevated).

b) Late Early Palaeocene to Late Palaeocene (Auradu Equivalent)

In the Coriole Basin, discoveries related to the Auradu Equivalent, in particular the Marai Ascia group are known from well Merca-1 (7858-7870'), which tested salt water and gas (Barnes, 1976). Compared to the previous thicknesses' maps, the Auradu equivalent surface shows less severe deformation with the exception of the south-eastern part of the survey area where it has the highest elevation. The thickness distribution throughout most of the area is constant, in the range of 1000-1700 meters (Figures 4.33 and 4.34).

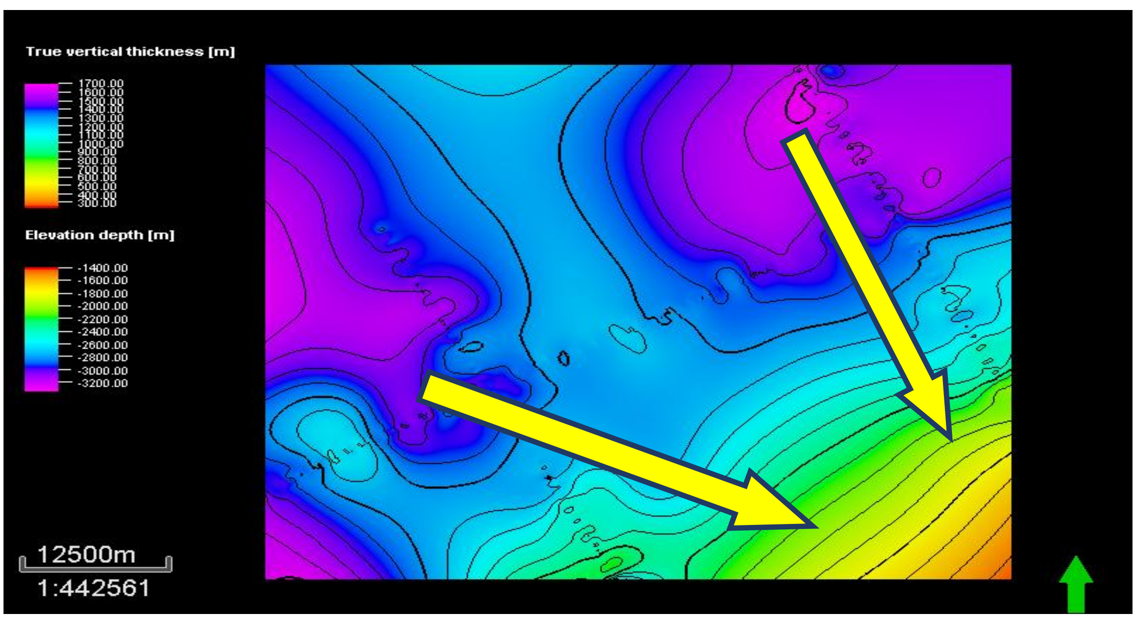


Figure 4.33: 2D Isochore (True Vertical Thickness) Map between Upper Lower Palaeocene and Lower Eocene (Auradu Equivalent Top and Base) Surfaces with arrows indicating Secondary Migration Pathways.

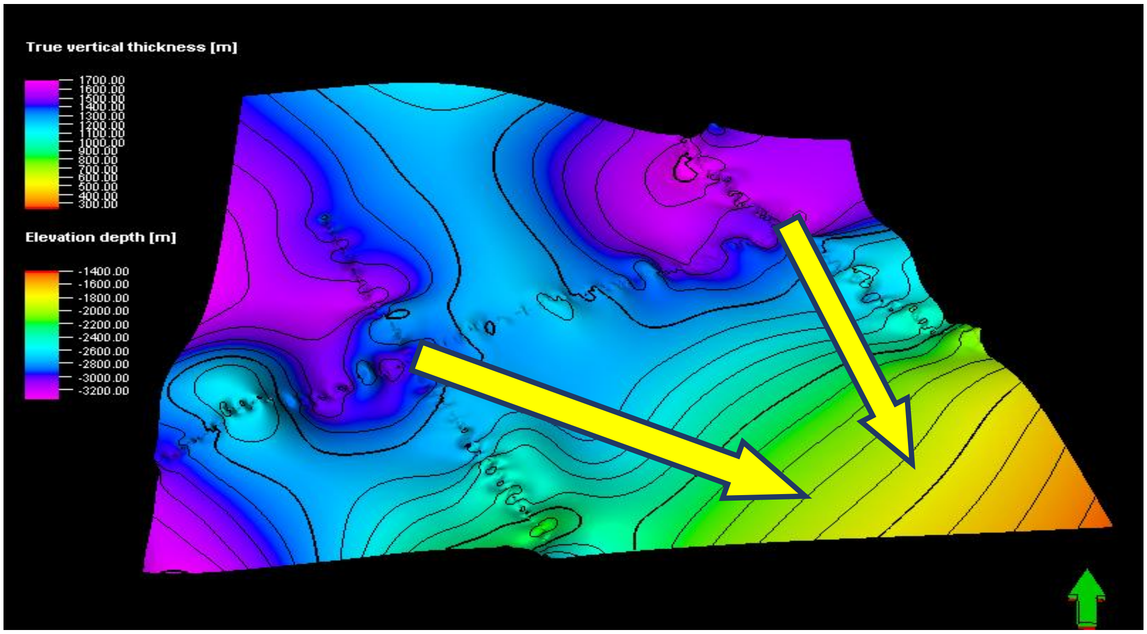


Figure 4.34: 3D Isochore (true vertical thickness) map between Upper Lower Palaeocene and Lower Eocene (Auradu equivalent top and base) surfaces with arrows indicating Secondary Migration Pathways.

The increased thicknesses of this source rock interval appear on the map to the north, west, and south-west, indicating secondary migration pathways from these three-kitchen zones to the elevated areas in the south-east.

c) Auradu Formation (top Marai Ascia-Coriole formations) of the Lower Eocene

The Auradu Formation, which is a correlative analogue of the Coriole Formation, was reported to have produced gas and oil from the neighbouring Coriole-1 well. The oil was paraffinic and had an API gravity of 44 degrees (Barnes, 1976).

As seen from the thickness maps presented in Figures 4.35 and 4.36, the reservoir formation has a completely different structural nature. The entire central part of the formation surface has undergone severe deformation with folded structures of the NE-SW orientation, and associated with large closures. The most prominent closure is located to the north-west of the Afgoi-2 well location (Figures 4.35). We propose that it should be tested with an infill drilling well.

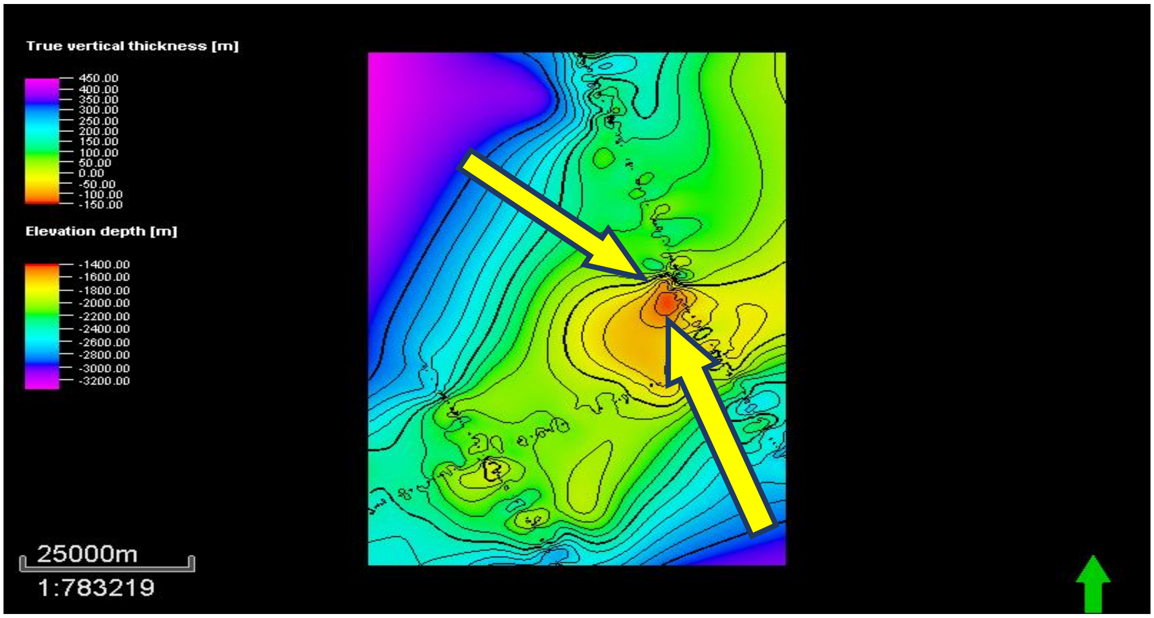


Figure 4.35: 2D Isochore (true vertical) thickness map between Lower Eocene and Middle Eocene (Auradu formation top and bottom) surfaces with arrows indicating possible Secondary Migration Pathways.

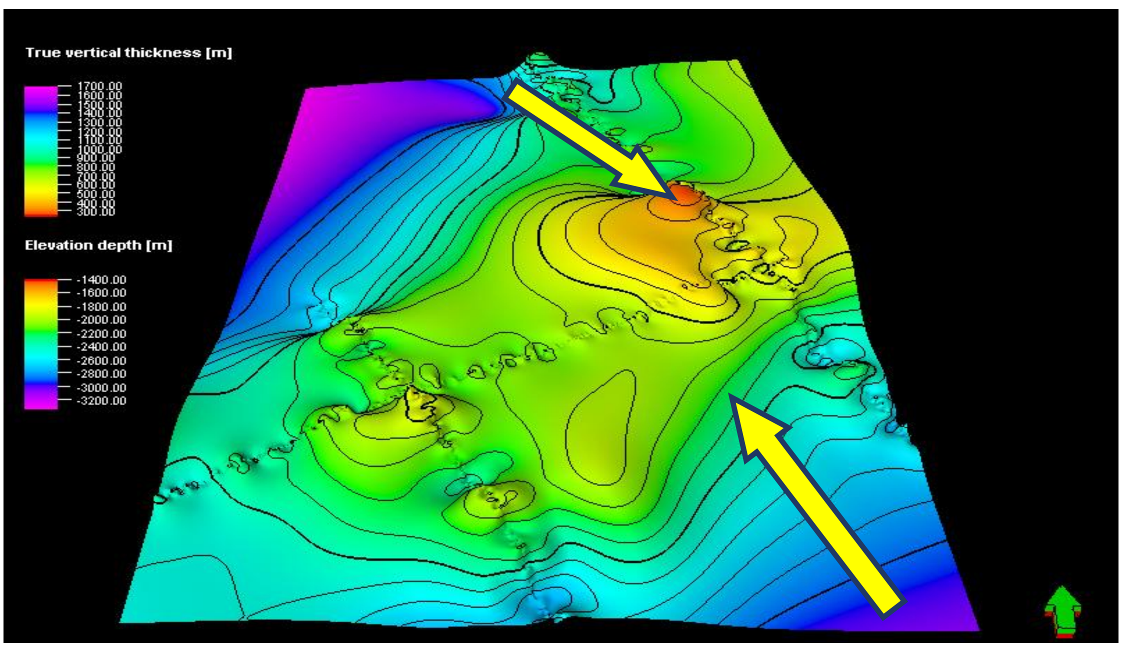


Figure 4.36: 3D Isochore (True Vertical) thickness map between Lower Eocene and Middle Eocene (Auradu Formation Top and Bottom) surfaces with arrows indicating probable Secondary Migration Pathways.

The source rock thicknesses thicken at the north-west and south-east parts of the area which are the kitchen zones, while the elevated areas are considered as the receiving zones.

4.6.3 Seal Rock Thickness Map

The Seriole-Auradu transition to the top Obbia Formations of the Middle Eocene–Lower Oligocene interval is considered here to represent the possible seal rock interval characterized by increased shale/clay content in relation to the other portions of the section. The steep dipping south-western edge of the seal rock formation suggests the presence of a longitudinal steep (either normal or strike slip).

Increased seal thicknesses are seen to the east and to the north of the Afgoi-2 well location, which increases the potential for finding a hydrocarbon column. Similar conditions probably occur to the south-west of the survey area (Figures 4.37).

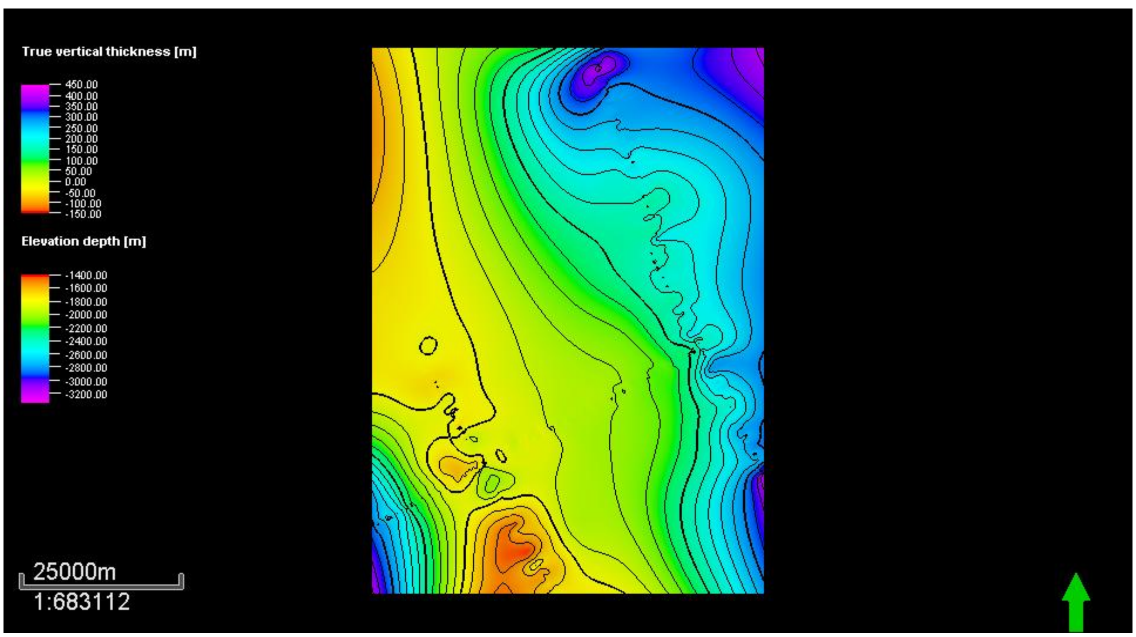


Figure 4.37: 2D Isochore (True Vertical) thickness map between Middle Eocene-Oligocene Base Surfaces (Seriole to Base Somal Formation).

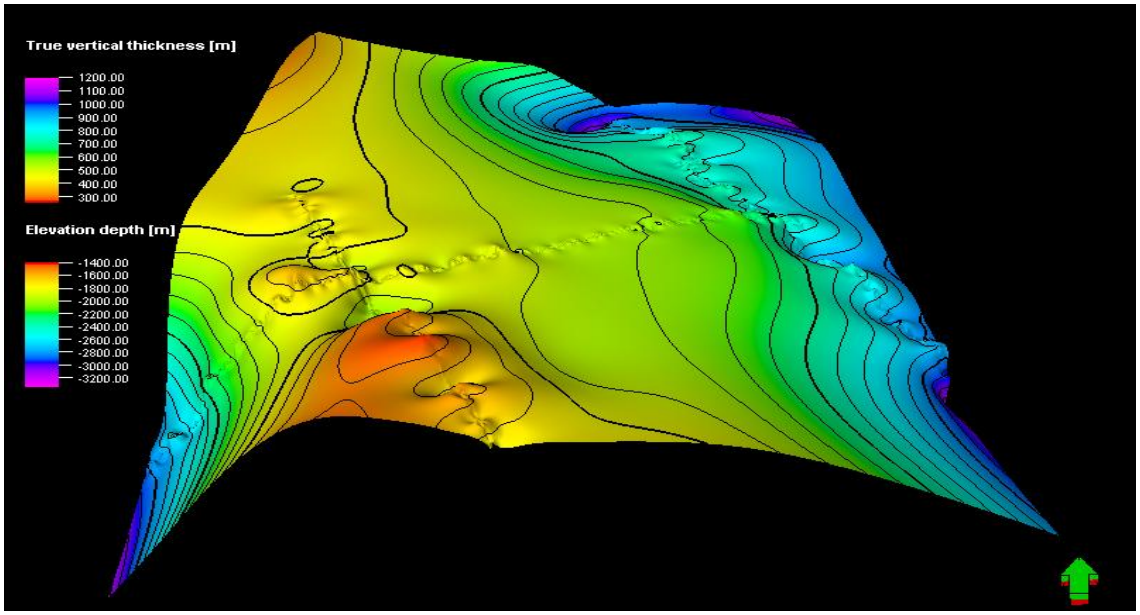


Figure 4.38: 3D Isochore (True Vertical) Thickness Map Between Middle Eocene-Oligocene Base Surfaces (Seriole to Base Somal Formation)

4.7 Potential Future Drilling Sites

The main drilling target within the Somalia Coastal Basin was and still remains the Late Cretaceous Jesomma sandstone reservoir formation. The generated surface maps for this formation (Figures 4.39 and 4.40) enabled us to select and propose at least three (3) potentially promising infill drilling sites.

