Mapping Break-Back Thrust Sequence Developments of the Orange Basin (offshore South Africa)

A mini thesis in Petroleum Geoscience

By

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KEYWORDS

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3-D Seismic Data

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Meteorite Impact

Gravity Collapse Systems

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ABSTRACT

In the present study thrust sequence developments in the sediments below the deep-waters of the Orange Basin are mapped. Four seismic sections are interpreted from four different locations of the study area. The interpreted seismic sections show various ranges of shortening as a result of the thrust developments. The Orange Basin provides exceptional 3-D structures of folds and faults generated during soft-sediment slumping and deformation which is progressive in nature. 3-D seismic section and structural evaluation techniques have been used to understand the geometric architecture of the gravity collapse structures. The interpretation of gravitational tectonics indicates a significant amount of deformation that is not accounted for in the imaged thrust belt structure. The Study area covers 8200 square kilometres (km^2) of the total 130 000 km^2 area of the Orange Basin offshore South Africa. The southern parts of the study area are largely featureless towards the shelf edge. The northern area has chaotic seismic tectonic thrust sequence features as a result of increase in shortening. Episodic gravitational collapse system of the Orange Basin margin characterizes the late Cretaceous post-rift evolution. This study area shows that implications of stress field and thrust faulting relating to the thickness change by gravity collapse systems are not only the result of a combination of geological processes such as rapid sedimentation, margin uplift, geotectonics and subsidence but also due to a possible meteorite impact. These processes caused gravitational potential energy contrast and created gravity collapse features that are observed between 3000-4500ms TWT intervals in the seismic data. The gravity-driven system in the study area is divided into three distinct structural domains, based on the cross strike variations in structural style. From northeast to southwest these are: an up-dip extensional domain characterized by basin-ward-dipping listric faults, a transitional domain with both contractional and extensional features and a down-dip contractional domain that consists of landward-dipping thrust faults and associated thrust fault-related folds. Gas escape structure features were identified in the study area and have been interpreted to have formed as a result of normal faulting and extension. Gravity collapse systems of the Orange Basin were the main driving mechanism behind the thrusting sequences that lead to break-back thrusts.

DECLARATION

I declare that "Mapping Break-Back Thrust Sequence Developments of the Orange Basin (offshore South Africa)" is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources used or quoted have been indicated and acknowledged as complete references.

Dumisa Kevin January

November 2017

Signed. ....

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1 CHAPTER ONE

1.1 Introduction

Records of tectonic activity exist in the west coast that developed on top of moving thrust sheets and these records show that tectonic activity was aided by erosion and sedimentation (Ori and Friend, 1984). The present study is carried out to better understand thrust sequences in which new thrust faults develop. This study explores the dynamics of stacked thrust fault tectonics and thrust fault developments with an aim to classify them. The study furthermore maps these in-sequence thrusts and explore the impact and implications the tectonic systems have on deformation style. The study seeks to draw an understanding of the driving mechanisms (contractional regime, extensional regime, gravity-driven system and a possibility of extra-terrestrial meteoric impact), behind the thrusting developments of the Orange Basin (Offshore South Africa).

The tectonically quiescent passive continental margins may experience a variety of stress states and undergo significant vertical movement post-breakup (Salomon et al., 2014). The development of major faults during the oceanic lithospheric extension is more likely caused by mantle plumes intruding on the base of the lithosphere driven by far-field stresses which causes thermal weakening, regional uplift and the development of deviatoric tensional stresses (Ziegler and Cloetingh, 2004).

The economic potential associated with the gravity collapse thrust systems has attracted structural geologists and geophysicists for many decades (Tavani et al., 2014). As a result, a large amount of subsurface seismic data on the deformation patterns from gravity induced thrust-related anticlines is available in literature (Tavani et al., 2014). A study by Jaboyedoff et al. (2013) showed that structures and fabrics formerly interpreted as purely of tectonic origin are instead the result of large slope-deformation, prompting an in-depth look into the mechanism responsible for the development of these structures. This led to the discovery of many inaccurately interpreted tectonic histories of many basins including the Orange Basin. The development of slope failures is progressive through time and space (Jaboyedoff et al.., 2013), and recognition of such structures using techniques like seismic evaluation (which have been applied in this study) can minimise misinterpretations of structural geology.

According to Barr and Dahlen, 1989, Beaumont et al., 1992 and Willet, 1992, in the evolution of a thrust wedge when considered on a large scale, surface processes are of paramount importance. This is why the evolution of thrust belts at a smaller scale needs to be understood. What role does erosion and sedimentation play in thrust development? Thick and thin-skin tectonics is explored to better understand thrust development. This study also explores possibilities that collapse structures in the study area might have been gravity driven. In the assessment of detachment faulting there is an increase in deformation distribution from a single detachment level into several detachment levels, thus producing the thickness variation noted in the study area.

The Orange Basin provides exceptional 3-D structures of folds and faults generated during soft-sediment slumping (Butler and Paton, 2010). The evolution of the slump systems, which are gravity-induced, shows a progressive move from initiation, translation, cessation, relaxation and finally the compaction phase resulting in the formation of thrust packages typically seen as piggyback sequences, break-back sequences and imbricate faults (Kuhlmann et al., 2010). This slumping and failure is categorized as either: coherent, semi-coherent, or incoherent domains. This classification reflects an increase in deformation and displacement of sediment (Alsop and Marco, 2013). Initial evaluation of the 3-D seismic data in this area of the Orange Basin shows that there is an increase in the degree of deformational features from the south to north. As the Orange Basin is prone to harbour hydrocarbons, it is important to map thrust development to understand how they affect migration and trapping integrity. It was observed that there were structural and stratigraphic implications in the study area. Detachment fault mapping analyses the development of structures through time in 2 dimensions (2D). Mapping thrusting development affects deep water hydrocarbon prospectivity, thus invoking this topic as a necessity.

Uncertainty is prevalent in the hydrocarbon exploration industry more particularly when managing seismic interpretation. Seismic data is the primary source of evidence of confirmation when attempting to portray the geometry of the subsurface topography which holds a large portion of the world`s reservoir stores which are situated in structural highs. It is therefore important that the horizons picked are properly correlated across faults during seismic interpretation and mapping. When mapping faults and structures a geological and a geometrical functionality must exist; furthermore, it is critical to realize that not all that is seen on seismic is what it seems, as seismic data always include uncertainties. These uncertainties are associated with acquisition and processing techniques resulting in multiple reflections or artefacts such as, fault shadow, migration smiles and frowns, velocity pull-up and push-down and many other flaws (Calvert, 2004).

Fault mapping is unique seeing that understanding the slight change in movement of faults can play an important role in producing hydrocarbons from a reservoir. Petrel© software was used to map stacked thrust fault developments with a prime importance in understanding the uncertainties related to the potential impact of these small faults on field performance. This study aims to use the limited data currently existing in the deep-waters of the Orange Basin to understand the change in movement/thickness of these stacked thrust faults with an increase in deformation in the study area and understanding the driving mechanism behind this phenomenon and its implications. By mapping these thrusts an investigation was initiated for interactions between sedimentary processes and tectonic movements to understand thrust development. For this purpose, the effects of parameter variations in the study seek to identify those that control structural evolution and implication of the break-back thrust fault development.

1.2 Aims and Objectives

This study aims at understanding the tectonic driving mechanisms behind thrust developments of the Orange Basin. We further map thrust developments of the Orange Basin and seek to classify them. Understanding the tectonic evolution of the region is important in determining the tectonic mechanism that leads to the development of thrusts in the study area. Another objective is to understand the relationship between the thrusts and migration pathways due to gas escape features that are identified in the study area. This study will present results aimed at describing the thrust development identified on seismic sections from different locations across the study area. In order to achieve this, the interpretation will evaluate 3-D seismic sections to determine thickness change and number of thrust fault developments in the form of shortening.

1.3 Background

The formation of Soekor (Pty) Ltd in 1965 by the government and the passing of new Mineral Rights Act and the granting of concessions in 1967 attracted big oil and gas companies like Total, Gulf Oil, Esso, ARCO, Superior, CFP and Shell. This inevitably led to the first offshore well being drilled in 1969 and the discovery of gas and condensate in the Ga-A1 well located in the Pletmos Basin (Petroleum Agency of South Africa (PASA); 2008).

Political sanctions against South Africa from 1970 stunted exploration and operation in the entire offshore area of South Africa and left Soekor (Pty) Ltd as a sole operator in the offshore basins until licensing Rounds for offshore areas were reopened in 1994. This was later followed by the establishment of Petroleum Agency of South Africa (PASA) in 1999 and the merging of Soekor (Pty) Ltd and Mossgas to form PetroSA in 2001.

Geological studies and early discoveries prove that Orange Basin has an early-Cretaceous-sourced petroleum system (Petroleum Agency South Africa, 2010). The Cretaceous source rocks (i.e. Albian and Aptian source) are rich in degraded and terrestrial organic matter, thus being more gas and condensate-prone and the quality of the source rock improves towards the north along the South-western African margin (Zimmermann et al., 1987, Hartwig et al., 2012a).

The main play elements in the Orange Basin are the Albian Gas Play, Upper Cretaceous shallow gas play, Barremian deep gas play and Upper-Cretaceous deep-water slope turbidite oil/gas play (Hirsch et al., 2010; van der Spuy, 2003; Petroleum Agency South Africa, 2010). The Orange Basin has proven to have two main source rocks; these are the Upper Jurassic-Neocomian lacustrine source rocks and the Barremian-Aptian marine source rocks. The Turonian-Cenomanian source rock and the older Permian source rock have been speculated to be present in the deeper sections of the basin (Herbin et al., 1987; Paton et al., 2008). With a rich source rock, the study area is no doubt rich in hydrocarbon and should be at the forefront for exploration.

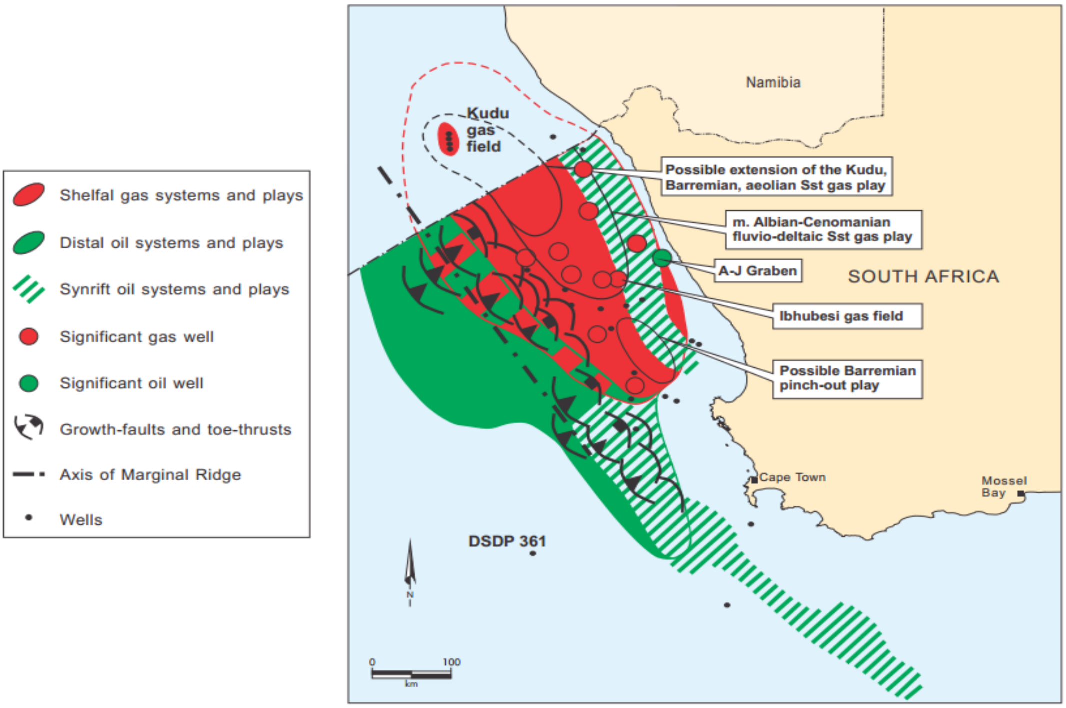

Figure 1: Conjectured petroleum system elements of the Orange Basin (Petroleum Agency South Africa, 2003).

