UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

TECTONIC IMPACT ON REGIONAL STRUCTURAL TRENDS IN ULTRA DEEP WATER CAPE THREE POINTS

DOKU DANIEL
(10242628)

THIS THESIS IS SUBMITTED TO THE DEPARTMENT OF EARTH SCIENCE OF THE SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCE UNIVERSITY OF GHANA, LEGON, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN GEOLOGY.

JULY, 2015.

DECLARATION

This is to certify that this thesis is a result of research work undertaken by Daniel Doku, towards the award of Master of Philosophy in Geology in the Department of Earth Science University of Ghana

……………………………. .   Date: ………………

DOKU DANIEL

(Student)

.

…………………………………   Date…………………

Prof. David Atta Peters

(Lead supervisor)

………………………………   Date………………

Dr. Isaac A. Oppong

(Co-supervisor)

ABSTRACT

A 3D seismic data merged with a regional 2D seismic data and well data acquired from Ghana National Petroleum Corporation were used to determine the tectonic impact on regional structural trend in the Ultra-Deep Water Cape Three Points. The Cape Three Point basin was fashioned from transform tectonic and has been severely influenced by the largest tectonic feature in the central Atlantic Ocean, the west-southwest – east-northeast (WSW-ENE) romanche fracture zone. The study area lies over water depth of 100 m in the east and 2500 m in the west. In the cube (three dimensional seismic data) four (Intra Late Albian, Cenomanian Unconformity, Top Cenomania and Seabed) surfaces were interpreted in addition to the interpreted regional seismic lines. Regional scale faults a long WSW-ENE (regional 2D) seismic line had NE-SW trend forming half grabens in the pre rift block accommodating syn rift sedimentation. In map view syn-rift faulting were trending NW-SE. This extensional regime in the study area was characterized by growth faults, relay structures and rotated fault blocks. Faulting died before Top Cenomanian. Moving deeper into the basin compression produced ridges (three way dip structures) which were trending NE-SW. The post-rift formation was characterized by polygonal faults. Tertiary sequence had an unconformity probably as a result of fall and rise in sea level. NE-SW Canyons also incised the seabed.

DEDICATION

I dedicate this thesis to the Almighty God for his blessings and grace throughout this research.

ACKNOWLEDGEMENT

My biggest gratitude goes to Mr. Gabriel Osatey for coming up with the thesis title and for his tremendous supervision. Also to Mr. Benjamin Asante and Mr. Eben Apesegah all of the Ghana National Petroleum Corporation, for their support.

My profound thanks to my spiritual father Michael Owusu Antwi for his enormous contribution in my life and also to my brothers Korletey Kweku Divine, Joshua Ayertey and Mr. William Nkrumah (GNPC) for their diverse help. Also to Mr. Hope Kodzie (GNPC) for his awesome assistance and Ernest Kodzie for their tireless support.

I wish to express my sincerest thanks to my supervisors: Prof. David Atta Peters, Dr. T. K Armah, and Dr. Oppong for their support, guidance and invaluable contribution towards the successful completion of this thesis. Special thanks to my Departmental head Prof. Prosper Nude and all the lecturers at the department of Earth Science, University of Ghana for the academic guidance offered to me throughout this research.

Appreciation is also extended to the Ghana National Petroleum Corporation (GNPC) for allowing me to have access to their data and workstation. I gratefully acknowledge the support of Mr. William Asam and Ernesto (GNPC). Not forgetting Shatta Victor, Johney, UG, Evelyn, Alfred, Nat, Sena, Stevo and the entire geophysics and geology team (GNPC).

Finally, I wish to quote from Philippians 4:13, ‘‘I CAN DO ALL THINGS THROUGH CHRIST WHO STRENGTHENETH ME’’

TABLE OF CONTENT

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

CFZ	Chain Fracture Zone
SFZ	St. Paul Fracture Zone
RFZ	Romanche Fracture Zone
CU	Cenomanian Unconformity
GNPC	Ghana National Petroleum Corporation
TU	Tertiary Unconformity
Ma	Million years
LA	Late Albian
ILA	Intra Late Albian
TWT	Two Way Time
TC	Top Cenomanian
NE	Northeast
SW	Southwest
WSW	West-Southwest

CHAPTER ONE

INTRODUCTION

1.1 Background

Basin formation is a direct result of tectonics irrespective of the setting, being it intracontinental or marginal. Since the Late Paleozoic, the progressive fragmentation of Gondwana has led to not only major basin formation along the present-day continental margins but also to the distinction of intra-continental rift stages of the basin development within the African continent (Dirk, 1991). In the South American and Africa lithospheric plates, the Equatocentral Atlantic province is one unique area. Geological evolution and Phanerozoic structures in this province have both been influenced by few but long transform faults which started at the end of Early Cretaceous and are active till this day. These transform faults are the Chain, the St. Paul, and the Romanche fracture zone which has mainly affected the Ultra-Deep Water Cape Three Points basin. This tectonic feature combine with the plate tectonic rifting have activated many structures within the basin and also influenced deposition of sediments within basins (Mascle et al., 1998).

The Cretaceous rift basins are important for assessing hydrocarbon prospectivity. This thesis is a contribution to further offshore recent explorations focused on deep water and summarizes the results of the tectonic evolution study of Equatocentral Atlantic in evaluating the impact of tectonics on regional structures. The result was based on interpretation of regional 2D and 3D seismic data. This involved Structural interpretation which has varied applications. This conventionally means picking and tracking consistent reflectors of processed seismic data aimed at mapping geological structures, reservoir architecture or stratigraphy (Rotima et al., 2010). Understanding subsurface configuration in detail is necessary to be able to accurately detect suitable structures for the accumulation of hydrocarbons. The reason is that hydrocarbons usually occur in geologic and structural traps, which could be any lithologic structure which prevents oil and gas from either horizontal or vertical escape. Trapping in the study area are both stratigraphic, related to depositional or diagenetic features in the sedimentary sequence and structural formed by deformation of rock (Sutherland and Kyei, 2010). However, the application of structural interpretation from tectonic evolution to this research has been narrowed to the description of structural trends.

1.2 Problem Statement

In the past, three dimensional marine geophysical (seismic) dataset of ultra-deep water basins were not available due to lack of appropriate technology. Available data sets were of shallow waters (less than one hundred kilometers) offshore in the Cape Three Points area. This mitigated work done in deep water part of the basin to effectively tell the structural trend inherited from tectonic impact. More so previous workers of deep water Ghanaian basins used only two dimensional regional seismic data in their interpretations which could not properly image the subsurface structure to tell the trends.

1.3 a. General Objectives

Identify the tectonic structural trend in the study area

13 b. Specific Objectives

This project will address the following objectives:

1) Identify tectonic regimes in the various rift stages which took place in the study area;
2) Map large scale structures and identify their structural trends within the study area;
3) Produce schematic models of localized structures and synoptic 3D diagram of the study area; and
4) Discuss the tectonic evolution of the study area.

1.4 Justification

In recent year's sophisticated technological advancement have led to the acquisition of a 3D dataset in the Ultra-Deep Water Cape Three Points area. Seismic Structural interpretation of this 3D data set merged with a 2D regional data will better image the subsurface, add knowledge to literature and help in the interpretation of the impact of tectonics in the Ultra-Deep Water Cape Three Points basin. Structural interpretation is also an important aspect of the development programme and also in 3D, aid to efficiently investigate controlling effects on the geometry of reservoir, position and also the pathway migration of hydrocarbons. Combination of structure and stratigraphy can agree to the spatial correlation of the tectono-stratigraphic sequence. Occasionally reserve estimation may depend on interpretation of structures when located fluid contacts on depth structure maps become essential for volumetric analysis.

1.5 Thesis Outline

Chapter two covers the tectonic background of the basin's history. It discusses the tectonic kinematics and explains the evolution of larger equatocentral Atlantic Basin through geologic times. It also discusses the contribution of tectonic activities to the faulting patterns and subsurface structure since the initiation of the Cape Three Points Basin.

Chapter three describes the systematic procedure for the interpreted results in chapter four. Chapter four shows and discusses the result obtained from the interpretation of the seismic volume and the regional 2D line based on the objectives and method applied. The interpreted result from the data is related to the geology, tectonic setting of the basin and stress strain relationship. Schematic modules are also created in this chapter to throw more light on the subsurface structural module of both localized and regional interpreted structures and surfaces.

Chapter five are conclusions which are summary of the results and discussion.

1.6 Software

The following software was used for the research project:

- Kingdom Suite: For geological and geophysical interpretation of seismic and well data.
- Adobe Photoshop: For regional structural module.
- Microsoft Office: For spreadsheet, word processing and image editing.

1.7 Description of Study Area

The Study Area covers a portion of the Vanco block in Ultra Deep Water Cape Three Points Basin (UDWCTP) offshore Ghana (Figure 1.1). It is approximately five thousand square kilometers, which includes a three dimensional seismic volume of approximately 760 square kilometers merged with several regional seismic lines. It is located about 110 km offshore. The Vanco block lies within the near the eastern part of the Cote d Ivoire Basin in western central Ghana between the continental shelf break and the lower slope and over water depth of 100 m in the east and 2.5 km in the west The coordinates of the study area lies between lattitude $4^0$00'N and $4^0$50'N and longitude $1^0$40'W and $3^0$25'W (GNPC 2014).

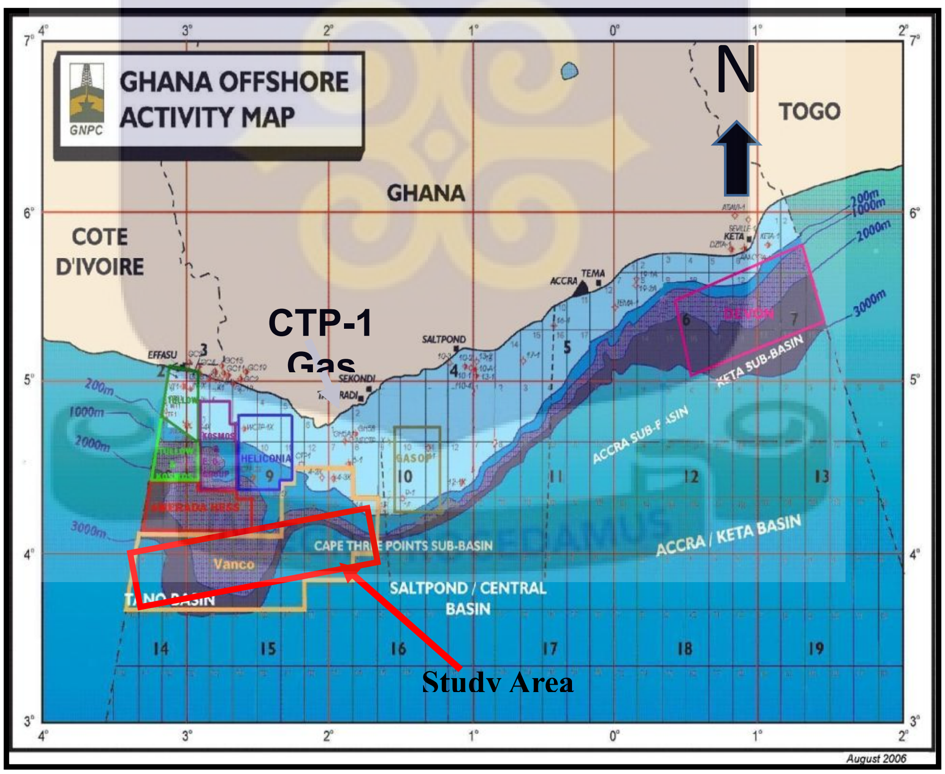


Figure 1.1 Activity map showing Cape Three Points (Vanco block) with other sedimentary basin (GNPC 2014).

1.8 Tectonic Setting of the Cape Three Points Basin

The Cape Three Points Basin is a Cretaceous wrench modified pull-apart basin (Chierici, 1996), bounded by the Saltpond Basin, Tano, Precambrian Birrimian shield and Romanche fracture zone to the east, west, north and south respectively. The basin is the eastern extension of the larger Cote d'Ivoire-Ghana Basin and also an east west basin which occupies an area of about 5142 km^2. The Cape Three Point basin was fashioned from trans-tensional movement during Africa and South America separation.

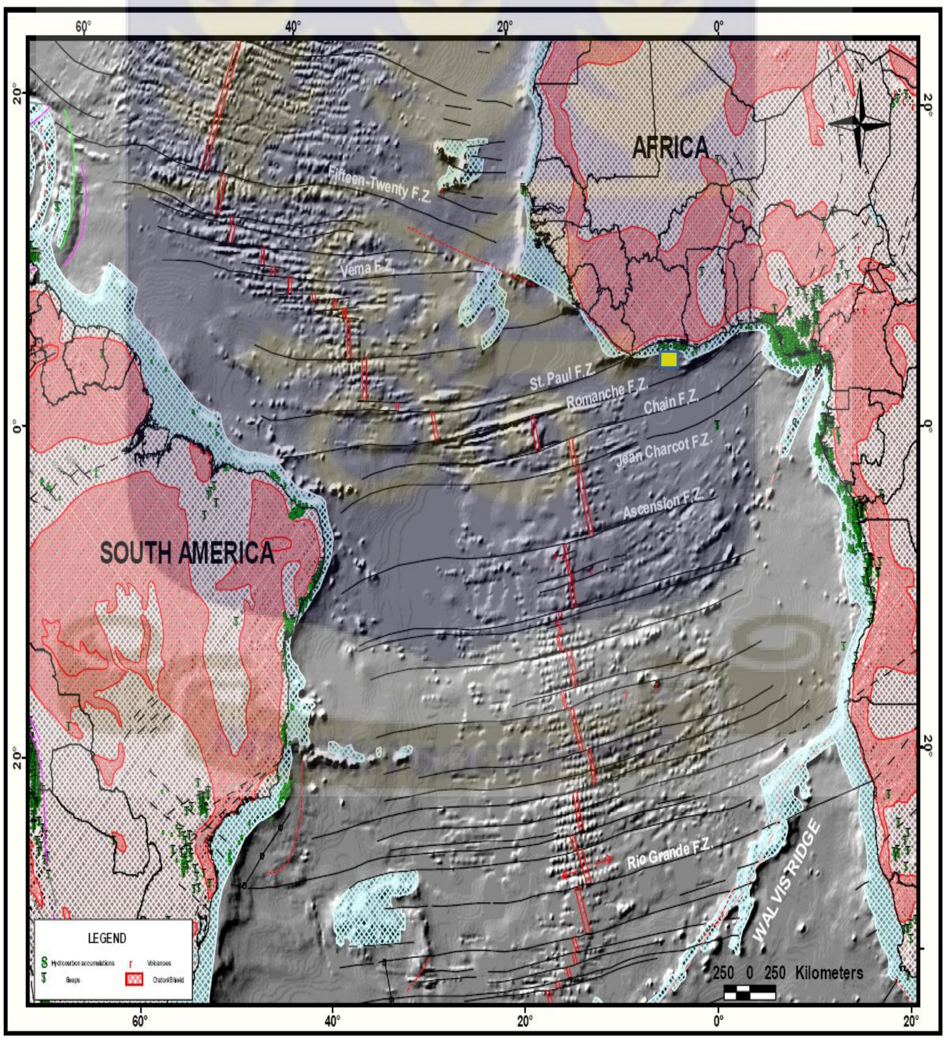


Figure 1.2: Map of South American and West African margins showing the series of transform faults and fracture zone, the yellow square shows the study area (Blarez and Mascle, 1988)

A large rift basin developed in the area by Aptian- early Albian time. Subsequently in middle-late Albian times there was widespread deposition characterized by shallow marine shelf to shore face sandstone and shale with minor limestone in several depositional units including newly named Bonyere Voltano and Tano formations (Sutherland and Kyei, 2010). Continental rifting propagated northwards from the South Atlantic, forming a continuous anoxic seaway in the West African Transform Margin between the Late Albian to Turonian. This led to the deposition and preservation of organic matter which now forms the Basin's lacustrine Upper Albian, Cenomanian and Turonian source rocks.

In the Upper Cretaceous, the Cape Three Points Basin became a focus of deposition and thick clastic sequence consisting of fluvial and lacustrine facies were deposited. This sequence, additionally to the thin Tertiary section, provided adequate thickness to mature the Cretaceous source rocks in the Basin (Kulke, 1995).

Stratigraphically trapped Albian and Cenomanian turbidite sandstones, form the thick clastic sequence act as the main reservoir within the basin, while marine shales form a seal. As reservoir rocks are predicted to be in close proximity to the source rocks, a minimal hydrocarbon migration pathway is assumed.

Also river system from onshore gave way to the deposition of large turbidite fan/channel complexes in deep water (Adda, 2013). Submarine fans are usually identified in map view as radial-, cone-, or fan-like morphologies across the seafloor. Submarine Canyons are erosional V- Shaped features that gash the world's continental margin. Again, incessant extension and subsidence made room for the deposition of thick shale and sandstone which formed stratigraphic traps for oil in the margin. The basin after the Cenomanian age received sediments deposition of many canyon sands ranging in age from Turonian to possibly Lower Paleocene.

In general sedimentation is over 4 km thick and has Cretaceous working play, which comprises of Cenomanian-Turonian and Albian shales as source rocks with Turonian slope fan, turbidite sandstones and Albian sandstones in tilted fault blocks as reservoirs (Sutherland and Kyei, 2010). Movement along a series of transform faults chiefly in the Romanche Fault Zone during this continental parting led to the development of the large rift basin.

1.9 Stratigraphy of the Western Basin

The information summarized in this section is in large part the result of the study conducted by Petro-Canada International Assistance Corporation on behalf of Ghana National Petroleum Corporation (RRI, 1998).

Sedimentary infill of the initial rift phase of the Western basin consists of more than 4000 m of lower cretaceous (Aptian to lower Albian) sandstone and shale, mainly non-marine in the lower section but increasing marine- influenced in the upper part, where thick sandstone units form oil and gas reservoirs in the area. This thick rift-fill unit, the Kobnaswaso formation, surrounds and buries a large tilted block, the central Cape Three Points structure, which may be cored either by early cretaceous or Paleozoic (including Devonian) rocks.

Middle and Upper Albian sedimentation in the Western Basin was characterized by shallow marine shelf to shore face sandstones and shales in several depositional units, including newly-named Bonyere, Voltano, and Domini formations. Fault-bounded tilted structural blocks are a product of early Albian tectonics (RRI, 1998).

Final separation of West African and Northern Brazil continental plates and opening of equatorial Atlantic ocean south of Ghana occurred at the of Early Cretaceous (Albian) or earliest Cenomanian time, and resulted in faulting, uplift and erosion along the outer margin of the Cape Three Points basin and creation of structural trend. Subsequent Upper Cretaceous sedimentation was dominantly open marine in character, with porous sandstones in the near shore and onshore settings. The end of Cretaceous time was marked by widespread deposition of very porous shelf and shoreline sands. A series of marine tertiary sediment wedges completed the sedimentary fill of the Western Basin (RRI, 1998).

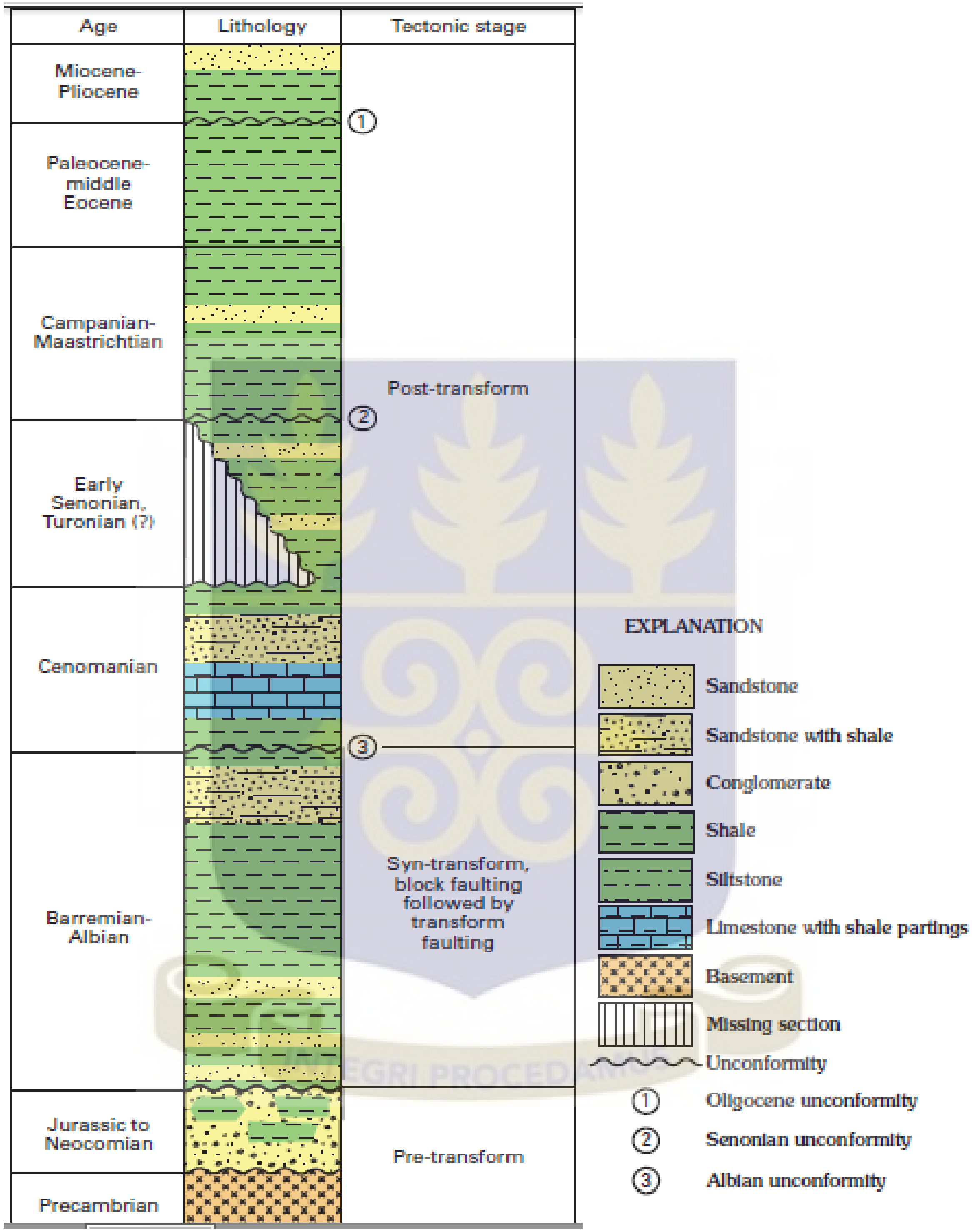


Figure 1.3 Generalized stratigraphy Cape Three Points, Gulf of Guinea Province Modified from Chierici (1996).

Earlier the oldest drilled section in the western basin was found to be Aptian to lower Albian Kobnaswaso formation, which is more than 2 km thick. The oldest drilled rocks are early cretaceous (Aptian) in age, but older cretaceous and possibly Triassic to late Paleozoic rocks may be present in the basal western basin. The Kobnaswaso consists of mainly thinly interbedded lithic and feldspathic sandstones and shales, and is interpreted to be dominantly fluvial plain and braided stream in origin. The formation is thick sequence of sandstones, shales and other intermixed lithologies. The sandstones are fine grained to conglomeratic poorly sorted and sub-angular to sub-rounded (RRI, 1998).

A complete section of Kobnaswaso formation has a thickness of 1997 meters. The formation shows a more distal environment of deposition with lower sand/shale ratios and finer grain size and better sorting. The age of the older rocks is Carboniferous. The sandstones have poor porosity and are well cemented. The deposition of the sequence was in terrestrial environment (RRI, 1998).

1.9.1 Aptian-Lower Albian (Kobnaswaso Formation)

The lower Aptian sediments of the Kobnaswaso formation overlie the carboniferous with an angular unconformity. In the basin two mega-sequences (lower and upper) are noticed. The lower mega-sequence comprise of interbedded sandstones which are thin to medium. They are normally fine to sporadically coarse grained, poorly sorted with the porosity being poor likely due to diagenesis. The zone is characterized by olive gery to dark grey, very carbonaceous and micaceous shales. The shales, siltstones and interbedded sandstone are gradational indicating soft-sediment deformation (Davies, 1986).

Shale units characterizes the Upper Kobnaswaso mega-sequence. It is approximately 200 meters thick with interbedded coarsening upward sequence of shales, sandstones and siltstones. According to Davies, (1998) the fine to medium grained sandstone are also poorly sorted, variably argillaceous, calcareous and dolomitic. The shales are sub fissile to fissle, medium dark grey, sporadically calcareous and silty (RRI, 1998). The upper mega sequence is identified by marginal marine conditions. The upper mega-marginal sequence is truncated at some points because of uplift and subsequence erosion in that zone.

1.9.2 Lower to Middle Albian (Bonyre Formation or b shale)

The first major long term open marine transgression in the basin is denoted by this formation. Description of the Bonyere formation is a dark grey, non-calcareous, micro-micaceous fissile, sandy and variably silty. During the deposition marginal to shallow marine condition with strong terrestrial were predominant (RRI, 1998). In the deep part of the basin the shale is blocky to sub fissile, medium to dark grey, variably silty to sandy and micro micaceous.

1.9.3 Uppermost lower Albian to middle Albian (Voltano Formation)

This formation was assigned an uppermost early Albian to middle Albian age according to a study done RRI (1998). The formation thickness is approximately 433 m. In this formation the shales are dark grey, micro micaceous, sporadically silty to very finely sandy and non-calcareous. The sand by stones are medium grained, calcareous with dark grey partings also occurring in parts of the lower formation. Shallow, near shore marine to intertidal depositional setting is credited to these sediments. Nevertheless, the existence of plank tonic foraminifera proposes occasional open marine impact, at inner neritic water depths.

1.9.4 Upper Albian (Domino Formation)

Interbedded sandstones, carbonates and shales are comprised in this formation. They are light grey to grey, moderate to well sorted, generally fine to medium grained, micaceous calcareous and pyretic. Very common is calcite cement yielding poor porosities. Limestone interbeds are generally white to buff, micritic to chalky in texture. The depositional environment of the Domini formation in the shallower areas was fluviatile to near shore becoming more marines towards the end of deposition (RRI, 1998).