We have offered to name them after the closest historical well names with a prefix “Potent”. These are Potent Duddumai-2 and Duddumai-3 located in the northern reservoir sector of the map, and Potent Coriole-3, located in the south-western corner of the map. All targets are located at depth ranges of 1400-1500 meters (!) below the surface.

These two (2) locations are edges of probable closed structures (beyond the surveyed area) with amplitudes (heights) reaching almost a maximum of 400 meters (!) and a minimum of 200 meters. As our TTI modelling suggests, the Jesomma (Yesomma) formation source rock material has currently entered the peak oil generating window (values). The expulsion of the proto-petroleum began approximately 12.5Ma (Serravalian time).

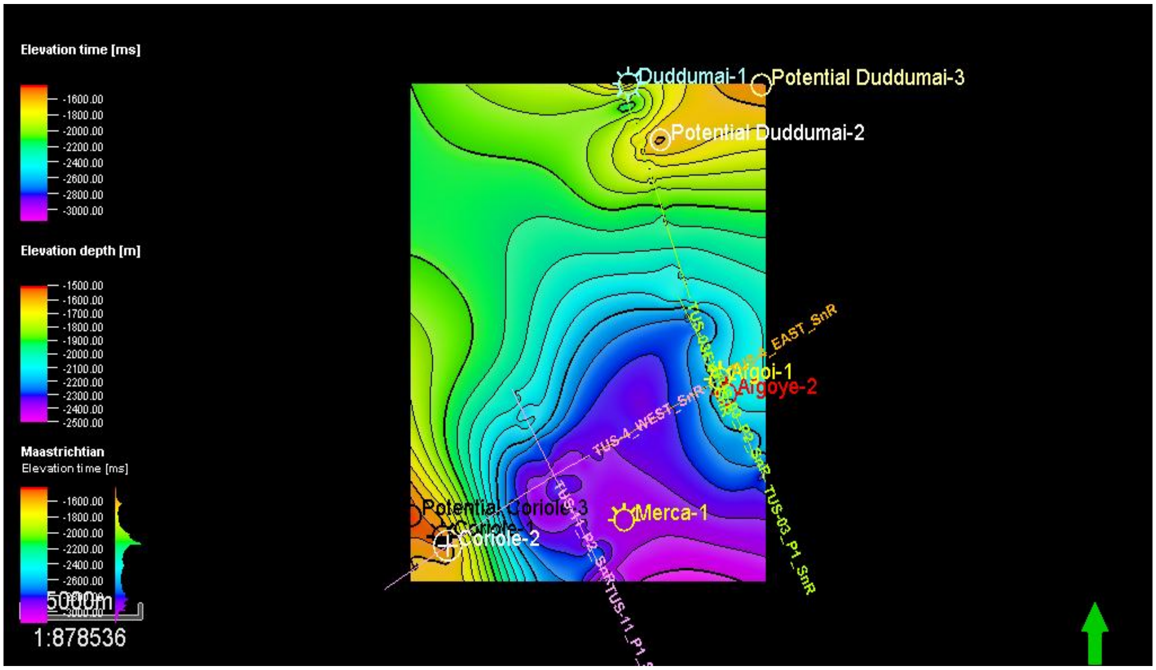


Figure 4.39: Locations of historical drilled wells and those proposed after the 2D Seismic interpretations for the (Jesomma Formation Surface)

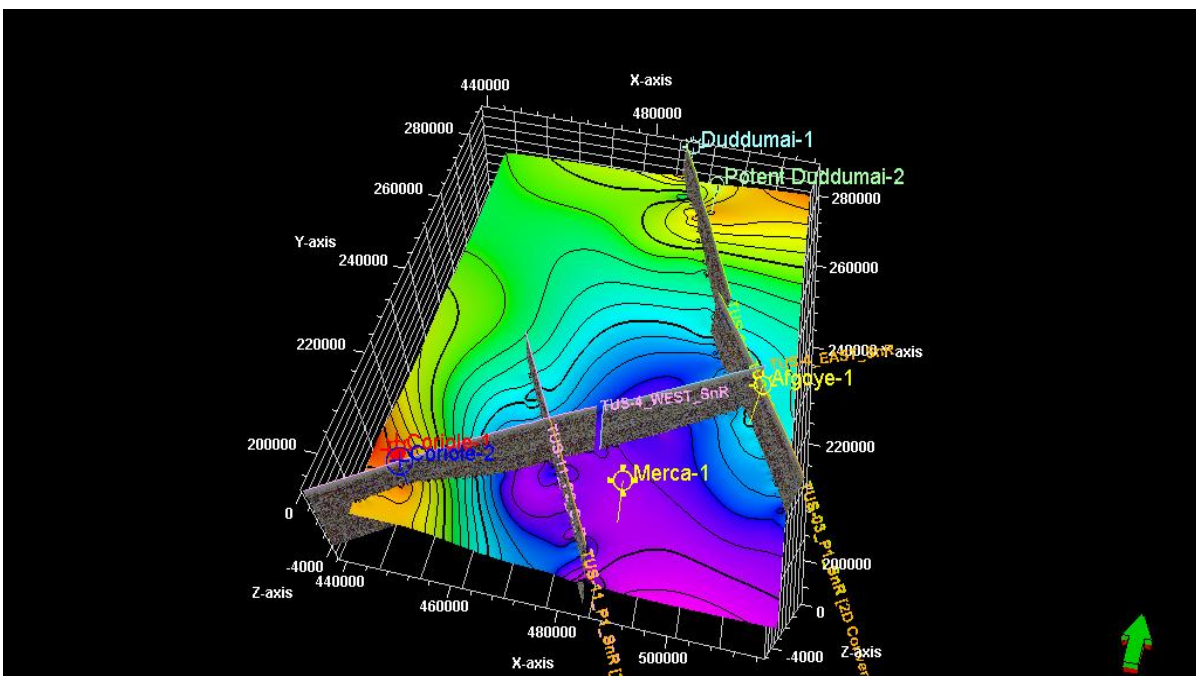


Figure 4.40: Locations of historical drilled wells and those proposed for the Jesomma surface with 2D Seismic profiles.

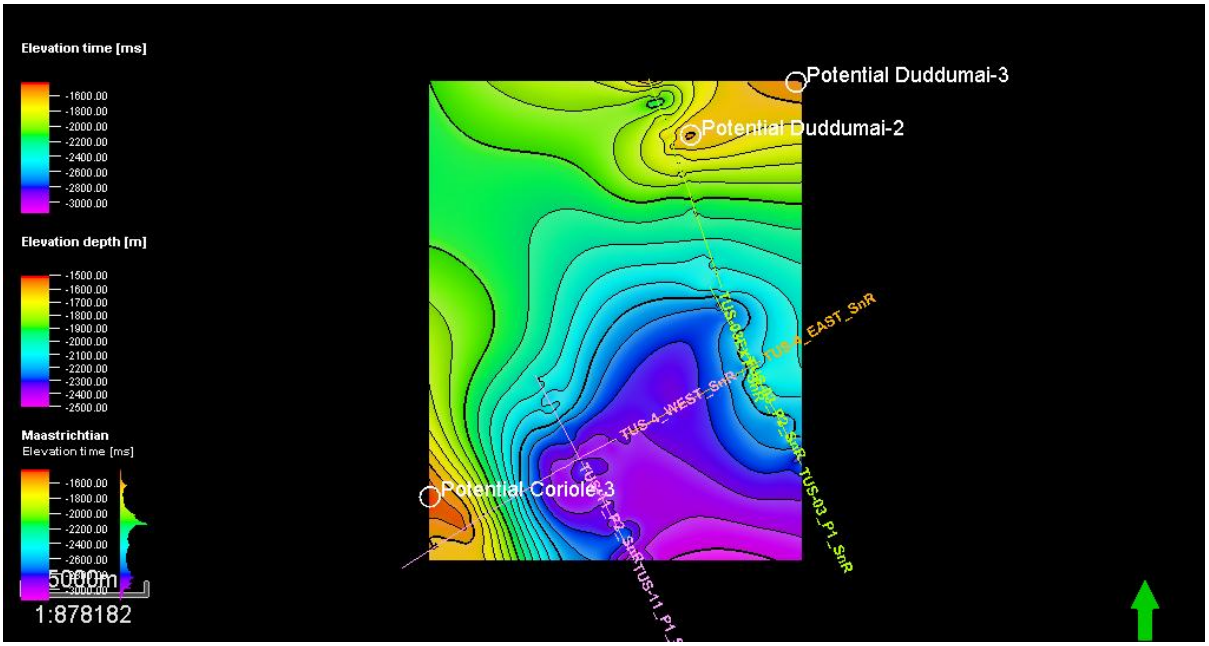


Figure 4.41: Map with the proposed infill exploration drilling locations based on top Jesomma Formation Surface

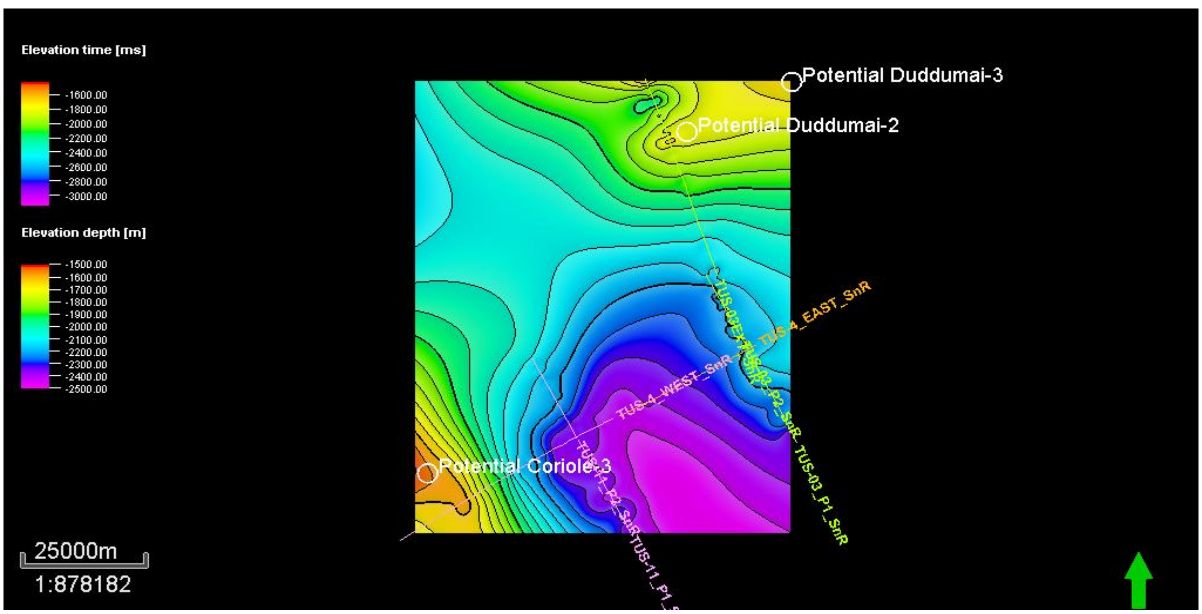


Figure 4.42: Map with only the proposed infill exploration drilling locations based on top Auradu-Jesomma Formations Transition Surface

The calculations also suggest that the likely hydrocarbon products trapped and stored in these two potentially mapped closed structures will be represented by normal-light oil products. Good indications for this are the reported production tests of 100 barrels/day of 44°API paraffinic oil from the Jesomma sandstone of the neighbouring Coriole-1 well at a depth of 11540', plus gas with a reported Gas-to-oil (GOR) of 14000, aromatics, and low sulphur (Barnes, 1976). The migration of the hydrocarbons occurred towards the elevated parts of the reservoir (Figure 4.43) located at the south-western corner of the survey area.

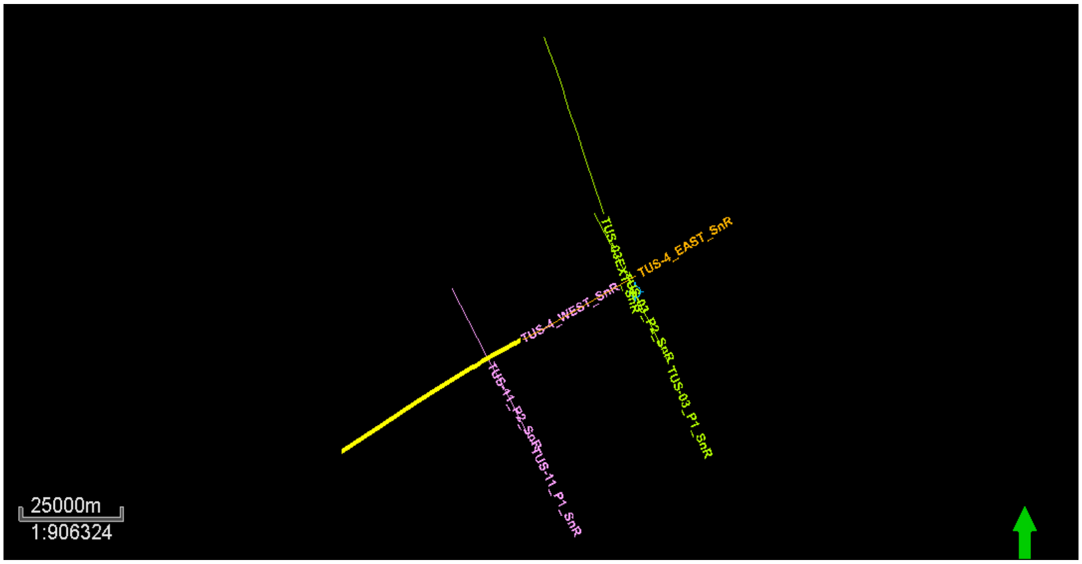


Figure 4.43: Location Map Tus_4_West_Snr Seismic Profile

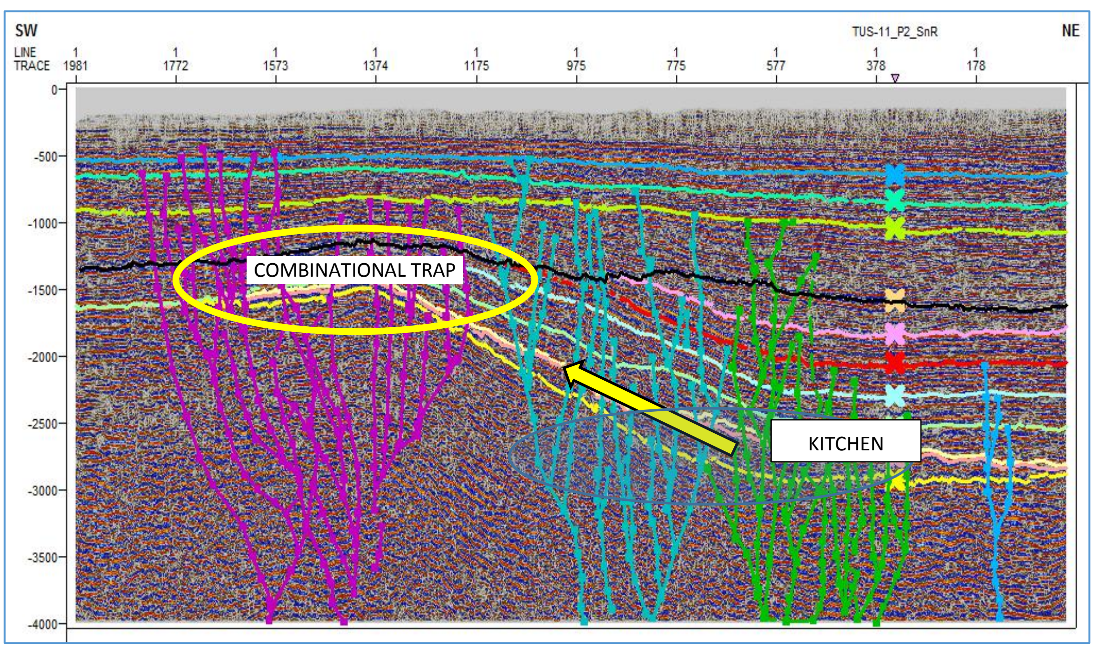


Figure 4.44: The interpreted seismic profile Tus_4_West_Snr with the location of the kitchen zone, possible migration pathways of expelled hydrocarbons and trapping mechanism