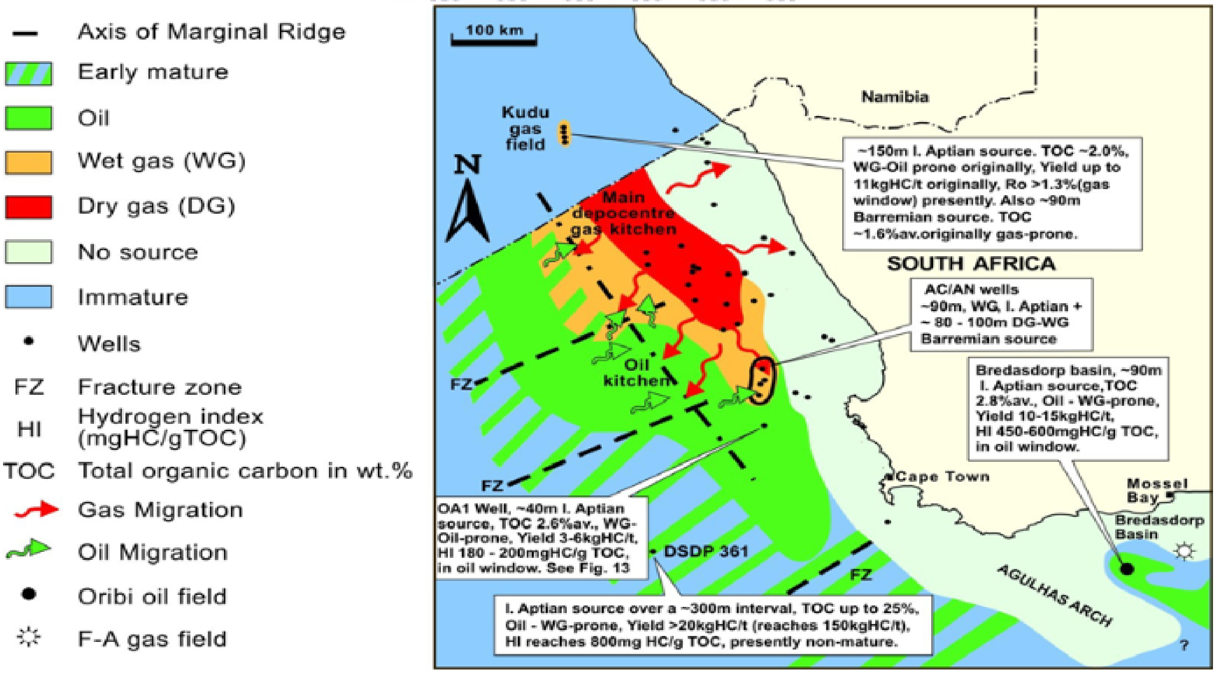

Figure 2: The main petroleum system elements and discoveries in the Orange Basin (from Jungslager, 1999).

The development of 3-D seismic data in pursuit of hydrocarbons has provided the tool to discover unprecedented geologic features buried deeply within the subsurface of sedimentary basins where the preservation potential of such features in general is the highest (Stewart, 2003). 3-D seismic data allows detailed structural analysis of well-preserved buried features through the use of high-resolution subsurface images (Wall, 2008). By using 3-D data the tectonic features that dominate the region were clearly mapped and this helped in understanding what tectonic mechanisms drove this phenomenon. However, positive identification and classification of buried structures often requires access to geological data in the form of rock specimens and drill core obtained at a specific study area (Stewart, 2003). Not surprisingly, it may never be possible for many buried structures to yield the necessary geological information since these may never be drilled because of the lack of economic incentive and the excessively high cost of drilling (Stewart, 2003). That is why a geological framework needs to be developed to better assist geologists who seek to understand thrust faulting development and what their implications are in deep-water hydrocarbon prospectivity. Mapping this phenomenon is unique seeing that an understanding of migration can be drawn from it as these stacked thrusts serve as pathways of hydrocarbon migration.

1.4 Location of the Study Area

The study area is located in the Orange Basin, off the south-west southern African margin extending offshore southern Namibia and South Africa (Boyd et al., 2012; Granado et al., 2009). The Orange Basin covers an area of approximately 130 000 km^2 and is filled with approximately 8 km of Late Jurassic to present day continental to deep marine strata located in deep water depths between 100-2850 m (PASA, 2008). The Orange Basin which borders Namibian waters at its northern most extent is located approximately 200 nautical miles NW of the port of Saldanha. The closest point for the block is 150 km offshore and the furthest is 350 km offshore (Kramer and Heck, 2013).

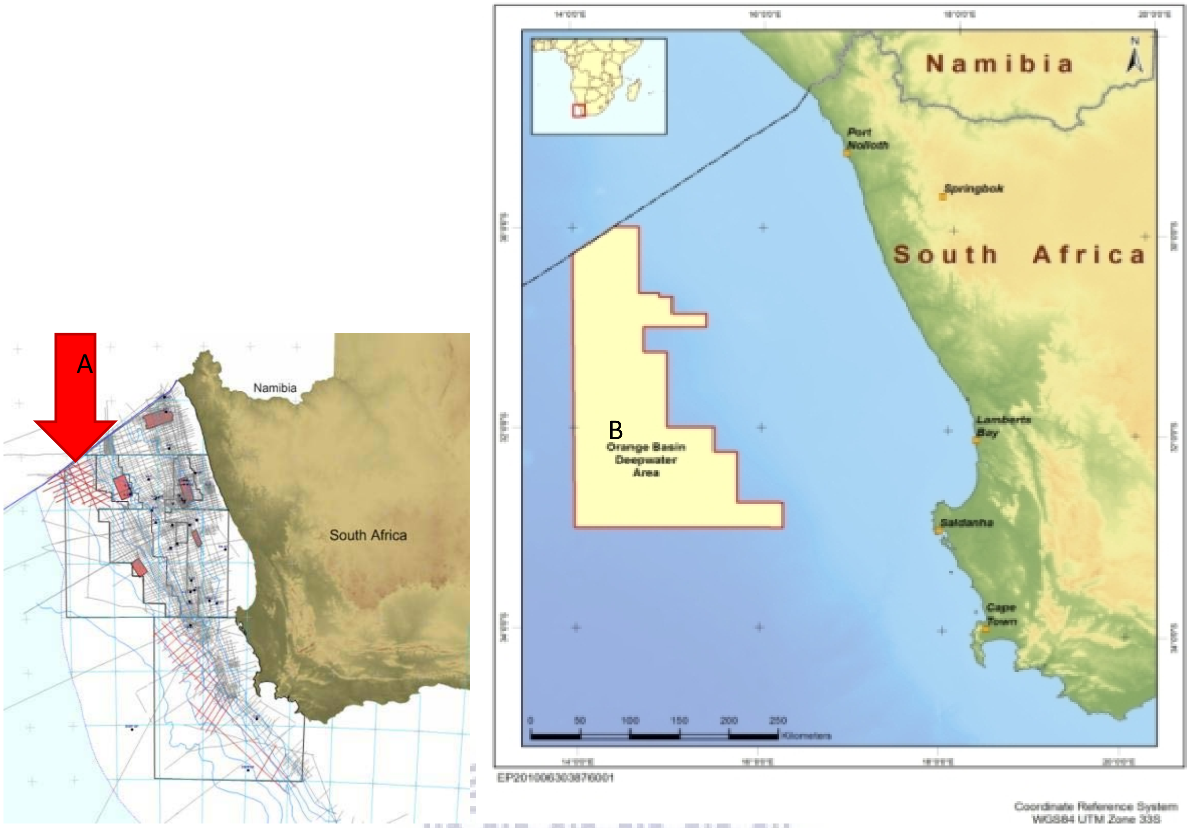

Figure 3: A- Location of Orange Basin indicating precise study area (red arrow) along the west coast of South Africa (Jungslager, 1999). B- Satellite imagery of the surveyed Orange Basin Deep Water, red rectangular box (Shell-SA website: http://southafrica.shell.com).

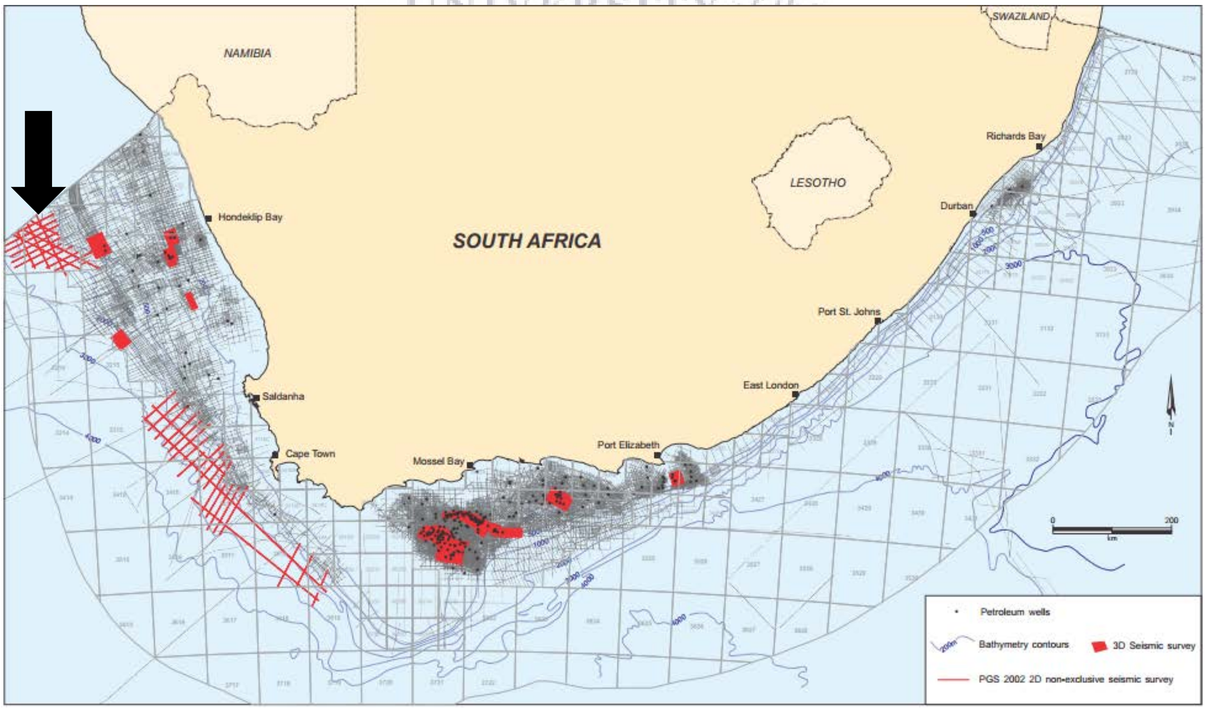

Figure 4: Seismic data acquisition in the offshore study area of the Orange Basin (South Africa) Petroleum Agency South Africa (PASA, 2008).