The base of the Domini formation in this area is placed at the top of the B shale in a prominent sandstone marker in the sub-basin (Davies, 1986). The thickness of the Upper Albian is about 433 metres. An angular unconformity exists between the top of the formation and the base of the Cenomanian. The Domini formation has been identified in all the deeper areas of the basin.

1.9.5 Cenomanian

In the Cenomanian interval it shows wide changes in lithology and thickness across the sub basin with a condensed carbonate-dominant section above the Cenomanian unconformity in the deeper area. The base of the Cenomanian, is picked at the top of sequence of interbedded sandstone and limestone overlain by a thin sequence of black shale (RRI, 1998).

Two facies of limestone of the Cenomanian are shown in this sub basin: deeper shelf oligostignid limestone that overlies shallow water shoal limestone. Sub formation of both are late Cretaceous in age (Davis, 1986 and RRI 1998). The lower middle Cenomanian in the shallow area is defined by interbedded fine to coarse grained sand with sporadic calcite cement and grey, variably silty mudstone (RRI, 1998). According to RRI, (1998) this unit was deposited under shallow, near shore and fully marine inner neritic conditions. However, slight open marine influence has been observed (RRI, 1998).

A deeper unit signifies a condensed sequence that overlies an eroded Upper Albian section. The middle to Upper Cenomanian sequence is described by thinly inter-bedded tan to brown oligostignid limestones, shales and sandstones. The sandstones are fine to very coarse grained, sometimes calcareous and carbonaceous. Mudstones and minor limestones of the Middle-Upper Cenomanian age here represent low energy, offshore marine conditions.

1.9.6 Turonian

Shallower in the western basin area, the top of the Turonian is picked at the top of series of thinly interbedded sandstones, limestones and shales. The Turonian shale ranges in thickness from 90 m and reducing to about 45 m and is overlain by coarsening-up sandstones (Davies, 1986 and RRI, 1998). Deep within the basin, the Turonian is picked at the top of a shale section overlying the Cenomanian limestones.

1.9.7 Coniacian-Santonian

This formation extends from the Turonian to the Campanian (or the basal Maastricthtian sandstone) and the formation thickness is approximately 412 m. Sediments in this formation are mostly dark grey shales interchanging with medium grey siltstones. Unconsolidated sand horizons are infrequently observed approaching the formation base. There is also a major fining upwards succession in the sequence showing a rise in marine deposition.

1.9.8 Uppermost Santonian to Intra Lower Campanian

The division matches to a sandstone division with thick shale sequences of two. Six unique para sequences are reported to be below the Campanian (Davis, 1986). The sediments include mudstones with occasional thin carbonate stringers. They are normally olive grey to brown sub fissile, black and occasionally silty or glauconitic. The depositional environment throughout the latest Santonian to early Campanian times according to RRI (1998), were marine shelf in the basin.

1.9.9 Lower Campanian to Upper Campanian

Sediments of this formation mostly consist of mudstones with slight carbonate-rich layers. The Upper is branded by the presence of sandstone (RRI, 1998).

Initial short-lived transgressive episodes reaching outer neritic water depths were followed by deposition in a chiefly middle to inner neritic setting. However within deeper part of the basin, deposition was under low energy settings, in chiefly distal shelf setting at outer neritic water depths (RRI, 1998).

1.9.10 Maastrichtian

The thickness of the Maastrichtian sequence is variable in the area. It ranges from about 138 m to 154 m. The Maastrichtian has two sub-divisions, the lower and upper units as stated by both Davies (1986) and RRI (1998). The lower Maastrichtian unit consist principally of coarse grained, unconsolidated and well to poorly sorted sandstone with mudstone interbeds. The mudstones are normally fossiliferous and glauconitic. A general down hole decrease in gamma values is observed as compared with the upper unit. Depositionally, an inner neritic environmental setting existed within the shallow area, while low energy conditions occurred in the Deep area of the Western Basin.

According to Davies (1986), the uppermost Maastrichtian sub-unit rest at the top of the sandy Maastrichtian sequence and is composed of shales or claystones. In the Middle to Upper Maastrichtian unit a conspicuous gamma spike is recognized at the base of the upper unit in disparity to the lower gamma values in the lower sandier unit. This conspicuous gamma spike is understood to signify a possible highly condensed section, (Davies, 1986). The Middle to Upper Maastrichtian is normally branded by the presence of glauconitic mudstones, which register high gamma values. Based on logs, the top is picked at the top of a coarsening up sequence in disparity to the overlying shale unit. Very fine to fine grained sandstones are also existent. The depositional environment for the Middle to Upper Maastrichtian is an offshore, of fully marine setting at middle neritic water depth.

1.9.11 Tertiary Sequences

These sediments range in age from the Paleocene to Upper Miocene. The Paleocene is unconformable on the Cretaceous, which is an interpretation for the nonexistence of the Lower Paleocene in the area (RRI, 1998). Upper Paleocene sediments have been recognized in deep area of the basin. The top of the Paleocene is marked by a down hole increase in gamma ray and resistivity and is composed of largely glauconitic shales. These glauconitic shales are plenty in the south. Normally mudstones here are brownish grey to brownish black, reasonably organic rich. They are also micro - micaceous and slightly pyritic. They indicate the first tertiary transgressive-regressive cycle of sedimentation which probably started during

Thenetian times mainly in the Southern areas of Dixcove (RRI, 1998). They indicate offshore, normally deep marine low energy settings at inner neritic to bathyal water depths.

In the RRI study Lower and Middle Eocene sediments have been noticed. Major regional unconformity in the area has rendered the Upper Eocene absent. The Lower Eocene comprises chiefly of mudstones. They are olive grey to sometimes brownish grey, slightly waxy, organic rich, slightly pyretic and rarely glauconitic. Very fine grained sandstones also occur in insignificant stringers (RRI, 1998). Throughout the interval studied, the sediments show outer neritic water depths and similarly across the western basin; nevertheless, faintly deeper marine conditions were believed to have occurred locally in other parts. Sediments in the Lower to Middle Eocene are brownish grey, organic rich mudstones with sporadic chert layers and thin horizons of somewhat glauconitic limestones.

According to RRI (1998), the sediments were deposited in deep offshore waters at inner water depths. The Lower Oligocene is absent in the shallower areas because of a regional unconformity but in the deeper areas they are present. The lithology comprises of glauconitic, brownish grey and pyritic mudstones with thinly interbedded argillaceous limestones. The Upper Oligocene zone is sparsely developed. The deposition of these sediments was under moderately deep water, offshore marine conditions at outer neritic water depths possibly.

Due to major erosional unconformity in the area, the Lower Miocene sediments are absent in the basin. Nevertheless sediments of Middle and Upper Miocene are present in the area (RRI, 1998) The interval of the Middle Miocene consists of light grey to medium grey, slightly calcareous, fossiliferous and glauconitic mudstones which were deposited in moderately deep open marine waters.

The Upper Miocene interval comprises mainly of mudstones. They are light brownish grey, sometimes silty to very finely sandy, faintly calcareous and occasionally glauconitic with carbonate stringers and minor thin sandstone layers. The deposition of these sediments was probably in deep, open marine condition at outer neritic to upper bathyal water depths (RRI, 1998).

1.10 Previous Work

The work summarized in this section is in large part the result of the study conducted by Luke oil Company on behalf Ghana National Petroleum Corporation (obtained from GNPC 2014).

The Cape Three Points Deep Water Block extends over the southern portion of the Romanche sub-basin within the Tano-Ivorian Basin of Ghana between the continental shelf break and the topographically high Marginal Ridge associated with the Romanche Fracture Zone. This block extends over 1.27 million acres in water depths from 100 m in the northeast to just over 2,500 m in the west. The eastern portion of the block consists of a thick foreland-type basin with compressional en-echelon folds and inverted syn-rift structures formed immediately landward of the ridge and south of the shelf-slope break. Stratigraphic pinch-outs in the foreland sequence and younger turbidite fan complexes are draped over the folded and inverted structures (RRI, 1998).

The seismic data acquired by Vanco revealed an unexpected and unusual structural history of the marginal ridge of Côte d'Ivoire and Ghana. Both reprocessed and new seismic data clearly image a large landward-verging overthrust system in the Cape Three Points Deep Water Block. Since the structural geometries are analogous to those found in classical fold belts and foredeep basins, the same play types can be defined within the Cape Three Points Deep Water Block, such as en-echelon anticlinal structures, stratigraphic up-dip pinch-outs within the foredeep basin and sub-thrust traps beneath the nappe system (RRI, 1998).

The regional structural evolution of the Cape Three Points Deep Water Block can be summarized as follows:

- During the Neocomian, Aptian and the Early Albian the opening of the South Atlantic was heralded by the deposition of continental and lacustrine sediments in trans-tensional basins formed by incipient dextral strike-slip faults. Due to the slightly oblique orientation of the Romanche Fracture Zone relative to the rifting direction between Africa and South America, transpression may have commenced as early as the Late Albian between the two continents. As the result of the compressional component of transpression, a deepwater flexural basin formed while shelfal siliciclastics were deposited on the up-dip basin margin (RRI, 1998).

- By Cenomanian time, the ongoing transpression produced a thin-skinned fold belt verging to the north. The load of this incoming nappe with numerous thrust units enhanced the subsidence of the late Albian basin forming a foredeep basin. The deepwater slope and basin floor fans deposited in this classical "flysch" stage of the basin evolution (RRI, 1998).

- By Senonian time African and South American continents departed each other and the Romanche Fracture Zone dissected the fold belt, producing a very steep escarpment on the seafloor. As there was renewed transform motion along the fracture zone during the Santonian, the entire foredeep sequence has been refolded producing en-echelon anticlines consistent with dextral transpression. During this time several large slope fans were deposited up-dip from the Cape Three Points Deep Water Block (RRI, 1998).
- The Mid-Tertiary saw clastics prograding into the deep-water basin. Frequent slumping and canyon formation characterized the unstable slope. A mid-Oligocene period of uplift in the adjacent onshore area produced truncation of the pre-Tertiary beneath the inner shelf. Presently, clastics still prograde over the shelf edge onto a fairly active slope. There is no expression of the underlying foredeep structures on the modern seafloor (RRI, 1998). The sandy slope fan turbidites are fed by amalgamated slope channels are delineated by the warm colours. These channels are updip spilling downdip into basin floor setting and after remobilized and injected into overlying younger sediments (Figure 1.4).

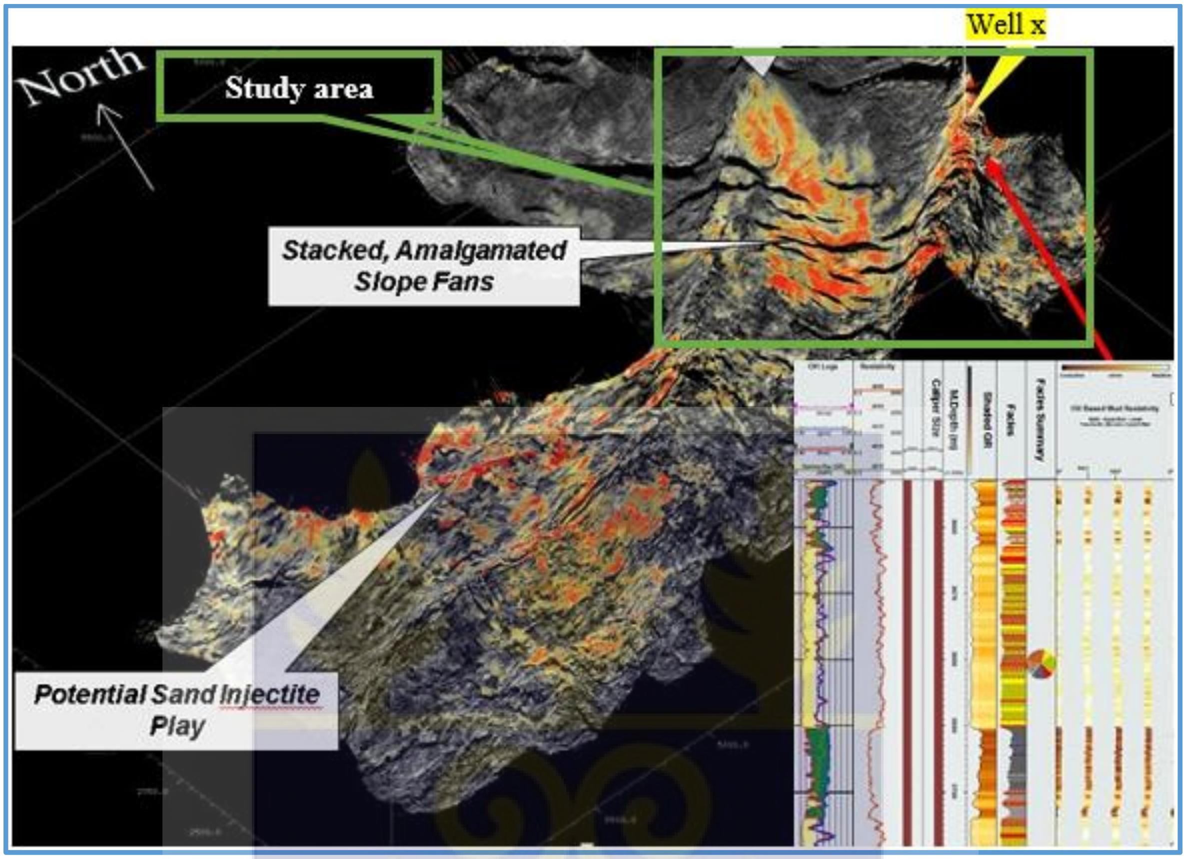


Figure 1.4: Middle Albian surface showing 3D view of far stackes amplitudes showing compressional folds Chierici (1996).

In the study area, recent well X shown above aimed at a compressionally formed structural trap of distinctive succession of outboard fore deep basin sediments, with the Ghana Marginal Ridge adjacent to it. This structural trap is an elongated three way deep closure, it is internally faulted and occur at various levels within the Cenomanian and Albian. The sealing was by overlying deposits of Late Cretaceous and Tertiary claystones. Identification was done by the geophysical anomaly of strong Class IIP AVO.

Gross hydrocarbon column of 94 m with 25 m of net stacked oil and gas pay was encountered in the Albian sandstones. At approximate depths of 3663 and 3690 m within the sandstones which acted as the primary reservoir were contained light oil and gas. Also at depth zone of about 3701 and 3709 m volatile black oil was recovered. From geochemical analysis of these hydrocarborn and the source rock penetrated, it predicted a petroleum system of two phase. The first which is an early lacustrine source facies oil and gas charged and subsequently the second, which is from a marine source facies oil charged. Gas influx was augmented from constant burial of source facies show to have changed or lowered the initial oil water contact down the structure. It also augmented the reservoir pressure until the gas seal was somehow penetrated charging the gas chimney visible on the structure (RRI, 1998).

Analysing the well showed a positive seismic anomaly. This provided basis for the application of seismic inversion technology and AVO on a regional scale to explore the three thousand two hundred square kilometers 3D survey within the Vanco Cape Three Points Deep Water block. A combination of these technology with seismic facies analysis and 3D visualization has exposed numerous chances in the Upper and Lower cretaceous plays that will be the aim of an upcoming drilling campaign in addition to appraising well x Discovery (RRI, 1998).

1.11 The Romanche Transform Fault/Fracture Zone

The Gulf of Guinea Province is divided structurally by three major transform fault zones with WSW-ENE trends. These set of parallel structures are the St. Paul, the Romanche and the Chain fracture zone. The St. Paul fracture zone forms the extreme eastern boundary of the Cote d'Ivoire basin with the Romanche fracture zone at the southern boundary and runs through to the eastern end of the keta basin. The Chain fracture zone terminates south of the Benin basin. A transform fault is an active tectonic intra-plate boundary where strike-slip faults usually has cut across a mid-ocean ridge and offset the ridge during seafloor spreading. The tectonic plate fault-boundaries slide past each other in opposite direction and distinctively describe the direction and sense of motion between offset ridges of two bounding plates (Kutu, 2013).

The Romanche fault is an en-echelon, right lateral transform fault developed from geometric misalignment of South Atlantic and Central Atlantic moving rift by some 1300 km. It was formed when they were connecting about 120 Ma ago (Basile et al., 1998). The Romanche transform fault is one of the major tectonic feature of the Central Atlantic. It prolongs over the equatorial zone from the coast of Africa to South America. Average spreading axis of the Mid-Atlantic ridge are displaced over this fault by 930 km. It is a typical long ridge-ridge transform offset with a longer fracture zone. The present-day transform offset is roughly 888 km long and the adjoining fracture zone is 1890 km (Antobreh et al., 2009).

The continental extensions of this fracture zone is associated with historic seismicity, signifying that these fracture zones are weak and still able to disperse stress into the neighboring continental areas (Scotese et al, 1988). The Romanche Transform and Fracture

Zone fault-splays are recognized to touch onshore Ghana. The main eastern end of the Romanche fracture zone spreads onshore some 100 km east of Accra, Ghana. Movement along the Romanche Transform fault and Fracture zone is active, triggering current seismicity of southern Ghana.

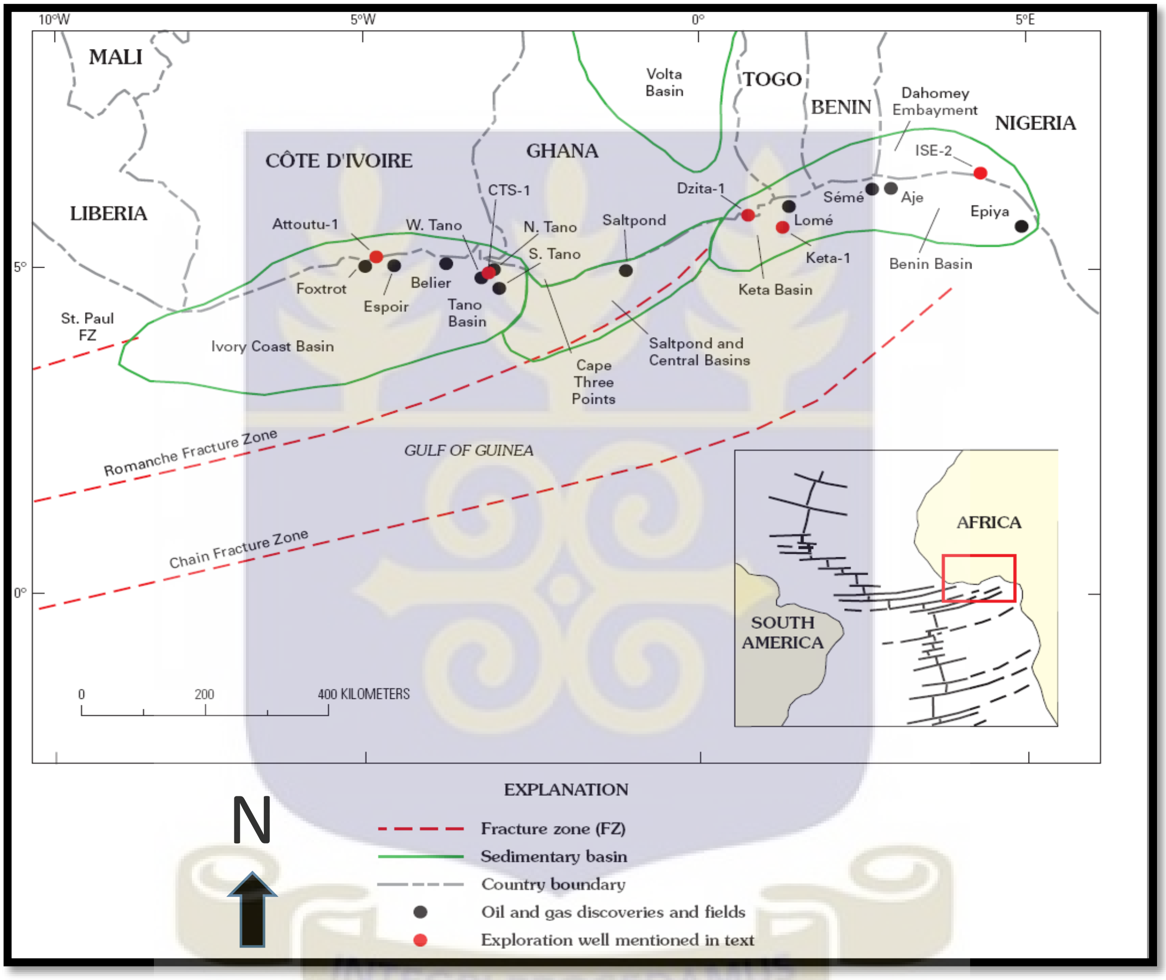


Figure 1.5: Map indicating the Romanche fracture zone which is related to the formation of the Cape three points basin (obtained from Chierici (1996).

CHAPTER TWO

LITERATURE REVIEW

2.1. REGIONAL TECTONIC EVOLUTION OF EQUATOCENTRAL ATLANTIC

Tectonic Evolution is the scientific study of the process or development of the lithological deformation that make up the Earth's crust and the corresponding deformational forces. It deals with the folding and faulting accompanying orogenesis; the large-scale, gradual upward and downward movements of the crust (epeirogenic movements); and rapid horizontal displacements along faults (Black, 1984).

The Equatocentral Atlantic tectonic evolution can be classified into three developmental stages; a pre-, a syn-and a post transform stage also known as the pre-, a syn-and a post-rift stage. The pre-transform stage spans from Palaeozoic up to Mid-Late Aptian. The syn-transform spans from Late Aptian to Late Albian and its end is noticeable by a basin-wide break-up unconformity. The post-transform spans from late Albian to Holocene, the break-up is complete and there is active deformation along the Romanch Fracture Zone. These distinct stages have their characteristic fault network and deformation style (Chierici 1996).

2.2 Latest Proterozoic to Triassic: pre-rift

The Equatorial Atlantic margins prolong over an assemblage of Proterozoic to earliest Paleozoic tectonic domains chiefly as a consequence from the Pan African-Braziliano orogeny (Black, 1984) which happened between ca. 720 and 520 Ma (Guiraud and Maurin, 1992). The development of this fold thrust belt was around the Guyana craton, the West African craton, the Sao Francisco craton and the Sao Luis craton-Eburnean shield. Through the Phanerozoic times it was linked with major strike slip faults which reactivated and relatively affected the

Equatorial atlantic development, as the central African fracture zone (Black, 1984), the Kandi-Transbrazilian fracture zone (Caby, 1989), and the Guinean-Nubian lineaments. Erosion and tectonic quiescence followed the Pan African-Brazilian orogeny. In Ghana (Kjemperud et al., 1992) and Cote d'Ivoire basins (Guiraud and Maurin, 1992) as in Brazil Solimoes, Amazonas and Parnaiba basins, (Milani and Thomaz, 2000), continental terrigenous sedimentation occurred from Ordovician times. Huge marine platforms prolonged from the Proto-pacific Ocean over South America between middle Devonian and Early carboniferous. This occurred during the global level highstands (Isaacson and Diaz, 1995). The total thickness of the preserved Paleozoic marine series can reach 1-1.2 km.

2.3 Late Triassic to Jurassic: rifting in the Central Atlantic

Rifting in the Central Atlantic was in Northern Brazil southwardly stretched during late Triassic and terrigeneous continental formation have been drilled in the offshore Marajo' and Cacipore basins (Milani and Thomaz, 2000). The rifting orientation in this northern zone was likely influenced by the trend of the Pan African Rockelides belt. In the earliest Lias, there was this rifting (around 200 Ma) and subsequently the Central Atlantic Magmatic theolitic province development (Burke et al., 2003). It stretched southward over the western side of the future equatorial Atlantic. Volcanism of tholeiites happened either intercalated within the sediments in Cacipore. Marajo, Solimo as and Amazonas basins, or in northnorthwest-south-southeast trending dykes in the western edge of Cacipore basin (Milani and Thomaz, 2000), French Guyana, and Liberia (Mauche et al., 1989). As oceanic accretion begun through the Jurassic in Central Atlantic, the Guinean-Nubian/Ouachita-Wichita fault zone served as a transfer zone between the divergent area northward and a nearly stable area southward. South of this fault zone were marked by divergent plate as restricted to limited subsidence and some volcanism. According to Guiraud and Maurin, (1992) Liassic to Tithonian continental sandstones and shales were deposited along the NW-SE trending Liberia basin. Continental terrigenous formation of Late Jurassic were also deposited offshore Cote d'Ivoire, in Ghana, Benin and in upper Benue (Guiraud and Maurin, 1992) basins. In this equatorial area, the Mesozoic sedimentation seems to have been independent from the PanAfrican structures, but was perhaps localized over Devonian basins. Basalt flows happened in the eastern Ghana basin during the Callovian, in the Benue basin and in the western part of the Maranhao basin since 147 Ma (Popoff, 1988). Basaltic dykes intruded around the northwestern Brazil Potiguar basin during Middle Jurassic (Guiraud and Maurin, 1992).

This Callovian to latest Jurassic local rejuvenation or initiation of basin sedimentation and magmatism synchronous with similar events occurring along the Central African Rift System, typified by the upper Benue, the central Sudan or the Anza basin in Kenya (Guiraud et al., 1992). These dissimilar clues witness of a change in the paleo-stress field that affected the African-Arabian/south American plates, described by the occurrence of local tensional regimes which signify far-field effects of the opening of the central Atlantic Ocean and the Somaili basin (western Indian Ocean). They existed before the strong rifting activity that happened from earliest Cretaceous times (Figure. 2.1).