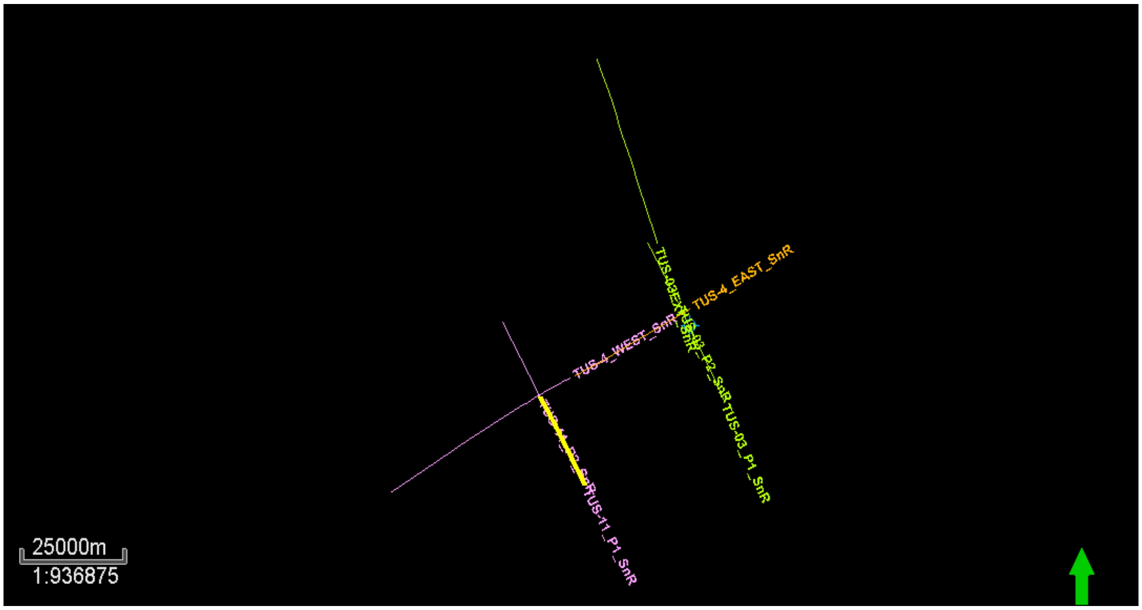


Figure 4.45: Interpreted Seismic Profile Tus-11_P1_Snr

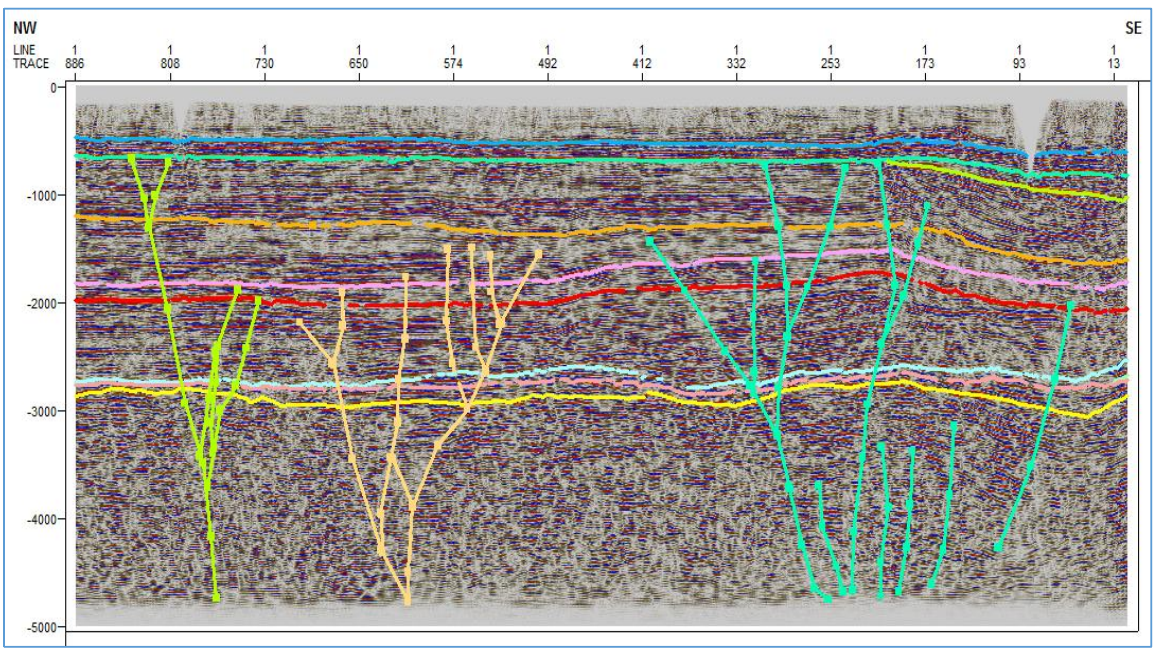


Figure 4.46: Interpreted seismic profile TUS-11_P1_Snr with positive flower structures and broad en echelon folds at the SE end characterizing a NW-SW convergent wrench fault system

The study area hosts a variety of hydrocarbon traps, including structural (anticlinal), stratigraphic (unconformity related) and combinational traps (structural-stratigraphic; Figure 4.46).

The asymmetrical configuration of the anticline mapped on seismic profile TUS_4_WEST_SnR suggests that it is either related to a basement high (Figure 4.44) that existed at this location before the Cretaceous times, or it may be a product of an inversion that took place in the Late Eocene-Early Oligocene times. The available results of planktonic foraminifera biostratigraphy from neighbouring Coriole-1 well indicate the presence of two unconformities (hiatuses) in the Late Palaeocene-Eocene section (A. S. Hussein, 1993). According to the Berggren et al., (1995) zonation, the first stratigraphic gap correlates with the missing P5 (M. velascoensis) – P6 (M. velascoensis – M. Formosa/M. lensiformis- M. aragonensis) Interval Zones corresponding to the topmost Upper Palaeocene (Thanetian) and lowermost Eocene (Sparnacian-Ypresian stages; 56-52.4 Ma). The second unconformity occurs within the Coriole formation, where strata from P12-P13 (M. lehneri – Gb. beckmanni) rest on those from Zone P9 (Pt. palmarae-H. nuttalli) indicating the absence of strata belonging to P10 (H. nuttalli) and P11 (Gb. kugleri/M. aragonensis) zones which correspond to the major part of the Lutetian stage. We suggest that these hiatuses correspond to the uplifting and subsequent erosion events in this part of the study area.

However, the constructed thicknesses (isochore) maps indicate that the proposed infill drilling locations (Duddumai-2 and -3) will likely only test the carbonate reservoir (dolomite) section of the Auradu formation, while the Late Cretaceous (Jesomma) sandstone reservoir will be thin (Figures 4.47). This concludes that there is a necessity of the increase of drilling density within the selected areas (vicinity of the Duddumai-1 and Coriole-2 well locations). Bulk estimates conclude that the targets are located at depths of approximately 2 kilometres (6561.7') deep. The Duddumai-1 location near the pre-Cambrian Bur Acaba uplifted block seems promising by offering additional stratigraphic (unconformity-related) hydrocarbon traps. To the south-west of the surveyed area, there is a buried uplifted (inversed) block with similar trapping configurations (Coriole-2 well location).

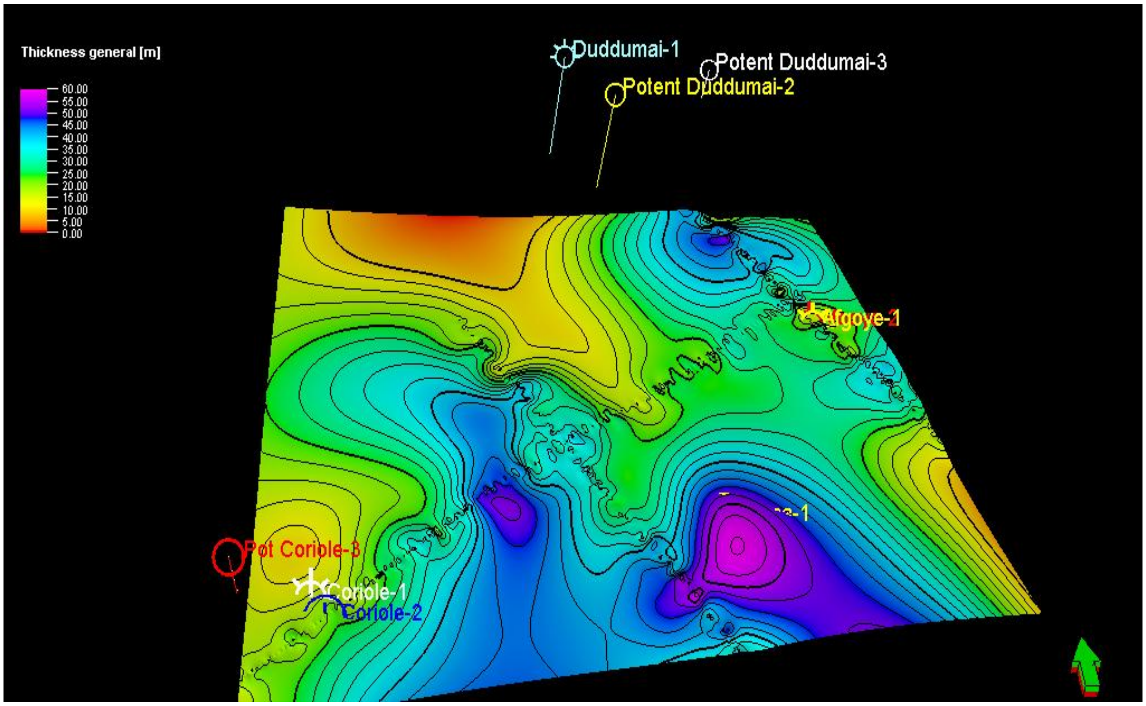


Figure 4.47: General thickness distribution map of the combined Jesomma and Auradu-Jesomma transition formations in the studied portion of the Somalia Coastal Basin

In addition to the known unconformities deduced from biostratigraphy studies, one more has been recognized and mapped during the current seismic interpretation. This is the hiatus between the Lower and Middle Miocene (profiles TUS-11_P1_SnR and TUS-11_P2_SnR) in Figure 4.46. It may have some trapping potential only if there is some increased shale and clay content of the overlying Middle Miocene (Somal-Scusciuban transition strata). These strata have average thicknesses across the surveyed area.

A series of isopach maps were prepared for the Jesomma and Auradu-Jesomma transition formations that resulted in the proposal of more additional infill locations. The Isopach maps for the levels of interest were generated by the identification of the average dip values multiplied by the obtained isochore (vertical thickness).

As seen from Figures 4.48 through 4.49, the dip values are constant through most of the survey area and represent the characteristic horizontal layering of the strata. Slight differences in the dips are seen along some probable faults.

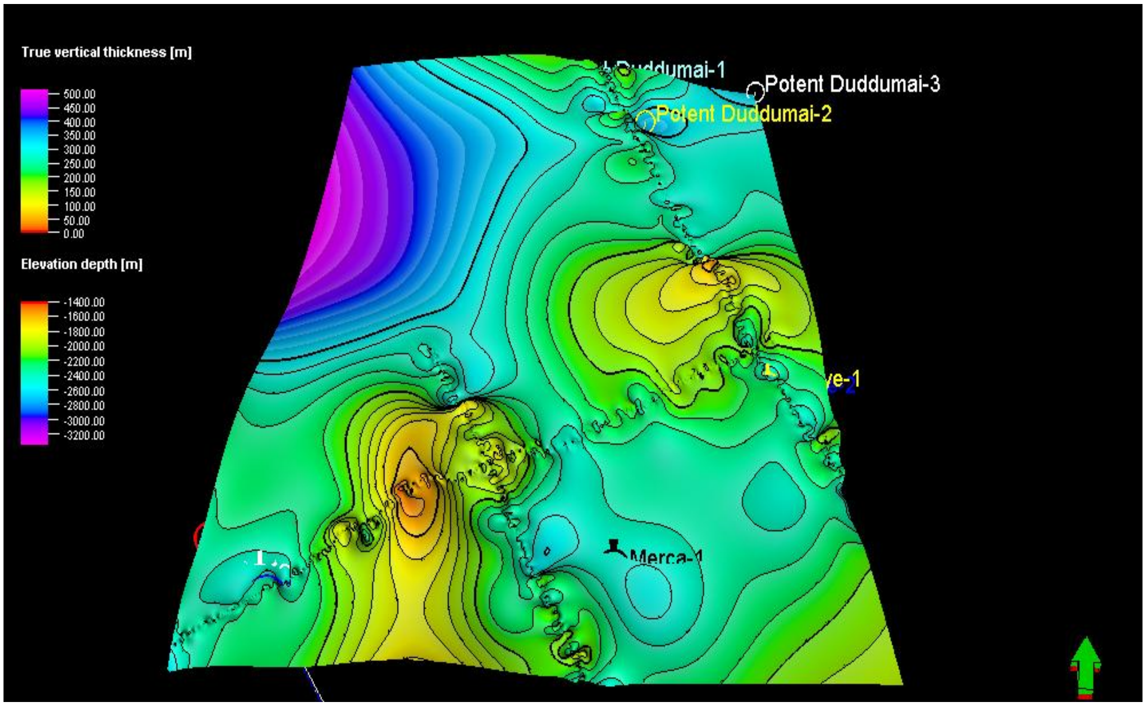


Figure 4.48: Isochore (Vertical Thickness) map between Lower Palaeocene-Upper Cretaceous and Maastrichtian base surfaces (Jesomma Formation)

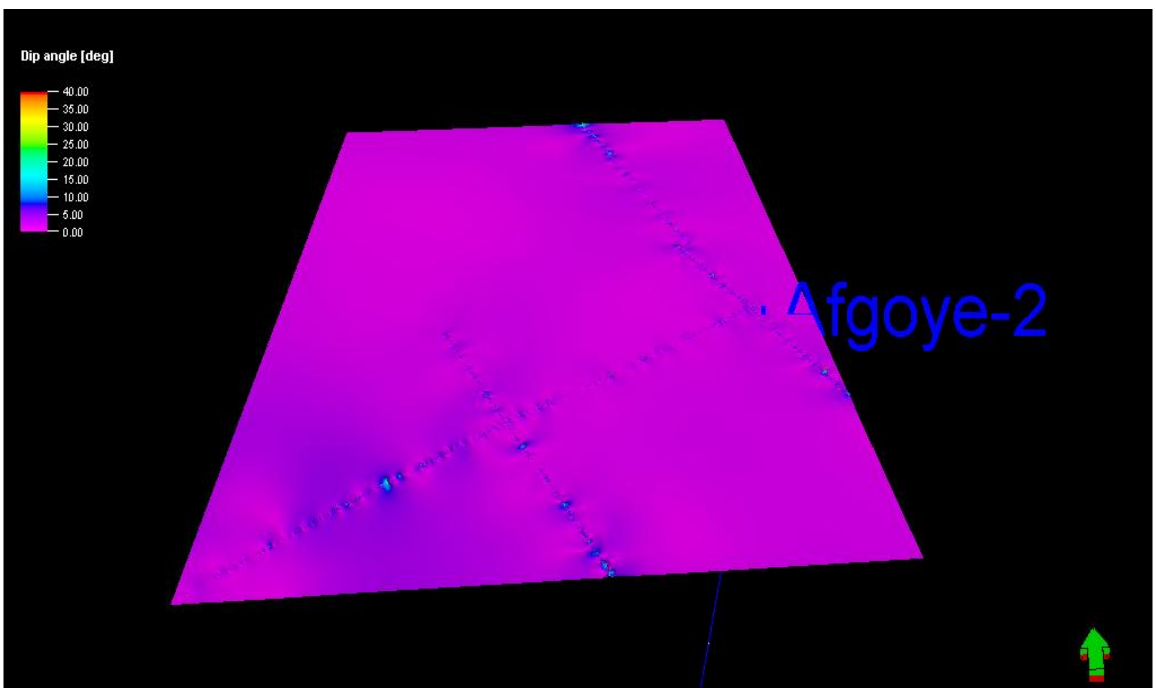


Figure 4.49: Average dip values of the Lower Palaeocene-Upper Cretaceous (Auradu-Jesomma Transition) base surface