The South Atlantic passive margins formed during Mesozoic time as a result of lithospheric extension followed by the breakup of the Gondwana supercontinent (Blaich et al., 2011). It is widely accepted in the literature that the separation of the two landmasses resulted in the formation of a passive continental margin – the western margin of southern Africa (Kuhlmann et al., 2010; Boyd et al., 2012; Hartwig et al., 2012b). The margin is locally displaced by transform faults (Ben-Avraham et al., 2002). It covers an area of approximately 130 000 square kilometers (Boyd et al., 2012). According to Gerrard and Smith (1982, cited by Boyd et al., 2012) the basin provides a record of the development of South Africa's volcanic-rifted passive continental margin from the Late Jurassic to the present. The break-up of Gondwana accompanied by Triassic to Jurassic intra-continental rifting along the South Atlantic subdivided it into synrift, rift-to-drift transition, and drift phases related to the progressive opening of the South Atlantic (e.g. Beglinger et al., 2012; Marcano, 2013; Torsvik et al., 2009).The rift structures of the South Atlantic margin basins host lacustrine organic-rich black shales of late Jurassic to early Cretaceous age and contain fluvio-deltaic and continental deposits (Karner and Driscoll, 1999; Loegering et al., 2013; Macdonald et al., 2003; Marcano, 2013).

The main episode for the accumulation of sapropelic black shales occurred during the Cenomanian-Turonian oceanic anoxic event. Jungslager (1999) suggests that, the oldest proven and high quality source rock of the syn-rift Upper Hauterivian (around 117 Ma) are lacustrine deposits. The source rock is oil-prone, with a TOC (Total Organic Carbon) of more than 10% and HI (Hydrogen Index) of more than 600 mg HC/g TOC (Muntingh, 1993). Another high quality interval found in the basin is of the Barremian to Aptian age (around 112 Ma) (Jungslager 1999 and van der Spuy 2003). This sequence which is up to 300m thick and has TOC values up to 25 % corresponds to a major lithofacies change; from restricted marine to open marine conditions (Herbin et al. 1987). These shales potentially are oil-and gas-prone source rocks along the southwest African margin, Brazilian margin and the ultra-deep offshore of the Angola Basin (Aldrich et al., 2003; Bray et al., 1998; Burwood, 1999; Mello et al., 1989; Anka et al., 2010).

1.5 Tectonic Setting of the Orange Basin

The Orange Basin is the youngest and the largest of all the basins in the South African offshore basins (Paton et al., 2008). During Gondwana break-up and the opening of the

South Atlantic in the late Jurassic, 8 km thick syn-rift and drift sedimentary successions were deposited in the Orange Basin (Gerrard and Smith, 1982; Paton et al., 2008; de Vera *et al*., 2010; Kuhlmann et al., 2010). The tectonic elements that were formed during break-up include the formation of the depo-centre, half-grabens and gravity-induced growth faults (Granado et al., 2009).

The Orange Basin passive-margin accommodation space shows that a single tectonic event resulted in a significant change to both the style and position of sediment accumulation during its post-rift evolution (Paton et al., 2008). The evolution of the Orange Basin passive margin has two stages. The first stage is composed of aggradational shelf margin deposits with little or no deformation during the Cretaceous. The Late Cretaceous deposition was punctuated by an episode of margin tilting that resulted in significant erosion of the inner margin and alteration of the margin architecture. The second stage is categorized by substantial margin instability and the development of a coupled growth fault and toe-thrust system that occurred in the Cretaceous and Tertiary shelf margin (Paton et al., 2008).

1.6 Basin Fill and Evolution

The underlying syn-rift succession comprises generally isolated and truncated remnants of half-grabens. The thick wedge of drift sediments underwent repeated deformation of the paleo-shelf edges and paleo-slopes due to sediment loading and slope instability, especially in the Upper Cretaceous (Kuhlmann et al., 2010). Prior to the onset of full drift open oceanic conditions there was a deposition of early drift successions which were the proto-oceanic successions consisting of restricted marine and red continental sediments which are intermittently interposed with basaltic lavas (Fig5. stage A). During this time mid to late Jurassic north-northwest trending half-grabens and rifting sequences were formed. These rifting sequences were overlain by a 2000-metres-thick Barremian-Aptian aged rift-to-drift transitional sequence (Fig.5. stage B) during the drifting phase. The drift phase successions display progradational stacking patterns with low tectonic and eustatic accommodation (Jungslager*,* 1999).

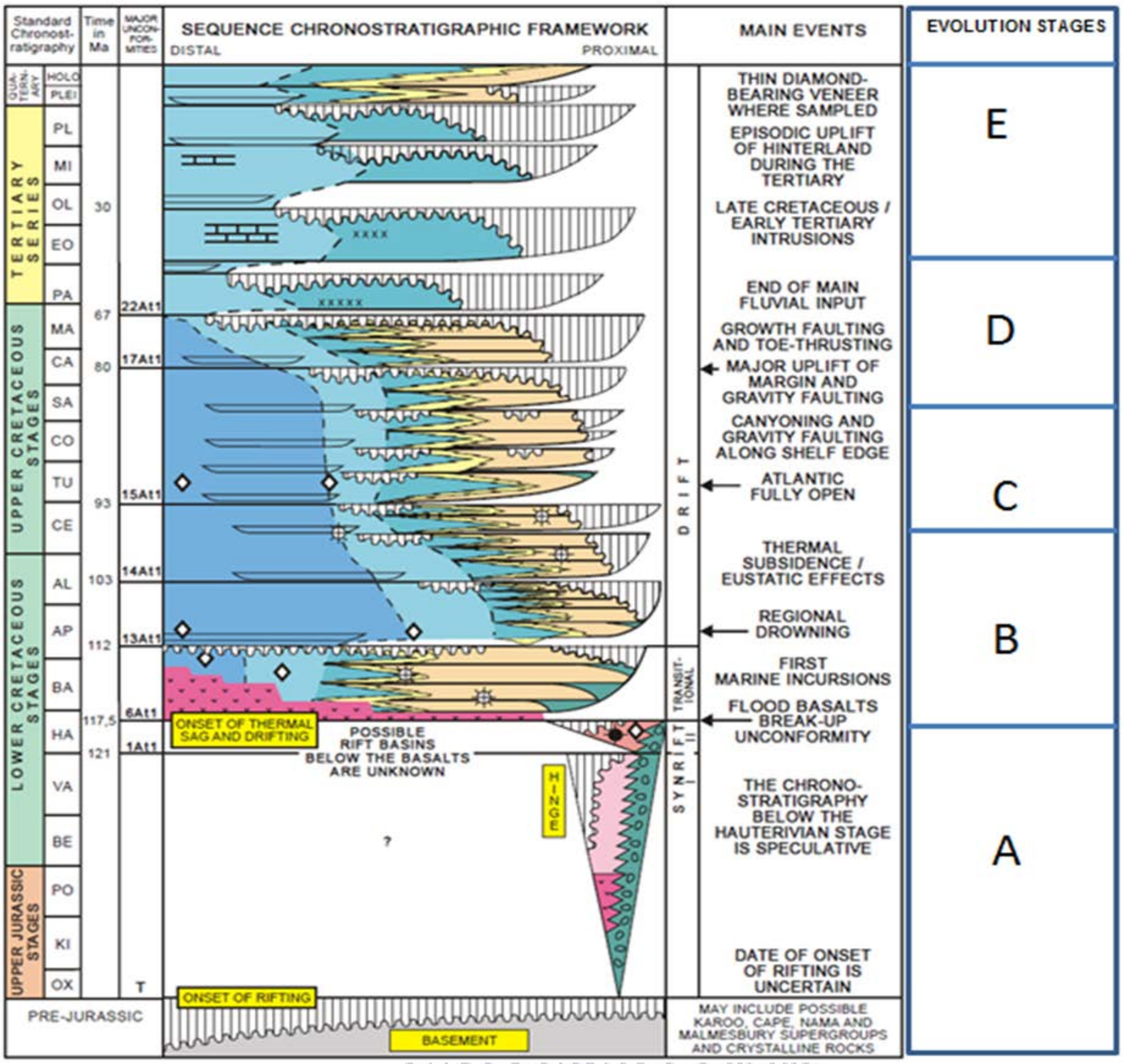

Figure 5: Chronostratigraphic displaying the evolution of the Orange Basin (after McMillan, 2003). The tectonic evolution of the Orange Basin has in this study area been separated into 5 evolution stages namely A to E. These evolution stages are based on the important stages for the basin's structural evolution leading to the formation of gravity collapse systems.

The opening of the Atlantic Ocean (Fig5. stage C) resulted in canyoning and gravity faulting along the shelf edge between Turonian and Coniarcian ages (Muntingh, 1993; Jungslager, 1999). The Orange Basin passive margin uplift (Fig5. stage D) resulted in mantle plume and massive denudation which was accompanied by growth faulting and toe-thrusting. The latter mechanisms resulted from gravitational potential energy contrasts and slope instability built up during the Campanian to Maastrichtian depositional epochs (Muntingh, 1993; Jungslager, 1999; McMillan, 2003).

The late Cretaceous Campanian-Maastrichtian progradational sequences (Fig5. stage D) were deposited as the result of margin uplift, tilting and subsequent erosion of the inner shelf which is clearly shown in the previously interpreted 2-D seismic data (Muntingh, 1993; McMillan, 2003; Paton et al., 2008). The poorly documented Tertiary to present sediment successions have well-developed siliciclastic sedimentary wedges which increase in thicknesses basin-ward and range between 200 to 1500 metres thick (Fig5.E). A major tectonic event between Tertiary and present is the Miocene episodic uplift.

The phases for the evolution of the Orange Basin according to Hirsch et.al*,* (2010) are summarized below.

- Rifting phase which composed of pre-rift successions (older than Late Jurassic, >130 Ma) that is overlain by syn-rift deposits of Late Jurassic to Hauterivian age (121-116.5 Ma) (Fig5.A)
- Early drifting phase which stretches from late Hauterivian to the Barremian-early Aptian depositional epoch (Fig5.B)
- Drifting phase which is occupied by sediments of Aptian age (113- 108 Ma) to the present day successions (Fig5.C-E).This phase composed of the Cenomanian-Turonian anoxic event and a thick sedimentary wedge with slump structures and toe thrusts.