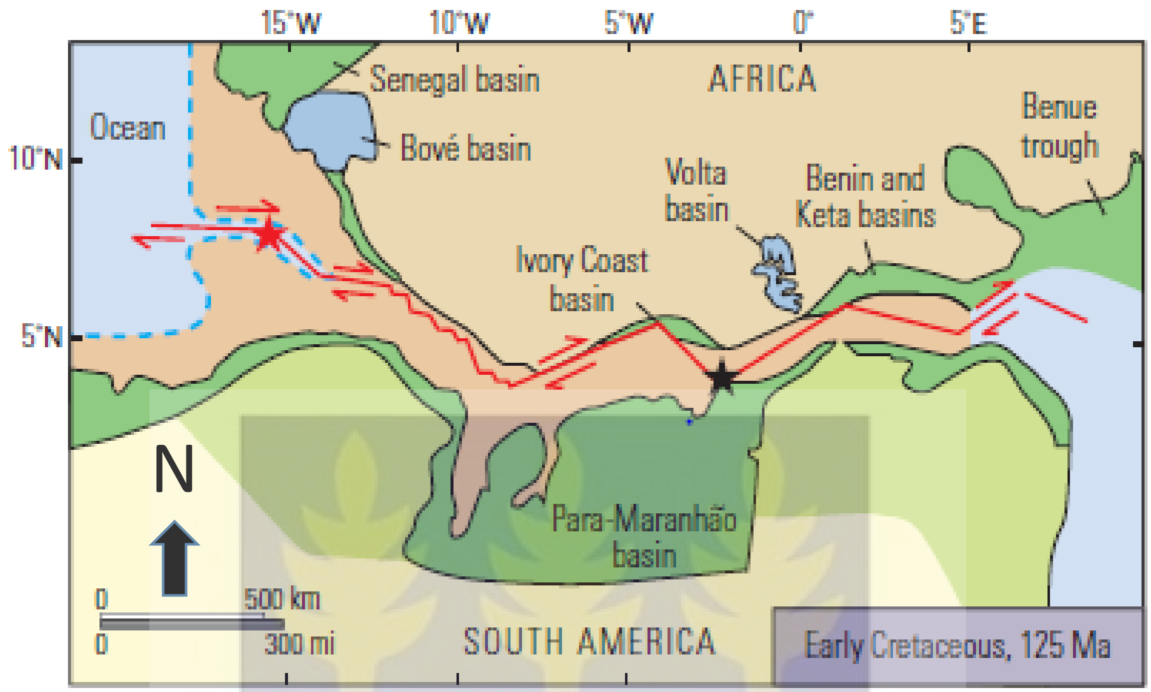


Figure 2.1 Early Cretaceous times (Brownfield and Charpentier, 2006).

2.4 Late Berriasian to late Aptian: rifting in the South and Equatorial Atlantic

A new rift axis appeared in the South Atlantic through the Early cretaceous, in linkage with the showing of the Parana' plume. The volcanic action of the plume head took place about 138 Ma ago (Stewart et al., 1996) with a chief magmatic event between 134 and 129 Ma (Peate, 1997). Volcanism took place in and about the Parana area, to north of Brazil in the east Maranhao 9115-122 Ma (Forder et al., 1990). Rifting extended northward to the Benue side, and cross Africa to Tethys realm from 130 to 120 Ma (Guiraud and Maurin, 1992). Since the Berriassian syn-rift sedimentation started in intracontinental basins in the potiguar basin and likely along the lineament in the Rio do Reixe and Araripe basins. During Early Barremian sedimentation started in the Benue Trough, Ghanaian Keta basin and Foz do Amazonas. During this first state of rifting in the equatorial area, the Niger delta area was a a triple junction between the South Atlantic rift, the Benue transtensional rift and the transform zone of en-echelon equatorial basins. The rifting of the northeastern subdivision of the south Atlantic failed around 120 Ma. This was the ultimate separation of Gondwana, when oceanic accretion initiated between Antarctica and India (Scotese et al., 1988). This incipient oceanic accretion enacted a kinemantic plate restructuring (Numberg and Muller, 1991), and the linking between South and Central Atlantic by the en echelon Romanche and Saint Paul right-lateral transform faults, cross-cutting the Pan African structures but localized on formerly subsiding areas.

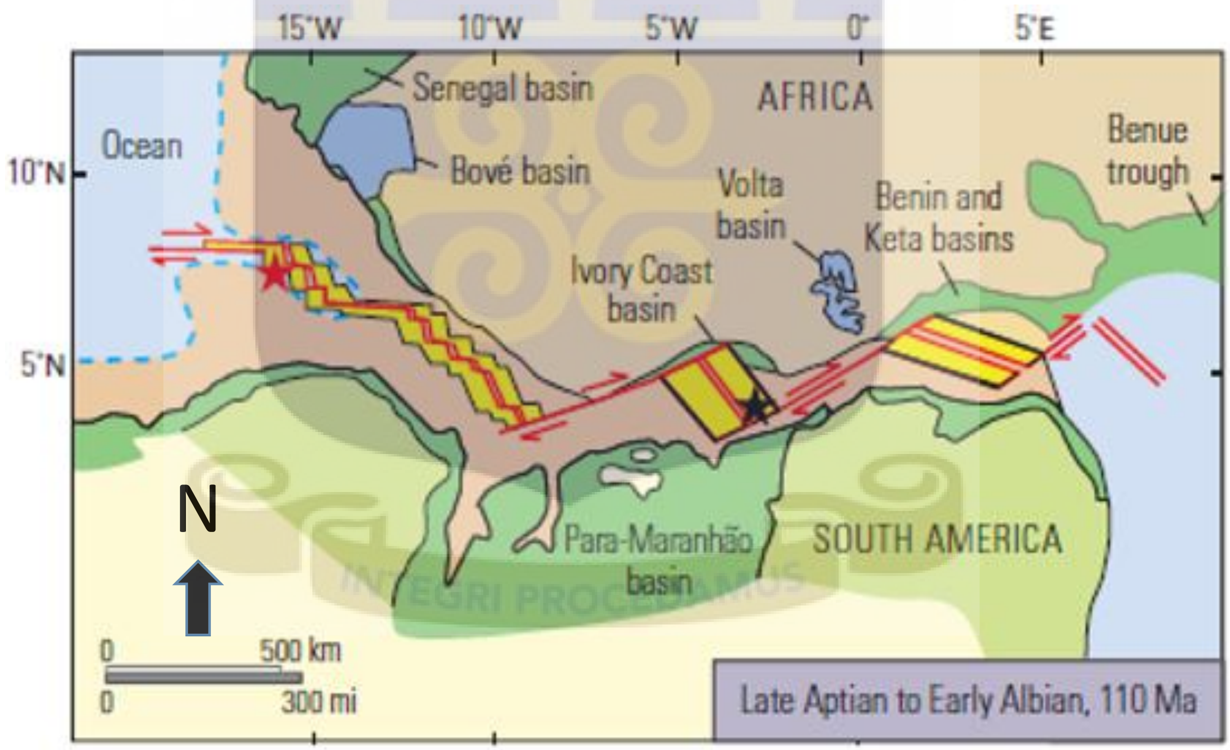


Figure. 2.2 Late to early Albian times (Brownfield and Charpentier, 2006).

Sedimentation of intracontinental clastic silica occurred in fluviatile to lacustrine environments everywhere along these two transform faults through Aptian times. This occurred in a very strong subsiding basin influenced by transtensional or strike slip faults (Zalan et al., 1985). Between the two transform faults, the Co'te d'Ivoire area represented a pull-apart structure (Figure 2.2), dominated by titled block in the central part of the deep Cote d'Ivore (Blarez and Mascle, 1988). Nevertheless according to Chierici, (1996), most crustal thining and connected subsidence was very localized along the coastal fault, which was the termination of the St. Paul transform fault in the extensional zone. In the same way there was an occurrence of horsetail splay at the link between the southern side of the rifted Cote d' Ivoire basin and the Romanche transform fault (Basile et al., 1998).

2.5 Late Aptian to Late Albian: post-rift, intracontinental transform

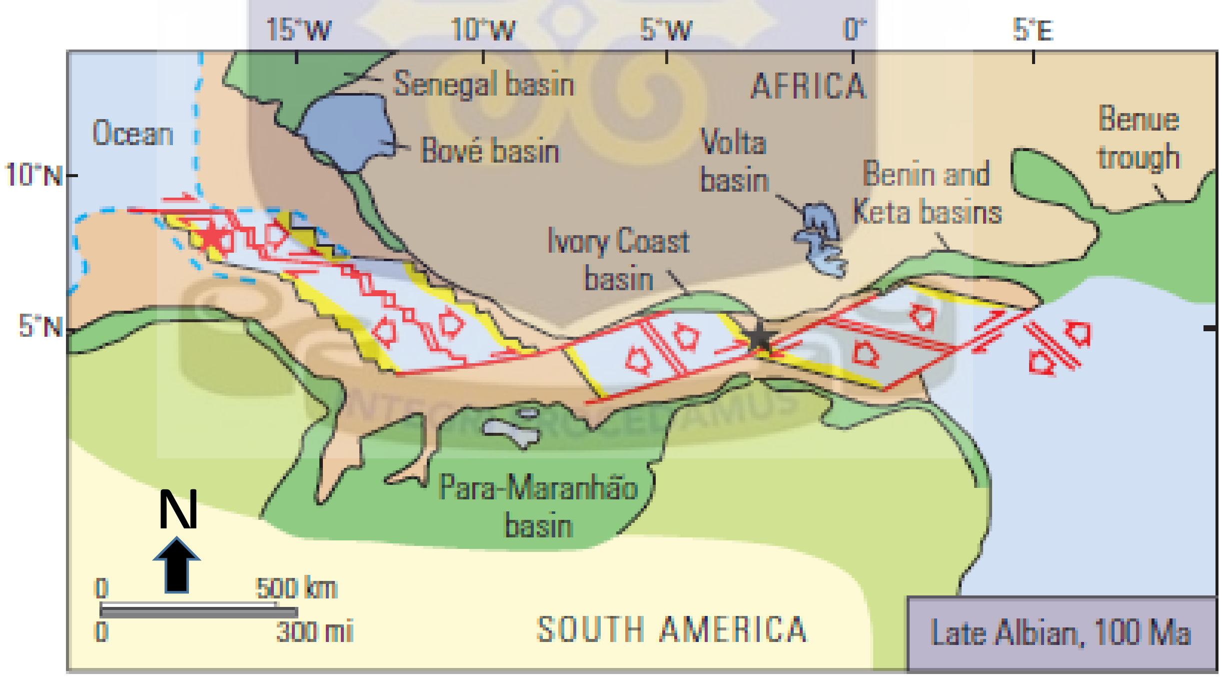


Figure 2.3 Late Albian (Brownfield and Charpentier, 2006).

Rifting equatorial divergent basins stopped when the first oceanic crust accreted during the cretaceous quiet magnetic zone (Figure 2.3). First accretion correlates with a Late Aptian post-rift unconformity noticed in the deep Ivorian basin (Basile et al, 1998) and in the conjugated Ceara basin (Zalan et al., 1985). Nevertheless, deformation was on going along the transform fault between the divergent accretion axis. There was also a development of rapidly subsiding intra continental basins along the transform faults, likely in structures close to the ones developed during the times of Cenozoic along the transform fault of Dead Sea. Siliciclastic sedimentation prevailed, likely fed in by the uplifted shoulders erosion during the late Aptian, but through the late Albian times open marine connection happened through thin but locally deep basins (Plestch et al, 2001). At the time of development of right lateral transform faulting in the Equatorial Atlantic, left lateral strike slip fault in the Benue trough was still active (Guiraud and Maurin, 1992) showing the Niger Delta, that up to the late Albian it was still a triple junction, even if displacement in the Benue zone were likely minor when matched within that of the Atlantic zone displacement. There was an end to the intracontinental phase transform fault at the time the active transform fault brought into contact the lithosphere of the ocean against that of the continent. Association of a second unconformity anticipated to have been diachronous along the transform fault and older on the eastern termination of the transform fault on the African side (correspondingly on the western end of the Brazilian side) (Mascle et al., 1988). Along the margin, accordingly the unconformity ages change; but compared to the Late Albian they are older, like the Westernmost of Africa of the Romanche transform in the Cote d'Ivoire Ghana marginal ridge zone (Bascle et al., 1989).

2.6 Latest Albian To Latest Santonian: Active Transform Margin

This phase begun ubiquitously on the margins of the Equatorial continent. This was by diachronous unconformity which after the deformation sealed it. Nevertheless, reconstruction of the oceanic opening suggest between the oceanic and continental lithosphere at the time the transform faults were still active. This shows that the deformation stopped on the margin of the continent (Basile et al., 1998). A distinctive event at this phase is the continental edge uplift along the continent-ocean transform boundary. Where the crust of the continent was deep and thinned, like in Liberia or the deep Ivorian basin, the marginal ridge formation parallel to the transform fault was the result of this. The crust of the continent was not thinned which led erosion uplift and erosion (Antobreh et al., 2009). This particular uplift along the margins of the transform continent has been chiefly described as a result of transient transfer of heat from the oceanic lithosphere which is the host to the continental lithosphere, which is the coldest. Nevertheless, two essential outcomes of the ODP leg 159 are that there was an occurrence of an uplift along Ghana- Cote d'Ivoire marginal ridge since middle Albian times (Basile et al., 1998), i.e. throughout the intercontinental phase, and proofs of heating linked with the contact between continental and oceanic lithosphere are not present (Wagner and Pletsch, 2001). The oceanic accretion against the transform margin was the end of this phase. (Figure 2.4).

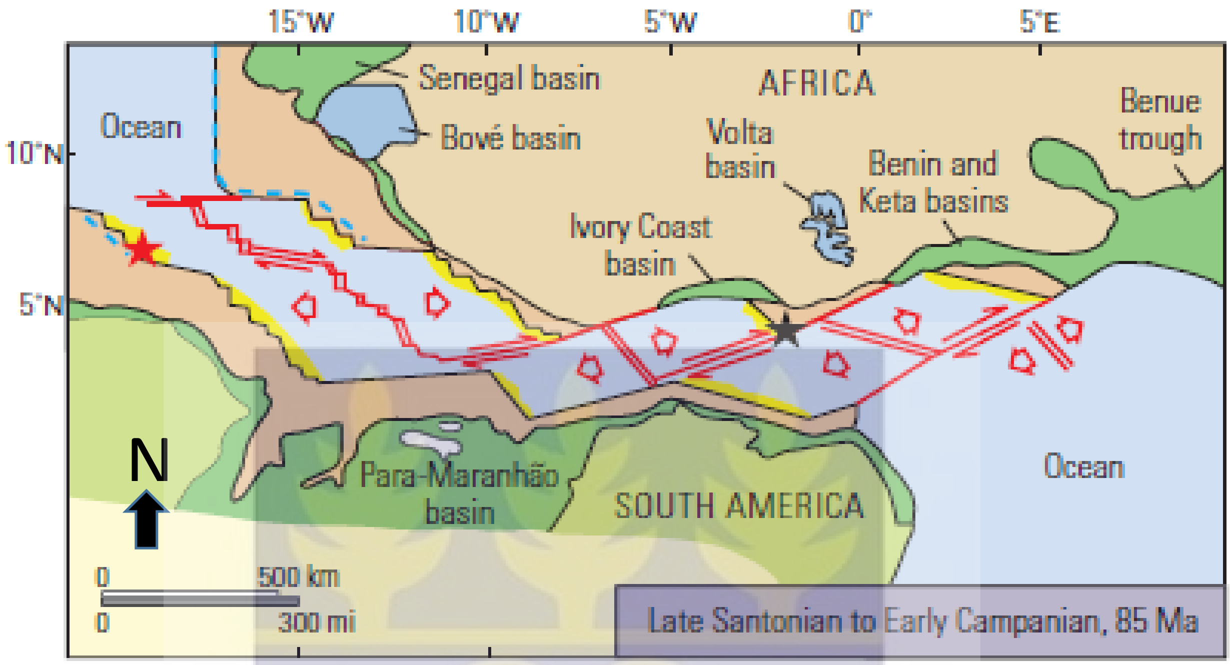


Figure 2.4 Late Santonian to Early Campanian (Brownfield and Charpentier, 2006).

As for the start of this phase, this completion is diachronous as the accretion axis progressed along the transform fault. During the Santonian (85 Ma) was the occurrence of the last contact between the accretion axis and the continental lithosphere (Figure 2.4). This was coeval with a major modification in kinematic for Africa plate (Guiraud and Maurin, 1992). Subsequently sea floor spreading began as oceanic crust were destroyed at trenches and new crust formed at ridges.

CHAPTER THREE

RESEARCH METHOD

3.1 Introduction

Seismic interpretation can be considered as the final piece of a series of techniques that are used in defining deeply buried subsurface phenomenon. Before interpretation is done a seismic survey is first acquired and then processed and displayed as 2D or 3D. The basic idea of seismic data acquisition is very simple. Low-frequency sound waves are produced at the surface by a high-energy source. They travel down through the earth, and are reflected back from the tops and bases of strata of rock where there is a variation in rock properties. The reflected sound journeys back to the surface and is noted by an array of receivers (hydrophones). The time taken for the sound to travel from the source down to the reflecting interface and back to the surface tells us about the depth of the reflector, and the intensity of the reflected signal tells us about the changes of rock properties across the interface (Bacon and Redshaw, 2003)

The following parameters are measured during acquisition;

- Two-way travel time
- Amplitude which is a measure of acoustic impedance change
- Reflection Polarity which, for interference free reflections, can show if the boundary has a positive or negative acoustic impedance and
- Interval velocity

The reason for seismic processing is to transform the data acquired into an image that is useful to deduce the sub-surface structure. Also at every stage of the processing, interpretation is made and mostly biased or skewed toward the level of knowledge or expertise of the processing geophysicist. It is therefore necessary that the interpretation geophysicist is involved at every stage of processing to serve as a check on the processing geophysicist for a very good interpretable result (Bacon and Redshaw, 2003).

According to Bacon and Redshaw, (2003), the processing structure can be generally classified as follows:

- improving signal at the expense of noise
- providing velocity information
- collapsing diffractions and placing dipping events in their true subsurface locations (migration)
- enhancing resolution (wavelet processing)

This chapter focuses on interpreting and recognizing major regional faults (hereafter referred to as the "large scale fault") from a three dimensional seismic reflection survey in Cape Three Points area of the Western Basin of Ghana. The major faults' geometry at deeper levels are not clearly visible due to limitations in seismic imaging with increasing time or depth. Interpretation of the studied 3D seismic survey was performed using different display orientations, picking modes and computed seismic attributes.

3.2 Data

The data used for the interpretation of the study included, checkshot, stratigraphic formation tops and well imaged 3D seismic acquired in 2010 and processed in 2011 merged with 2D regional seismic data. The 2D lines are represented in deep black lines and 3D cube represented in green (Figure 3.1). The cube shows a WSW-ENE direction of survey (inlines) and NNW-SSE cross-lines. The data for both 3D and regional 2D are in time domain making the merging of the data easier to work with and interpret. The 3D survey was shot by Deep Sea Geo-Services (DSGS) for deep water exploration together with partners Vanco and Ghana National Petroleum Corporation, and covers a total area of 760 km. The data are sampled with the DSGS Geostreamer technology. The quality of the data is good and faults and stratigraphic events are easily recognizable.

3.3 Kingdom Seismic Micro Technology (SMT)

The software used for this study was the Kingdom SMT geoscience software, developed by Kingdom. This software offers several advantages which include;

- The ability to view sections through the data in any orientation (X,Y and Z)
- Automatically transfer picks from one line to other lines on multiple view windows
- Semi-automated horizon picking and Ability to see volume in 3D and not just in section.
- Generation of attributes that can be used to extract additional information.

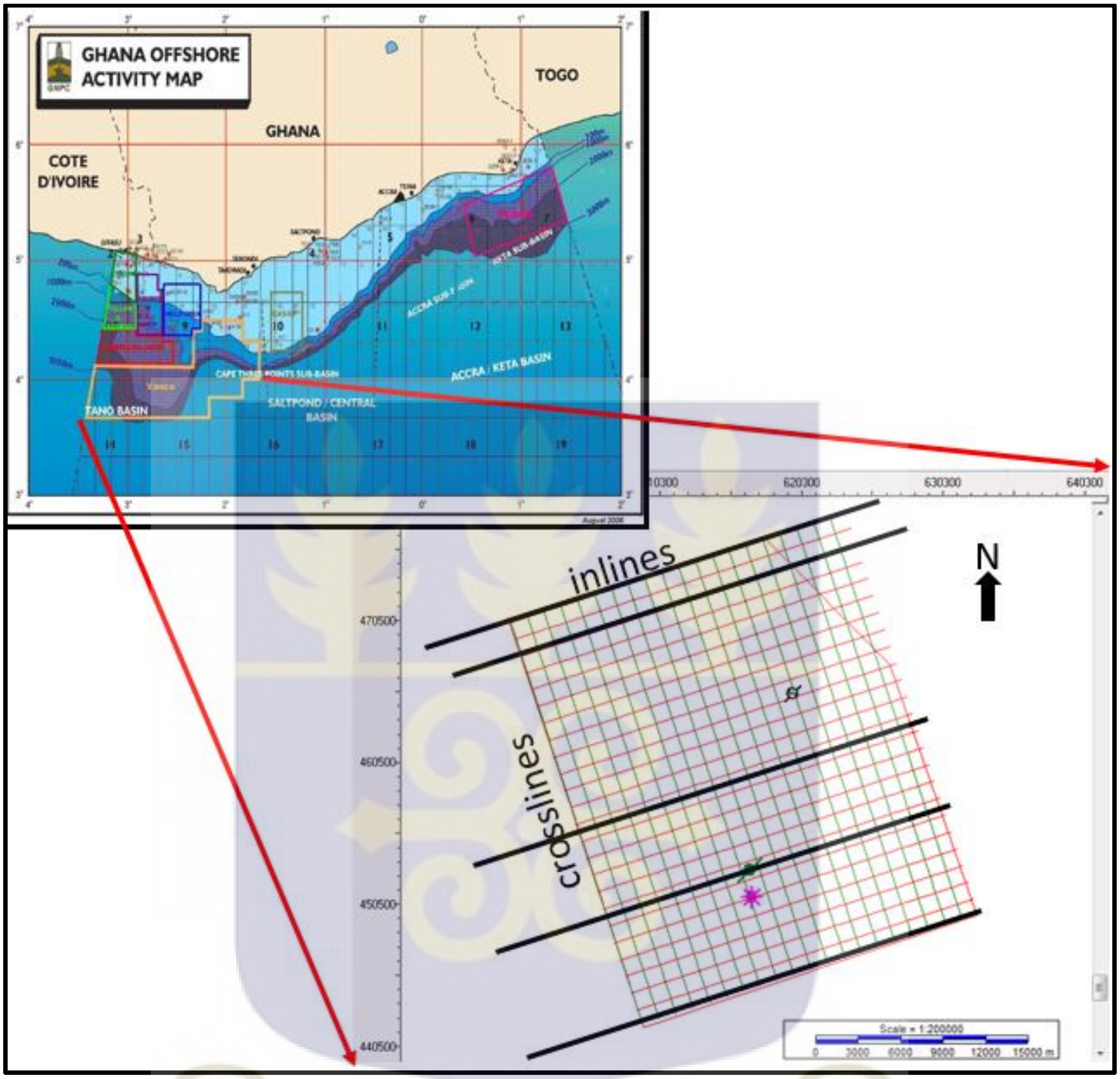


Figure 3.1 Base map of study area The thick black lines show the regional 2 D lines passing through the three survey and the wells x, y and z (modified from RRI, (1998)).

The Base Map was a chart showing certain fundamental information, it was used as a base upon which additional data of specialized nature were compiled or overprinted. Time structure maps (gridded and contour) were printed on top of the base map. The base map survey annotation lines were taken off when geologic maps were about to be produced, so it does not interfere with visibility of the geologic features on the map. The geology is represented by colours, lines, and special symbols unique to geologic maps (like fault strike and dip). Understanding these features allows better interpretation of time structure map and any other standard geologic map (Bacon and Redshaw2003).

3.4 Well to Seismic Tie

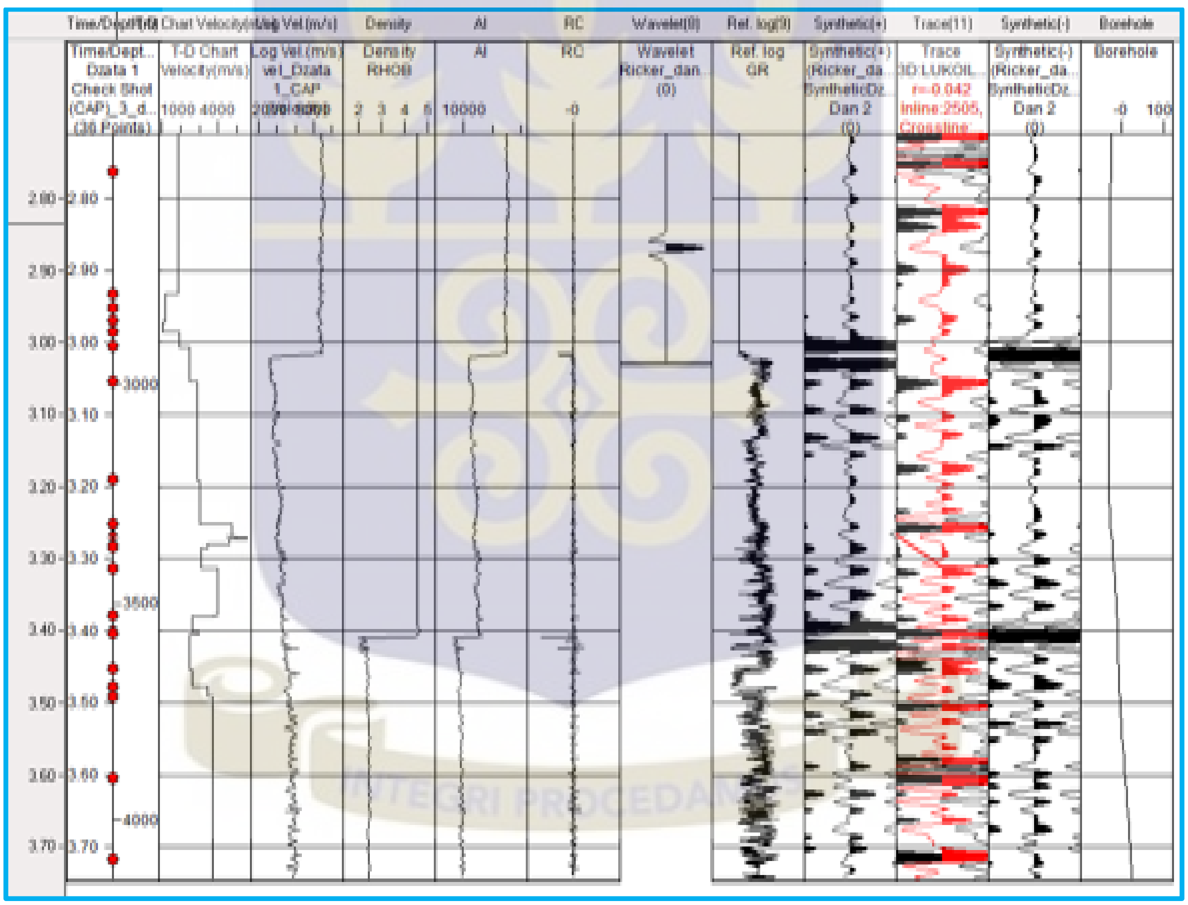


Figure 3.2 Synthetic seismogram window showing generated synthetic traces

Tying wells usually involves forward modeling a synthetic seismogram from well logs, then matching that synthetic to the seismic reflection data, thus producing a relationship between the logs (measured in depth) and the seismic (measured in travel time). Using well x in the cube (Fig., 3.3), well-to-seismic tie was carried out using check-shot data, well data and seismic data to generate the synthetics seismograms. The input parameters included DT (sonic) log, used to compute velocity. This was repeated for the others density log RHOB, and Ref(rence) log, GR. A computed theoretical wavelet was created using Ricker of frequency of 25 Hz.