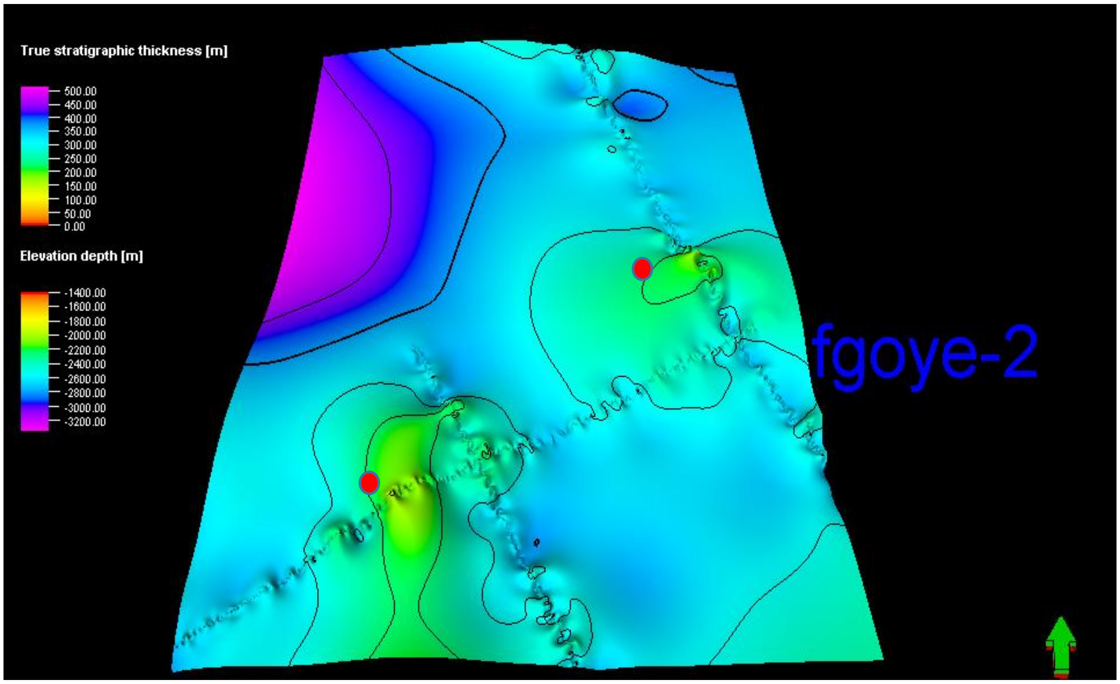


Figure 4.50: 3D Isopach (True Stratigraphic Thickness) map between Lower Palaeocene-Upper Cretaceous and Maastrichtian base surfaces (Jesomma Formation) with potential infill drilling sites

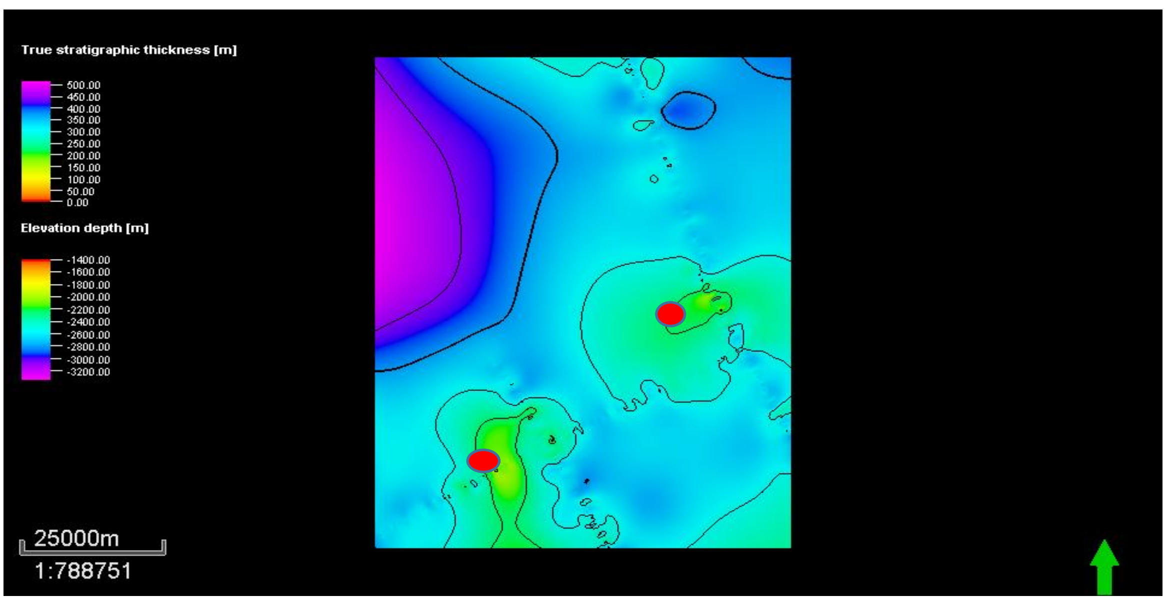


Figure 4.51: 2D Isopach (True Stratigraphic Thickness) map between Lower Palaeocene-Upper Cretaceous and Maastrichtian base surfaces (Jesomma Formation) with potential infill drilling sites

Table 4.1: Proposed infill drilling locations to test the potential sandstone reservoirs based on Isopach map data

№	LATITUDE	LONGITUDE	DEPTH, M (FT.)
1	1°54'48.4774"N	44°41'49.5098"E	2000-2400 m (6561.67-7874.01’)
2	2°11'56.7847"N	45°00'19.9265"E	2000 (6561.67’)

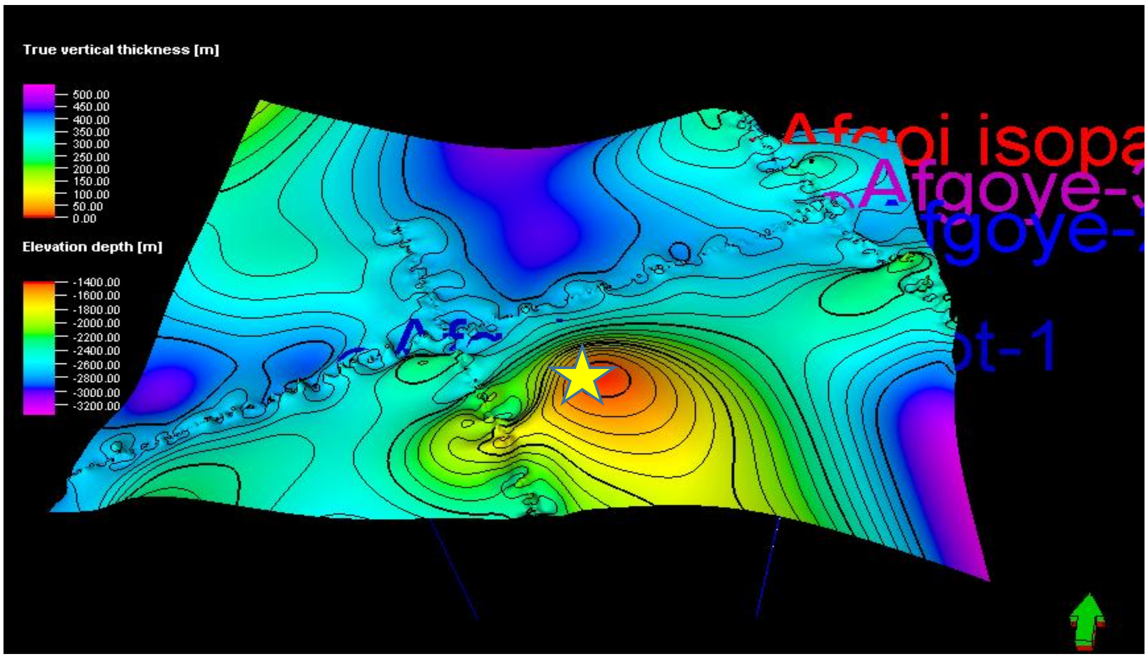


Figure 4.52: Isochore (vertical thickness) map between Upper Lower Palaeocene and Lower Palaeocene-Upper Cretaceous (Auradu-Jesomma Transition)

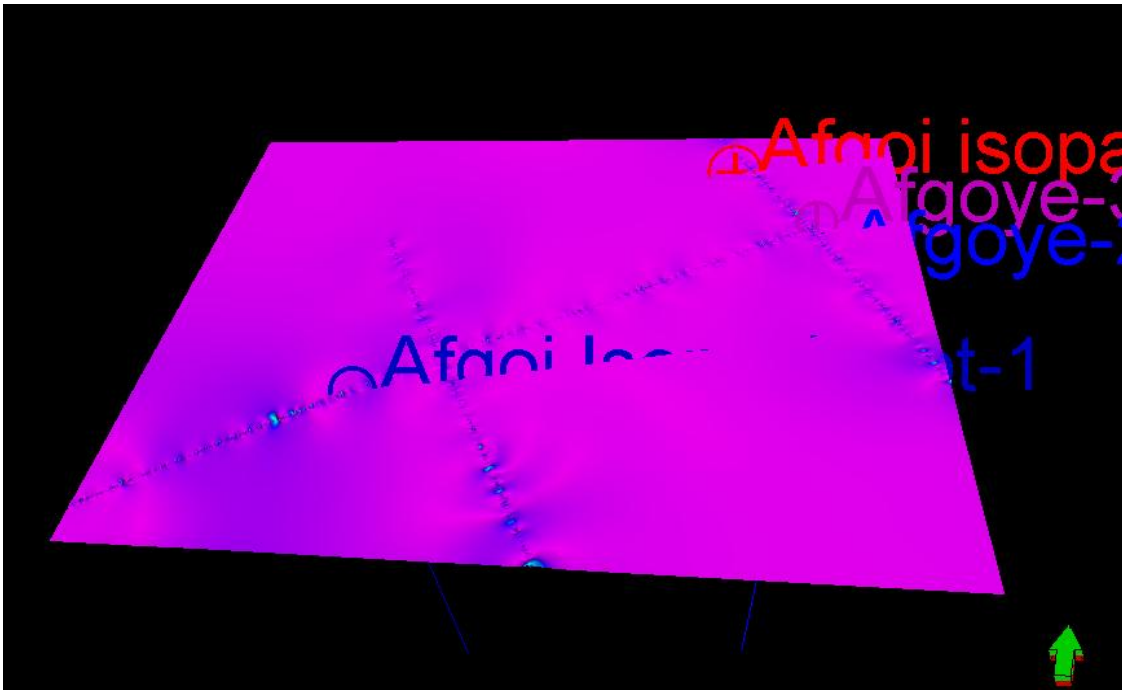


Figure 4.53: Average dip values of the Upper Lower Palaeocene (Auradu Equivalent) base surface

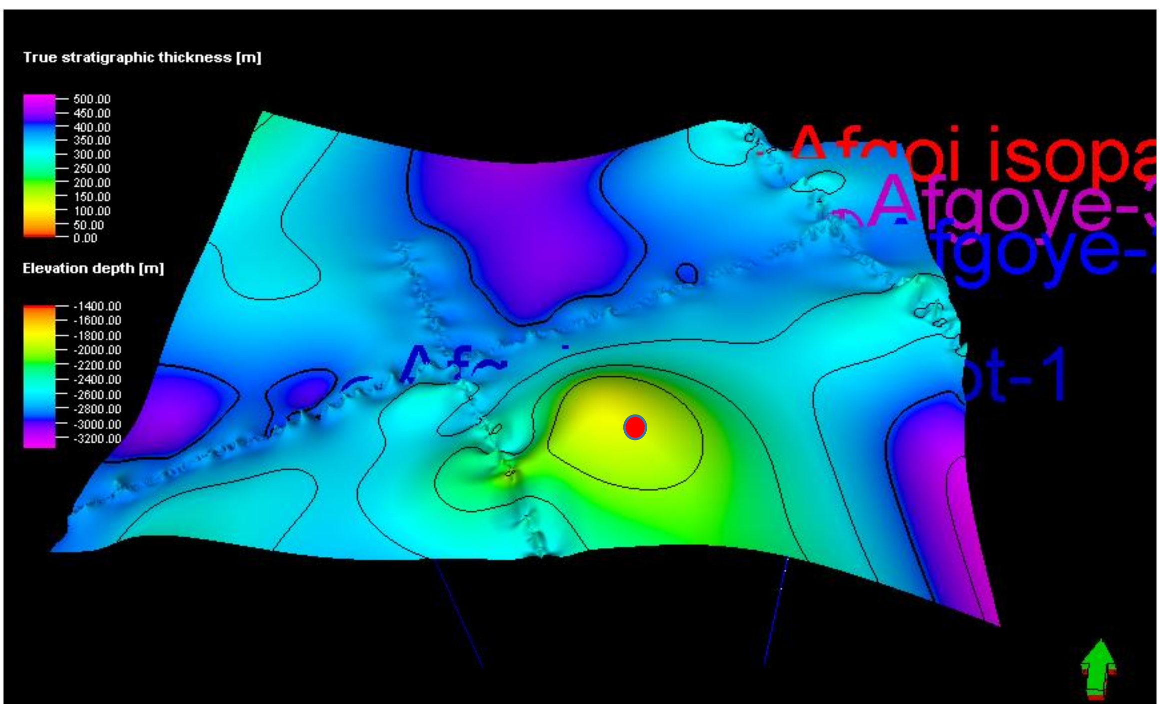


Figure 4.54: 3D Isopach (True Stratigraphic Thickness) map between Upper Lower Palaeocene and Lower Palaeocene-Upper Cretaceous (Auradu-Jesomma Transition)

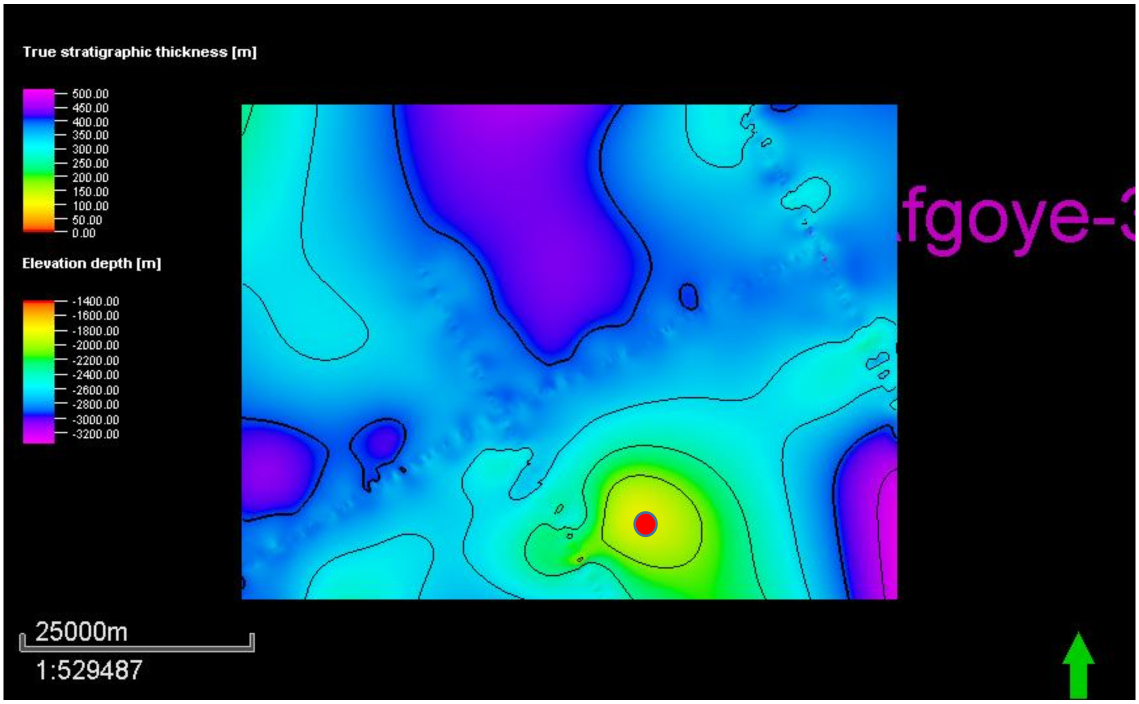


Figure 4.55: 2D Isopach (True Stratigraphic Thickness) Map between Upper Lower Palaeocene and Lower Palaeocene-Upper Cretaceous (Auradu-Jesomma Transition)

Table 4.2: Proposed infill drill locations for Auradu-Jesomma Transition based on Isopach map data

№	LATITUDE	LONGITUDE	DEPTH, M (FT.)
3	1°50'40.7239"N	44°54'0.2247"E	1800-2000m (5905.5-6561.67’)

4.8 Temperature Time Index (TTI) Source Rock Maturation Modelling

Time Temperature Index (TTI) modelling was applied to estimate the source rock maturation and potential for generating oil and gas accumulations. TTI analysis also provides information about the time when hydrocarbon products were expelled, and what product types are expected to occur in the area of interest. The TTI modelling was done for the Afgoi-2 well section and for some neighboring exploration wells (Afgoi-1, Coriole-1 and Merca-1). For better modelling results, a series of sedimentation rate curves for the wells were constructed. These curves provide important information on the depositional environment and also enable us to track the levels of hiatuses (unconformities) and their probable durations.