2 CHAPTER TWO

2.1 LITERATURE REVIEW

There has been long-standing academic interest in deep-water fold and thrust belts, particularly along subduction zones and early stage collisional margins. Over the last two decades interest has surged following advances in deep-water drilling technology by the oil industry. Deepwater exploration encompasses many different potential traps and geological settings including deep-water fold thrust belts, which have featured prominently because they contain numerous large anticlines with associated hydrocarbon seeps (Morley and Guerin, 1996). The broad division of deep water fold thrust belts into passive and active margins, shale vs. salt detachments, and gravity sliding vs. gravity spreading mechanisms has been proposed previously (e.g. Morley and Guerin, 1996; Rowan et al., 2004). Simple grouping of passive margins and lithospheric stress that is driven by tectonically active margins does not encompass all settings of deep-water fold thrust belts (e.g. Rowan et al., 2004). A classification system for deep-water fold and thrust belts is proposed, based on the driving mechanism, detachment type and tectonic setting. Fold and thrust belts are characterised by two major detachment levels and large piggyback basins. The step-by-step history of the thrust belt predicts that each change in tectonic location is recorded with large unconformities in basins (Rowan et al., 2004).

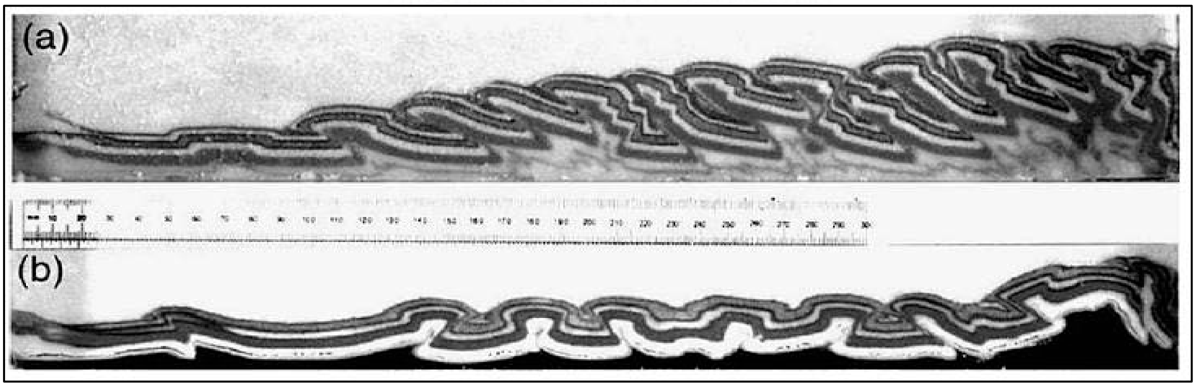

Figure 6: Effect of experimental conditions on the structure of (a)-on a viscous foundation stone (b)-on a frail foundation stone (Costa et al. 2002).

Figure 6 above is an illustration of thrust faults observed at the end of deformation of the main basal detachment block; (a) the amount of detachments is not the same as seen in (b) for the break-back thrusting sequence. The detachments in Figure 6 (a) break into thrust faults that increase as deformation propagates. Figure 6 (b) illustrates the initial state of the area before deformation occurred and the detachment faults are less (Costa and Vendeville, 2002).

The difference between break-back thrust sequence and piggy-back thrust sequence is mostly confused and this study seeks to classify the difference between the two. McClay (1992) suggests that, Break-back thrust sequence to be the sequence of thrusting where new (younger) thrusts nucleate in the hangingwalls of older thrusts and verge in the same direction as the older thrusts. Piggy-back thrust sequence occurs when topographically higher but older thrusts are carried by lower younger thrusts. We rely on literature to draw a correlation between the interpreted thrust sequences identified on the seismic sections and we compare the features analysed with the correct terminology as suggested by McClay in his glossary.

2.2 Geology Setting of the Study Area

During the Late Jurassic to Early Cretaceous, west Gondwana, comprising South America and Africa, began to fragment and an oceanic crust began to form between them leading to the initiation of the Atlantic Ocean (McCarthy and Rubidge, 2005). It is widely accepted in literature that the separation of the two landmasses resulted in the formation of a passive continental margin – the western margin of southern Africa (Kuhlmann et al., 2010; Boyd et al., 2011; Hartwig et al., 2012a). The margin is locally displaced by transform faults (Ben-Avraham et al., 2002).

Furthermore, following the break-up of Gondwana a series of grabens and half-grabens trending North-South and immediately overlain by sedimentary successions consisting of siliciclastic, lacustrine sediment infills and volcanic intrusions (Kuhlmann et al., 2010; Boyd et al., 2011) developed along the present-day margin. This marks the synrift phase of the Orange Basin (Kuhlmann et al., 2011). Subsequently, a transitional Lower Cretaceous sequence comprising a deepening-upward sequence of fluvial red beds and deltaic deposits was deposited (Boyd et al., 2011; Kuhlmann et al., 2011). This sequence is overlain by marine sandy sediments (Kuhlmann et al., 2011).

The Orange Basin has gravity driven system with extension above the submarine slope and contraction towards the toe of the slope (Paton et al., 2008). The gravity driven system is responsible for the detachment and thrust faulting distribution which has altered the thickness of sedimentary layers in the Orange Basin (de Vera et al., 2010; Butler and Paton, 2010). The gravitational tectonics of the Orange Basin has been well documented; however the large scale driving mechanisms are poorly understood. Using the recently acquired 3D seismic data of this area, this study will contribute to an understanding of large-scale tectonic processes associated with gravity collapse systems of a passive continental margin.

2.2.1 Regional Seismic Stratigraphy of the Orange Basin

A more recent study on the 2-D regional seismic stratigraphic interpretation of the Orange Basin was conducted by de Vera et al. (2010) based on the work by Séranne and Anka (2005) and Paton et al. (2008). This 2-D seismic interpretation divided the seismic stratigraphy of the Orange Basin in two Megasequences (Fig.7): (1) The Synrift Megasequence and (2) The Post rift Megasequence.

2.2.2 Synrift Megasequence

The deposition of the Syn-Rift Megasequence took place between late Jurassic and late Hauterivian (160-127 Ma) with low frequency continuous to discontinuous seismic reflections with fanning geometries and basin-ward dipping high amplitude reflectors (Fig.7). During the late to early stages of continental rifting volcanic wedges were deposited (Séranne and Anka, 2005). These volcanic wedges are now reflected and interpreted as seaward dipping reflectors.

2.2.3 Post rift Megasequence

The Post-Rift Megasequence consists of a late Hauterivian to present day depositional sequence (Fig.7). A Late Hauterivian break-up unconformity (ca. 127 Ma) separates Post-Rift Megasequence from the seaward dipping reflections of the Syn-Rift Megasequence. de Vera et al. (2010) subdivided the Post-Rift Megasequence in five distinct depositional sequences referred to as Post-rift sequence I-V.

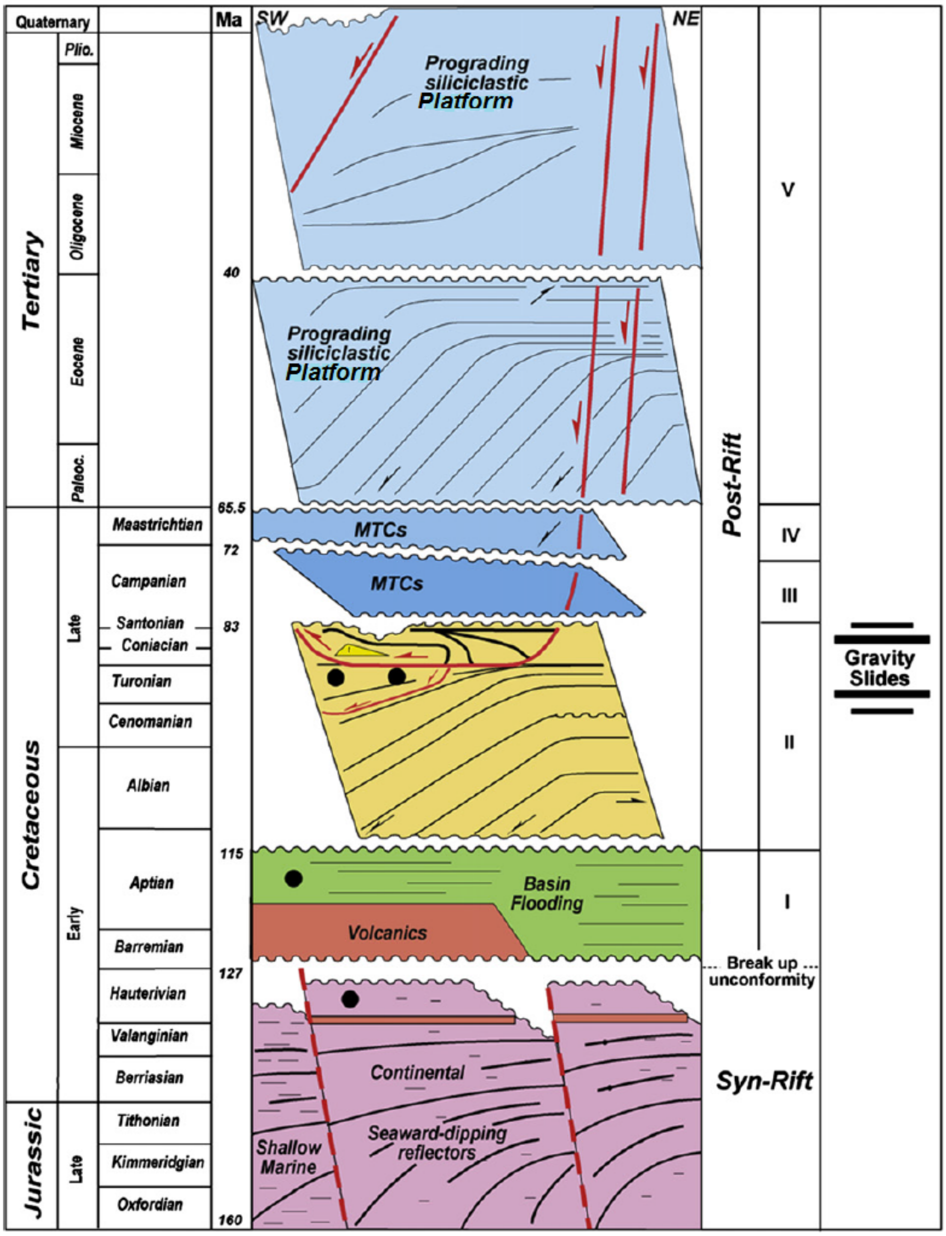

Figure 7: Chronostratigraphy of the Orange Basin based on the results of seismic interpretation. Lithostratigraphy compiled by de Vera et al. (2010) from Séranne and Anka (2005) and Paton et al. (2008).

Post-rift seismic sequence I unconformably overlies the Syn-Rift Megasequence of Barremian-Upper to Aptian age (Fig.7). Post-rift II is of an Upper Aptian to Santonian age and includes the gravity collapse systems of the Orange Basin. Post-rift seismic sequence II is overlain by post rift sequence III which is of Santonian-Campanian age and deposited on the outer continental shelf. Post-rift seismic sequence III is unconformably overlain by Post-rift IV which stretches from late Campanian to Maastrichtian and is characterized by mass transport complexes (MTCs). Post-rift seismic sequence V is characterized by a basin-ward shift of siliciclastic platform sedimentation with well-developed prograding clinoforms. Post-rift seismic sequence V was deposited between the present day and the base of Tertiary (65 Ma).