Acoustic Impedance information form the seismic was used to generate Reflection coefficients. These were convolved with the theoretical 25 Hz Ricker wavelet to generate the synthetic seismograms. The generated synthetics were overlain on the seismic data to ensure a good seismic to well tie (Figure 3.3). The significance of this step was to align the synthetic trace computed from the well log and to the corresponding reflective events of the seismic to check its correlation. This matching increases confidence of the seismic interpretation as verified by well data**.**

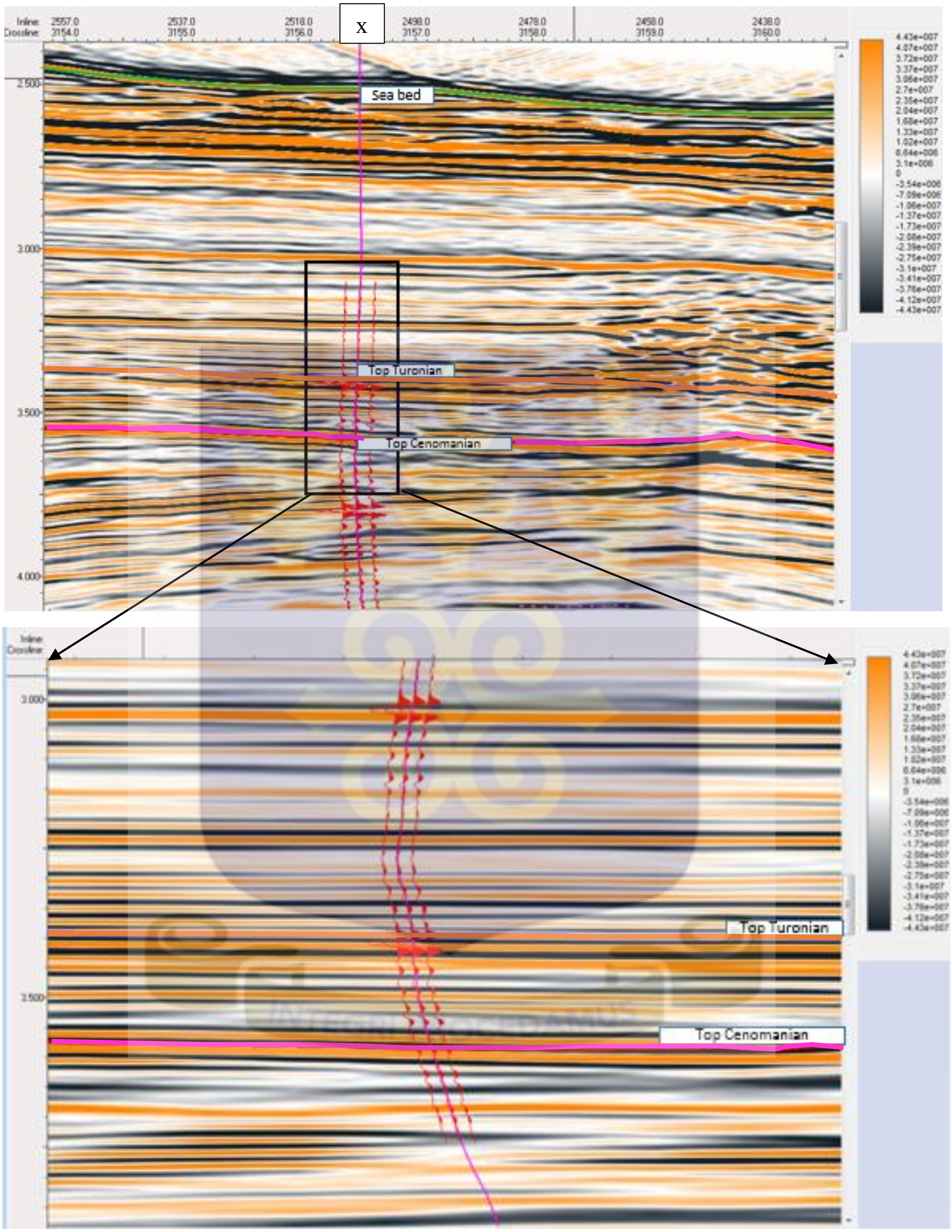


Figure 3.3 Synthetic overlay showing a good tie between the seismic and the well.

The synthetic peaks are the red, the scale bar (orange to white to black 200) shows the orange colour as the peak (those with positive figures) and the black colour with the negative figures as the trough. The orange horizon (Top Turonian) shows a good tie and was picked as a peak and the violet horizon (Top Cenomanian) shows a good tie and was picked as a trough. The well to seismic tie was particularly done for post rift interpretation since seismic picks in the syn rift were made on the basis of finding the most consistent and continuous reflection events, and not necessarily as a vehicle for lithology determinations, therefore the picking of a constant polarity on any of the two interpreted horizons in the syn rift was occasionally ignored in favour of generating a continuous surface.

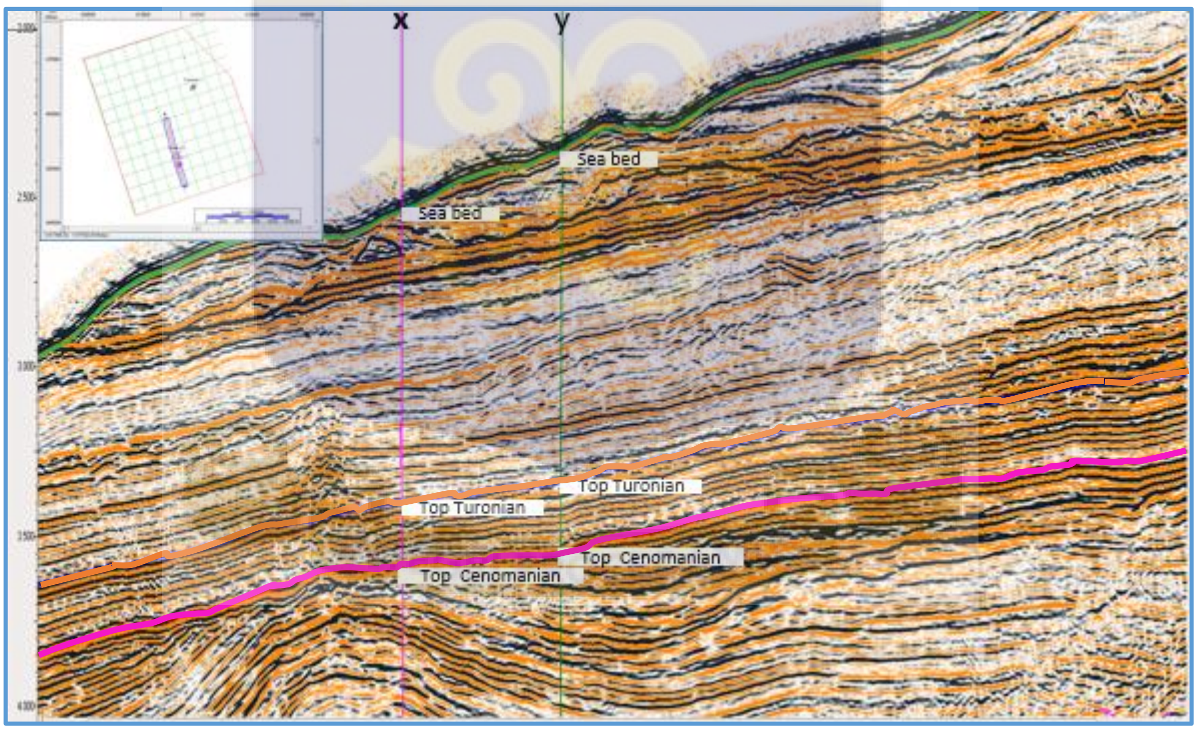


Figure 3.4 Digitized arbitrary line through wells x and y serving as quality control.

3.5 Horizon Interpretation

Procedure for horizon picking can be summarized as follows:

The interpreted horizons are:

I. Sea bed
II. Top Cenomanian
III. Cenomanian Unconformity
IV. Intra Late Albian

Horizon picking of trough, peak or zero crossing were picked using loaded formation tops and also depending on amplitude (most consistent reflector) closest to well tie for the seabed, Top Cenomanian event. Amplitude is the main seismic attribute that was employed in interpreting the horizon. Seismic attribute analysis was based on using quantitatively derived measures of seismic waveform to enhance geologic features and to improve the visual ability of the interpreter. This basic concept was described by Taner and Sheriff (1977). The strength of the signal is measured by the amplitude and it is mainly able to envisage regional characteristics which include sequence boundaries, structure, thickness and variation in lithology. Dim spots and bright spots were also gas indicators. Tuning characteristics were observed using this attribute (amplitude) which could assist in local scale identification of reservoirs. The amplitude attribute uses the seismic signal amplitude. These seismic responses (e.g. peak and troughs) resemble differences in acoustic impedance between different earth materials. The continuous same-phase reflections were interpreted as horizons representing strata surfaces, whereas discontinuities are interpreted to represent fault displacements or unconformities. Horizon interpretations of the 3D seismic volume began on vertical sections at the well-tied location and extended outward. Observations of the seismic images were made on different display orientations, vertical sections of inlines, crosslines and arbitrary lines.

Horizons were mainly interpreted from seismic reflection amplitudes on vertical sections. Selected inline and crossline sections were initially analyzed to gain a regional perspective of the subsurface structure related to the geological history of the area. Alternating between inlines and crosslines served as a validation tool for checking the consistency of horizons picks along their associated reflectors.

3.6 Fault and Fold Identification

Identification of fault networks (synthetic faults and other related secondary faults) on the seismic sections was made. Faults are generally indicated by observations of discontinuities or breaks in reflections (i.e. hanging-wall and footwall cut-offs. The horizontal time slices reveal the general orientation of most faults' strikes. Unlike vertical sections, the frequency content of horizontal sections is the same as the trace interval in the data (i.e. spatial sampling). The folds were observed on the vertical sections as bending reflectors. Multiple folds were recongnised as undulatating reflectors localized in sections. Folds were confirmed from time structure maps. The scale bar in the time structure map shows a higher time for top of the anticlines compared to the (adjacent sides) limbs of the anticline and vice versa for synclines.

3.7 Mapping

The mapping procedure is summarized as follows:

I. Horizon picking

II. Fault picking

III. Gridding

IV. Contouring

V. Map generation

I. Horizon Picking

Seismic interpretation software, Kingdom suit, provides different picking modes for both horizons and faults. These picking modes can be manual, automated, or semi-automated. Both manual and automated picking were used in interpreting the studied survey. Manual picking allows for picking data along reflectors regardless of the phase. In the cube the identified horizons were tracked on the reflections, on both the inlines and crosslines across the field with 50x50 picking lattice for the seabed, top Cenomanian because their reflectors were strong hence picking was easy but the Cenomanian Unconformity and the Intra Late Albian reflectors were picked with a 25x25 picking lattice due to the complexity of reflector patterns.

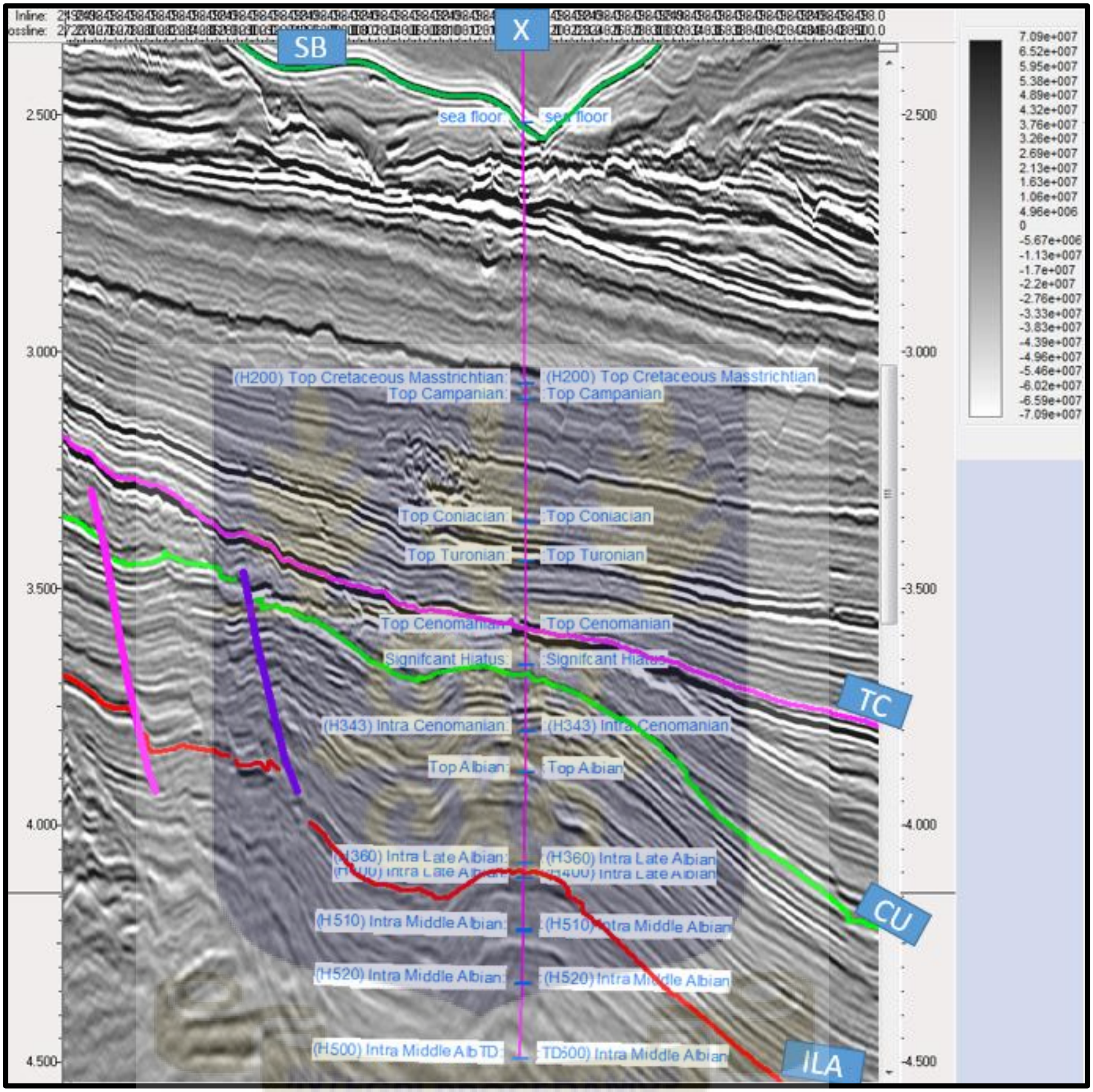


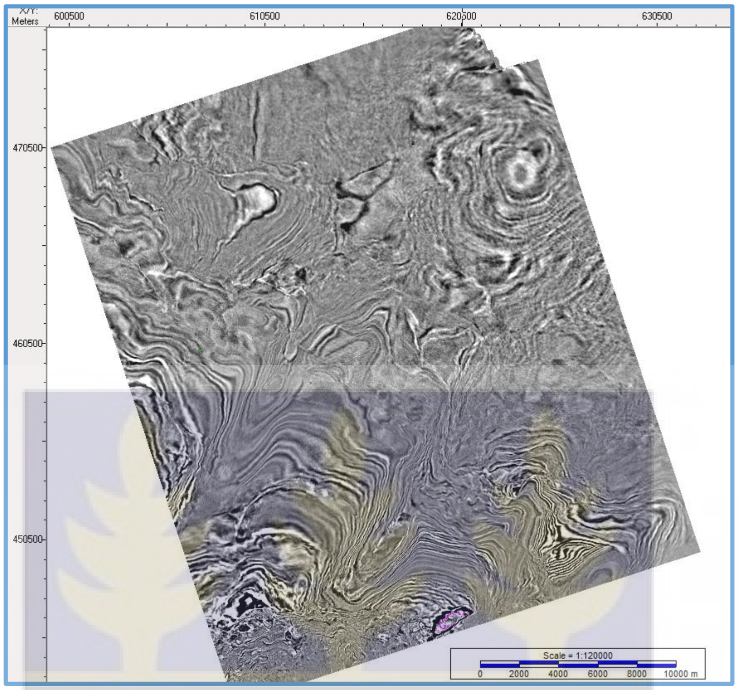
Figure 3.5 horizons picked, faults and formation tops from well x, TC=Top Cenomanian, CU= Cenomanian Unconformity, ILA=Intra Late Albian, SB= Sea Bed

Manual picking was also the basis for horizon picking near faults intersections and in complex areas such as narrow fault blocks. Picking closer line spacing was performed for higher level of details in more complex areas. In areas characterized with good quality and high amplitude continuity in the shallower reflections, horizon autopicking was performed, using manual picks as seed points to infill uninterpreted. In general, horizon autopicking in the 3-D volume was reasonable for shallow reflectors in the post rift especially the sea bed.

II. Fault Picking

Fault surfaces were primarily digitized using manual picking since it provides more control than the other picking methods. When autopicking was performed for a horizon, poor data areas and fault zones were isolated in map views by polygons. Fault polygons were also used to exclude fault gaps during the horizon autopicking process. Interpreted faults in the deep sections were detected and tracked on time slices which were also used to assist fault picking (Figure 3.6) and subsequently picking with a 10x10 lattice. All fault sticks were picked with black in the pre-rift and post-rift units but were coloured in the synrift unit and subsequently name for easy interpretation. Fault arrows showing direction of movement of hanging wall or footwall are red arrows. Fault planes were mapped only for the deeper horizon within syn rift. Fault picks were then quality controlled to verify that correlated faults are of the same type, age, and of compatible throw. Fault picks are extended upwards and downward until the fault trace is near flexure or invisible. Fault picks were mainly made on inlines. Fault picks forming a single fault plane must be of the same name or colour in the kingdom suite to distinguish a particular fault plane from the others. Fault plane were smoothen which was an auto alignment of the picked faults with the discontinuity or displacement in the horizon. Fault planes are three dimensional and can only be viewed or displayed as such. Three dimensional displays in the Kingdom suite were done by using the computer mouse to select the section, horizon, grid or fault plane and ther corresponding “Vupak” from the pop up menu.

A



B

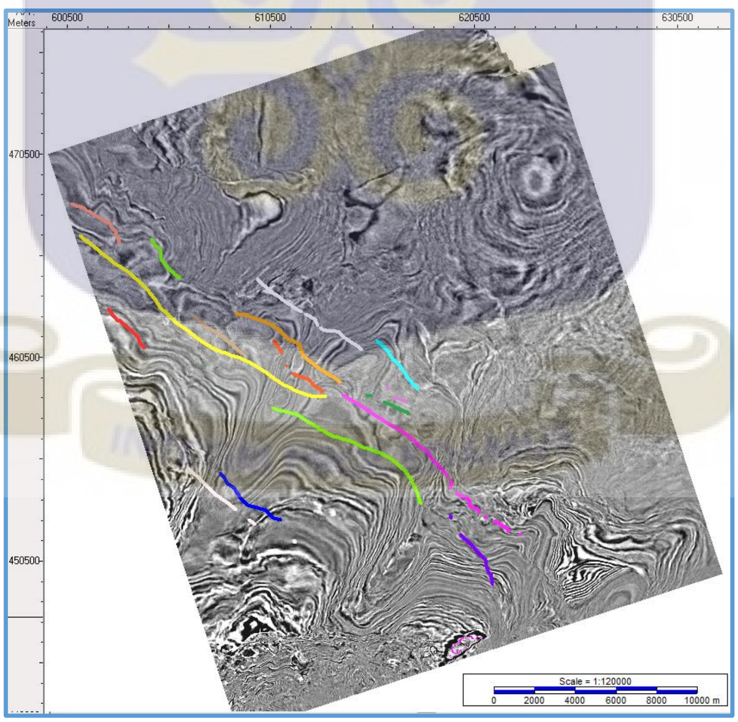


Figure 3.6 Uninterpreted(A) Interpreted(B) horizontal time slice at 3.944s, coloured lines are faults

III. Gridding

There were many gridding algorithm options but the Flex Grid was opted for because it builds accurate maps quickly, by allowing to preview how the input parameters will affect the resulting contours. With this, there was no need to generate a grid blindly, discover inaccuracies, and re-grid repeatedly as do the others.

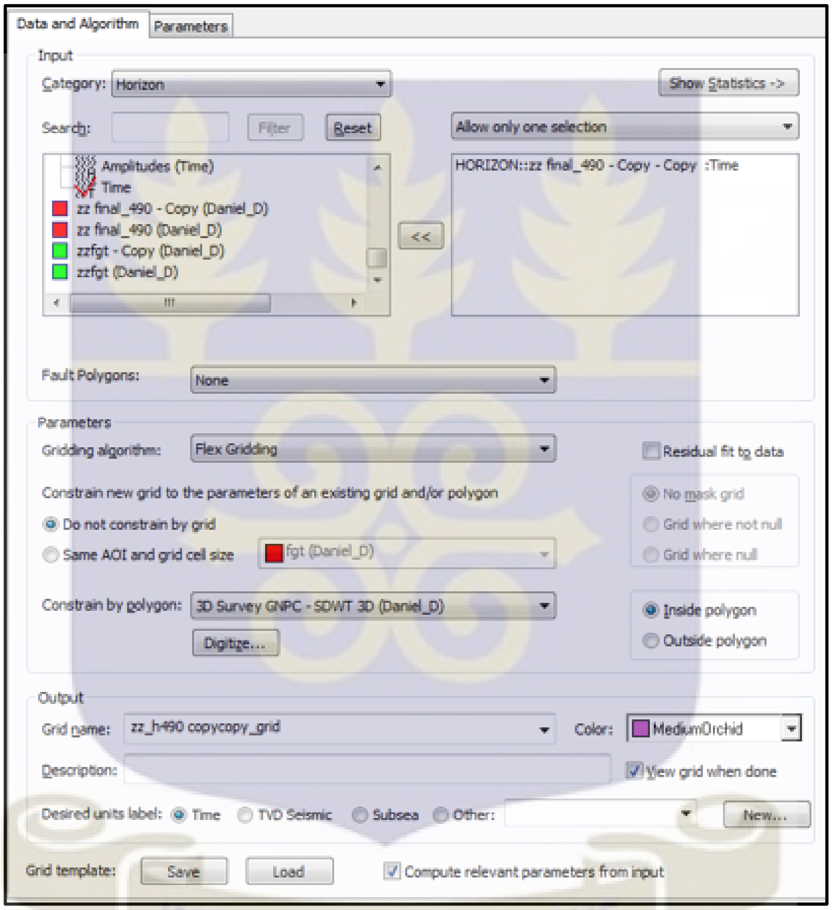


Figure 3.7 dialogue box for gridding picked horizons in the Kingdom suit

From the Kingdom suit, the gridding was done by selecting grid from the main menu bar (Figure 3.7). Select 'create grid' from the draw down button to open the above dialogue box. Select the horizon to be gridded, the data type in this case, time, the gridding algorithm (flex), name the output and apply.

IV. Contouring

Contouring was the most common method for topographical mapping. Contour line connects points of equal elevation, the contour interval represents the vertical distance between contour lines, and the base contour is the contour from which contouring starts. The contour line represented by the shoreline separates areas that have elevations above sea level from those that have elevations below sea level (Hiremath, 2010). Depending on the topography of the area mapped, the contour in interval for the map was selected. The contour intervals were increased in areas with high topographic relief to prevent clumsy contour lines which could affect reading of the map. There is no variation in contour in intervals of generated maps and could be identified by observing the number of lines between a labeled contour line and the next. The generated map with contour lines has identification of topography as an advantage over just gridded map. It is impossible however to give elevation label for each contour line.

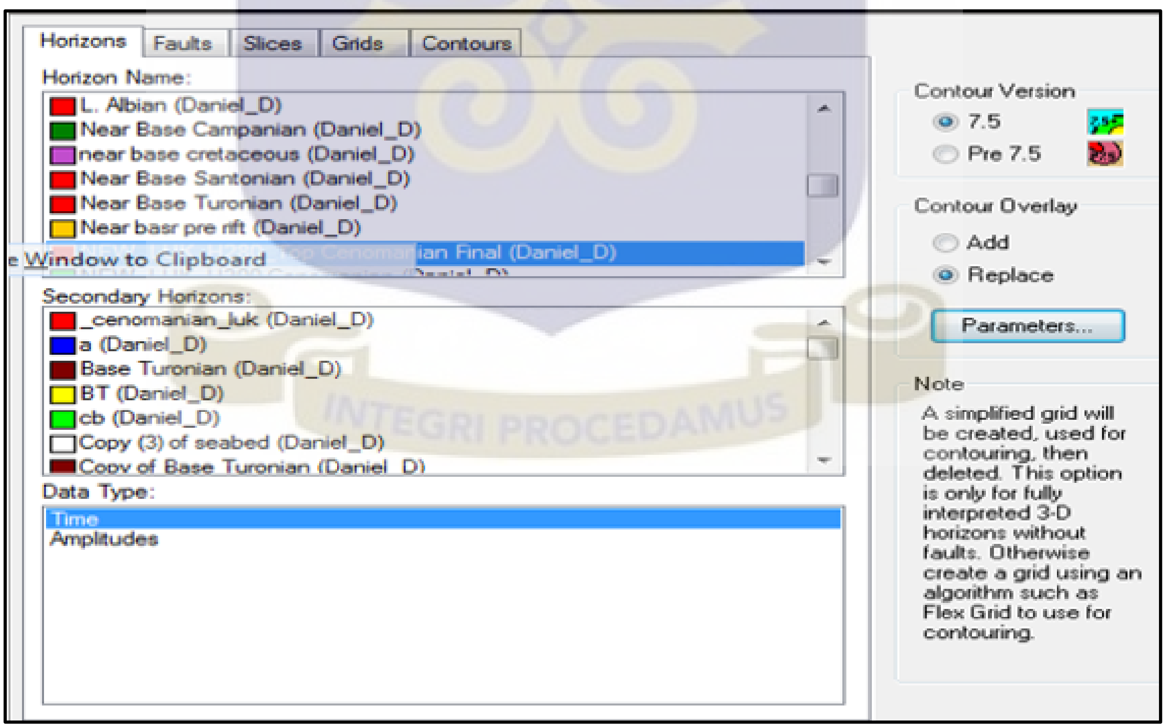


Figure 3.8 Dialogue box to compute contour from the Kingdom Suite

Every fourth or fifth contour lines was an index contour to enhance reading of the contoured map. The index contour lines were the dark, bold and labeled lines on the map. The contouring was done in Kingdom suit by selecting compute contour from the main menu to open the dialogue box above (Figure 3.8). Select the horizon to be contoured and the data type (time) and click parameters to open a dialogue box which gave options for the contouring. Smoothing high was used in contouring, the solid line type was chosen and polygon was digitized around the portion of grid to be contoured. It was better to constrain the gridding and contouring to areas where horizons have been picked only from the base map. The portions where horizons were not picked was a result of poor quality data. The digitized polygon was very important not to change the geology of the area since the software has an ability to generate grid in unpicked areas.