4.9 Sedimentation Rate Curves and Burial History curves for Coriole Basin

4.9.1 Sedimentation Rate Curve for Afgoi-2 Well in Coriole Basin

Afgoi-2 well encountered formations ranging from the Late Cretaceous to the present. From the curve presented in Figure 4.56, it can be concluded that sediment accumulation in the Afgoi-2 well site occurred within average to high sedimentation rates (47.7'/1Ma to 217.7'/1Ma). With the exception of a short-duration unconformity (0.2 Ma) at the Eocene-Oligocene boundary, the accumulation of Late Cretaceous – Recent sediments in the Coriole basin was quite continuous.This hiatus is detected with the help of planktonic foraminifera biostratigraphy – by the absence of T. Cerroazulensis (P17) Index Zone of Berggren et al. 1995).

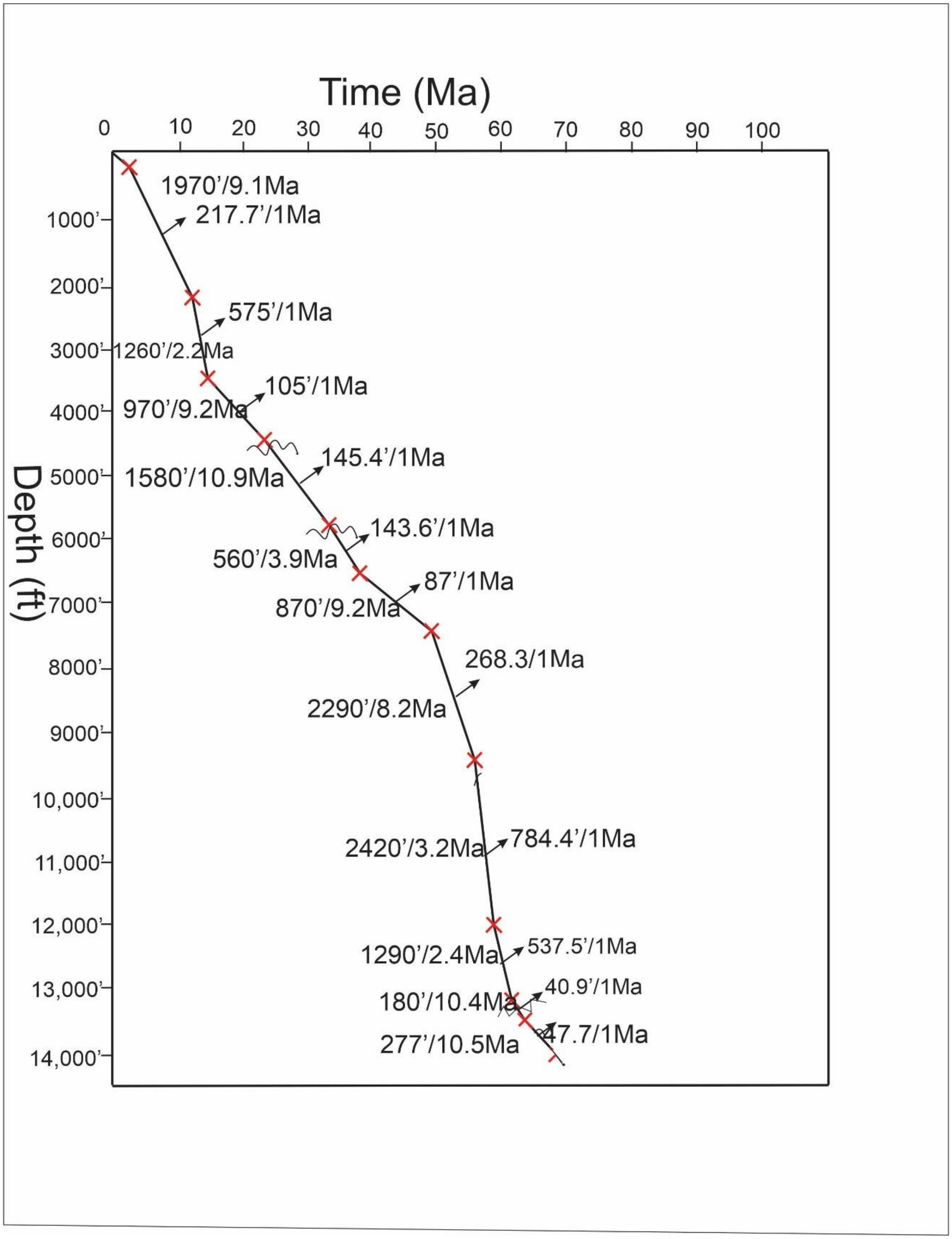
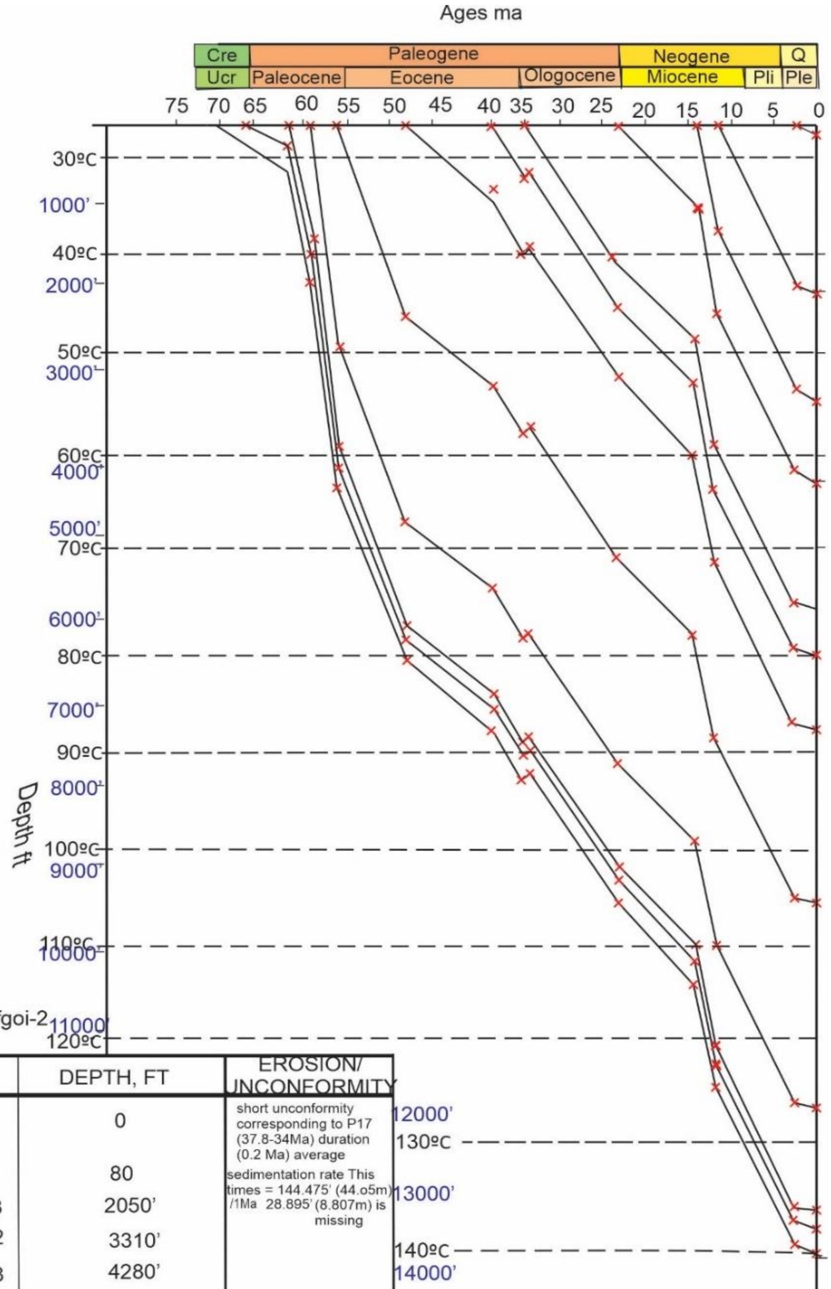


Figure 4.56: Sedimentation Rate Curves for Afgoi-2 well (Coriole basin)

4.9.2 Burial History Curve for Coriole Basin Afgoi-2 Well

The burial history curve for the Afgoi-2 well consists of a family of 12 curves, each corresponding to a separate formation encountered by the well section. These formations range from the oldest Jesomma to the Mid-Miocene and younger Scusciuban formations (Figure 4.57) with a total duration of about 72 million years. The burial curve also indicates that the formations preserved their thickness throughout history. Some regional deformation might have taken place around 13.82 Ma (base Serravalian, Mid Miocene) when all formation thicknesses were slightly reduced, reflecting a deformation related to either folding (flexuring) or faulting (an uplift), or wrenching, or a combination of both.

The burial history curves chart was overlaid with the subsurface temperature grid. The grid assumes that both the surface temperatures and gradients have remained constantly stable throughout the Late Mesozoic to present times. The next subsections provide detailed discussions of the TTI modelling, results and their correlations with similar analysis done for neighbouring wells (Afgoi-1, Coriole-1, Merca-1, and others). The TTI analysis was calibrated with vitrinite reflectance (Ro) values and all results demonstrated a good correlation.



Time Stratigraphic Data For Afgoi-2

AGE (MA)		DEPTH, FT	EROSION/ UNCONFORMITY
Present	0	0	short unconformity corresponding to P17 (37.8-34Ma) duration (0.2 Ma) average sedimentation rate This times = 144.475' (44.o5m) /1Ma 28.895' (8.807m) is missing
Pleistocene/Pliocene	2.58	80	
Middle Miocene	11.63	2050'	
Middle Miocene	13.82	3310'	
Lower Miocene	23.03	4280'	
Oligocene	33.9	5860'	
Upper Eocene	37.8	6420'	
Middle Eocene	47.8	7290'	
Lower Eocene	56	9580'	
Upper Paleocene	59.2	12000'	
Upper/Lower? Pliocene	61.6	13290'	
L. Paleocene-Upper cretaceous		13470'	
Maastrichtian	72.1	13747'	

Figure 4.57: Family of Burial History Curves for Afgoi-2 Well (Coriole basin).

BHT-, 140oC, ST-27oC, TD - 13747ft

A) TTI Calculations for the Upper Cretaceous (Jesomma Formation)

A TTI value result of 121.44 (Table 4.3) indicates that the Upper Cretaceous (Jesomma formation) is located within the Late Oil generation. The TOC values are fairly average, with a carbon content of 0.9%, suggesting some good possibilities for oil generation. These results correlate well with vitrinite reflectance (Ro) of 1.25% determined from a sample located at a depth of 13710'.

Table 4.3: TTI calculations for Upper Cretaceous (Jesomma Formation)

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°*C*	-8	5.1	$1/256$	0.02	0.02	72.1-67 Ma
30 – 40°*C*	-7	7	$1/128$	0.05	0.07	67 – 60 Ma
40 – 50°*C*	-6	2.2	$1/64$	0.04	0.11	60 – 57.8 Ma
50 – 60°*C*	-5	1	$1/32$	0.03	0.14	57.8 – 56.8 Ma
60 – 70*C*	-4	3.3	$1/16$	0.2	0.34	56.8 – 53.5 Ma
70 – 80°*C*	-3	5.3	$1/8$	0.7	1.04	53.5 – 48.2 Ma
80 – 90°*C*	-2	10.2	$1/4$	2.6	3.64	48.2 – 38 Ma
90 – 100 °*C*	-1	10.5	$1/2$	5.3	8.94	38 – 27.5 Ma
100 – 110 °*C*	0	11.5	1	11.5	20.44	27.5 – 16 Ma
110- 120°*C*	1	3.5	2	7	27.44	16 – 12.5 Ma
120 – 130°*C*	2	3.5	4	14	41.44	12.5 – 9 Ma
130 – 140°*C*	3	8	8	64	105.44	9 – 1 Ma
140 - 150°*C*	4	1	16	16	121.44	1-0 Ma
					TTI 121.44	

B) TTI calculations for the Lower Palaeocene to Upper Cretaceous (Auradu Equivalent to Jessoma Transition)

Early oil generation from the Lower Palaeocene-Upper Cretaceous (Auradu equivalent-Jesomma) transition began around 26.25 Ma (Chattian, Late Oligocene) and entered into the peak phase approximately around 10.17 Ma (Tortonian, Late Miocene until present). The expected hydrocarbons from this source rock interval with these TTI values with an 80% confidence level was represented by normal-light oil to condensate wet gas (Waples, 1985).

The total calculated TTI value for the Auradu Equivalent to Jesomma Transition source rocks with TOC of 1 (weight %) corresponds to a vitrite reflectance (Ro) value of 1.1. This suggests that these source rocks are mature and within the Late Oil generation window, just as the previous Jesomma formation. Table 4.4 gives the TTI values for the Auradu-Jesomma transition source rock.

Table 4.4: TTI calculations for Lower Palaeocene-Upper Cretaceous (Auradu-Jesomma Transition) Formation.

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°C	-8	4.5	$1/_{256}$	0.02	0.02	66 – 61.5 Ma
30 – 40°C	-7	2	$1/_{128}$	0.02	0.04	61.5 – 59.5 Ma
40 – 50°C	-6	1.8	$1/_{64}$	0.03	0.07	59.5 – 57.7 Ma
50 – 60°C	-5	1.7	$1/_{32}$	0.05	0.012	57.7 – 56 Ma
60 – 70°C	-4	5.5	$1/_{16}$	0.2	0.32	56 – 52.5 Ma
70 – 80°C	-3	6.5	$1/_{8}$	0.8	1.12	52.5 – 46 Ma
80 – 90°C	-2	11	$1/_{4}$	2.8	3.92	46 – 35 Ma
90 – 100°C	-1	15	$1/_{2}$	7.5	11.42	35 – 20 Ma
100 – 110°C	0	4	1	4	15.42	20 – 16 Ma
110- 120°C	1	4	2	8	23.42	16 – 12 Ma
120 – 130°C	2	6	4	24	47.42	12 – 6 Ma
130 – 140°C	3	6	8	48	95.42	6 – 0 Ma
					TTI=95.42	

C) TTI Calculations for the Upper-Lower Palaeocene (Auradu Equivalent)

The total calculated TTI for Auradu Equient (Table 4.5) was estimated at a value of 90.264, suggesting that these rocks are mature and correspond to a vitrinite reflectance of 0.6% (Ro). The calculated organic carbon content for the depth range of 9490 to 13290 feet resulted in a fair 0.8% TOC from dark grey shales. The formation is within the Late Oil generation (late maturity) window.

Table 4.5: TTI calculations for Upper Lower Palaeocene (Auradu Equivalent)

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°C	-8	1	$1/_{256}$	0.004	0.004	61 – 60 Ma
30 – 40°C	-7	1.5	$1/_{128}$	0.01	0.014	60 – 58.5 Ma
40 – 50°C	-6	1	$1/_{64}$	0.02	0.034	58.5 – 57.7 Ma
50 – 60°C	-5	2.5	$1/_{32}$	0.08	0.114	57.7 – 55 Ma
60 – 70°C	-4	3.5	$1/_{16}$	0.2	0.314	55 – 51.5 Ma
70 – 80°C	-3	6.5	$1/_{8}$	0.8	1.114	51.5 – 45 Ma
80 – 90°C	-2	18	$1/_{4}$	4.5	5.614	45 – 27 Ma
90 – 100°C	-1	2.5	$1/_{2}$	1.25	6.864	27 – 24.5 Ma
100 – 110°C	0	9.6	1	9.6	16.464	24.5 – 14.9 Ma
110- 120°C	1	4.9	2	9.8	26.264	14.9 – 10 Ma
120 – 130°C	2	4	4	16	42.264	10 – 6 Ma
130 - 140°C	3	6	8	48	90.264	6 – 0 Ma
					TTI=90.264	

D) TTI Calculations for the Upper Palaeocene (Auradu Equivalent)

The rocks range from 7290 to 9490 feet and consist chiefly of carbonate rocks. The calculated TTI value (Table 4.6) is 44. The value suggests that these source rocks are mature. The age of the rocks is about 59.2 Ma (Thanetian Stage, Late Palaeocene). The sediments showed a fair organic carbon content of 0.5% TOC.