The generation of hydrocarbons during the Late Cenomanian to Early Turonian source rocks (Fig.7) reduced friction at the base of the slide and enhanced the efficiency of the shale detachment faulting (Muntingh and Brown (1993). The interpretation by Séranne and Anka (2005) and de Vera et al. (2010) puts gravity sliding in Post-rift II sequence between the Turonian and the Coniarcian occurring only during these two periods. The interpretations by Muntingh (1993), Jungslager (1999) and McMillan (2003) suggested that massive gravity faulting in the Orange Basin occurred in the Turonian-Coniarcian and also in the Campanian-Maastrichtian depositional epochs.

The opening of the Atlantic Ocean during Gondwana started from the north and continued towards the south (Kuhlmann et al., 2010). Late Cretaceous rifting resulted in the separation of the South American and African plates and generated the accommodation space in the form of grabens and half-grabens in the Orange Basin. This late Cretaceous structural change resulted in highly aggradational deposition which resulted in the development of a complex zone of slumps, rollover anticlines and tilted fault blocks (Brown et al., 1995).

2.3 Geology of the Namibian and South African rifted continental margin

Passive continental margins develop at the junction of continental and oceanic crust within plate interiors as a result of continental splitting either by rifting at sites of generation of the ocean crust or by transform faulting. After splitting, the margins formed by predominantly vertical tectonics. According to (Bott 1980), the history of a rifted continental margin can be subdivided into four stages:

- a rift valley stage which may involve thermal uplift and graben formation before continental splitting (e.g. East African rift system and the Baikal rifts)
- a youthful stage lasting about 50 Ma after splitting of the continents. During this stage the thermal effects of the split are strongly felt (e.g. Red Sea margins)
- a mature stage during which more subdued development starts
- a fracture stage when subduction starts, terminating the history as a passive margin.

In general, the time statements are reported unchanged in this story. For the modelling study, the timescale of Haq et al (1988) was chosen. The stratigraphic subdivision of the southwestern African continental margin is shown in Fig. 10.

2.4 Outline of the break-up of Gondwana and the subsequent evolution of the southwest African continental margin

The continental margins of south-western Africa and Argentina are rifted plate margins underlain by pre- and synrift graben basins and covered by post rift or passive margin sediments (Broad and Mills 1993). The formation of the margins resulted from the breakup of the Gondwana supercontinent which originally comprised Africa, South America, Antarctica, Madagascar, India and Australia at the end of the Precambrian/Cambrian (Dingle and Scrutton 1974; Lawver et al. 1992). Following successive late Carboniferous to Early Jurassic rifting episodes major intracontinental rift developed between Africa and South America, in crust composed of granitic, metamorphic, and sedimentary rocks ranging from Precambrian to Carboniferous to Permian age (Emery et al. 1975; Gerrard and Smith 1983). Initiation of this Late Jurassic / early Cretaceous rifting in the southern portion of the South Atlantic is estimated by e.g. Uliana et al. (1989) and Stolhoffen (1999) to occur at 160 Ma and by Nurberg and Muller (1991) at 150 Map. The opening of the South Atlantic was diachronous, rejuvenating from South to North (e.g. Rabinowitz 1976; Rabinowitz and Labrecque 1979; Figure 8) and occurring close to the Japetus Suture which is a hint that the new rift used an old line of weakness for its development (Wilson 1966).

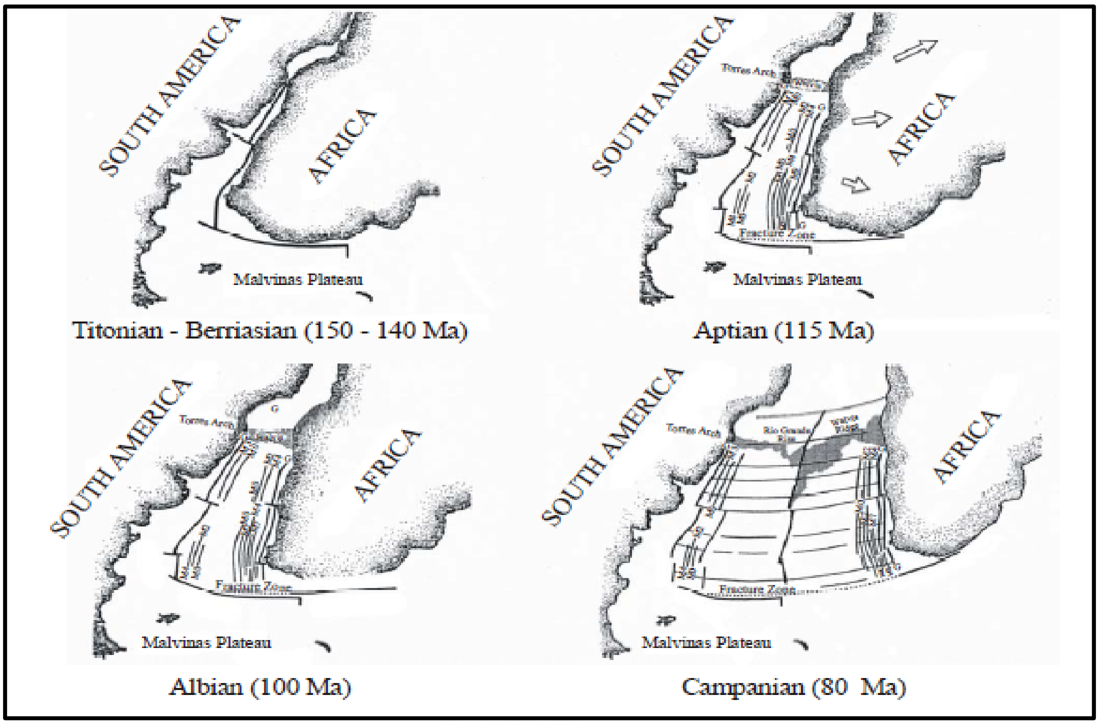

Figure 8: Reconstruction of the opening of the South Atlantic Ocean based on magnetic anomalies M0 to M9, modified from Rabinowitz and Labrecque (1979).

Today, the south-western African offshore region is divided into four basins which essentially record post rift geometries above earlier pre-South Atlantic rift structures. These basins are termed from north to south: Namibia, Walvis, Lüderitz and Orange Basin (Miller 1992, Figure 9). Initially, these basins were well defined and separated according to their basement structure but since the Upper Cretaceous the basins are connected thus losing their individuality (Gerrard and Smith 1983). The Orange Basin in which the Kudu gas field, the main focus of the study at hand, is located is underlain by several stacked rift basins of an Early Cretaceous minimum age. The basin is filled with post rift Cretaceous siliciclastic rocks ranging in age from late Hauterivian drift onset to Tertiary (Brown et al. 1995). At least 8000 m of drift sequence sediments accumulated in the Orange Basin, which is by far the largest drift sequence sediment thickness along the southwest African margin.

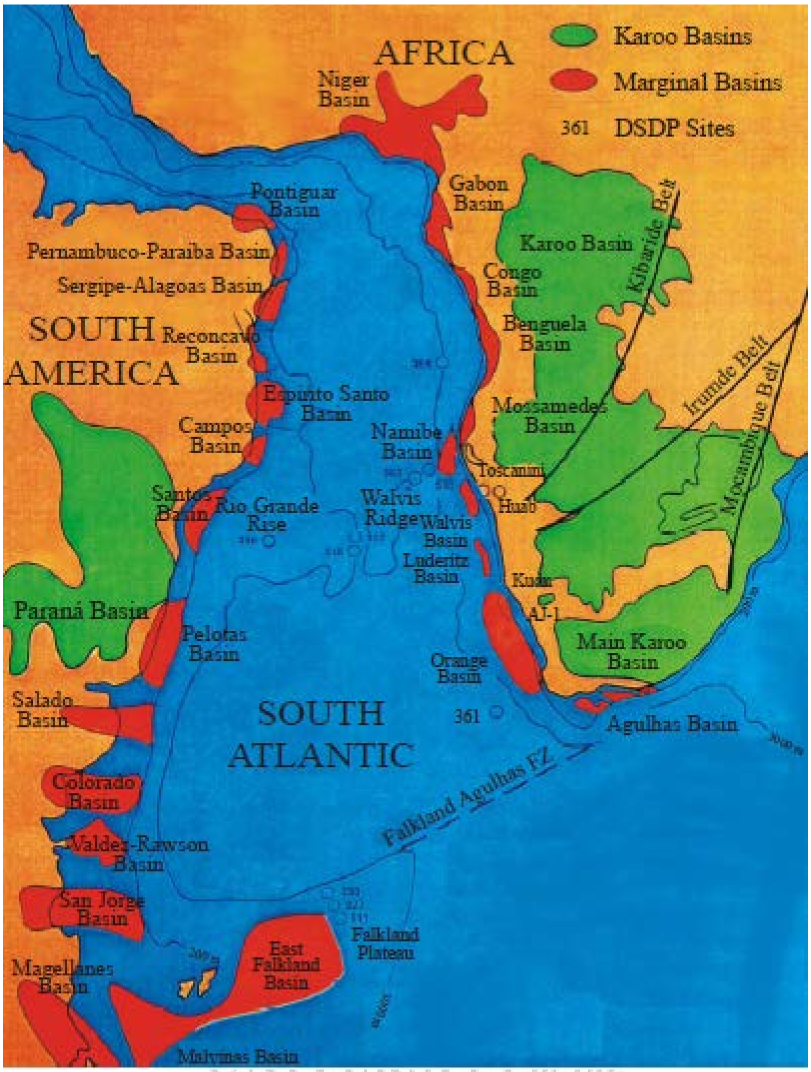

Figure 9: Structural framework of the south-western continental margin of Africa and southwestern South America (Miller 1992).

The width of the South Atlantic is not to scale and was chosen arbitrarily in order to show both continental margins in one picture. At the Argentine margin, the basins from north to south are termed Salado Basin, Colorado Basin, Valdes Basin, Rawson Basin, San Jorge Basin, Magellanes Basin and Malvinas Basin (Urien and Zambrano 1973, Figure 9). In contrast to the southern African basins which all are elongated parallel to the continental margin, the South American basins can be subdivided into different basin types: Some of the basins are perpendicular to the continental margin (Colorado and Salado Basin) and some do not reach the continental margin and are developed only on the continental shelf (e.g. San Jorge and Valdes Basin). The Magellanes and Malvinas Basins finally are true geosynclines according to Urien and Zambrano (1973). At the South African continental margin, the opening of the

South Atlantic is recorded by five main tectono stratigraphic sequences (Figure 10): The Basin and Range or prerift Megasequence, the synrift I and II Megasequences, the transitional and the thermal sag Megasequences (Maslanyi et al. 1992; Light et al. 1993b).