V. Map Generation

Time structure maps were generated from the picked horizons and faults. This was done from the Kingdom suit by dragging and dropping the desired gridded horizons on to the base map. The corresponding contour were also dragged and dropped onto the based map. Depending on the on the interpretation the time structure map was displayed in gridded form, contoured form or in three dimension (perspective view). The colour bar and scale of the generated map were changed, from the base map dialogue box for better presentation and interpretation purpose.

3.8 2D Interpretation Procedure

Power point is a Microsoft Office suite and has other tools which enabled scaling, writing of text on section and applying geologic information for interpretation. The vertical scaling was done with the kingdom software but the horizontal scaling was read from the kingdom suit but was done with power point. The rectangular shape was reshaped into a thin horizontal rectangle and the length was measure with a meter rule in accordance to scale reading from the kingdom suit (figure 3.9). From the Kingdom software, the full section was captured and pasted on power point without altering the scale. The section and the prepared scale are grouped (Control G) as one before resizing. The text box helped writings on sections. Section of the regional 2D line was displayed for interpretation by picking regional scale faults and tops of the various rift stages. The regional two dimensional seismic section was purported to map major structural trend in the pre rift section. The freeform shape tool was used to design the pre, syn and post-rift unit. Also in the cube flipping was done across entire seismic data (both inlines and crosslines) for a snap shot of some seismic sections. The line tool was used as the faults. Right clicking and choosing format shape gave options for the shape to be edited like filling with colour, increasing or decreasing transparency, increasing or decreasing line thickness among others. Digitised arbitrary lines were taken through named faults and across ridges on gridded time for vertical sections for interpretation.

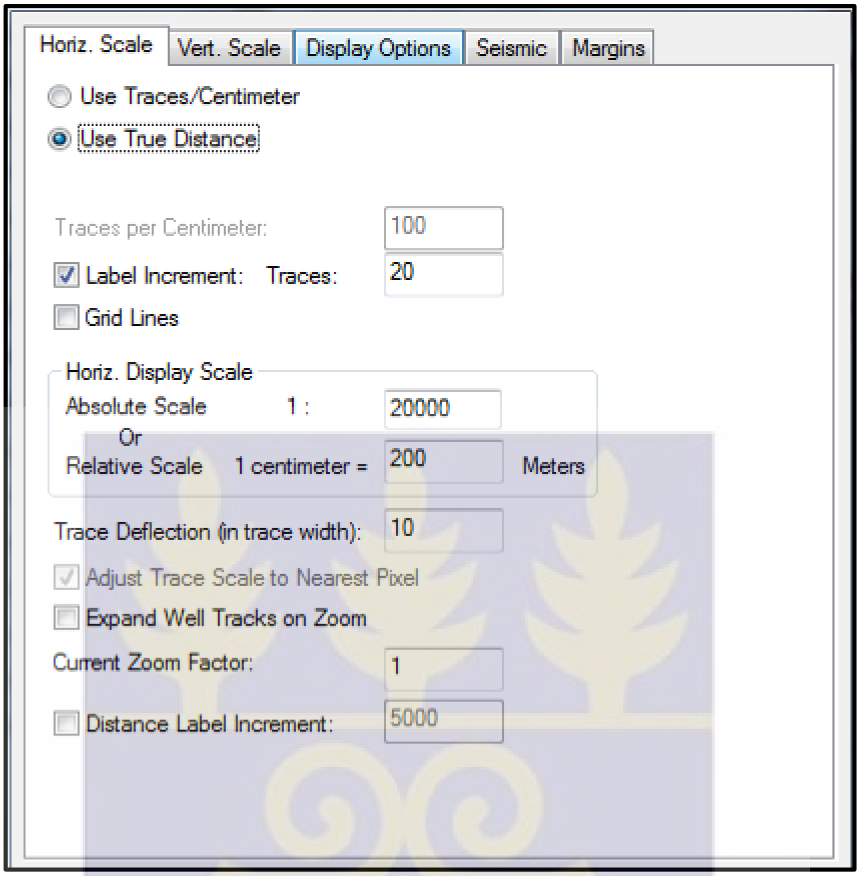


Figure 3.8 Dialogue box for scale setting

3.9 Schematic and Synoptic Modules

Perfectly fitting modules for structural interpretation were created. The schematic and synoptic diagram were done by the use of graphics software called the adobe photoshop. Adobe photoshop is both a vector and a bit map based software that was used for the modification of images and the drawing of objects and diagram. The software has a variety of tools which enabled me to draw the diagram. The drawing was most importantly based on a three dimesional perspective from the results obtained from the large scale structural mapping (Figure 3.10).

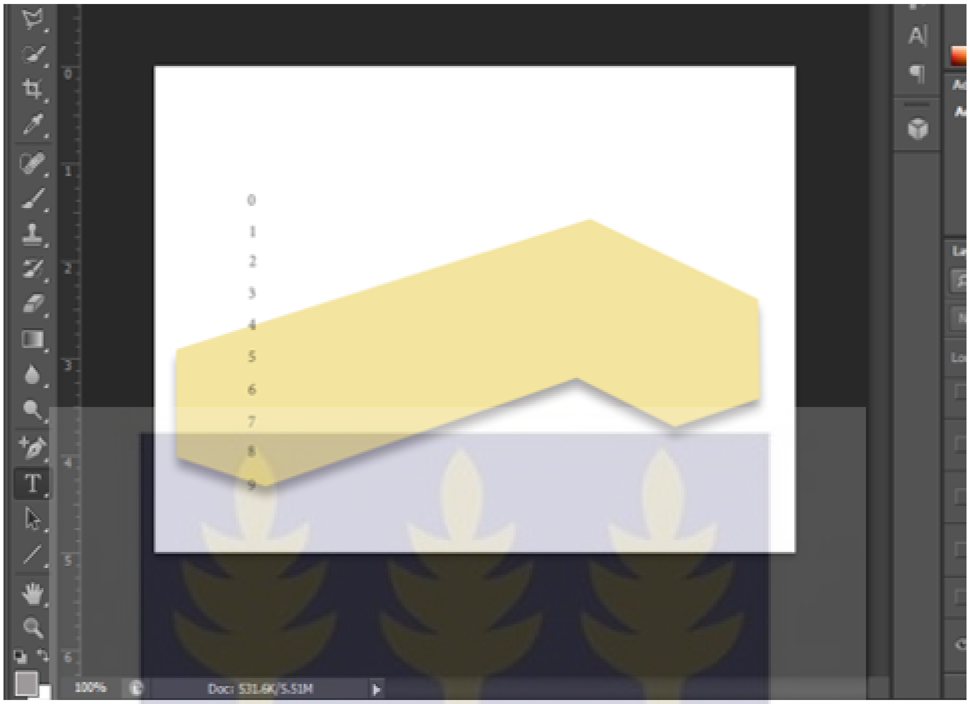


Figure 3.10 module for regional structural trend in the study area from Adobe Photoshop.

- The Rectangular tool was used to draw the rectangular shape.
- Anchor and convert point tool was used to transform rectangle into the shape of the diagram.
- The line tool was used in the projection of the wells xyz.
- The brush tool was used to demarcate folds and for curvy lines.
- The horizontal type tool was used to label diagram or image with a name.
- The ruler tool was used to make ruler on the diagram as a standard of measurement.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Pre-Rift

The WSW-ENE 2-D regional seismic section (AB) in Figure 4.5 showed significant thinning of the pre rift basement from the east to west of the study area. In the west, a 7.25 s and more pre-rift block. In the eastern portion toward the shore thick pre rift block was observed from about 6.25 s and more. The pre rift was identified as areas with die off reflectors in the seismic section. Large scale Normal faulting of the pre rift blocks were observed to be widely spaced which caused half grabens and accommodation space for syn rift sedimentation. These faults were trending northeast-southwest and dipping southwest (Figure 4.1B). These faults may be due to rifting superimposed across the Paleozoic basin. According Blarez and Mascle, (1988), transform faulting was initiated between the African and South American continental plates in Early Cretaceous time, forming divergent basins or pull-apart grabens.

Based on the interpretation in Figure 4.1B the tectonic evolution was summarized below with the schematic diagram (Figure 4.2). At first there was a crustal weakness within the pre rift unit during Pre-Aptian times, when rifting started faults were formed along these zones of crustal weakness. As rifting continued sedimentation and faulting were also occurring synchronously within the syn-rift unit during Mid Aptian to Albian times. This was followed by a first post-rift sedimentation during Cenomanian to Campanian times and then subsequently a second post-rift sedimentation from Campanian to present day (Figure 4.2).

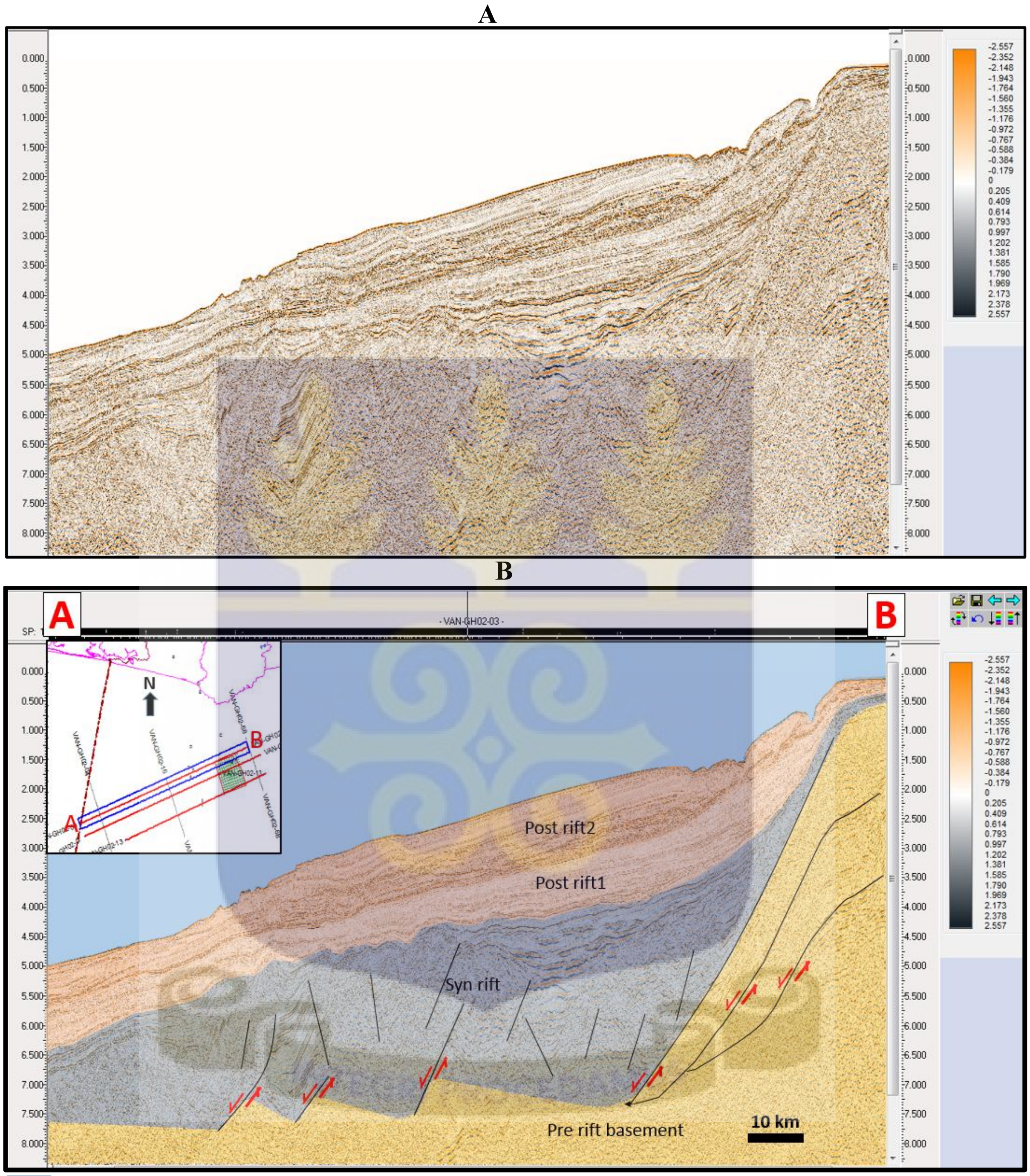


Figure 4.1(A) Uninterpreted and (B) Interpreted regional 2D line showing widely spaced normal faulting in the pre rift block creating accommodation space for syn-rift sediments.

4.1.1 Regional Tectonic Evolution Ultra Deep Water Cape Three Points

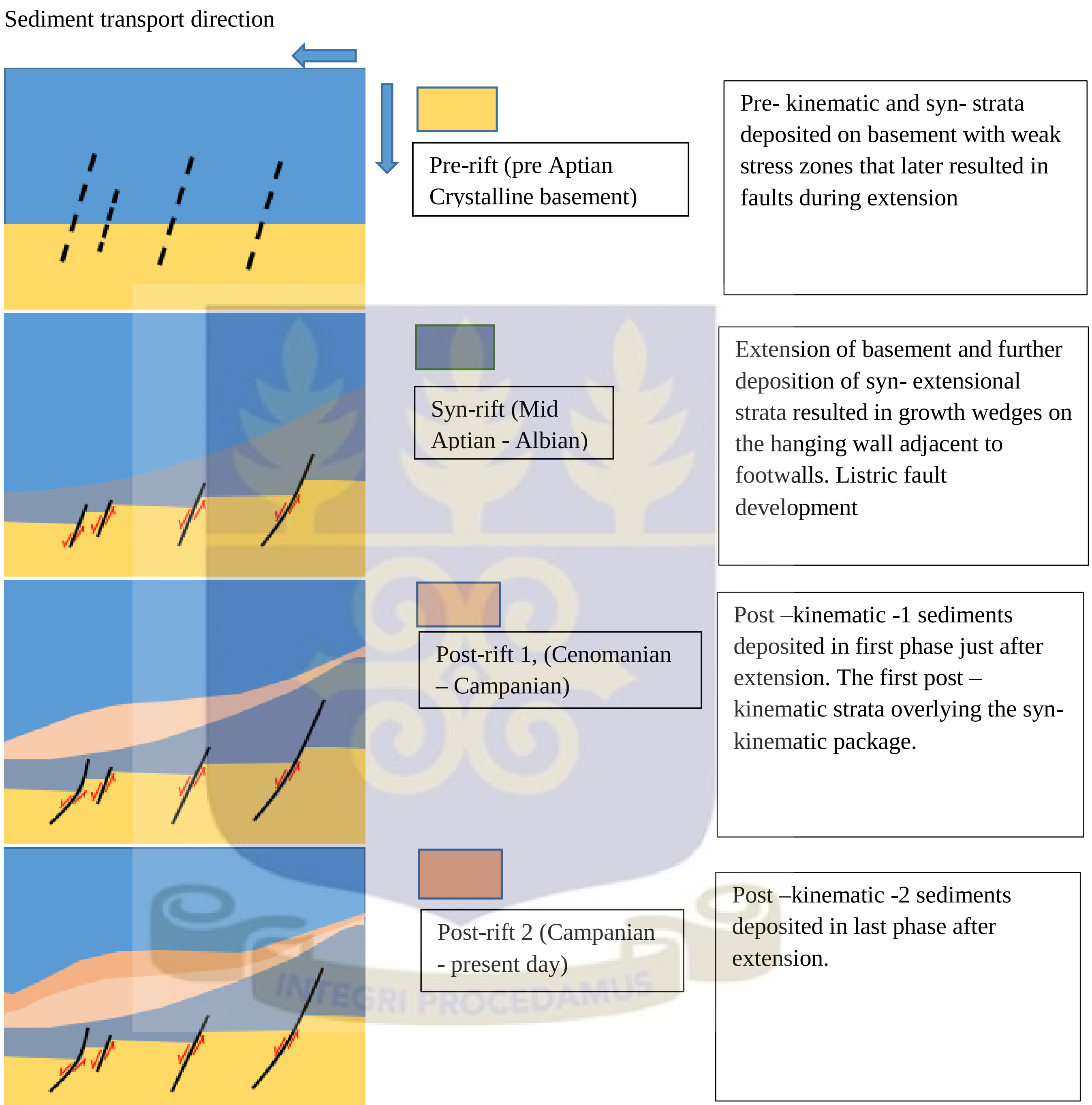


Figure 4.2 schematic diagram of the tectonic evolution of the basin based on interpreted regional 2D line in figure 4.1

4.2 Syn Rift

The Cenomanian Unconformity surface showed normal faults trending northwest-southeast. From the colour bar the red to black colour represented a higher to lower elevation respectively. The faults were more in the shallower part of the basin and going deeper into the basin two ridges were observed. The surface also showed that these two ridges were three way dip fault assisted closure. A three way dip structure is a geologic structure dipping in three directions. The two ridges (red polygons) are parallel and are typical of en echelon structures and the contouring shows a three way dip closure of the ridges (Figure 4.3).

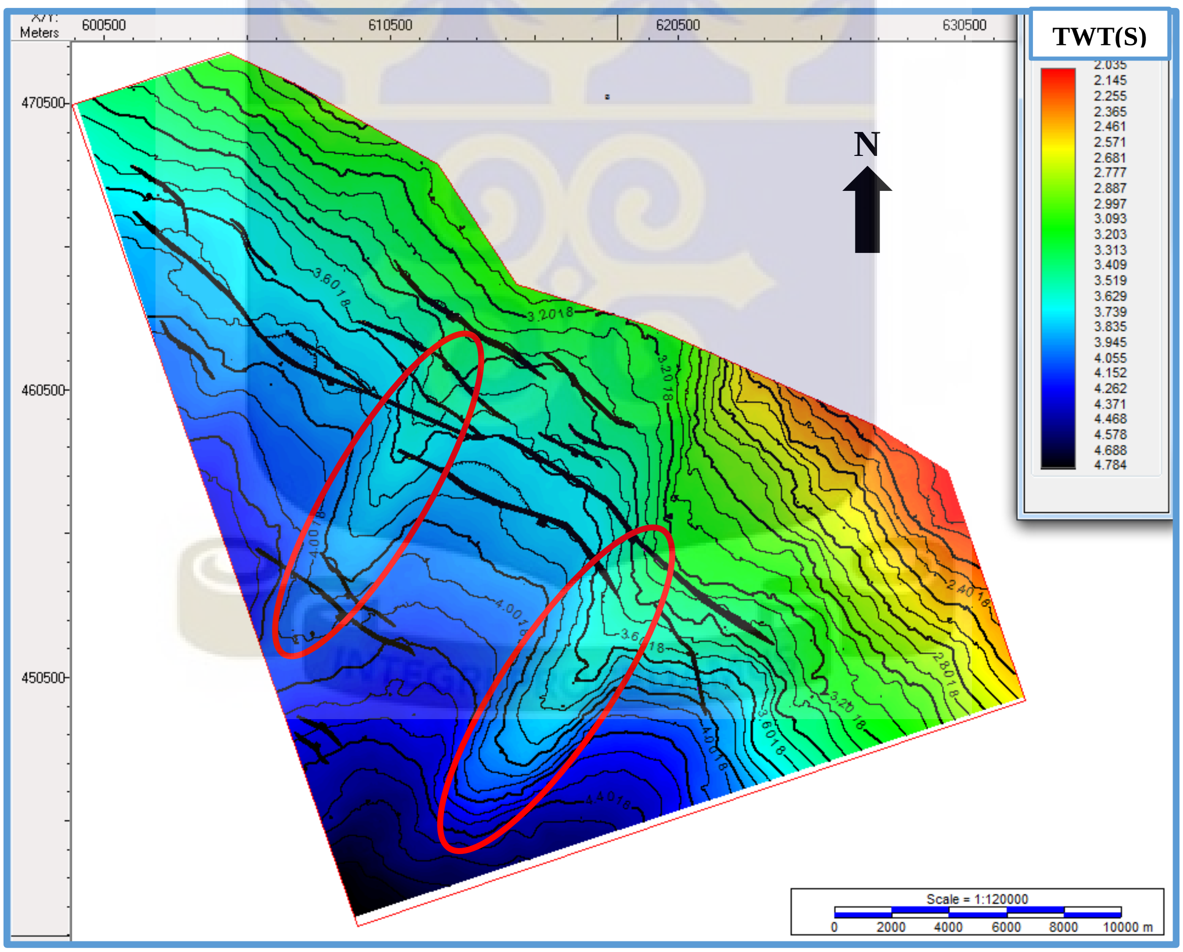


Figure 4.3 Cenomanian Unconformity contoured time structure map showing NW-SE striking faults and two NE-SW trending ridges.

The Cenomanian Unconformity gridded surface for interpretation purpose had the faults assigned into different colours and were named as well. All the faults were trending in the same direction. Faults 2 and 8 are major faults on this surface with 1, 3, 4, 5, 6, 7, 9, 10, 11 and 13 synthetic to these two faults. The faults 12 and 2 show a relay ramp between them. All the faults were dipping southwest except opposite dipping faults 17 and 18. The surface also show a minor graben between faults 15 and 17.

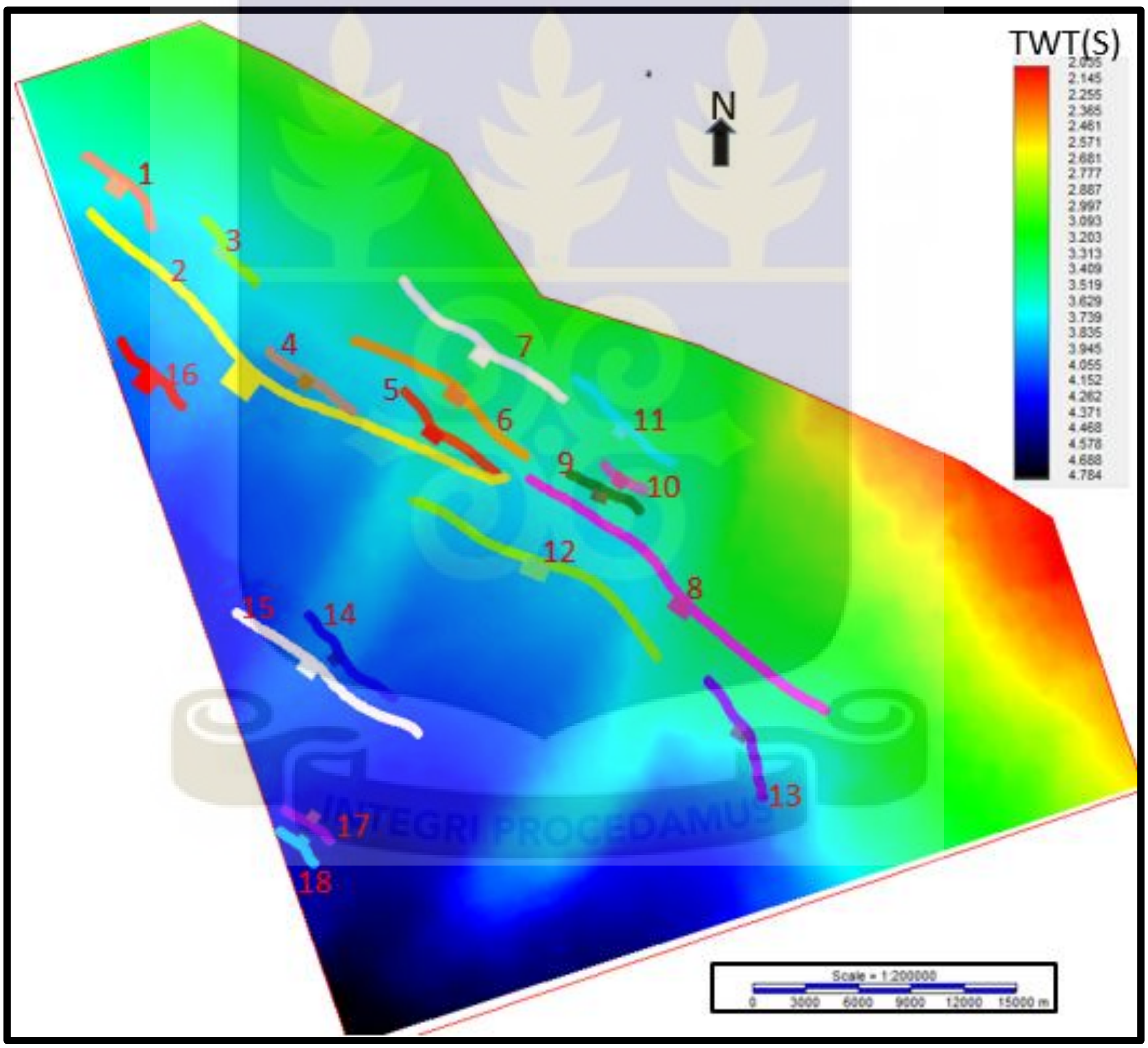
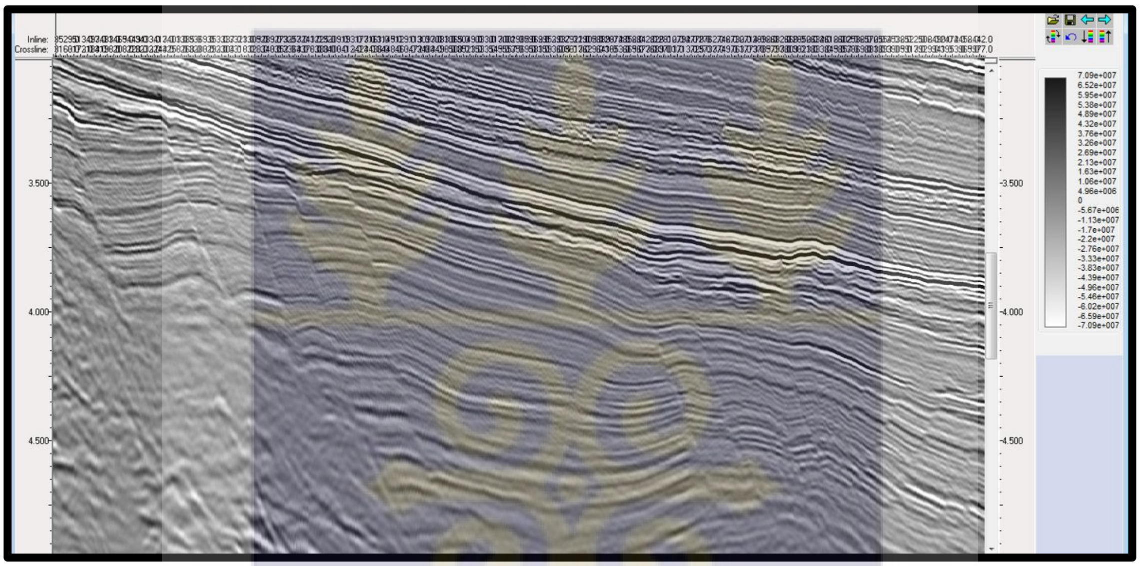


Figure 4.4 Cenomanian Unconformity gridded time structure map showing assigned coloured faults and names.