Table 4.6: TTI calculations for Upper Palaeocene (Auradu Equivalent)

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages Ma**
20-30°C	-8	1.2	$1/_{256}$	0.005	0.005	59.2 – 58 Ma
30 – 40°C	-7	1	$1/_{128}$	0.008	0.013	58 – 57 Ma
40 – 50°C	-6	1.5	$1/_{64}$	0.02	0.033	57 – 55.5 Ma
50 – 60°C	-5	3.1	$1/_{32}$	0.01	0.043	55.5 – 51.9 Ma
60 – 70°C	-4	6.9	$1/_{16}$	0.4	0.443	51.9 – 45 Ma
70 – 80°C	-3	20.1	$1/_{8}$	2.5	2.943	45 – 24.9 Ma
80 – 90°C	-2	1.9	$1/_{4}$	0.5	3.443	24.9 – 23 Ma
90 – 100°C	-1	8.5	$1/_{2}$	4.25	7.693	23 – 14.5 Ma
100 – 110°C	0	3.7	1	3.7	11.393	14.5 – 10.8 Ma
110- 120°C	1	5.8	2	11.6	23	10.8 – 5 Ma
120 – 130°C	2	5	4	20	44	5 – 0 Ma
					TTI=44	

E) TTI Calculations for the Lower Eocene (Seriole – Auradu Transition)

A TTI value of 10.334 (Table 4.7) was allocated for the Lower Eocene source rock, suggesting that it was mostly premature or just entering the oil window. The sediment thickness is about 340 feet (6950 and 7290 feet). In a mid-shelf paleoenvironment, Middle Eocene silt tones and limestone transitional between the overlying deep marine siltstones and the underlying shallow marine limestones were deposited. The age of the rocks is about 56 Ma. The rocks have a fair organic content of 0.6%. The oil window is under middle maturity age (middle oil generation).

Table 4.7: TTI calculation for the Lower Eocene (Auradu formation).

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°C	-8	1	$^1/_{256}$	0.004	0.004	56 – 55 Ma
30 – 40°C	-7	4	$^1/_{128}$	0.03	0.034	55 – 51 Ma
40 – 50°C	-6	8.5	$^1/_{64}$	0.1	0.134	51 – 42.5 Ma
50 – 60°C	-5	17	$^1/_{32}$	0.5	0.634	42.5 – 25.5 Ma
60 – 70°C	-4	2	$^1/_{16}$	0.1	0.734	25.5 – 23.5 Ma
70 – 80°C	-3	10.3	$^1/_{8}$	1.3	2.034	23.5 – 13.2 Ma
80 – 90°C	-2	3.2	$^1/_{4}$	0.8	2.834	13.2 – 10 Ma
90 – 100°C	-1	5	$^1/_{2}$	2.5	5.334	10 – 5 Ma
100 – 120°C	0	5	1	5	10.334	5 – 0 Ma
					TTI=10.334	

Table 4.8: Summary of the TTI calculations for the source rock intervals intersected by Afgoi-2 well

Formation	**TTI**	**HC State**
Upper Cretaceous-Maastrichtian (72.1Ma) Jesomma Fm	121.44	Peak oil
Lower Paleocene-Upper Cretaceous (66Ma) Auradu-Jesomma transition	95.42	
Upper Lower Paleocene-Selandian (61Ma) Auradu Equivalent	90.264	
Upper Pleocene Thanetian (59.2Ma) Aurdu Equivalent	44	Early oil
Lower Eocene-Ypresian (56 Ma) Auradu Formation	10.334	
Middle Eocene-Lutetian (47.8Ma) Seriole-Auradu transition	5.9	
Upper Eocene (37.8Ma) Seriole Formation	3.5	
Oligocene (33.9Ma) Obbia formation-Somal Sand Member Fm	3.089	
Middle Miocene-Serravalian (13.8Ma) Somal Fm	1.3	Immature
Late Miocene-Tortonian (11.6Ma) Scusciuban-Somal transition Fm	0.3	

4.9.3 Sedimentation Rate Curve for Afgoi-1 Well

This curve demonstrates that the accumulation of Late Cretaceous – Recent sediments within the Coriole basin was continuous with an exception of an unconformity between 34 to 23 Ma. The basal part of the Upper Cretaceous (Maastrichtian) section underwent rapid burial of 14.9'/Ma from about 68 Ma to about 61 Ma and was followed by Lower/Upper which increased sedimentation rates at 46.2'/Ma from about 61 Ma to about 56 Ma. These are represented by Auradu equivalent formations. The Lower/Upper Eocene experienced the highest sedimentation rate of about 77.7 ft. /Ma from about 56 Ma to about 35 Ma. It was followed by an uplift at around 33Ma. The Neogene deposited at rate of 78’/Ma. These include the Obbia and Somal formations (Figure 4.58), deposition of which were interrupted by another uplift around 25 Ma.

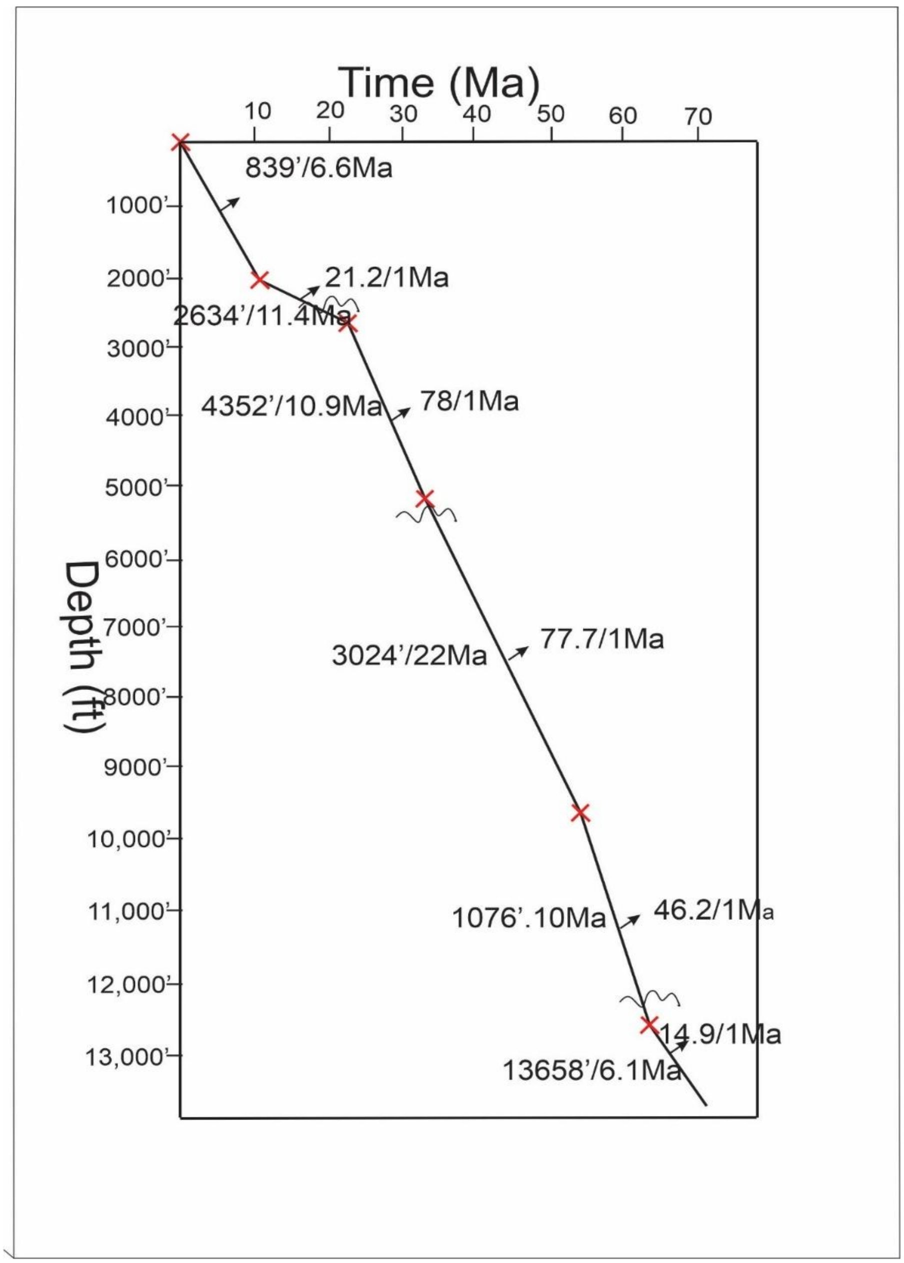


Figure 4.58: Sedimentation Rate Curve for Afgoi-1 well in Coriole Basin

4.9.4 Burial History Curve for Coriole Basin Afgoi-1 Well

Similar to the previous well, Afgoi-1 intersected Upper Cretaceous and Middle Miocene rock successions. The average surface temperature at the Afgoi-1 well site is 26ºC and the bottom hole temperature is 137ºC. The burial history curve (Figure 4.59) comprises a family of five (5) burial curves corresponding to the formations intersected by the well. Similar to the Afgoi-2 well, the burial history curves also indicate that the formations have preserved their thickness throughout history. An uplift event is depicted from the curve took place at about 22 Ma, during the Aquintanian Stage of the Early Miocene.

Age M.a	Age M.a	Formations	Depth (ft)	Thickness (ft)	TTI	HC State
	11.6	Merca FM				Immature
11.4	23	Somal Fm	2539'	2634'	0.4	
10.9	33.9	Obbio Fm	5182'	4352'	1.7	
22.1	56	Maria-Ascia Fm	9534'	3024'	56.5	Normal Oil
10	66	L.Paleo-U.Cre	12532'	1076'	224.9	Wet Gas
6.1	72.1	Jesomma/ Sagahley	13658'	13658'	428.9	

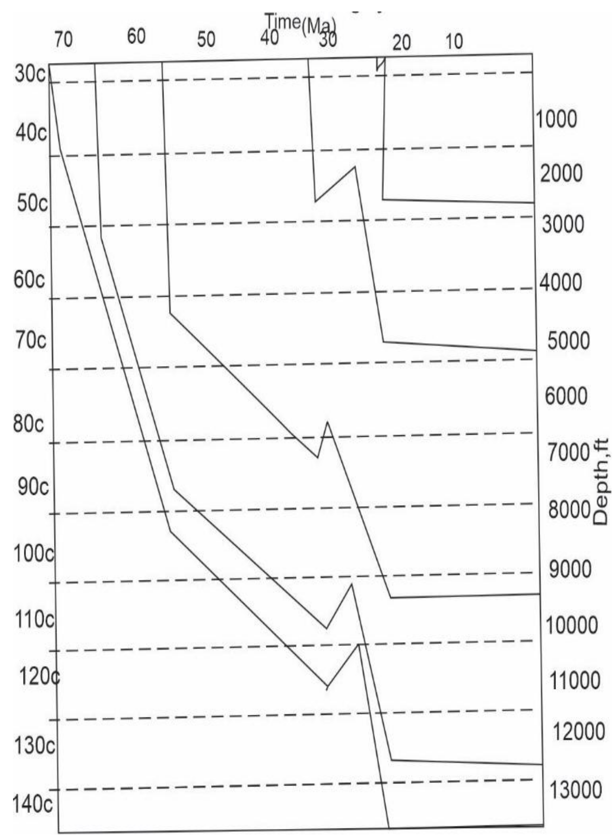


Figure 4.59: Families of Burial History Curves for Afgoi-1 Well (Coriole Basin).

BHT: 137°C ST: 27°C T.D: 13658 ft

A) TTI Calculations for Upper Cretaceous (Jesomma Formation) in Afgoi-1 well

The total calculated TTI for (Table 4.9) was estimated with a value of 428.9 that suggests that these rocks are mature. The formation is within the Wet Gas generation (late maturity). With the exception of unconformities (20 Ma) at the Lower Miocene – Upper Oligocene boundary, (33 Ma) Middle Oligocene-Lower Miocene boundary, and (62 Ma) Upper to Lower Palaeocene boundary, these curves show that the accumulation of upper Cretaceous – Quaternary sediments in the Coriole basin was continuous.

Table 4.9: TTI Calculations for Upper Cretaceous (Jesomma Formation)

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°C	-8	0.1	$^1/_{256}$	0.004	0.0004	72.1-72 Ma
30 – 40°C	-7	1	$^1/_{128}$	0.008	0.008	72 – 71 Ma
40 – 50°C	-6	3	$^1/_{64}$	0.02	0.06	71 – 68 Ma
50 – 60°C	-5	2	$^1/_{32}$	0.03	0.06	68 – 66 Ma
60 – 70°C	-4	3.5	$^1/_{16}$	0.06	0.21	66 – 62.5 Ma
70 – 80°C	-3	2.5	$^1/_8$	0.125	0.3125	62.5 – 60 Ma
80 – 90°C	-2	3	$^1/_4$	2.6	0.75	60 – 57 Ma
90 – 100 °C	-1	7	$^1/_2$	5.3	3.5	57 – 50 Ma
100 – 110 °C	0	10	1	11.5	10	50 – 40 Ma
110- 120°C	1	14	2	7	28	40– 26 Ma
120 – 130°C	2	1.5	4	14	6	26 – 24.5 Ma
130 – 140°C	3	1.5	8	64	12	24.5– 23 Ma
140 - 150°C	4	23	16	16	368	23-0 Ma
					TTI 428.9009	

B) TTI Calculations for Middle Eocene (Marai Ascia Formation) in Afgoi-1

The total calculated TTI for the Middle Eocene (Marai Ascia Formation was estimated with a value of 56.5353 (Table 4.10) that suggests that these source rocks are mature. This TTI value corresponds to a vitrinite reflectance (Ro) of approximately 0.93, and a probably generated normal oil to nomal light oil hydrocarbons (Waples, 1985).

Table 4.10: TTI Calculations for Middle Eocene (Marai Ascia Formation)

Temperature interval	**n**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages Ma**
20-30°C	-8	0	$1/_{256}$	0.004	0	56 – 56 Ma
30 – 40°C	-7	0.1	$1/_{128}$	0.008	0.0008	56 – 55.9 Ma
40 – 50°C	-6	0.1	$1/_{64}$	0.02	0.002	55.9 – 55.8 Ma
50 – 60°C	-5	0.8	$1/_{32}$	0.03	0.024	55.8 – 55 Ma
60 – 70°C	-4	7.5	$1/_{16}$	0.06	0.45	55– 47.5 Ma
70 – 80°C	-3	10.5	$1/_{8}$	0.125	1.3125	47.5 – 37 Ma
80 – 90°C	-2	6	$1/_{4}$	0.25	1.5	37 – 31 Ma
90 – 100°C	-1	3.5	$1/_{2}$	0.5	1.75	31 – 27.5 Ma
100 – 110°C	0	3.5	1	1	3.5	27.5 – 24 Ma
110- 120°C	1	24	2	2	48	24 – 0 Ma
					TTI= 56.5353	

4.9.5 Sedimentation Rate Curve for Coriole-1 Well

The sedimentation rate curve demonstrates that the accumulation of Late Cretaceous–Recent sediments within the Coriole basin was continuous with the exception of an unconformity between 30 and 20 Ma. The formations preserved their thickness throughout the depositional history. During the last 1.3 Ma, the youngest stratum was deposited at a high sedimentation rate of about 1187 ft. /1 Ma. The Upper Cretaceous (Maastrichtian) part experienced sedimentation rates of about 1107’/Ma from about 68 Ma to about 61 Ma, and is represented by the Jesomma and Auradu-Jesomma transition formations. This was followed by an uplift at around 58 Ma (Thanetian Stage, Late Paleocene). The Lower/Upper Paleocene (Auradu equivalent formations) times experienced sedimentation rates of about 409’/Ma. The Lower/Upper Eocene started with low sedimentation rates of about 91’/Ma which was succeeded by an uplift at around 35 Ma (Priabanian Stage, Late Eocene). The sedimentation rates then rise up to 163’/1 Ma between 30-10 Ma (Rupelian-Tortoinian Stages, Oligacene – Late Miocene times). It was preceded by an uplift of around 23Ma (Aquitanian Stage, Early Miocene). Lastly, the Sciuscuban formation accumulated at moderate sedimentation rates of about 146’/Ma.