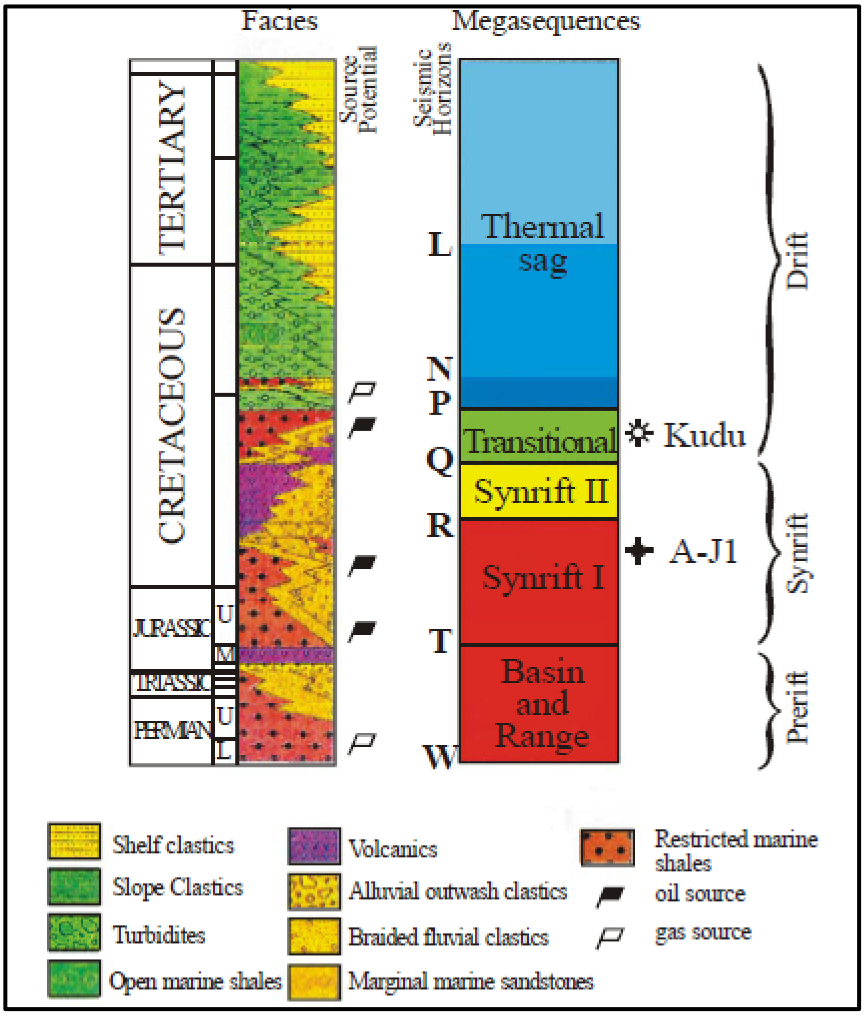

Figure 10: Stratigraphy and seismic horizons of the south-west African offshore, modified from Light et al. (1993b).

The Basin and Range Megasequence is terminated by the Late Jurassic (i.e. Kimmerdgian-Oxfordian, 155.5 Ma) angular rift onset unconformity (horizon T) marking the onset of the synrift I Megasequence (Maslanyi et al. 1992; Light et al. 1993b). Stratigraphic information from onshore and offshore Namibia is compiled in Figure 11.

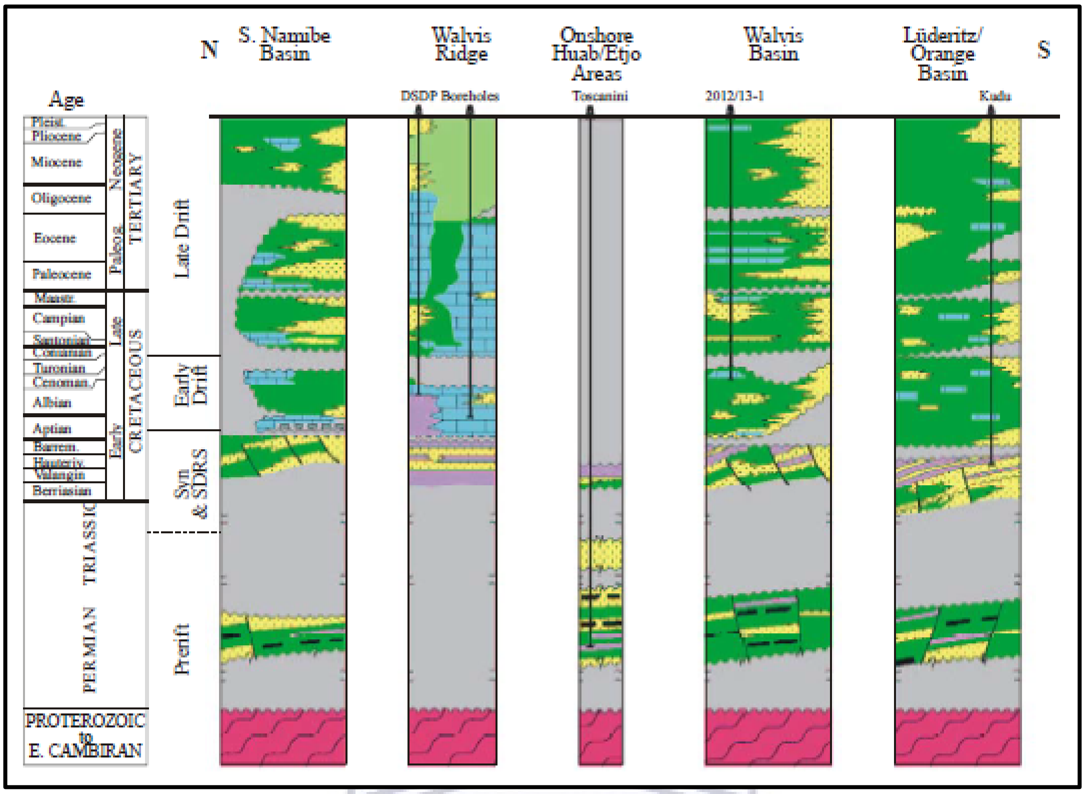

Figure 11: Stratigraphic columns modified from Namcor (information from the 3rd licensing round 1999). The colours in the figure indicate: green = shale; yellow = sand; pink = basement; blue = carbonates; purple = basalt; grey = hiatus; light green = ooze. The borders between the phases prerift to late drift indicated left of the stratigraphic columns are not sharp in time and vary along the continental margin. They are only shown for a rough orientation (Light et al. (1993b).

2.5 Comparison of the Orange Basin with other gravity collapse systems

There are numerous gravity collapse systems which could be compared to the ones in the Orange Basin like those in the Niger Delta and the Mississippi Delta. The work on and interpretation of gravity collapse structures in the Mississippi Delta has been focused on the loose sediments on the continental margin or deltaic setting (Hersthammer and Fossen, 1999) which is not within the scope of this project. Judging from the seismic data for this Study area, it is concluded that the tectonic history of the Niger delta is comparable to the one in the Orange Basin.

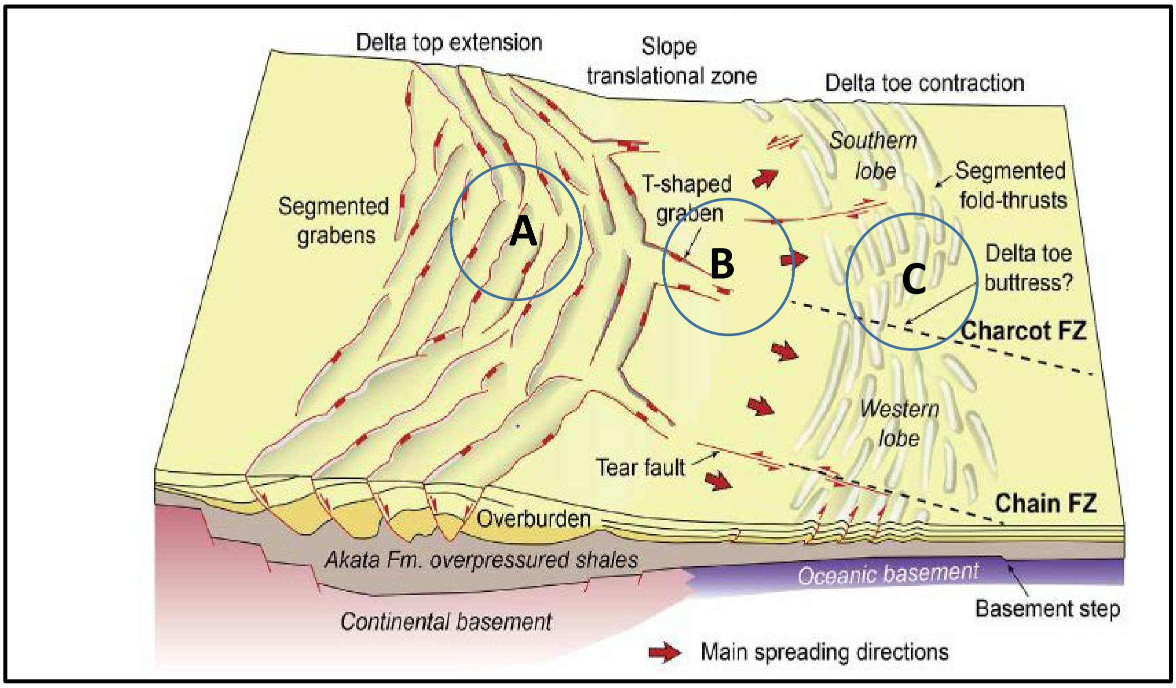

Figure 12: Gravity collapse model for the Niger Delta. The Figure shows the structural evolution of the delta to be similar to the Orange Basin. The Model is separated into three parts. A represents the extensional phase, B is the transitional zone and C is the compressional zone where overpressured shales detached (After Khani, 2013).

The Niger delta has contrasting structural styles as compare to the Orange Basin. The Niger delta shows structural styles related to low strength detachments while the Orange Basin indicates a comparatively strong frictional detachment (Butler and Paton, 2010). This comparability between the Orange Basin and the Niger Delta is illustrated through the recent work by Maloney et al. (2012) and Khani (2013) using 3D seismic data. Work by Maloney et al., (2012) demonstrated that the Niger Delta's gravity driven system has a basin-ward dipping extensional system with one listric master fault plane.

The extensional system creates detachment faulting that switches from a deeper compressional system to a shallower extensional domain similar to the Orange Basin. 3D seismic reflection data was used in these collapse systems to investigate the architecture of the Niger Delta. This study discovered that detachment faulting transfers hanging wall rocks into the footwall, branching off pre-existing detachment levels along zones of mechanical weakness, thus altering the apparent thickness of sedimentary packages (Khani, 2013). Differential sedimentary loading in the Niger Delta played a critical role in causing gravity distribution along with the basin subsidence but in the Orange Basin the deltaic progradation stopped the gravity sliding.

2.6 Possible Genesis of the Crater

2.6.1 Meteorite Impact

Historically, the concept of impact cratering can be traced back to 1609 when Galileo first turned his telescope towards the moon. Shortly thereafter he published Sidereus Nuncius in which he mentioned circular spots on the surface of the moon (Mazur, 1999). Mazur (1999) also discusses that classical geological studies favour an endogenic mode of formation as was first suggested by Hooke (1665). Alfred Wegener's 1920 publication, The Origin of Lunar Craters, supported the impact hypothesis (Koeberl, 1997; Mazur, 1999). As Koeberl (1997) wrote, "It is almost ironical that it was Alfred Wegener who published a little-known study, in which he concluded that the craters on the moon are of meteorite impact origin. The history of study and acceptance of impact cratering over this century is somewhat similar to the record of the acceptance of plate tectonics." According to Glikson and Uysal (2013), large meteorite impact structures on Earth were first discovered by Robert Dietz. These structures include the 2023 ± 4 million-year-old Vredefort crater with a diameter of 298 kilometres as stated by Dietz (1961) and the 250 kilometre-wide Sudbury crater (1850 ± 3 Ma) (Dietz, 1964). These discoveries signalled the imminence of a whole new era in the study of the meteorite impact history of Earth (Glikson and Uysal, 2013). Since then, the development of geophysical exploration (seismic, gravity and magnetics) and drilling has led to the discovery of numerous large buried impact structures including the 170 kilometre-wide Chicxulub impact crater (64.98 ± 0.05 Ma) (EID – Earth Impact Database, 2011; Glikson and Uysal, 2013).