The digitized arbitrary line AA' (Figure 4.5)through the faults 7, 6, 5, 2, 12 14, 15, 17 and 18 showed that all the faults on this section were normal fault dipping in the same direction except 17 and 18 dipping in the opposite direction which formed a minor graben between 15 and 17. Average throw of faults on the Cenomanian Unconformity horizon is about 0.2 s TWT. Between faults 7 and 6 of the Intra Late Albian horizon is a rotated fault block (red arrow).

A



B

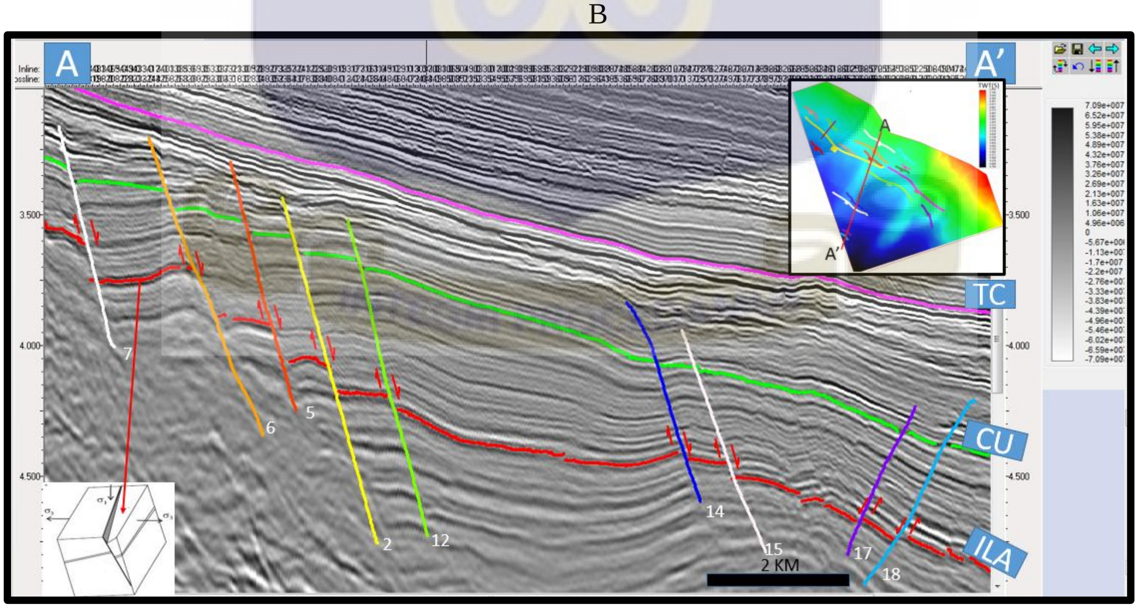


Figure 4.5 Digitized arbitrary line AA' passing through faults 7, 6, 5, 2, 12, 14, 15, 17 and 18. TC = Top Cenomanian, CU = Cenomanian Unconformity and ILA = Intra Late Albian

The Intra Late Albian time structure map had the same surface morphology as the Top Cenomanian time structure map. Same faults in the Cenomanian Uncomformity also went through this surface. The faults were growth faults. These step like faults occurred in the shallower parts and then moving deeper into the basin the ridges were formed.

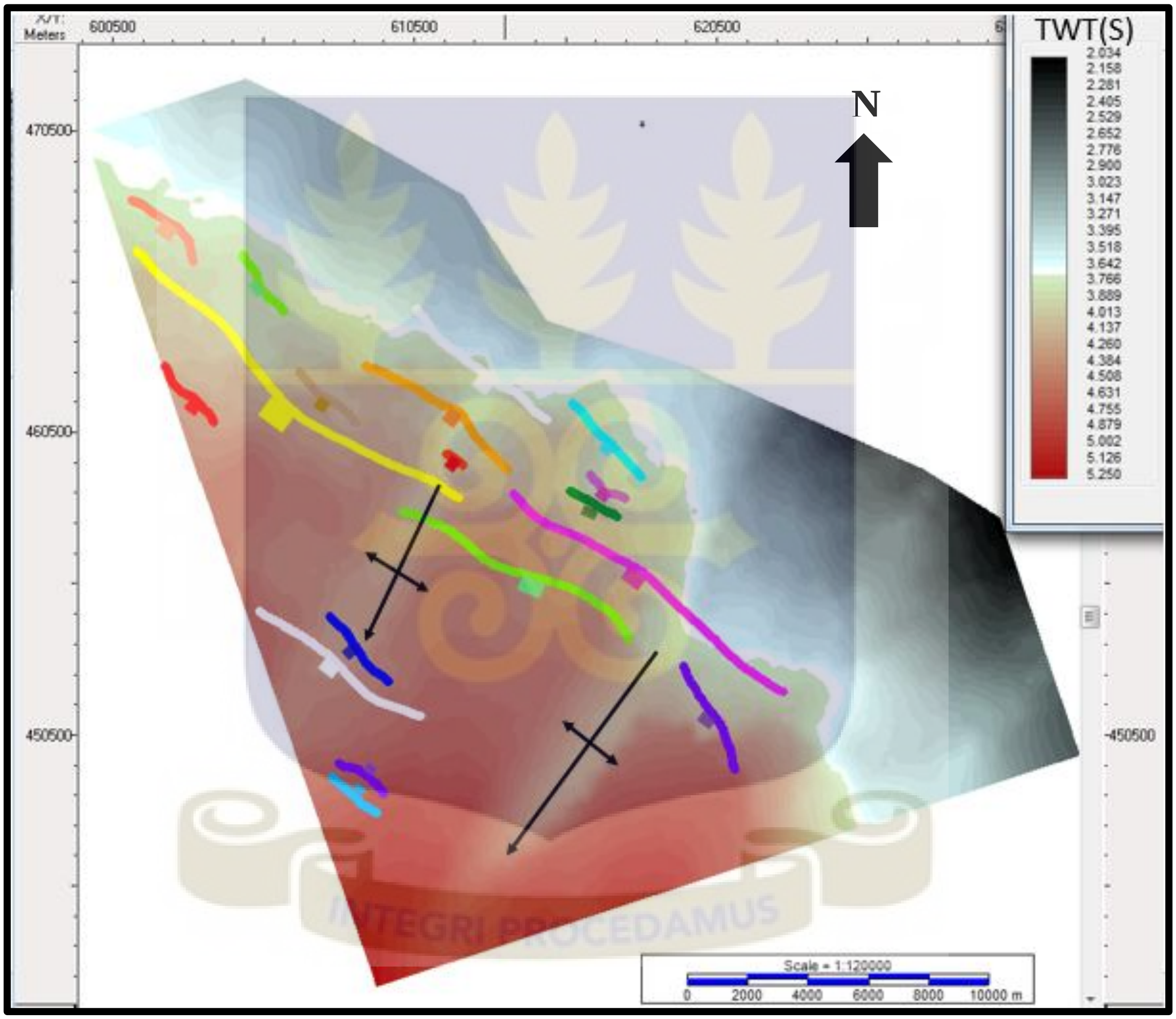


Figure 4.6 Intra Late Albian gridded time structure map showing fault trends and ridges. The black areas showing areas of higher elevation and the red shows areas of lower elevations from the colour bar.

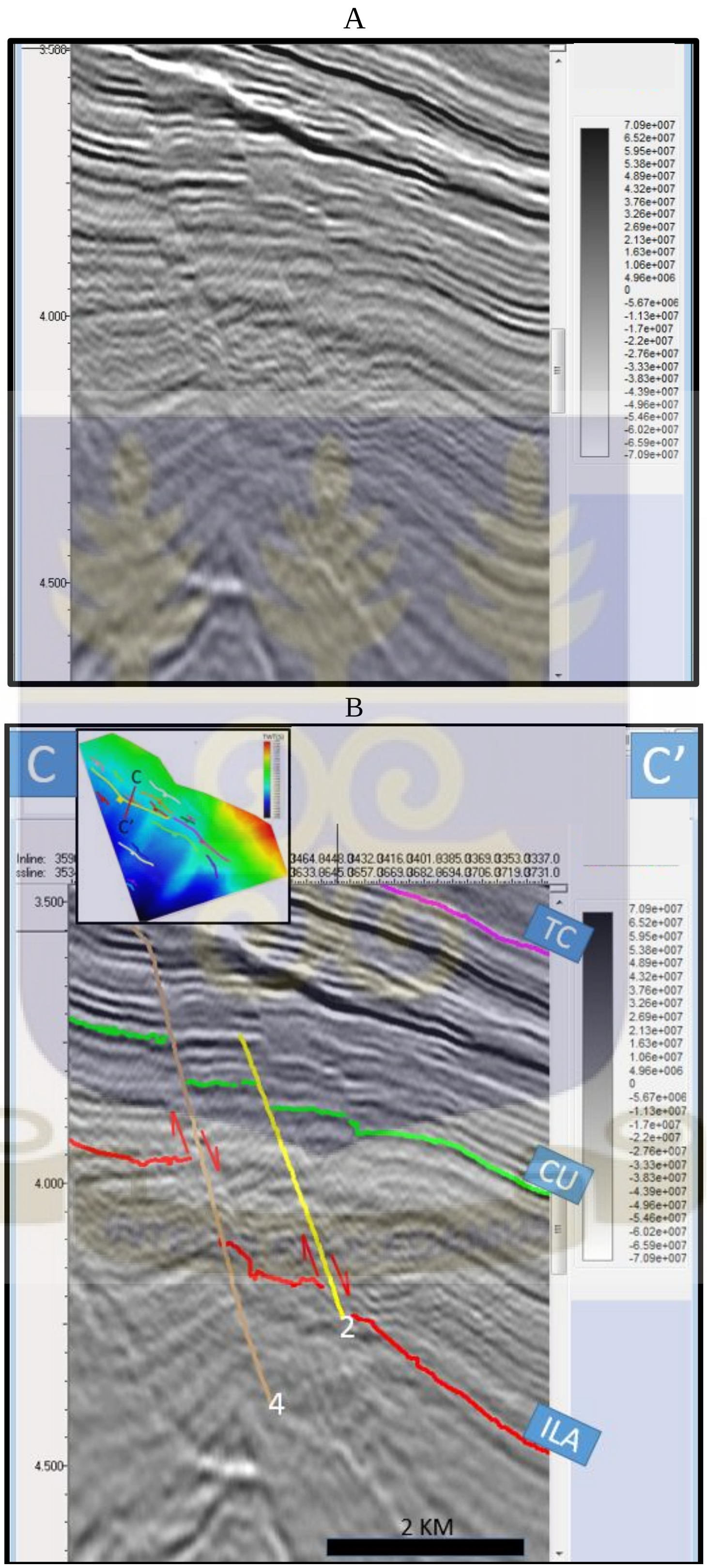


Figure 4.7 Uninterpreted (A) and Interpreted (B) digitized arbitrary line CC' passing though faults 4 and 2 of the Cenomanian Unconformity and Intra Late Albian surfaces showing sedimentation thickening with faulting.

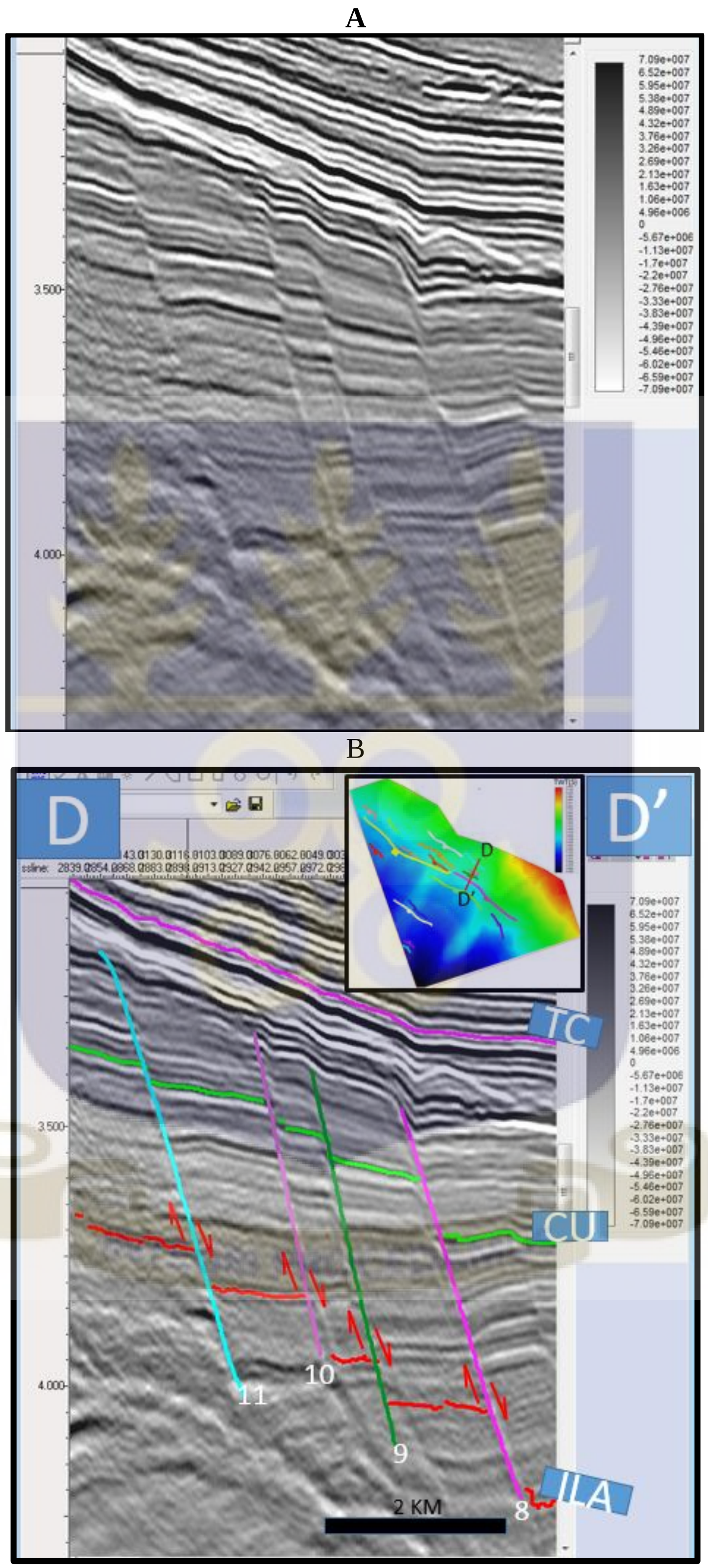
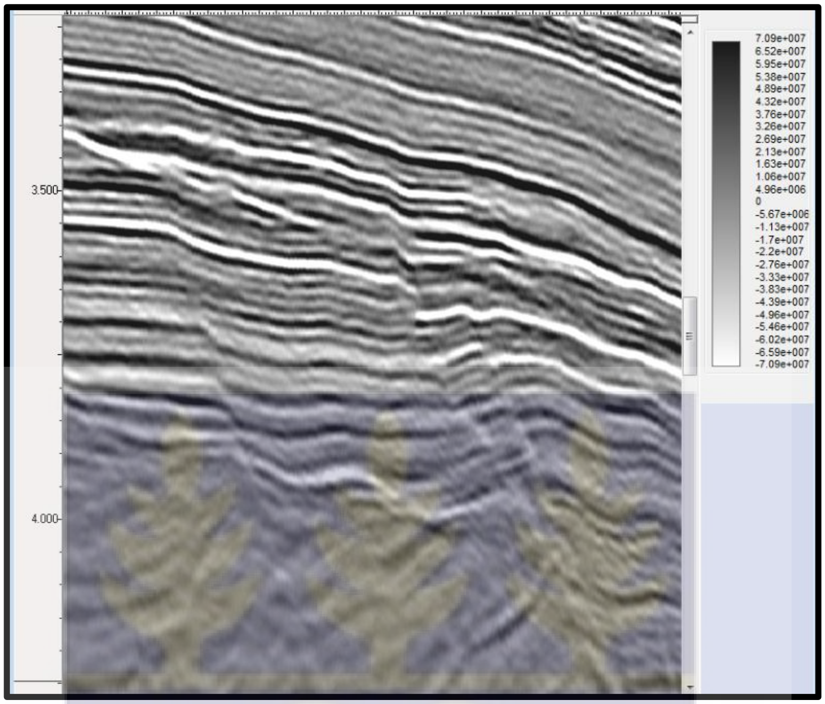


Figure 4.8 Uninterpreted (A) and Interpreted (B) digitized arbitrary line CC' passing though faults 11, 10, 9 and 8 of the Cenomanian Unconformity and Intra Late Albian surfaces showing sedimentation thickening with faulting.

A



B

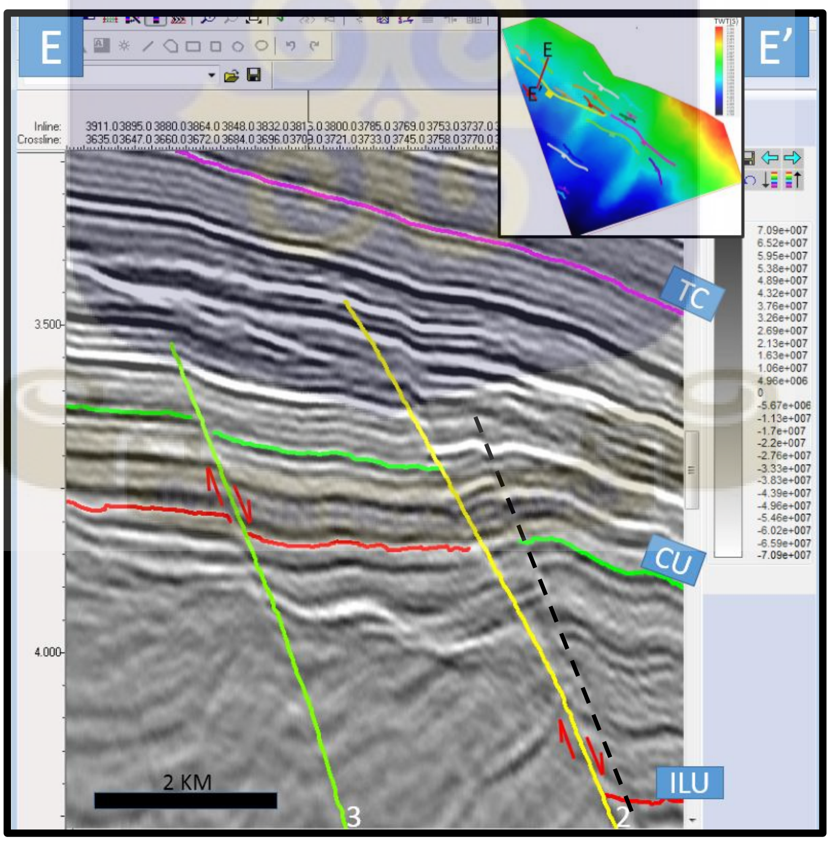


Figure 4.9 Uninterpreted (A) and Interpreted (B) digitized arbitrary line CC' passing though faults 3 and 2 of the Cenomanian Unconformity and Intra Late Albian surfaces showing sedimentation thickening with faulting (growth faults).

The three dimensional view on the Cenomanian Unconfomity surface showed the deformational structures clearly. The ridges which were three way dipping, fault planes which were three dimensional surfaces along which displaced faulted blocks moved and relay structures. The relay ramp on this perspective view was highlighted by the schematic diagram at the right corner which showed the displacement transfer between two normal fault segments. The overlap zone between the fault segments is called a relay, and within the horizontally bedded sequence was characterised by a relay ramps. The breached relay structure was an increase in displacement on relay which inevitably led to the breaching of the relay ramp, generally by propagation of either the footwall or hanging wall fault segment at the top or the base of the ramp. Relay ramps, especially sub-seismic relays, could be quoted as a mechanism for fluid-flow communication within faulted reservoirs. Relays may provide bed continuity within otherwise breached reservoir horizons and communication across faults which may reduce or stop flow.

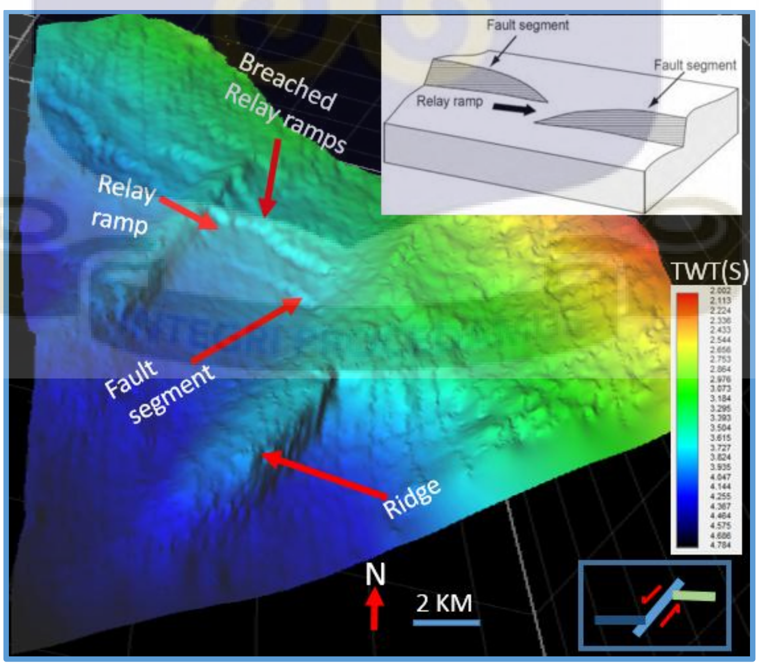


Figure 4.11 Three dimension (Perspective close up) view of a Cenomanian Unconformity gridded surface highlighting ridge, relay ramp, breached relay structure and faults segment.

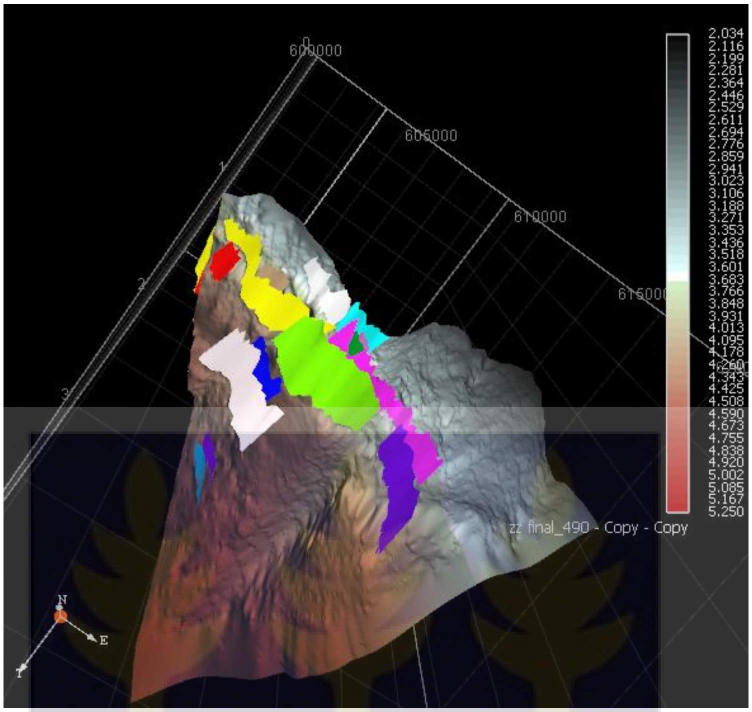


Figure 4.12 Intra Late Albian gridded time structure map showing fault planes and ridges in three dimensions.