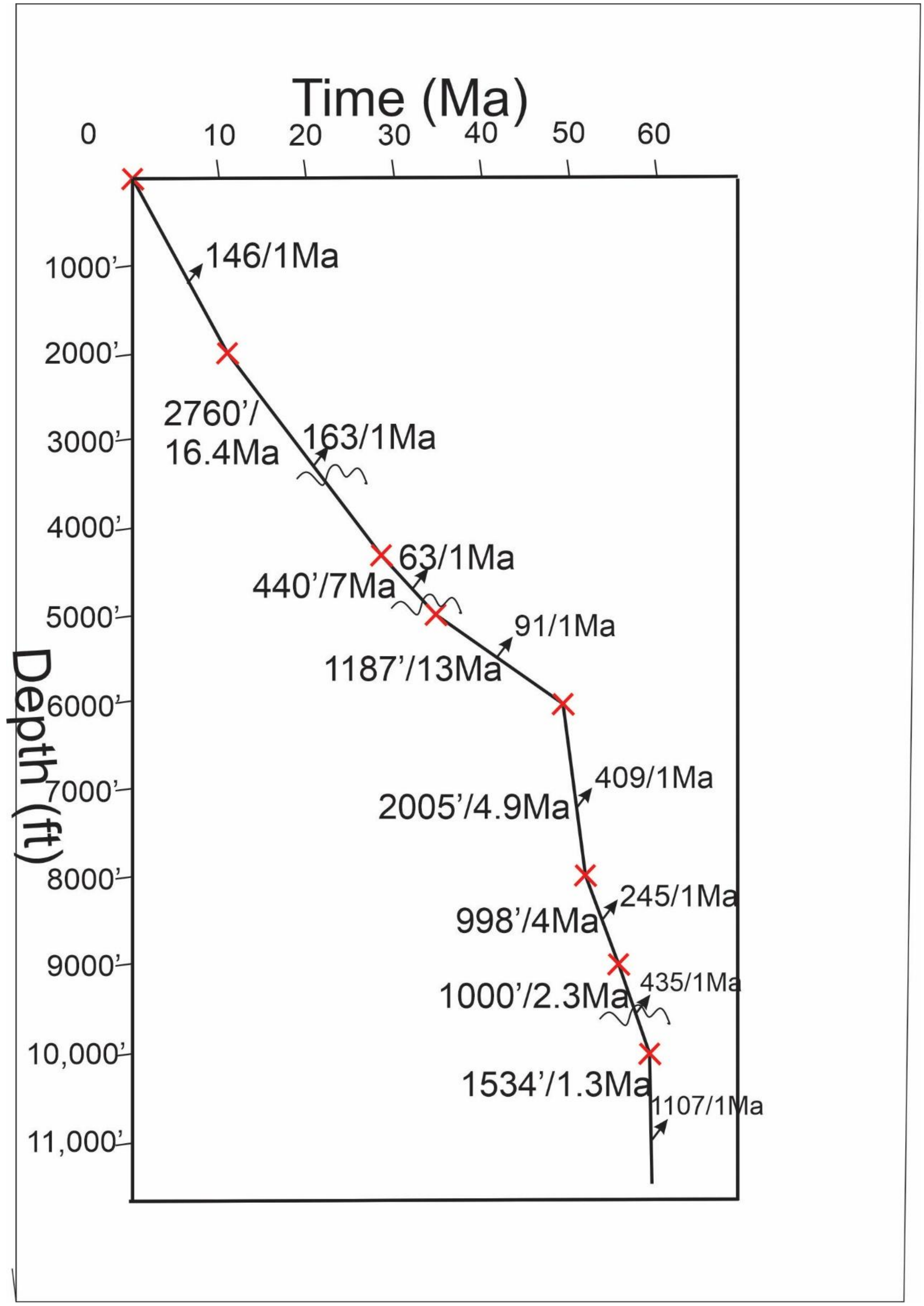
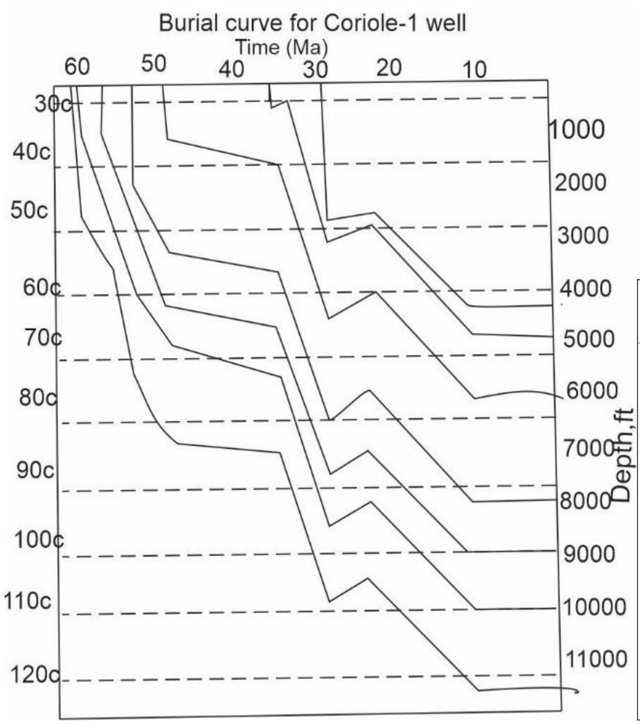


Figure 4.60: Sedimentation Rate Curve for Corriole-1 Well in Coriole Basin

4.9.6 Burial History Curve for Coriole Basin Coriole-1 Well

The burial history curves for Coriole-1 well consists of a family of seven (7) corresponding to the formations encountered by this well (Figure 4.61). Jesomma/Sagalei formation has a TTI value of 82.0068 which corresponds to light oil and normal oil hydrocarbon products (Waples, 1985). The average surface temperature at the Coriole-1 drill site is 27ºC and the bottom hole temperature (BHT) is 123ºC.



Age M.a	Age M.a	Formations	Depth (ft)	Thickness (ft)	TTI	HC State
	11.6	Merca FM	1700'			Immature
16.4	28	Somal Fm	4370'	2670'	1.8	
7	35	Obbio Fm	4810'	440'	2.6	
13	48	shabeele Fm	5997'	1187'	3.1	
4.9	52.9	Coriole Fm	8002'	2005'	10.4	Early Oil
4	56.9	Maria-Ascia _Coriole Tr	9000'	998'	11.8	
2.3	59.2	Maria-Ascia Fm	10000'	1000'	31.3	Normal Oil
1.3	60.5	Jesomma/ Sagahley	11543'	1534'	82	Light Oil

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Figure 4.61: Burial History Curve for Corriole Basin Corriole-1 Well

BHT. ---123°C, ST.-----27°C, T.D ----11543 FT

a) TTI Calculations for Lower Palaeocene-Upper Cretaceous (Jesomma/Sagalei transition) Formation in Coriole-1 well

The total calculated TTI for this interval was estimated with a value of 82.0068 that suggests that these source rocks are mature. The TTI value corresponds to a vitrinite reflectance (Ro) 1.1 and normal light oil hydrocarbon type (Waples, 1985).

Table 4.11 TTI Calculations for Lower Palaeocene-Upper Cretaceous (Jesomma/Sagahley Transition) Formation in Coriole-1 well

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°C	-8	0.5	$1/_{256}$	0.004	0.002	60.5 – 60 Ma
30 – 40°C	-7	0.1	$1/_{128}$	0.008	0.0008	60 – 59.9 Ma
40 – 50°C	-6	1.9	$1/_{64}$	0.02	0.038	59.9 – 58 Ma
50 – 60°C	-5	3	$1/_{32}$	0.03	0.09	58 – 55 Ma
60 – 70°C	-4	2	$1/_{16}$	0.06	0.126	55 – 53 Ma
70 – 80°C	-3	3	$1/_{8}$	0.125	0.375	53 – 50 Ma
80 – 90°C	-2	16.5	$1/_{4}$	0.25	4.125	50 – 33.5 Ma
90 – 100°C	-1	2.5	$1/_{2}$	0.5	1.25	33.5 – 31 Ma
100 – 110°C	0	11	1	1	11	31– 20 Ma
110- 120°C	1	7.5	2	2	15	20 – 12.5 Ma
120 – 130°C	2	12.5	4	4	50	12.5 – 0 Ma
					TTI=82.0068	

b) TTI Calculations for Upper – Middle Eocene (Marai Ascia-Coriole Transition) in Coriole-1 Well

The total calculated TTI for (Table 4.12) was estimated at a value of 10.835. This suggests that this source rock has just entered the oil generating window, and might be responsible for the expulsion of protopetroleum from this interval.

Table 4.12: TTI Calculations for Upper – Middle Eocene (Marai Ascia-Coriole Transition) in Coriole-1 well

Temperature interval	**N**	**Time factor**	r^n	**TTI Interval**	**TTI Cumulative**	**Ages** Ma
20-30°*C*	-8	0	$1/_{256}$	0.004	0	56.9 – 56.9 Ma
30 – 40°*C*	-7	1	$1/_{128}$	0.008	0.008	56.9 – 55.9 Ma
40 – 50°*C*	-6	2.9	$1/_{64}$	0.02	0.058	55.9 – 53 Ma
50 – 60°*C*	-5	4.5	$1/_{32}$	0.03	0.135	53 – 48.5 Ma
60 – 70°*C*	-4	17.5	$1/_{16}$	0.06	1.1025	48.5 – 31 Ma
70 – 80°*C*	-3	11	$1/_{8}$	0.125	1.375	31 – 20 Ma
80 – 90°*C*	-2	7.5	$1/_{4}$	0.25	1.875	20 – 12.5 Ma
90 – 100°*C*	-1	12.5	$1/_{2}$	0.5	6.25	12.5 - 0 Ma
					TTI=10.835	

4.9.7 Sedimentation Rate Curve for Merca-1well

The Upper Cretaceous (Maastrichtian) shows moderate sedimentation rates of 82.8’/Ma from about 68 Ma to about 61 Ma (Late Maastrichtian to Selandian times) which is represented by the Jessoma and Auradu-Jesomma transition formations. The deposition was interrupted by an uplift during the Selandian (mid-Paleocene) time (60Ma)

The highest sedimentation rate of about 990'/Ma comes from Selandian – early Ypresian times (61-56Ma) and the Priabonian (35Ma). The Lower/Upper Eocene began with low sedimentation rates of about 37.7’/Ma, succeeded by an uplift at around 35Ma. During the Bartonian – Chattian (Mid Eocene – Late Ologocene, 39–26Ma) period, the rates increased again to 225.6/1 Ma. An uplift probably occurred at the Chattian time (25Ma). These are represented by sedimentation rates for Late Oligocene – Early Pliocene (Obbia-Somal formations) times estimated at 153’/1Ma. The Sciuscuban formation demonstrated the lowest sedimentation rate of about 6.6 ’Ma (Figure 4.62).

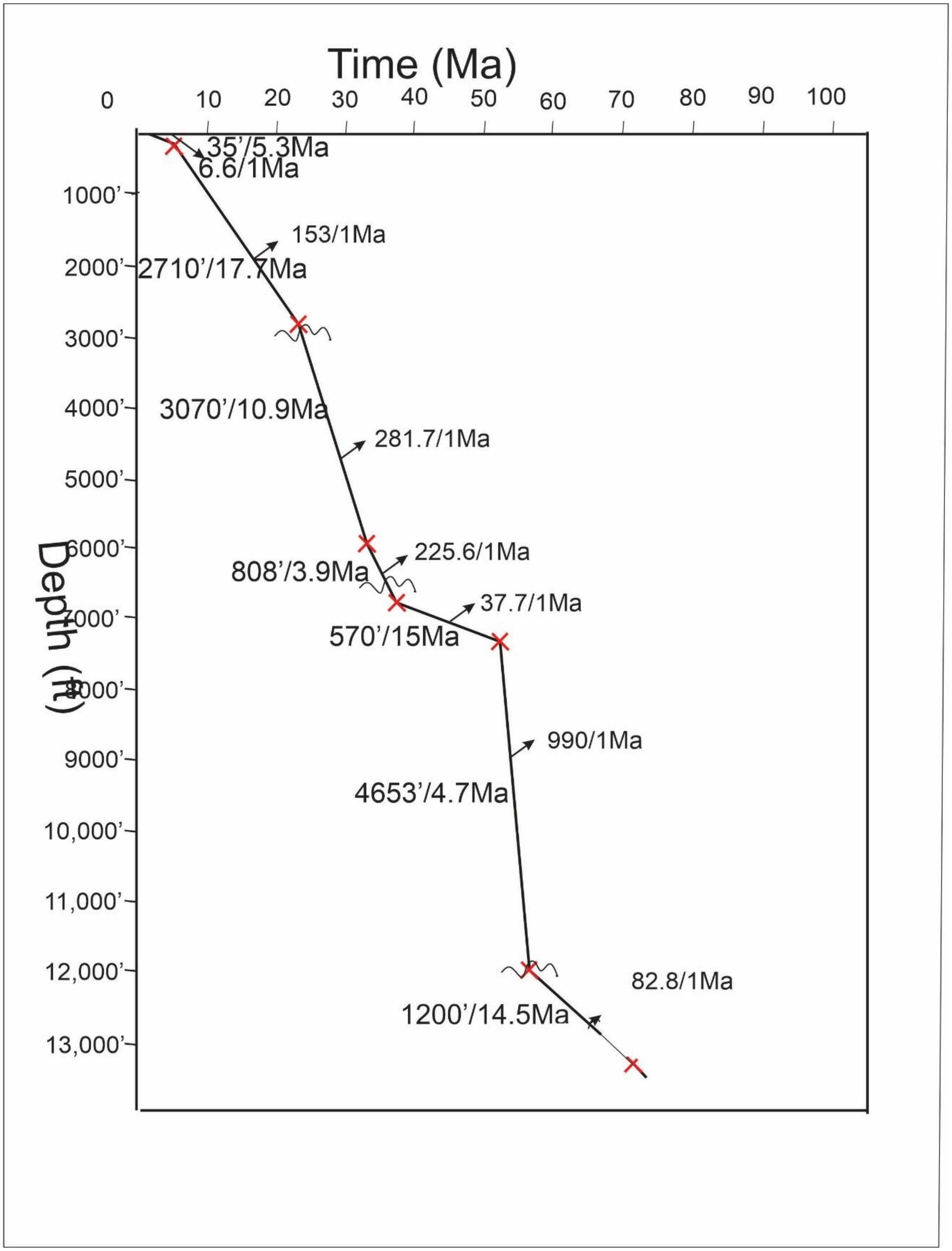

Figure 4.62: Sedimentation Rate Curve for Merca-1 Well in Coriole Basin

4.9.8 Burial History Curve for Coriole Basin Merca-1 Well

Burial history curves are generated for the well, comprising of 6 curves corresponding to the oldest (Jesomma) and youngest (Pliocene-Present) rock layers, for the last 72.1 million years. These curves demonstrate that the accumulation of Late Cretaceous – Recent sediments within the Coriole basin was continuous with an exception of the three unconformities between 43 to 29 Ma, 60 to 50 Ma and 26 to 15 Ma. The formations preserved their thickness all along throughout the sedimentation. According to the TTI modelling, the Middle Eocene Taleh formation has a TTI of 84.8 corresponding to Peak oil window. The temperature gradient at the surface of the Merca-1 well is 27ºC/Km and the bottom is 167ºC/Km.

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Burial curve for Merca-1 well

BHT----------------- 170°*C*

ST-------------------- 27°*C*

T.D-------------------- 13118 ft

Age M.a	Age M.a	Formations	Depth (ft)	Thickness (ft)	TTI	HC State
	5.3	Pliocene	35'			Immature
17.7	23.03	Merca Fm	2745'	2710'	1.14	
10.9	33.9	Somal sandy Mb	5815'	3070'	3.2	
3.9	37.8	Karkar Fm	6695'	808'	24	Early Oil
15.2	52.9	Taleh Fm	7265'	570'	84.8	Peak Oil
4.7	57.6	Auradu Fm	11918'	4653'	440	Wet Gas
14.5	72.1	Jesomma Fm	13118'	12000'	824	Dry Gas

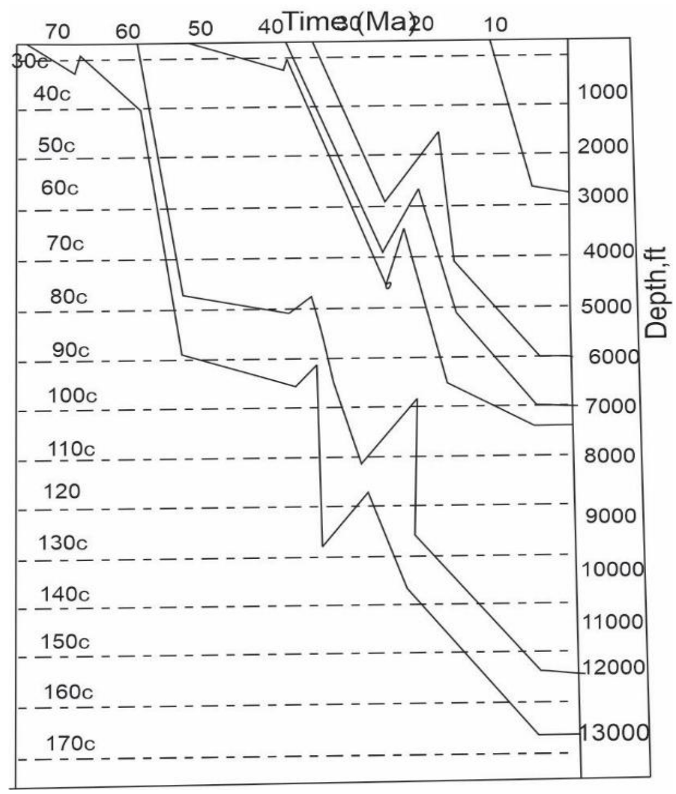

Figure 4.63: Burial History Curve for Merca-1 well

4.10 Discussion

Afgoi-2 penetrated thick sedimentary rock formations ranging in age from the Upper Cretaceous to the Tertiary. Table 4.13 includes all the data characterizing the maturation of the source rock intervals developed in the Afgoi-2 well section. These include the formations, sedimentation rates, Time Temperature Index (TTI), Total Organic Carbon (TOC), vitrinite reflectance (Ro), and unconformities.