2.6.2 Identifying Buried Impact Structures

Impact craters on earth are continually erased by erosion, weathering, re-deposition, volcanic resurfacing and tectonic activity; the physical markers disappear (Pillalamarri, 2008; Wall, 2008). Moreover, certain geological features generated by means other than impact can have comparable circular form, such as volcanoes, salt diapirs and glacigenic features. Hence, a circular geometry alone is not evidence for impact (Pillalamarri, 2008). In the literature, it is revealed that geophysical measurements have always played a major role in the investigation and study of impact structures (Wall, 2008; Ernstson and Claudin, 2013). In another aspect, geophysical measurements have contributed to the discovery of craters deeply buried in and below older and younger sediments (Ernstson and Claudin, 2013). In most cases, reflection seismics carried out for oil and gas exploration purposes could delineate impact structures by their typical structural features like rings, central uplifts, distinct circular and radial fault patterns, abruptly terminating reflectors and reduced seismic velocities caused by impact brecciation and micro-fracturing (Ernstson and Claudin, 2013; Glikson and Uysal, 2013). Even though the methods of seismic interpretation can aid in the identification of buried impact structures (Mazur et al., 1999; Wall, 2008), they do not provide unequivocal evidence of impact (Pilkington and Grieve, 1992).

Nonetheless, structural features of impact structures that may be imaged on seismic data are often very distinct from structural features associated with salt diapirs, volcanic craters or glacigenic features (Glikson and Uysal, 2013). By way of illustration, Penfield and Camargo (1981) recognized that the gravity and magnetic anomalies centred on the village of Chicxulub, at the tip of the Yucatan peninsula in Mexico resembled those identified at large impact structures. Magnetic anomalies represent changes in rock type or thickness of rocks. The contour maps generated from magnetic surveys provide information to consider whether there is a crater or other geologic formation in that region (Reid, 1980). Magnetic anomalies in and around impact structures may result from displacement of magnetized rocks in the impact cratering process, decomposition of existent rock magnetization (by shock, for example), and formation of new magnetic phases in rocks (Ernstson and Claudin, 2013). According to Grajales-Nishimura et al. (2000), once an impact structure has been identified as such, core-log-seismic data integration for high-resolution seismic stratigraphy can reveal information about the timing of impact (geologic age information) since an impact can alter subsurface rocks. That is to say that, in theory the position of a crater within strata could be used to constrain its age: sediments that were deposited prior to impact might be strongly deformed by the impact, whereas those that are younger than the impact will not (Stewart and Allen, 2002; Grajales-Nishimura et al., 2000).

2.6.3 Marine Impact Craters

Sections 2.6.1 and 2.6.2, above, highlight the fact that the study of impact processes is biased toward terrestrial, rather than marine environments. Wall (2008) noted that the investigation and study of impact craters is based on laboratory experiments, extra-terrestrial examples (Galileo, 1610) and evidence from terrestrial impacts (Penfield and Camargo, 1981; Ernstson and Claudin, 2013; Glikson and Uysal, 2013). In comparison, very little work has been published regarding marine impact craters (Wall, 2008). Dypvik and Jansa (2003) noted the imbalance and came up with ways of quantifying the geological features that evolve when a meteorite strikes the marine environment. Furthermore, the presence of a water column in the marine environment affects all the stages of crater formation (Wall, 2008). As a result, there are obvious geological and morphological characteristics of impact craters formed at sea which may be different from those formed on land (Dypvik and Jansa, 2003; Wall, 2008), as can be seen on Figure 13.

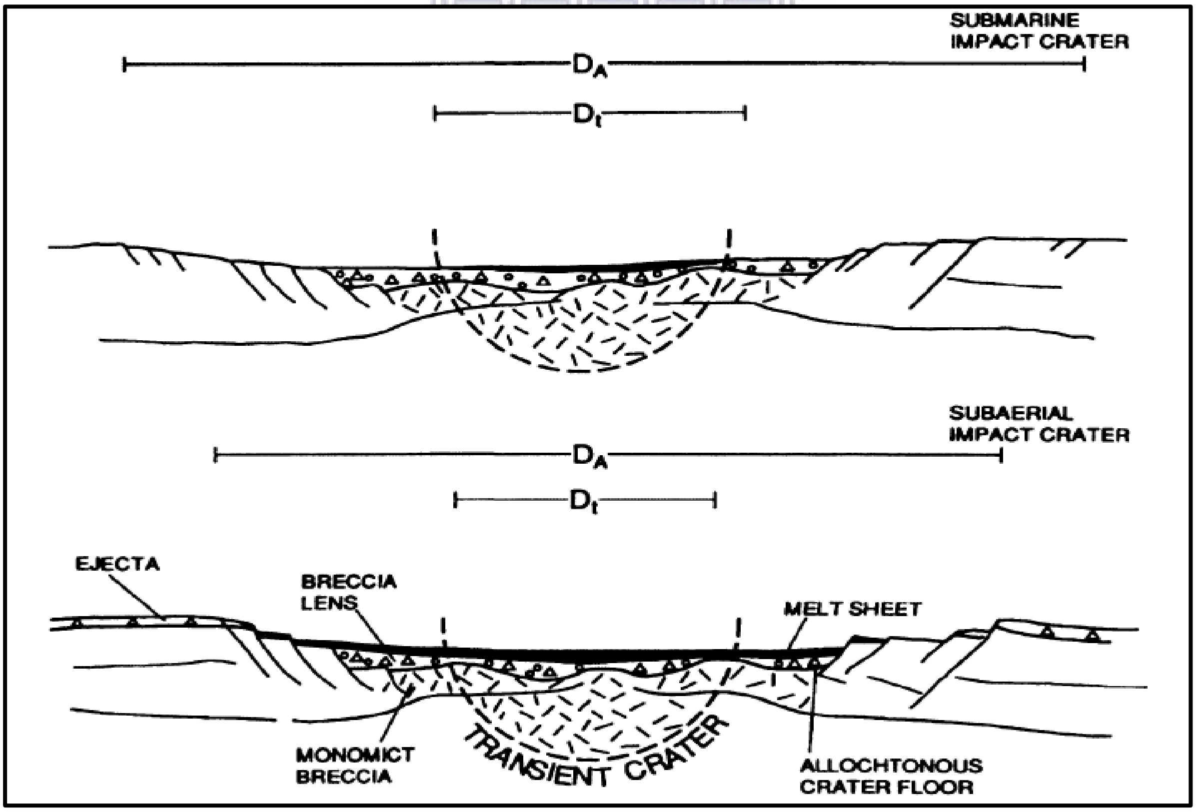

Figure 13: Schematic diagram illustrating the main morphological differences between a simple submarine and sub-aerial impact crater. Note: DA is the apparent diameter and Dt is the transient diameter (Dypvik and Jansa, 2003).

Thus, the characteristics of marine impact craters are as follows:

- Higher preservation potential compared to sub-aerial craters, however more difficult to explore for
- Concentric nature
- Often lack melt sheets and rim walls
- Larger apparent diameters

The section that follows presents a description of some of the possible causes of circular geological structures. It aims to provide a set of criteria that may be used to aid in excluding other circular geological features to demonstrate impact origin.

2.7 Other Possible Origins

2.7.1 Natural Gas Escape (Gas Chimney)

Analysis of regional two-dimensional seismic lines by Boyd *et al.* (2011) led to the proposal that the crater analysed in this study formed as a result of natural gas leakage in the Orange Basin. For this reason, the circular feature was thought to be a gas chimney that resulted when a number of smaller chimneys coalesced to form one giant gas chimney (Boyd *et al.*, 2011). If this is indeed the case, the seismic reflectors would be expected to bow upward in the centre of the feature if methane hydrate occurs and downward where pore-filling methane gas occurs due to acoustic-velocity differences (Scholl et al., 2007). The reason for this is that sound waves travel faster through methane hydrate and slower through gas-filled sediments (Scholl et al., 2007). Hovland et al. (2002) and Betzler et al. (2011) also suggested that concave crater-like depressions caused by gas escape occur mainly in siliciclastic and muddy sea beds as is the case in the Orange Basin. Indeed, many authors have identified gas chimneys, pockmarks, seafloor mounds and, seismic anomalies associated with gas expulsion throughout the basin (Ben-Avraham et al., 2002; Boyd et al., 2010; Hartwig et al., 2010; Boyd et al., 2011). It was suggested that the chimneys are mainly sealed within the Miocene section (Hartwig et al., 2010; Boyd et al., 2011). Hartwig et al. (2010) also stated that some of the chimneys terminate at the Cretaceous-Paleogene uncomformity (22At1).

2.7.2 Volcanic

In addition to natural gas escape, there are many other geologic processes that may result in structures that are circular in map view (Stewart, 2003). For example, the feature could result from another form of fluid expulsion in which case it might be a maar-diatreme volcano which principally consists of a maar crater at the surface underlain by a cone-shaped diatreme, an irregular-shaped root zone at the lower end of the diatreme, and finally a narrow feeder dike at depth (Lorenz, 2003). Additionally, it is also quite possible that the feature is an igneous caldera (Troll et al., 2000). These are characterised by certain morphological elements including collapse craters, topographic ring, inner wall, bounding faults, structural caldera floor and intracaldera fill (Kim et al., 2013).

2.7.3 Salt Diapirism and Salt Withdrawal

Another endogenic mode of formation would be salt diapirism which could have been triggered by extensional faulting (Davison et al., 2000), perhaps during formation of the basin. This leads to the next possible cause of formation of crater-like structures – salt withdrawal. It has been suggested that the removal of buried salt by processes such as dissolution, salt flow or mining results in subsidence of the overburden giving rise to the formation of collapse structures (Ge and Jackson, 1998). As a way of illustration, Underhill (2004) presented an alternative origin for the southern North Sea crater which was named Silverpit (Stewart and Allen, 2002). Underhill (2004) argued against the impact hypothesis and stated that withdrawal of Upper Permian salt at depth was a better explanation.

2.7.4 Mud Volcano

Moreover, the circular feature could be a mud volcano. Interestingly, seismic reflection data acquired over the Orange Basin also gave a record of the extensive occurrence of mud volcanoes in the region (Ben-Avraham et al., 2002). Mud volcanoes are generally characterised by vertical chimneys with almost complete data wipe-out (Graue, 2000) as well as a feeder complex that connects the volcano to its source stratigraphic unit (Basu et al., 2012).

2.8 Background to Research

The development of three-dimensional seismic data in pursuit of hydrocarbons has provided the tool to discover unprecedented geologic features buried deeply within the subsurface of sedimentary basins where the preservation potential of such features, in general, is the highest (Stewart, 2003). Three-dimensional seismic data allows detailed structural analysis of well-preserved buried features through the use of high-resolution subsurface images (Wall, 2008). However, positive identification and classification of buried structures often requires access to geological data in the form of rock specimens and drill core obtained at a specific study area (Stewart, 2003). Not surprisingly, it may never be possible for many buried structures to yield the necessary geological information since these may never be drilled because of the lack of economic incentive and the excessively high cost of drilling (Stewart, 2003). Studying the tectonic driving mechanisms that yield structural features in the Orange Basin may lead into future studies that can guide geologists in better understanding the tectonic phenomenon of the Orange Basin.