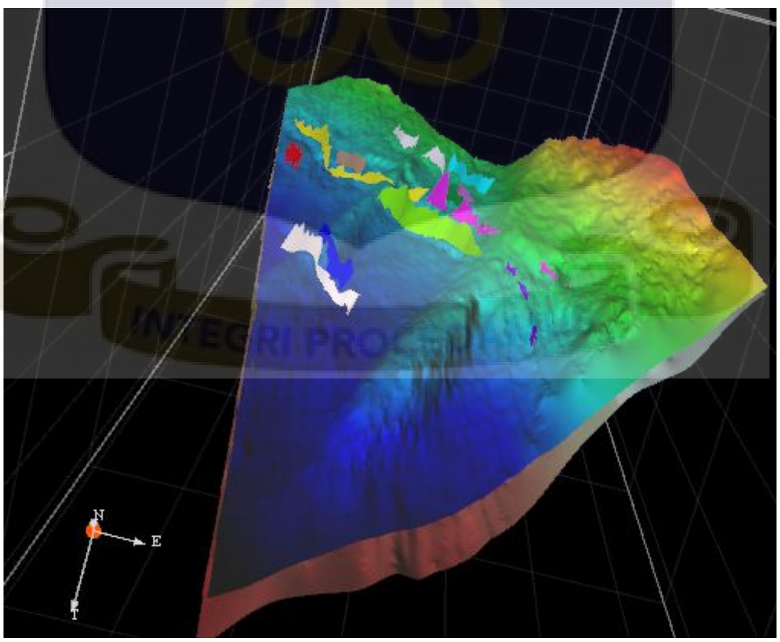


Figure 4.13 Intra Late Albian and Cenomanian Unconformity gridded time structure map showing fault planes and ridges in three dimensions.

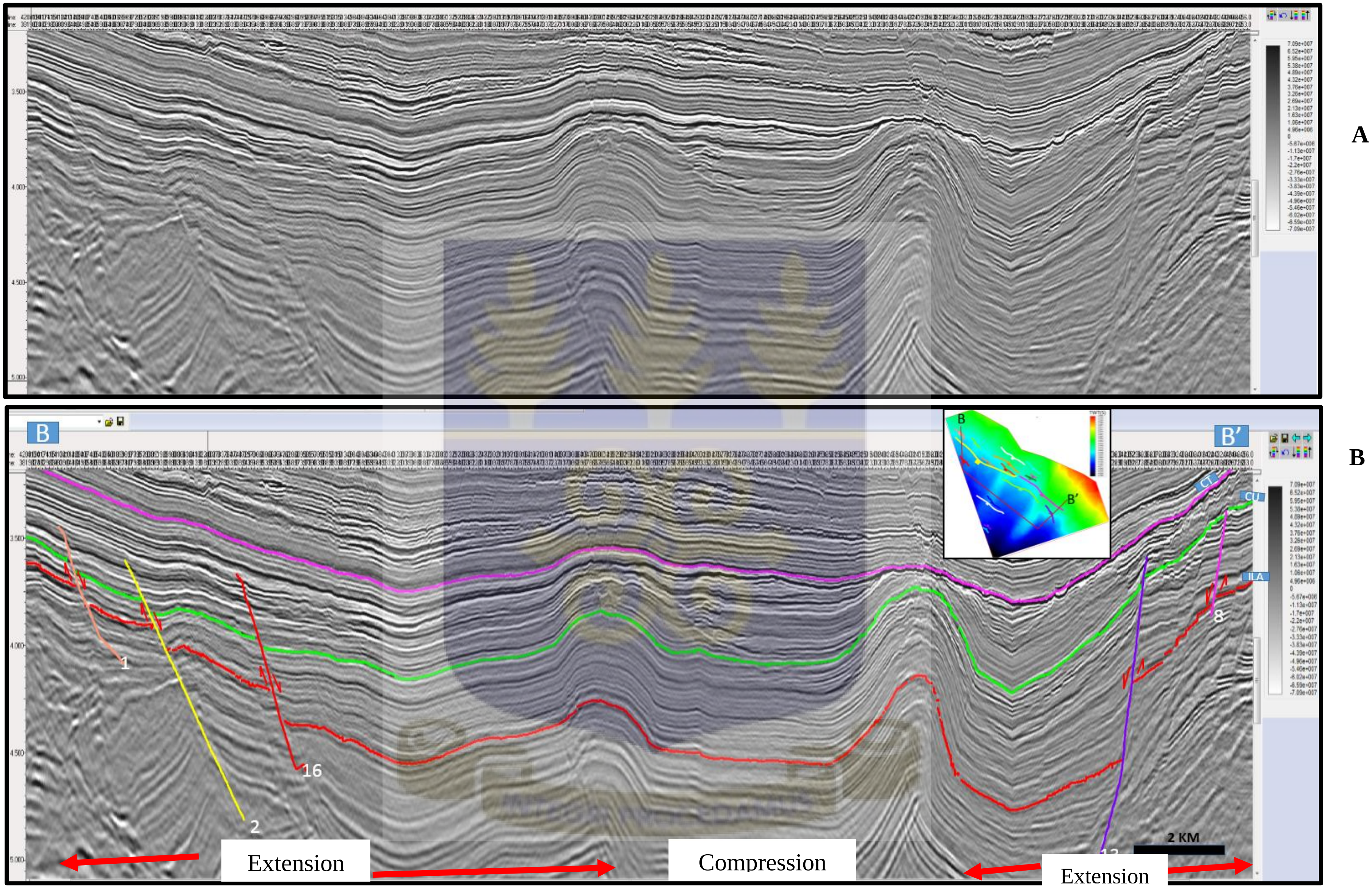


Figure 4.14: Uniinterpreted (A) and Interpreted (B) arbitrary line BB' passing through faults 1, 2, 16, 13 and 8 showing extensional and compressional regimes

4.2.1 Stress And Strain

From the section (digitized arbitrary line BB') above (figure 4.14) basically two regimes (extension and compression) of tectonism was identified in the Ultra Deep Water Cape Three Points base on deformation observed from the interpreted surfaces within the syn rift. Since the basin was formed as a result of strike slip tectonic movement between Africa and South America these two tectonic deformational regimes could be better classified as a transtensional and transpressional. The transtension caused normal faults which showed that the minimum stress is in the shoreward (NE) - basin ward (SW) plane which was probably due to rifting in early Albian times. The maximum principal stress is in the direction of the hanging wall of the faulted blocks and perpendicular to the minimum principal stress plane. The shear stress is parallel to the southwest dipping fault planes and the normal stress is perpendicular to the dip of the fault plane. The intermediate stress is parallel to the northwest-southeast striking faults. Deformation here was brittle.

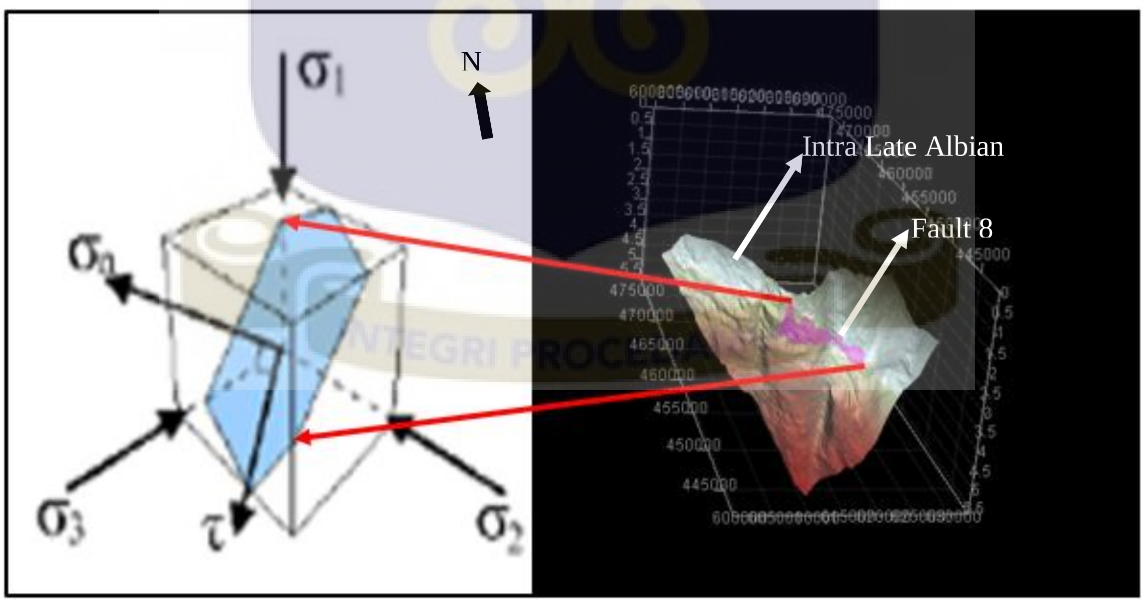


Figure 4.15 schematic model showing stress (shear (τ), normal (σ_n), maximum, minimum and intermediate) geometry in three dimension from major fault plane 8 within Intra Late Abian Surface

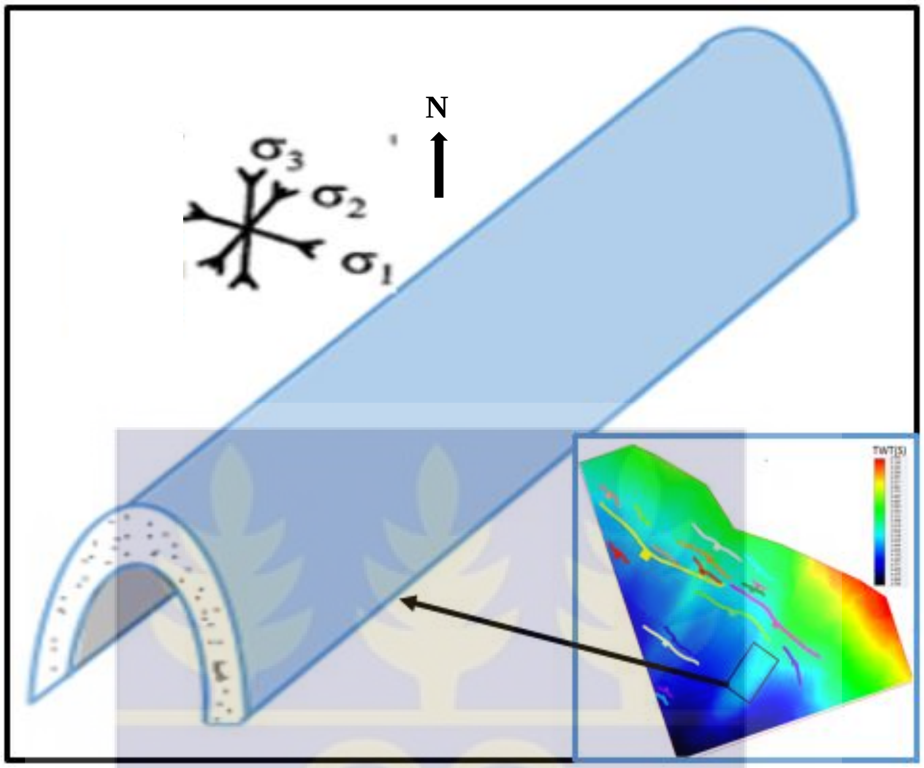


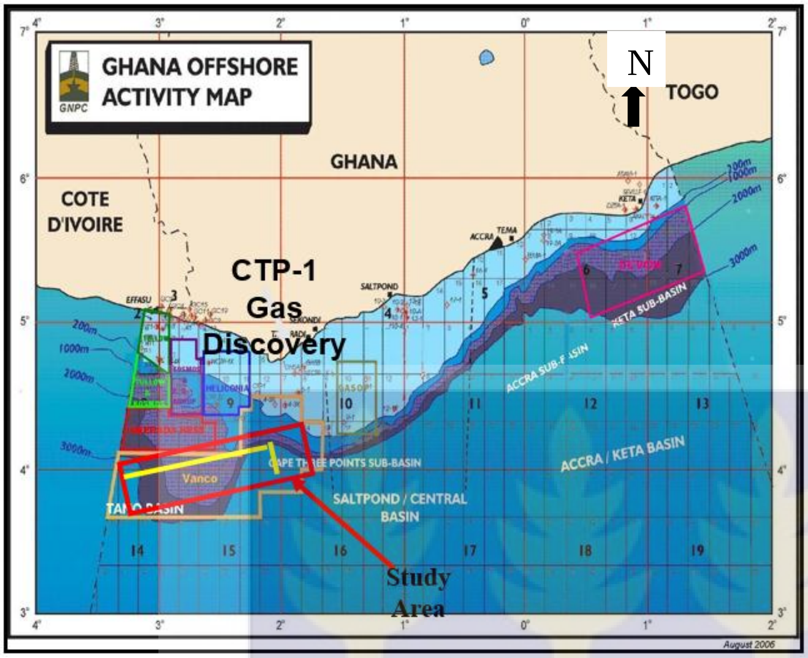
Figure 4.16 schematic module showing stress geometry σ_1 (maximum principal stress), σ_2 (intermediate principal stress), and σ_3 (least or minimum, principal stress) geometry in three dimension of the transpressional polygoned section of the Cenomanian Unconformity surface.

The second regime was a regional transpressional regime, not very conspicuous in the regional 2D but clearly seen in the cube which started probably during the Late Albian to Cenomanian. This may be due to slightly oblique orientation of the Romanche fracture zone relative to the drift direction of Africa and South America moving rift. This produced a set of en echelon structures (ridges) as seen in the southwestern portion of the cube deep into the basin. From the interpreted syn rift surfaces the occurrence of “en echelon” structures (ridges) within and adjacent to the principal displacement zone is one distinctive features of strike-slip tectonics. The term ‘en echelon’ refers to a stepped arrangement of relatively short, consistently overlapping or underlapping structural elements that are approximately parallel to each other, but oblique to the linear zone in which they occur (Christe-Blick and Biddle, 1985). Anticlines from these en echelon structures were trending northeast-southwest and plunging southwest with maximum principal stress from tectonic transpression in the NW-SE plane. The deformation here was ductile. The syncline formed between these ridges also created accommodation space for sedimentation (figure 4.16). These transpressional structures observed in the study area are in agreement with previous studies by (Zalan et al., 1985).

According to de Maisey (2000), sub-basins in the Central Area of Gulf of Guinea and away from the fracture zones are flowing the NW-SE trends as dictated by the large scale faults. Basins in the vicinity (50-100 km) of the bounding St. Paul and Romanche Fracture Zone had their deposition controlled by dextral oblique-slips. Small basins located in compressional quadrants near propagation tips of the marginal strike-slip faults, such as in the Piaui, Camocim, Acarau and Accra Basins, underwent transpression resulting in local transpressive belts. These basins are characterized by oblique strike-slip faults with reverse component of displacement, en echelon folds and ridges (Zalan et al., 1985). Spreading directions during Albian-Cenomanian were striking from NE to SW, interpreted from magnetic anomalies related to sea floor spreading made by (Maisey 2000).

The pre rift unit interpreted from the regional 2D line merged with the interpreted syn rift (Cenomanian Unconformity and Intra Late Albian) surfaces from the cube led to the possible regional synoptic module below showing the pre-rift unit and the syn-rift unit in the study.

A



B

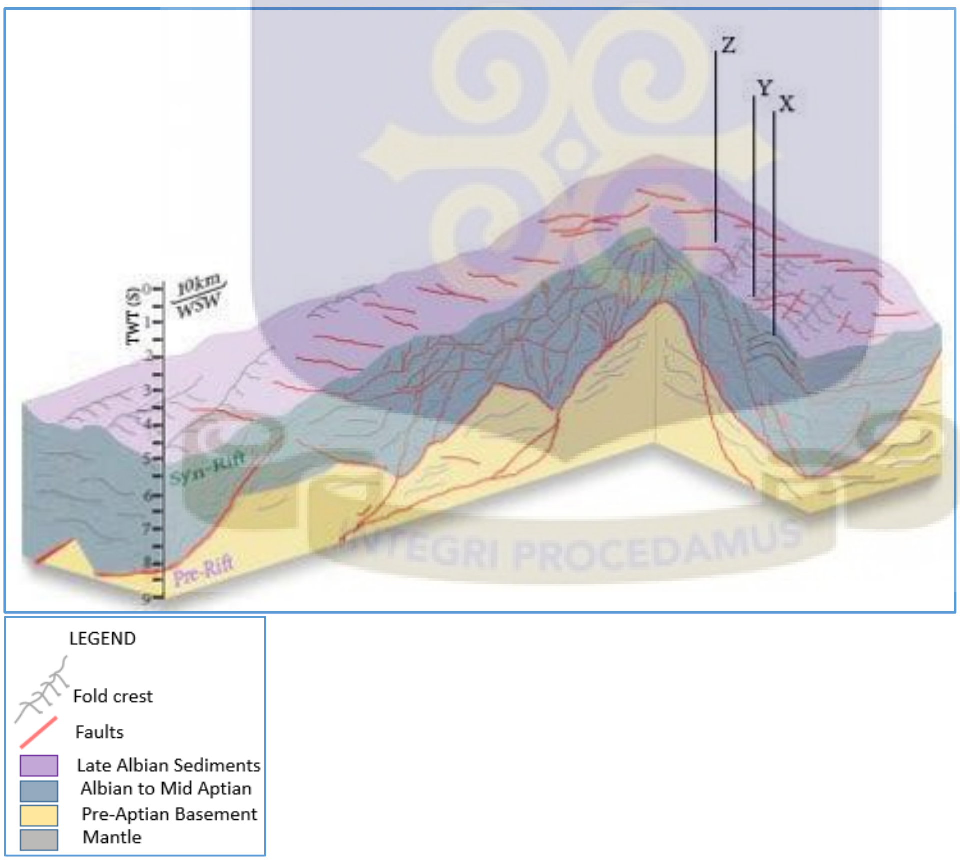


Figure 4.17 Synoptic 3-D diagram of syn rift and pre rift unit (B) of a section (yellow line) from the map (A)

4.3 Post-Rift

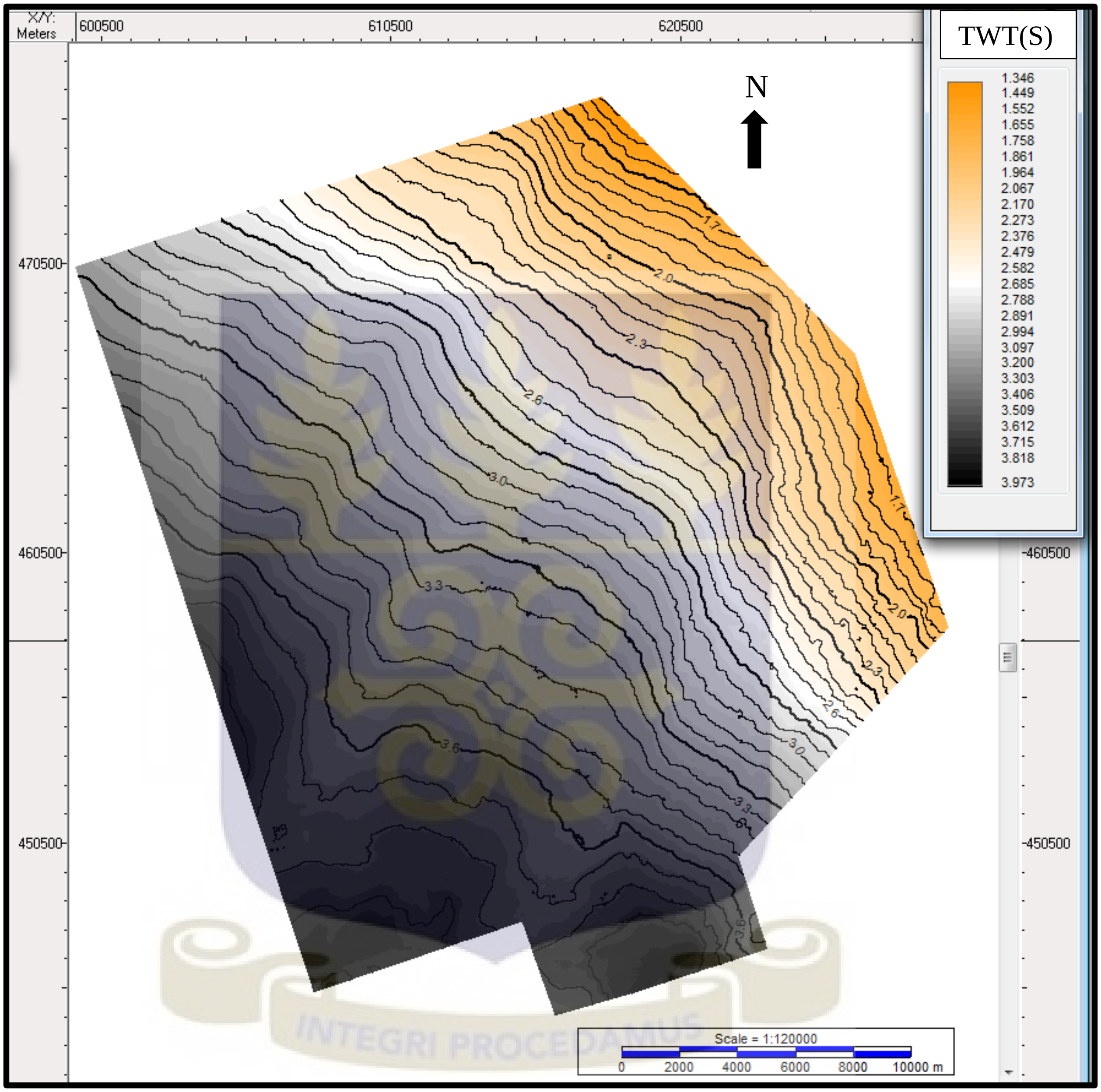


Figure 4.18 Top Cenomanian contoured time structure map. Colour bar showing an increase in time from orange to black. The orange areas represent shallow areas whereas the black areas representing the deep areas.

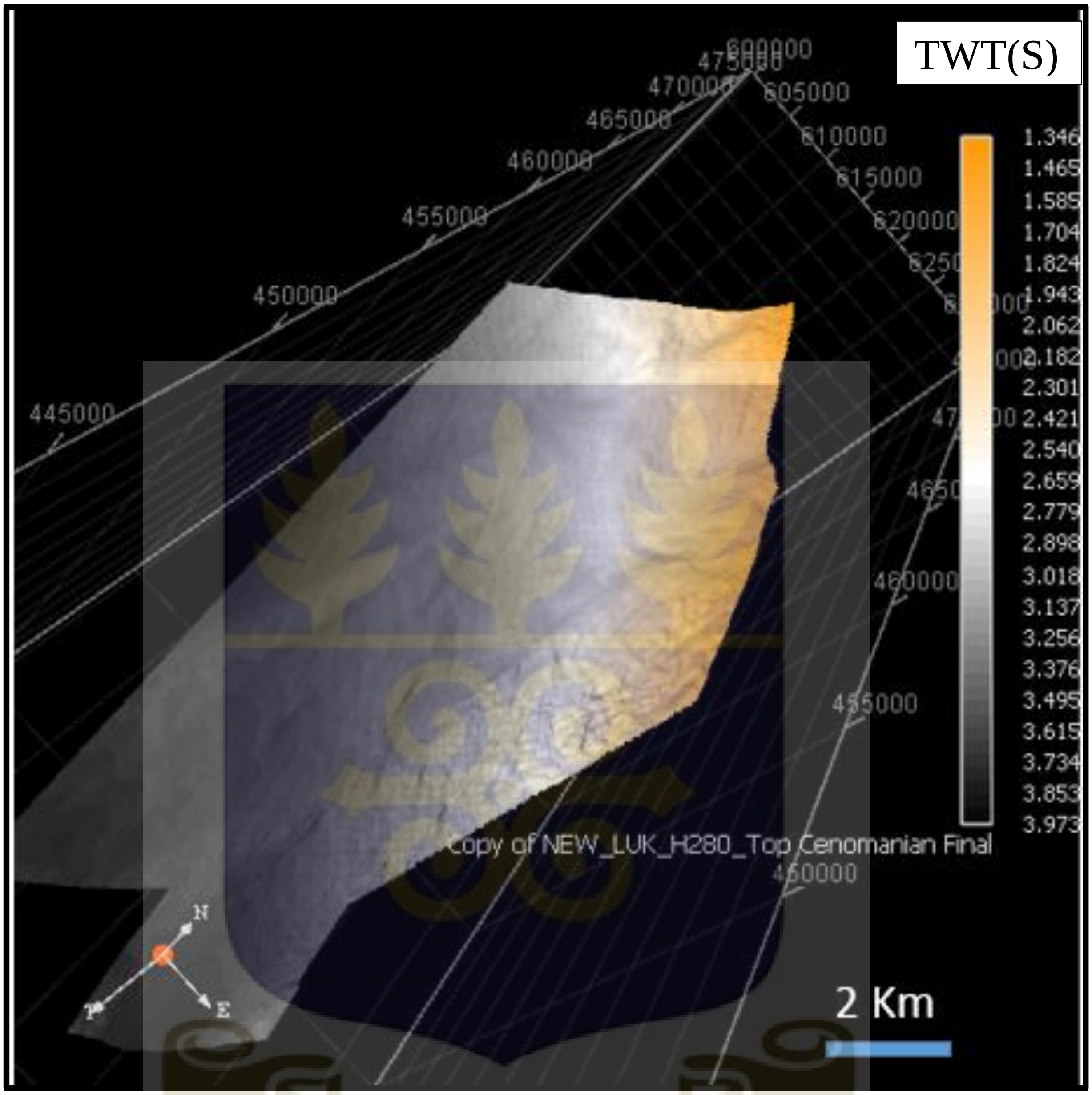
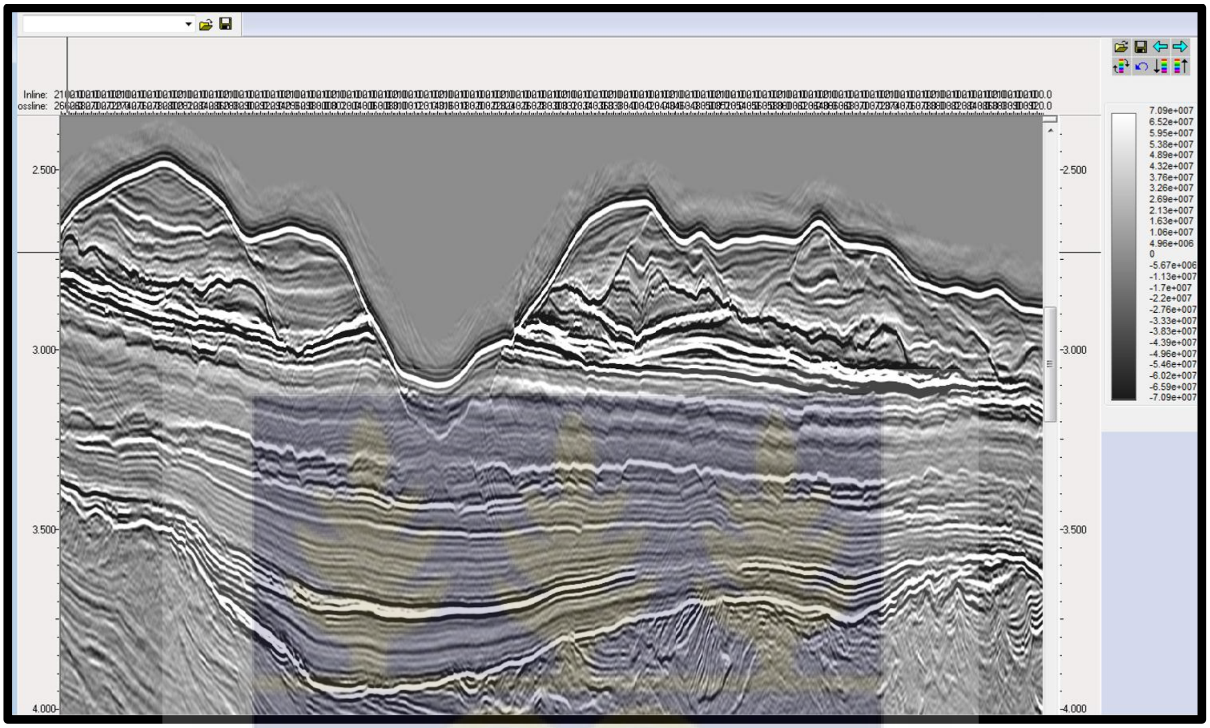


Figure 4.19 Top Cenomanian 3D gridded time structure map. Colour bar showing an increase in time from orange to black. The orange areas represent shallow areas whereas the black areas representing the deep areas.