A comparison of TTI values for contemporaneous rock formations from neighbouring wells (Afgoi-1, Merca-1 and Coriole-1) is provided in (Figures 4.64 and 4.65)

According to it, Jesomma formation from wells Afgoi-1 and Merca-1 is within the wet and dry gas window (TTI values = 224.9 – 824.1). The Paleocene-Eocene source rock intervals (Seriole-Auradu transition-Obbia-Somal-sand member formations) for almost all 4 wells are within the Early and Peak Oil zones (TTI = 11.8- 82).

The Oligocene – Miocene (Scusciuban-Somal-transition-Somal formations) are immature throughout the Coriole basin. The TTI values provide additional information on what hydrocarbon products will be expected within the Coriole basin. These are dry – wet gas and normal oil products.

Table 4.13: Comparison Chart of the Ages, Depth, Formations, Thicknesses, Sedimentation Rates, TTI, TOC, Vitrinite Reflectance (Ro), and Erosion and their source rock Status for Afgoi-2 well in Coriole Basin

O	Ages Ma		Depth (FT)	Formations	Sedimentation rate	TTI	TOC	Ro	Erosion	Source Rock Status
1	Pleistocene	0 Ma	0o							
2	Pliocene	2.5 Ma	80-	Scusciuban fm	217.7’	0.06	0.3 %			IIMMATURE
3 4	Middle-Miocene - Tortonian - Serravalian	11.6Ma 13.5Ma	2050’- 2670’- 4650’	Scusciuban-Somal transition Somal fm	575’	0.3 1.3	0.5 % 0.2 %	0.001 %	**B/w** M-Miocene – Oligocene unconformity eroded section around 610ft an age 4ma	
5	Oligocene/Miocene	23.03 Ma	5000’	Somal sand member	105’	2.9	1%	0.004 %		
6	Eocene/Oligocene	33.9 Ma	6030’	Obbia fm	145.5’	3.08	1%			
7	Eocene (Priabonian)	37.8 Ma	6850’	Seriole fm	143.6’	3.5	0.8 %	0.1%		
8	Eocene (Lutetian)	47.8 Ma	7290’	Seriole-Auradu transition	87’	5.9	0.6 %			
9	Lower Eocene (Ypresian)	56 Ma	9490’	Auradu fm	268.3’	10.3	0.5 %	0.1%		
	Upper palaecene-Thanetian	59.2 Ma	12000’	Auradu equivalent	784.4’	44	0.8 %	0.3%		MATURE
10	Upper Lower Palaeocene-Selandian	61.6 Ma	13290’	Auradu Equivalent	537.5’	90.2	0.8	0.6%		
11	Lower Palaeocene – Cretaceous	66 Ma	13470’	Auradu equivalent - jesomma transition	40.9’	95.4	1%	1.2%		
12	Maastrichtian	72.1 Ma	13761’	Jesomma fm	47.7’	121.8	0.9 %	1.3%		

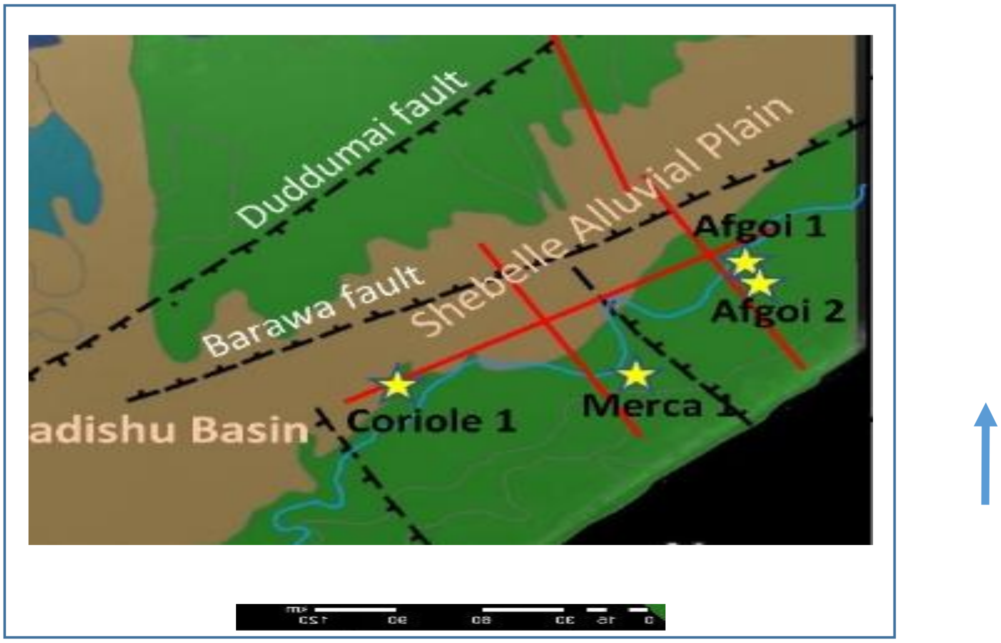

Figure 4.64: Location map of the wells used for the regional Time Temperature Index (TTI) modelling

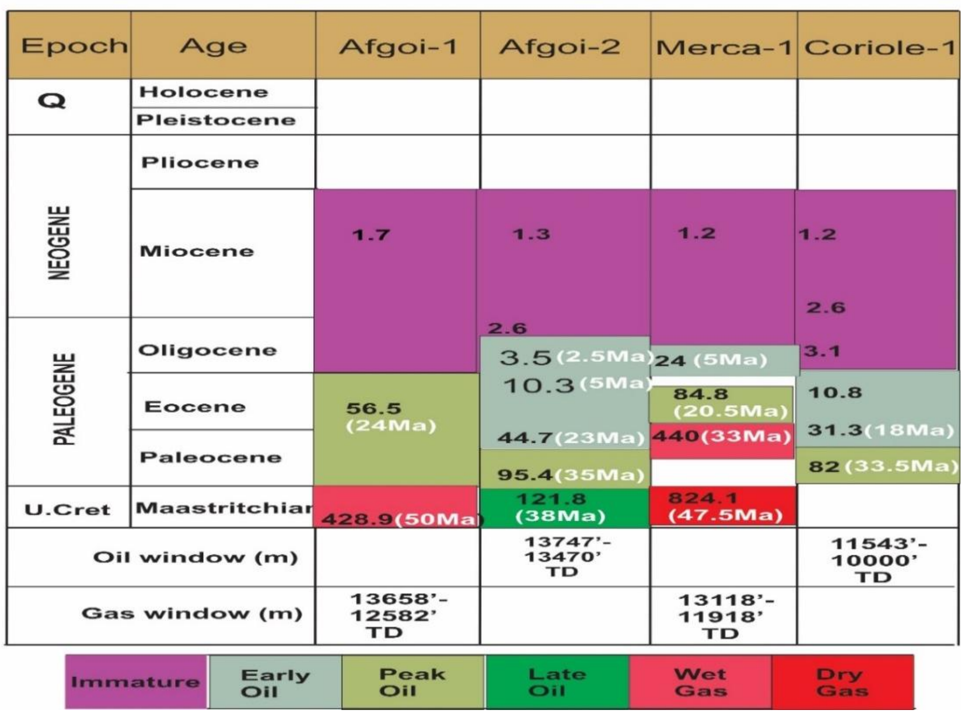

Figure 4.65: A comparison chart with the Time Temperature Index TTI values obtained for Afgoi-2 well and the comparison with the four neighboring wells and their Coriole Basin oil or gas expulsion time.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i) The mapping of the stratigraphic sequences has been achieved through the integration and interpretation of 2D seismic and well-log data. Both datasets revealed that the Coriole sedimentary basin is infilled with sediments belonging to twelve (12) formations. From the bottom to top, these are: a) Maastriachian (Jesomma Formation), b) Upper Lower Paleocene – Upper Cretaceous (Aurada-Jesomma transition), c) Upper Lower? Paleocene, d) Upper Paleoceone (both Auradu Equivalent), e) Lower Eocene (Auradu Formation), f) Middle Eocene, Pnabonian (top Seriole-bottom Obbia formations, h) Oligoceone (Obbia-Somal Sand Member – bottom Somal formations), i) Lower Miocene (mid-Somal formation); j) Middle Miocene (top Somal-Scusciuban – Somal transition) and k) Middle Miocene and younger (Scusciuban formation). This mapping exercise resulted in the generation of a series of 2D/3D elevation time and depth maps for the above listed formations.

ii) All components of the petroleum system (source rock, reservoir rock, hydrocarbon traps and seals, and migration pathways) have been determined within the thick sedimentary infill. Their distribution across the survey area has been mapped, enabling the development of a synthesized basin model.

Based on the classification, all petroleum systems (PS) developed within the Coriole basin are hypothetical or fictional (!). Magoon et Dow (1994) define this PS type as one that has an identified source rock interval but does not have geochemical data correlating the source rock and oil/gas accumulations.

Petroleum system analyses of the available data from the Coriole basin enabled us to specify (select) three (3) petroleum systems. These are (a) the hypothetical or fictional (!) Jesomma – Auradu Equivalent (Sagaleh-Marai Ascia), (b) the hypothetical or fictional (!) Seriole (Sebeli) – Obbia – Auradu, and (c) the hypothetical or fictional (!) Somal Petroleum Systems.

iii) The 2D seismic data interpretations resulted with elevation (time and depth) and thicknesses (isochore and isopach) maps that were the basis in the understanding of the major structures developed within the Coriole basin. According to these results the basin is a product of wrench (strike-slip) tectonics which is characterized by specific type of structures and deformations. This led to the formation of flower structures whose control on the petroleum occurrence has yet to be determined. Wrench fault tectonic settings are known for prominent hydrocarbon discoveries with classical examples, such as, Newport-Inglewood and Whittier Fields in the Los Angeles Basin, oil fields of the San Joaquin Valley in California, Scipio-Albion Oilfield in Michigan basin, oilfields of central and south Sumatra, Panuco field in Mexico, and many others. The obtained interpretations provide encouraging results suggesting that similar hydrocarbon discoveries can be made within the onshore sector of Somalia. The recognition and significance of wrench tectonics in the Coriole basin will influence future preparations of the exploration program. A total of six (6) additional drilling locations have been proposed based on the elevation structural and thicknesses maps interpretations.

iv) The interpreted 2D seismic sections revealed the common development of flower structures whose splays merge at different depths. These faults are associated with wrench (strike-slip faulting) tectonic settings. Similar structures have been reported from the Lugh-Mandera basin, located to the north of the study area and also from the offshore in the Somalia basin, indicating its regional character. Hydrocarbon traps associated with wrench faults are structurally complex. Seismic data indicates that these faults have affected most of the stratigraphical column, and they ceased somewhere in the middle of the Miocene, or possibly later. The generated elevation time and depth maps detected at least two regional structure highs located in the south-western (Coriole drill site) and north-eastern (Duddumai drill site) areas. Historically, the south-western Coriole high has reported some commercial oil and gas shows from the Cretaceous and Eocene reservoirs. Several additional infill drill sites have been proposed, and denoted as potential wells, i.e, Potent. Coriole-3 Potent. Duddumai-2 potent and Duddumai-3 in Figures 4.13-4.28.

v) Three (3) source rock intervals have been selected from the obtained Afgoi-2 TOC values. These are: a) Jesomma-lower Auradu formation interval (9190-13710’) with an average TOC value of 0.86 wt. % and b) Seriole-Auradu transition – lower Somal Sand Member interval

(4920-7330’) with an average 0.90 wt. % TOC content, c) Somal formation (2080-4560 with an average of 0.34 wt% TOC content.

Among them, the TTI calculations have demonstrated that the first two intervals are mature and have/ are still potentially generating hydrocarbons, namely light oil products. Their thicknesses increase towards the offshore part of the Somali Coastal basin. The third topmost source rock interval is largely immature and has no HC generating potential.

TTI modeling calculations provided a convenient and relatively simple guide method for evaluating the source rock's maturation and HC generating potential.The results demonstrate that the Jesomma and Jesomma-Auradu formations are mature to generate some normal light oil to condensate wet gas hydrocarbon products. In Afgoi-2, the Jesomma-Auradu Equivalent formations have considerable TTI values in the range of 44.71-111.79 corresponding to virtriate reflectance (Ro, %) of 0.85-1.15 (Waples, 1985). The correlation of the selected TTI values with the hydrocarbon generation corresponds to the peak or late oil generation. TOC values for these formations range between 0.20-1.86 (wt%), with an average of 0.79 (wt%) which qualifies it as a fair source rock. It is expected that these formations with average TOC values could have potentially generated normal light oil and condensate wet gas products. The TTi also suggested that the Lower Eocene Auradu Formation began to expel some oil around 9.48 Ma (Tortonian, Late Miocene) and is still within the Early oil generating window (Waples, 1985). The remaining, overlying stratigraphic section is immature with TTI values ranging between (3.089 for the Lutetian, and Mid Eocene) and 1.3003 for the Eocene/Oligocene strata.

Well Merca-1 which is located to the southwest of Afgoi-2 encountered these contemporaneous rock formations. The TTI values demonstrate that the Jesomma-Sagaleh and Auradu formations of this well are within the wet gas generation window (401.13 – 868.91), and correspond to Vitrinite reflectance (Ro) values of 1.35-2.00 (Waples, 1985). This implies, that the maturity of the Late Cretaceous – Early Paleogene source rock increases towards the south-west.

vi) The results of isopach and isochore mapping indicate that the kitchen zones of the source rocks are located in the central and southern parts of the survey area (Figure 4.49). The reservoirs identified include the Combined Jessoma-Auradu Transition Zone Formation of the Late Cretaceous to Early Paleogene Period, the Auradu Equivalent comprising the Sagaleh/Marai Ascia (composed of mainly limestone and sandstones), and the lower parts of the Marai Ascia Formation of the Early Palaeocene to Late Palaeocene and the Auradu Formation, including (top Marai Ascia-Coriole Formation) of Early Eocene carbonates (dolomite) composition. There is only one seal within this petroleum system, which is the Seriole-Auradu Transition Formation of the Middle Eocene-Lower Oligocene due to its increased shale/clay content. The formation is about 2030' thick. Two main structural features that acted as the traps and are common in the survey area combination are a) stratigraphic traps related to unconformities (hiatuses) between Middle Miocene and Lower Miocene, between Lower Oligocene and Upper Eocene, between Lower Palaeocene and Upper Cretaceous, b) structural traps are related to anticlinal folds, wrench fault positive flower structures. The third trap includes the combination of structural and stratigraphic features that form anticlinal traps and stratigraphical (unconformity) times. The migration of the expelled hydrocarbons occurred toward the elevated parts of the reservoirs, creating primary and secondary migration pathways. Future 3D seismic surveys could assess the conduit and entrapment potential of the wrench/strike-slip faults.

5.2 Recommendations

These interpretations should be considered for future exploration activities. The main target drilling formation within the Somalia Coastal Basin was and still remains the Late Cretaceous Jesomma sandstone reservoir formation. The generated subsurface maps for this formation (Figures 4.42 and 4.44) enabled us to select at least three (3) potentially promising infill drilling sites. These are Duddumai-2 and Duddumai-3, located in the north system reservoir sector of the map, and Coriole-3, located in the south-western corner of the map (for location see coordinates provided in subchapter 4.5-Potential Future Drilling Site). The depth targets for all sites are in the range of 1400-2500 meters below the surface. The TTI calculations suggest that the likely hydrocarbon products trapped and stored in these two potential mapped closed structures are represented by normal-light oil products. A good indication for this is the results of test production of 100 barrels/day of 44°API paraffinic oil shown from the

Jesomma sandstone from the neighbouring Coriole-1 well at 11540’, in addition to gas with a reported GOR of 14000, aromatics, and low sulphur (Barnes, 1976).

The Temperature Time Indexes (TTI) modelling and geochemical analysis of the Afgoi-2 well were compared with those of neighbouring wells (Afgoi-1, Coriole-1, Merca-1). This can be used to aid proper decision-making for an upcoming drilling exercise within the Coriole subbasin. The nearby Coriole structure reported 2 billion barrels (bbl) of oil discovered in Eocene limestones and 2 million cubic feet per day (MMCF/D) of gas and condensate from Upper Cretaceous volcanics.

The obtained results promise future discoveries of hydrocarbons, in particular, light crude oil. More seismic lines would be necessary and should be positioned to map the area along the southern and northern sectors.

The proposed infill drilling locations should be additionally examined through a set of 3D seismic survey profiles. Detailed geochemical analysis must be undertaken to assess the results of the TTI modelling.

The proposed target zones for the drilling have been achieved based on the analysis and results of isochore and isopach map preparations. The proposed infill drilling locations will test the potential sandstone reservoirs of the Jesomma Formation.

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APPENDIX A: GSA Geological Time Scale