The colour bar of the time structure map of the Top Cenomanian showed an increase in time from NE to SW with closures at the southern portion. It showed a good sequence boundary since the horizon along which it was picked showed very strong reflection (figure 4.18). The inline 2100 below is a vertical section showing the activities within the post rift. Faulting died before the Top Cenomanian horizon as shown also on the surface (no faults). This was probably due to the end of rifting in the study area and the beginning of the post rift sedimentation. Nontectonic faults were observed within Top Cretaceous to Base Tertiary horizon. Usually mud deposit are observed within post rift sequence, these structures could be mud cracks. Alternatively these faults could be polygonal which in Late Cretaceous times, probably very fine grained sediments were deposited over the area. These fine grained sediments initially probably had a very high water content that escaped during the subsequent burial and compaction. This compaction probably resulted in the characteristic polygonal faulting. Tertiary Unconformity was also observed which may be due to fall in sea level with erosional activities taking place afterward. The sea bed time structure map showed an increase in time from NE to SW from the colour bar (Figure 4.21). The sea bed was picked as a consistent peak. This horizon provides high resolution imaging of seafloor manifestation of gravity collapse and contractional deformation in the Ultra Deep Water Cape Three Points. The overall seaward sloping pattern of the bathymetric map, suggests a strong control of gravity in sedimentation in the Ultra-Deep Water Cape Three Points. Canyons incised the seabed and even deep into the base tertiary horizon. These canyons probably developed as a result of a river system which cut the seafloor from onshore. The canyons within the seabed were observed to be northeast-southwest incised. These canyons typically provide routes for sediment transportation from the shelf to the slope to deepwater settings. These cuttings across bathymetry and even deep into part of the Base Tertiary horizon implies that the canyons post-date these strata in the study area.

A



B

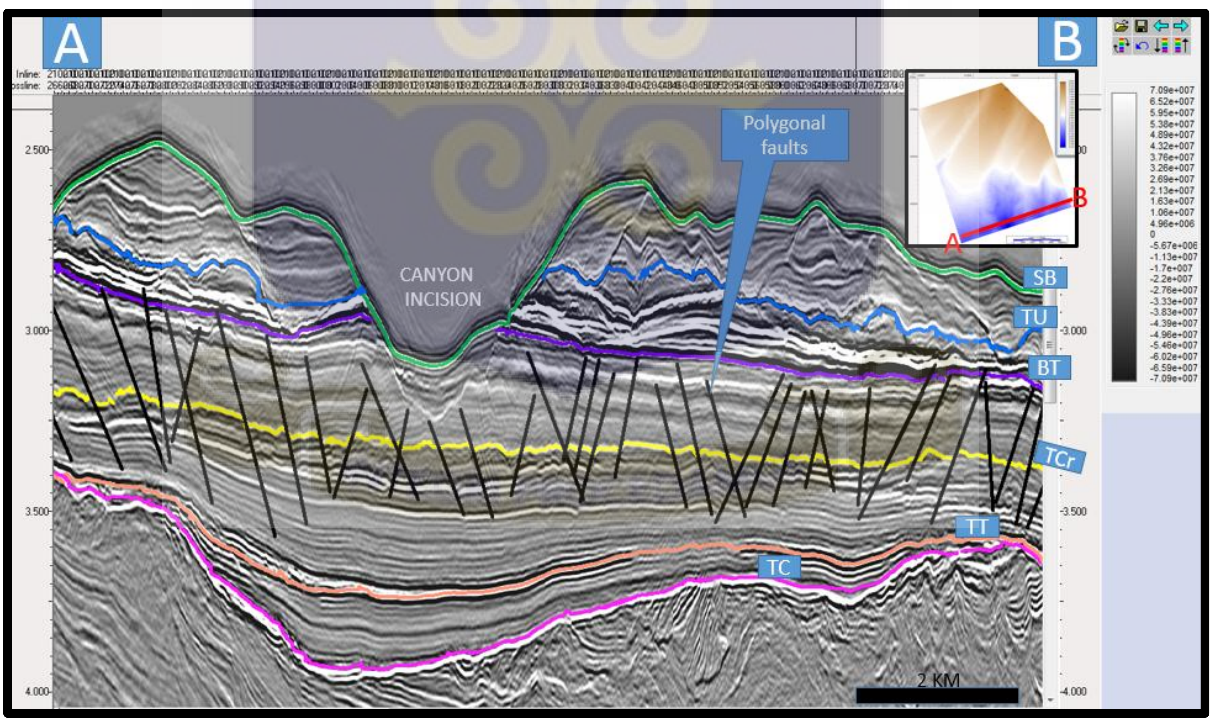


Figure 4.20 (A) Interpreted and Uninterpreted (B) Inline 2100 BT=Base Tertiary, TU = Tertiary Unconformity, BT = Base Tertiary, TCr = Top Cretaceous, TT = Top Turonian, TC = Top Cenomanian.

A

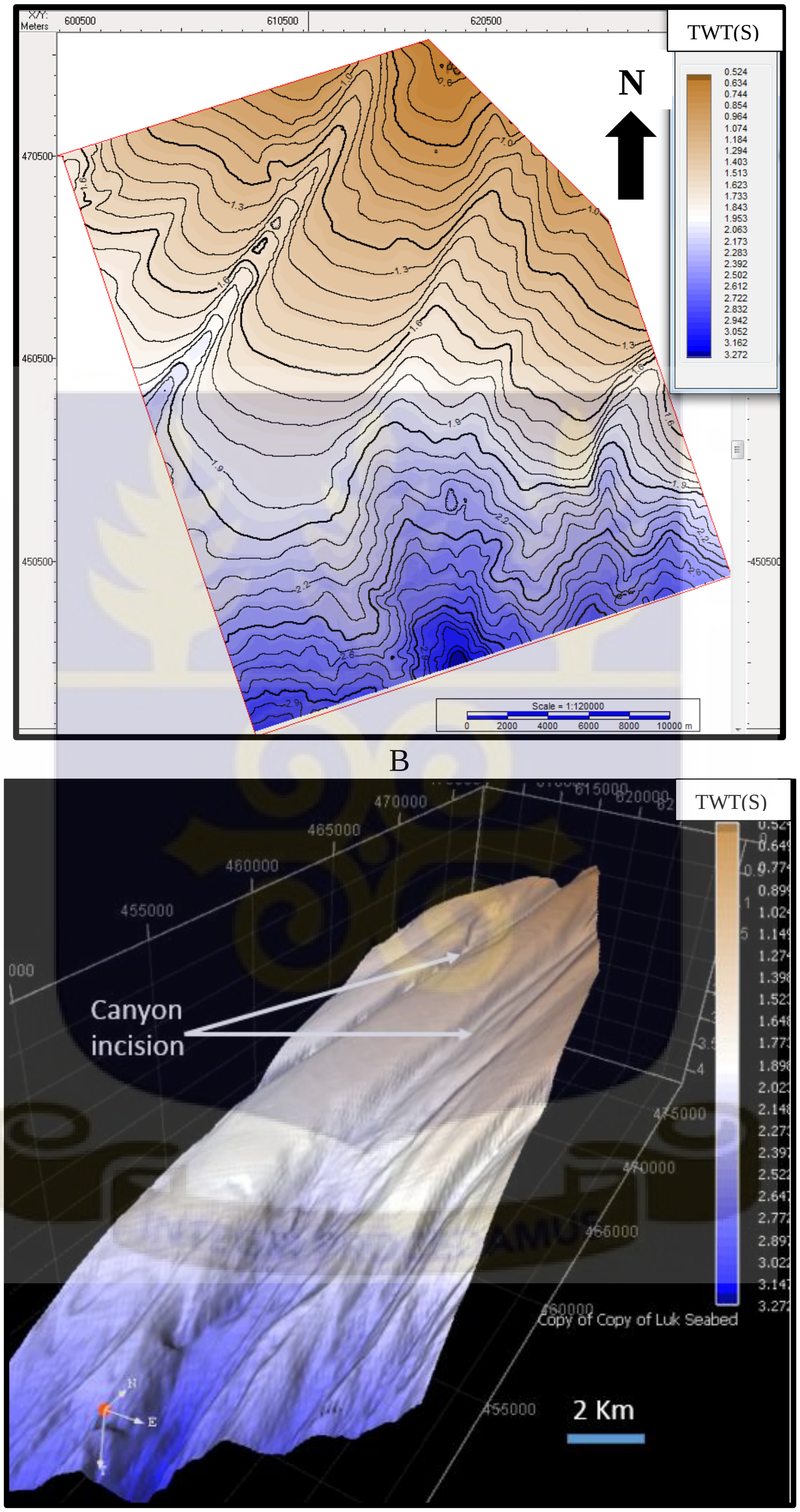


Figure 4.21 seabed contoured (A) and 3 D gridded (B) time structure map showing sea bed canyons incising bathymetry. The colour bar shows an increase in time from brown to blue. The brown areas are the shallowest and blue areas are the deepest

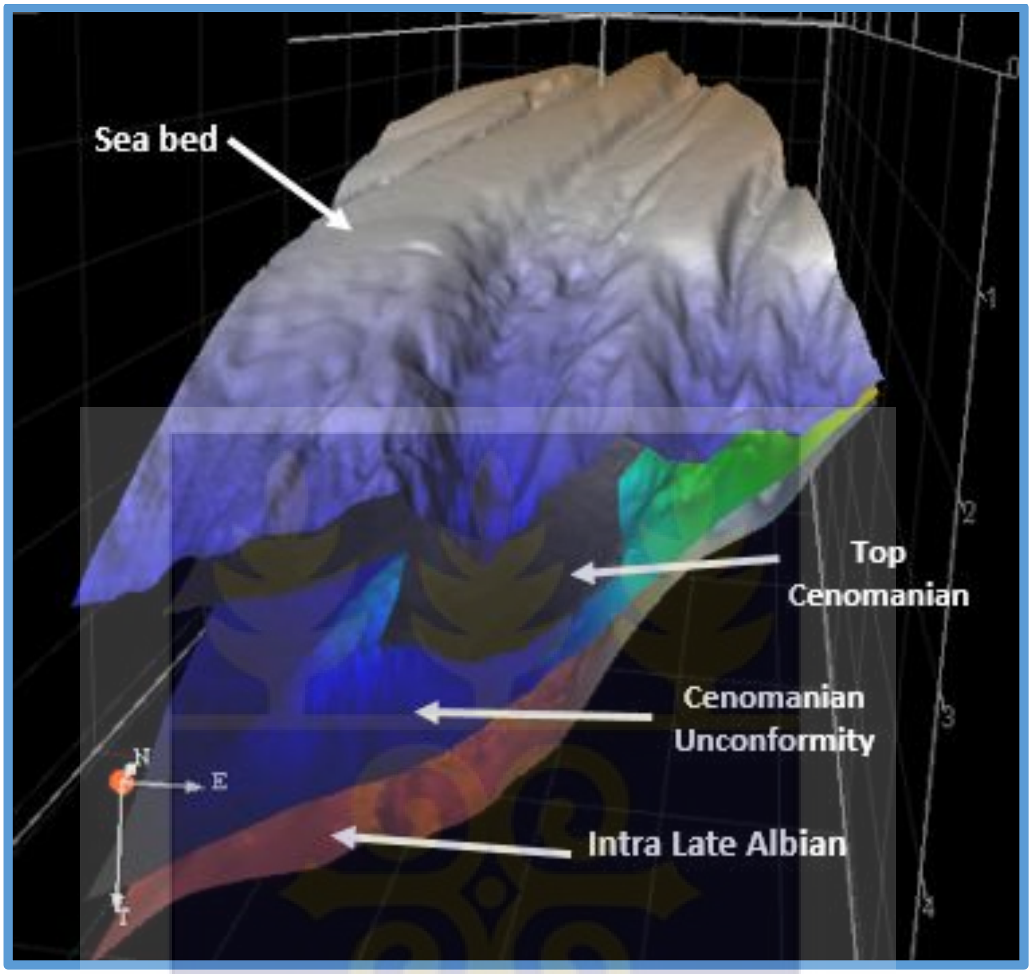


Figure 4.22 showing the various gridded time structure maps of the pick horizons: Sea bed, Top Cenomanian, Cenomanian Unconformity, Intra Late Albian displayed in three dimension

CHAPTER FIVE

CONCLUSION

The newly acquired 3D seismic cube merged with a regional seismic line covering approximately five thousand square kilometers of the Ultra-Deep Water Cape Three Points block helped to reveal the subsurface structural trend inherited from tectonic impact which form the basis of this study. With focus on the different seismic interpretation techniques, a detail study of the subsurface structural trend in the different rift stages has led to the following conclusions:

1. The regional WSW – ENE (AB) seismic line showed widely spaced NE-SW trending normal faults of the pre rift block which also thinned from east to west. Faulting within the pre rift block may be as a result of continuous rifting superimposed across Paleozoic basin between Africa and South America in early Cretaceous time and continuing up to early Albian times in the Cape Three Points area.

2. Large scale normal faults trending northwest – southeast in map view within the syn-rift probably from early to middle Albian syn times may be as a result transtensional regime in shallower part of the Ultra-Deep Water Cape Three Points. Subsequently a regional transpressional regime in the deeper part of the Ultra-Deep Water Cape Three Points may be caused by oblique orientation of the romanche fracture zone in relation with the moving rift. This produced en echelon a structures (ridges) plunging southwest and trending northeast – southwest.

3. Deformation in the syn-rift was both ductile and brittle. Major faults in the syn rift died before Top Cenomanian horizon. Polygonal faults mask the Late Cretaceous unit in the study area. The polygonal faults may have been caused by significantly reduced moisture content due to compaction from subsequent sedimentation. Tertiary unconformities may be due to fall and rise in the sea level. Possible river system cut the bathymetry forming canyons.

5.1 Recommendations

Based on the results and the interpretation done the following recommendations are suggested:

1. Hydrocarbon exploration should be focused in deep water in the central Gulf of Guinea targeting syn-rift structural traps which are very prospective.
2. 3D Post-rift structural interpretation should be done to be able to see the polygonal faults in map view.
3. There is a possibility of numerous other smaller faults not interpreted hence a detail structural mapping should be done by decreasing picking lattice since this project focused on picking large scale structural mapping view.

REFERENCES

Adda, G. W. (2013). The Petroleum Geology and Prospectivity of the Neo-Proterozoic , Paleozoic and Cretaceous Sedimentary Basins in Ghana , 10544.

Antobreh, A. A., Faleide, J. I., Tsikalas, F. and Planke, S. (2009). Rift-shear architecture and tectonic development of the Ghana margin deduced from multichannel seismic reflection and potential field data: Marine and Petroleum Geology, 26, 345–368.

Aryeetey, M. N. A. (2014). The Hydrocarbon Potential of the Devonian Saltpond Basin offshore Ghana.Atlantic, N. (2013). Archimer, 49(December 2012), 1395–1415

Atta-Peters, D., and Kyorku, N. A. (2013). Palynofacies analysis and sedimentary environment of Early Cretaceous sediments from Dixcove 4-2x well, Cape Three Points, offshore Tano Basin, Western Ghana. International Research Journal of Geology and Mining, 3(7), 270–281.

Attoh, K., Brown, L., Jingru G. and Heanlein, J. (2004). Seismic stratigraphic record of transpression and uplift on the Romanche transform margin, offshore Ghana: Tectonophysics, 378, 1–16.

Bahorich, M. S., and S. L. Farmer, (1995), 3-D seismic discontinuity for faults and stratigraphic features: the coherence cube.The Leading Edge, v. 14, p.1053-1058

Bacon, M. Simm, R. and Redshaw T. (2003). 3D Seismic Interpretation. 222 p Cambridge University Press

Basile, C., & Mascle, J. (2005). Phanerozoic geological evolution of the Equatorial Atlantic domain, 43, 275–282.

Basile, C., Mascle, J., Benkhelil, J. and Bouillin, J. P. (1998). Geodynamic evolution of the Cote d_Ivoire-Ghana transform margin: an overview of Leg 159 results. In: Mascle, J., Lohmann, G.P., Moullade, M. (Eds), Proc. ODP, Sci. Results, vol. 159, 101–110.

Black, R. (1984). The Pan-African event in the geological framework of Africa. Pangea 2, 6–16.

Blarez, E. and Mascle, J. (1988). Shallow structures and evolution of the Côte D'Ivoire and Ghana transform margin: Marine and Petroleum Geology, v. 5, p. 54–64.

Brown, L. F., Benson, J. M., Brink, G. J., Doherty, S., Jollands, A., Jungslager, E. H. A., Keenan, J. H. G., Muntingh, A., and van Wyk, N. J. S. (1995). Sequence stratigraphy in offshore South African divergent basins: American Association of Petroleum Geologists Studies in Geology 41, 184 p.

Brownfield, M. E. and Charpentier, R. R. (2006). Geology and total petroleum systems of the West-Central Coastal Province (7203), West Africa: U.S. Geological Survey Bulletin 2207-B, 52 p.

Burke, K., MacGregor, D. S. and Cameron, N. R. (2003). Africa's petroleum systems: four tectonic _Aces_ in the past 600 million years. Petroleum Geology of Africa: New Themes and Developing Technologies, 207. Geological Society, London, pp. 21–60, Special publications.

Caby, R. (1989). Precambrian terranes in Benin, Nigeria and northeast Brazil and the late Proterozoic south Atlantic fit. Geol. Soc. Am. Special Paper 230, 145–158. Caby, R., 2003.

Chierici, M. A. (1996). Stratigraphy, palaeoenvironments and geological evolution of the Cote d'Ivoire-Ghana basin, p 293–303.

Chopra, S., (2002), Coherence cube and beyond. First Break v. 20, p. 27-33

Chopra, S., and K. J. Marfurt,(2005), Seismic attributes – a historical perspective. Geophysics v. 70 No. 5, p. 3SO-28SO

Chopra, S., and K. J. Marfurt, (2006), Seismic attributes – a promising aid for geologic prediction. CSEG Recorder, Special Edition, p. 110-121

Christe-Blick, N., and Biddle, K. T. (1985), Deformation and basin formation along strike-slip faults, in K.T. Biddle, and N. Christie-Blick, eds., Strike-slip deformation, basin formation, and sedimentation: SEPM Special Publication, p.1-34.

Davies, D.W. (1986). The Geology and Tectonic Framework of the Republic of Ghana and the Petroleum Geology of the Tano Basin, Southwestern Ghana. Internal Report, G.N.P.C.

Dirk, N. (1991). The tectonic evolution of the South Atlantic from Late Jurassic to present, 191.

Edwards, R. A., Whitmarsh, R. B. and Scrutton, R. A. (1997). The crustal structure across the transform continental margin off Ghana, eastern equatorial Atlantic. J. Geophys. Res. 102 (B1), 747–772.

Fodor, R. V., Sial, A. N., Mukasa, S. B. and McKee, E. H. (1990). Petrology, isotope characteristics, and K-Ar ages of the Maranha˜o, northern Brazil, Mesozoic basalt province. Contrib. Mineral. Petrol. 104, 555–567.

Ghana National Petroleum Corporation, Private Mail Bag, Petroleum House, Tema- Ghana.

Guiraud, R. and Maurin, J. C. (1992). Early Cretaceous rifts of western and central Africa: an overview. Tectonophysics 213, 153–168.

Hiremath, P. S. (2010). Generating contour lines using different elevation data file formats. International Journal of Computor Science and Applications, 3(1), 19–25.

Isaacson, P. E. and Dıaz M. E. (1995). Evidence for a middle-late Paleozoic foreland bazin and significant paleolatitudinal shift, Central Andes. In: Tankard, A.J., Sua´rez, R.S., Welsink, H.J. (Eds.), Petroleum Basins of South America, 67. AAPG Memoir, pp. 231–249.

Kesse, G.O. (1986). Oil and gas possibilities on- and offshore Ghana, in Halbouty, M.T. Future petroleum provinces of the world, Proceedings of the Wallace E. Pratt Memorial Conference, Phoenix, December 1984: American Association of Petroleum Geologists Memoir 40, p. 427–444.

Kjemperud, A., Agbesinyale, W., Agdestein, T., Gustafsson, C. and Yükler, A. (1992). Tectono-stratigraphic history of the Keta Basin, Ghana with emphasis on late erosional episodes 52, p. 55–69.

Kulke, H. (1995). Regional petroleum geology of the world — Part II, Africa, America, Australia, and Antarctica: Berlin, Gebrüder Borntraeger, p. 129–135.

Kutu, J. M. (2013). Seismic and Tectonic Correspondence of Major Earthquake Regions in Southern Ghana with Mid-Atlantic Transform-Fracture Zones. International Journal of Geosciences, 4, 1326–1332.

Maisey, J.G. (2000). Continental break up and the distribution of fishes of Western Gondwana during the Early Cretaceous. Cretaceous Res. 21 (2–3), 281–314.

Mascle, J., Lohmann, G. P. and Clift, P. D. (1996). Proceedings of the ocean drilling program. Initial Rep. 159, 616.

Mascle, J., Guiraud, M., Benkhelil, J., Basile, C., Bouillin, J. P., Mascle, G., Cousin, M., Durand, M., Dejax, J. and Moullade, M. (1998). A geological field trip to the Coˆte d_Ivoire-Ghana transform margin. Oceanolog. Acta 21 (1), 1–20.

Mauche, R., Faure, G., Jones, J. M. and Hoefs, J. (1989). Anomalous isotopic compositions of Sr, Ar, and O in the Mesozoic diabase dikes of Liberia, West Africa. Contrib. Mineral. Petrol. 101, 12–18.

Milani, E. J. and Thomaz F. A. (2000). Sedimentary basins of South America. In: Tectonic evolution of South America, Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds), 31st International Geological Congress, pp. 389–449.

Numberg, D., Muller, R. D. (1991). The tectonic evolution of the South Atlantic from Late Jurassic to present. Tectonophysics 191, 27–53.

Peate, D. W. (1997). The Parana´-Etendeka Province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Ignous Provinces: Continental, Oceanic and Planetary Flood Volcanism, 100. Geophysical Monograph, pp. 217– 245.

Pletsch, T., Erbacher, J., Holbourn, A. E. L., Kuhnt, W., Moullade, M., Oboh-Ikuenobede, F. E., So¨ding, E. and Wagner, T. (2001). Cretaceous separation of Africa and South America: the view from the West African margin (ODP Leg 159). J. South Am. Earth Sci. 14, 147–174.

Popoff, M., (1988). The West African connection, Soujy, J., Rodgers, J. (Eds), J. Afric. Earth Sci., Special Public, vol. 7 (2), pp. 409–431.

Rotima, O. J., Ameloko, A. A., & Adeoye, O. T. (2010). Applications of 3-D Structural Interpretation and Seismic Attribute Analysis to Hydrocarbon. International Journal of Basic and Applied Sciences, 10(04), 28–40.

RRI (1998). Southern Ghana regional Biostratigraphic and Geochemical Review .Volume 1. Report Number 5322/1b

Scotese, C. R., Gahagan, L. M. and Larson, R. L. (1988). Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins.Tectonophysics 155, 27–48.

Senant, J. and Popoff, M. (1991). Early Cretaceous extension in northeast Brazil related to the South Atlantic opening. Tectonophysics 198, 35–46.

Stewart, K. S., Turner, S., Kelley, C. J., Hawkesworth, C. J., Kirstein, L. and Mantovani, M. S. M. (1996). 3-D40Ar-39Ar geochronology in the Parana´ flood basalt province. Earth Planet. Sci. Lett. 143, 95–110.

Sutherland, R., & Kyei, A. (2010). Ghana Exploration & Appraisal Exploration Manager – Gulf of Guinea Robin Sutherland Appia Kyei Ghana : Material stratigraphic traps in a new oil basin. Takoradi

Taner, M. T. and Sheriff R. E. (1977). Application of amplitude, frequency and other attributes to stratigraphic and hydrocarbon determination, in Payton C. E., Ed., Seismic stratigraphy-applications to hydrocarbon exploration; Am. Assn. Petr. Geol., Mem, 26, 301-327.

Vanco 2011 Passport of Capitaine Prospect (Stratigraphic Trap) Ivorian Basin CI-101 Block Republic of Côte d'Ivoire Vanco Côte d'Ivoire Ltd. January, 2011

Wagner, T. and Pletsch, T. (2001). No major thermal event on the mid-Cretaceous Coˆte d_Ivoire-Ghana transform margin. Terra Nova 13, 165–171.

Zalan, P. V., Nelson, E. P., Warme, J. E. and Davis, T. L. (1985). The Piauibasin: rifting and wrenching in an Equatorial Atlantic transform basin. In: Biddle, K.T., Christie-Blick, N. (Eds), Strike-slip deformation, basin formation, and sedimentation. Spec. Publ. Soc. Econ. Paleontol.Mineral, vol. 37, pp. 143–158.