2.9 Scope and Limitations of Research

The scope of this research is to fulfil the objectives as far as possible, given the limitations of seismic reflection data and the fact that there is no geological information at the structural features themselves. Complete analysis of the data could support a project far beyond a mini thesis project: there is clearly scope for more detailed future research.

2.10 Problem Statement

An understanding of the tectonic driving mechanisms behind thrust developments of the Orange Basin is not well understood. Mapping and classifying these thrust developments will bring a scholarly understanding of the tectonic driving mechanism of the Orange Basin. In order to achieve this, the interpretation will evaluate the 3-D seismic section to determine thickness change and number of thrust fault sequencing in the form of shortening. A detailed study is particularly important as it may provide key insights into the understanding of subsurface features and can be used to investigate fundamental scientific questions regarding the origin of these features. The interpretation of gravity collapse structures of the Orange Basin have given some answers on the deformational structures observed in the 3-D seismic data. A well-established deformational model can improve structural integrity which can be used to explain how the study area has been differentiated into curvilinear listric faulting, localized thrusting, lateral compaction and ductile deformation. So to better understand the origins of the deformational features in this Basin, this study aims to focus on, what is the development in deformation from the south to the north? What are the factors which influenced observed apparent thickness variations? What is the relationship between the structural features in the study area with the gas escape structures?

2.11 Glossary of Thrust Tectonics Terms

The glossary by McClay (1992) is an essential when trying to understand the differences between these thrust terms. Not understanding the minor differences between the terminologies can lead to wrong identifications and interpretations. In this study we seek to identify these differences and illustrate our interpretation in our results chapter. This will be aligned with the terminologies reviewed by McClay (1992). Aligning the right terminology with the interpretation results is a major objective, seeing that the differences are technical. In the "Glossary of thrust tectonics terms", (McClay, 1992) the author illustrates and defines some of the more widely used terms in thrust tectonics. Even though "it is presented on a thematic basis- individual thrust faults and related structures, thrust systems, thrust fault related folds, 3-D thrust geometries, thrust development, models of thrust systems, and thrusts in inversion tectonics"(McClay,1992), understanding of thrust development terminology is drawn from McClay's glossary. McClay (1992) acknowledges that his glossary is not meant to be exhaustive but attempts to cover many of the terms used in thrust tectonics literature in general. He further alludes to the fact that, the reader will recognise the difficulty in precisely defining many of the terms used in thrust tectonics as individual usages and preferences vary widely (McClay, 1992). In this study, results observed present structures that are classified by different styles and an understanding of this observation has an impact on the kinematic evolution from the centre of the study area towards the west. McClay (1992) gives a more realistic terminology for the structures identified in this study, hence the reference.

2.11.1 Thrust Faults

McClay (1992) defines a thrust fault as a contraction fault that shortens a datum surface, usually bedding in upper crustal rocks or a regional foliation surface in more highly metamorphosed rocks. McClay (1992) defines terms in his glossary which applied to individual thrust faults (McClay 1981, Butler 1982, Boyer & Elliott 1982, Diegel 1986).

2.11.2 Back Thrust

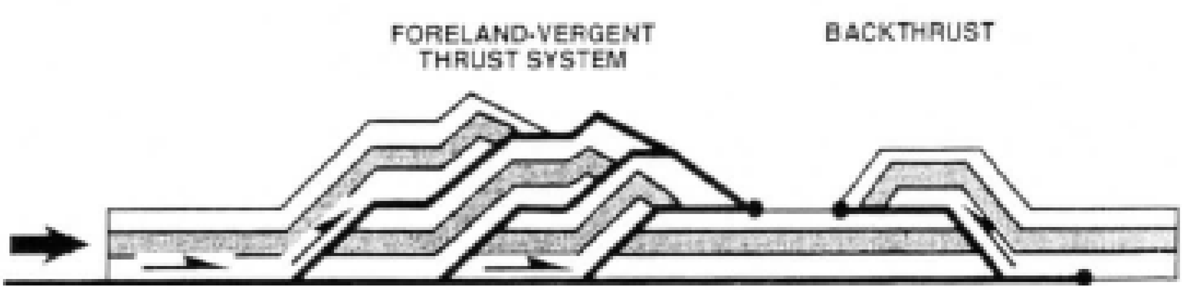

Figure 14: Back thrust showing an opposite sense of vergence to that of the foreland vergent thrust system (McClay, 1992).

Figure 14 above illustrates a back thrust, which is defined as a thrust fault which has an opposite vergence to that of the main thrust system or thrust belt. Back thrusts are commonly hinterland-vergent thrusts (McClay, 1992).

2.11.3 Thrust Sequences

McClay (1992) defines thrust sequences as the sequence in which thrust faults develop. This study seeks to map these developments and an understanding of how these thrusts develop is important. The development of thrust faults within a thrust belt or thrust system is also an important parameter needed for the interpretation of both the geometry and the kinematic evolution of the thrust belt (McClay, 1992). These terminologies are important in this study even though more emphasis is made on foreland settings; the study identified characteristics of thrust development in the West coast passive margin. Reference is made on thrust sequences, because they were dominant in the seismic structural interpretation.

McClay (1992) stated that these sequential developments of thrust faults are essential for the construction of balanced and restored sections (Boyer and Elliott 1982, Boyer 1991, Butler 1987, Morley 1988, Suppe 1985, Woodward et al. 1989). McClay (1992) further states that, a long accepted paradigm for thrust faults to develop sequentially in a sequence that both nucleates in a forward-breaking sequence and verges towards the foreland (Dahlstorm

1970, Bally et al. 1966, Boyer & Elliott 1982, Butler 1982). The former not being the case in this study due to illustrations that (McClay, 1992) clearly demonstrates from literature which will be presented below.

2.11.3.1 Breaching

McClay (1992) cited Butler (1987) when he stated that breaching occurs where an early formed thrust is cut by later thrusts. The term describes the local geometric relationships between thrusts.

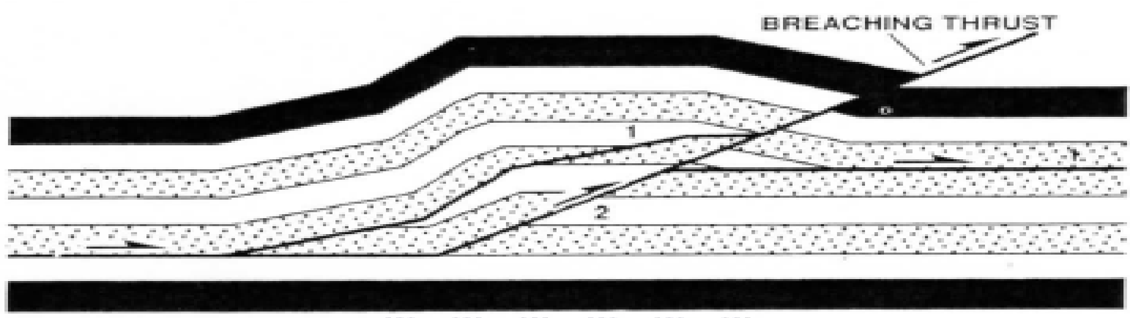

Figure 15: Breaching thrust- an early formed thrust cut by later thrust, numbers indicate sequence of faulting (McClay 1992).

2.11.3.2 Break-back Sequence

McClay (1992) defines a break-back sequence as the sequence of thrusting where new (younger) thrusts nucleate in the hanging walls of older thrusts and verge in the same direction as the older thrusts (Fig. 16). Identifying these sequences is not an easy task as eluded by (McClay, 1992). In this study we strive to determine which type of thrusting has taken place in the study area.

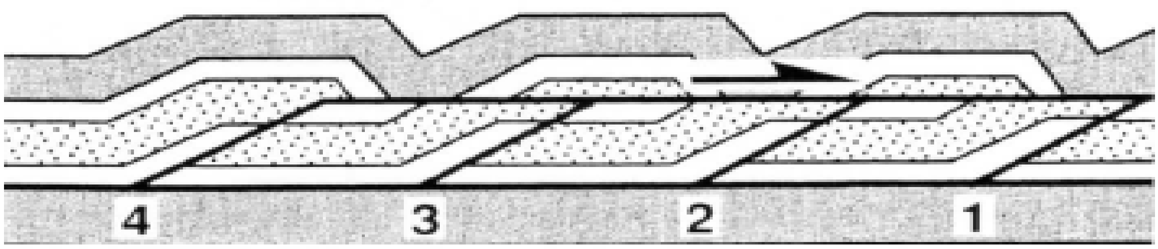

Figure 16: Break-back thrust sequence; numbers indicate sequence of faulting (McClay 1992).

2.11.3.3 Forward-breaking Sequence or Piggy-back thrusts

McClay (1992) defines a forward-breaking sequence as a sequence of thrusting in which new (younger) thrust faults nucleate in the footwalls of older thrusts and verge in the same direction as the older thrusts (Fig. 17).

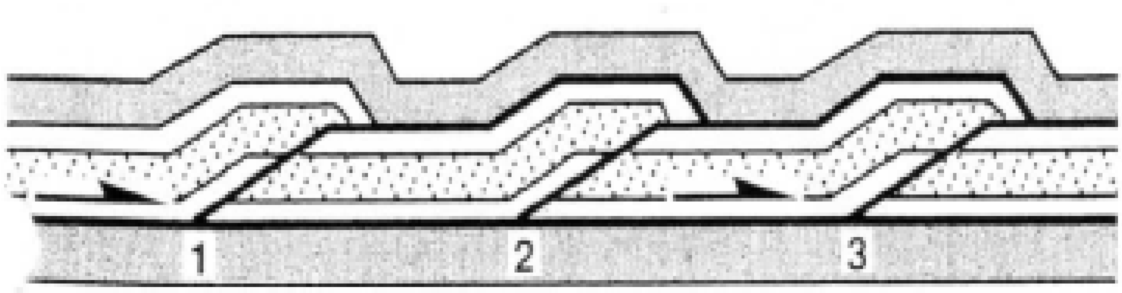

Figure 17: Forward-breaking or "piggy-back thrust" sequence. Numbers indicate sequence of faulting (McClay, 1992).

A Piggy-back thrust sequence occurs when topographically higher but older thrusts are carried by lower younger thrusts (Fig.17) (McClay, 1992). The same as forward-breaking thrust sequence. This sequence could be easily mistaken for what has been mapped in this study but however with McClay's glossary, we seek to identify what kind of sequences are observed in this study area.

2.11.3.4 In-Sequence Thrusting

McClay (1992) defines an in sequence thrust as a thrust sequence that has formed progressively and in the proper order in one direction (i.e. either a forward-breaking sequence or a break-back sequence). Figure 16 and 17 show in-sequence thrusting.

2.11.3.5 Out-of-Sequence Thrusting

Out -of-Sequence thrusting is defined by McClay (1992) as the opposite to in-sequence thrusting. Thrust faulting which develops in a sequence other than in sequence (Fig. 18). Break-back sequences of thrusts have commonly been called out-of-sequence thrusts but the term should be more appropriately used to describe thrust sequences which do not conform to either a progressive forward-breaking or break-back sequence (Fig. 18) (McClay, 1992). Out of sequence thrusts commonly cut through and displace pre-existing thrusts.

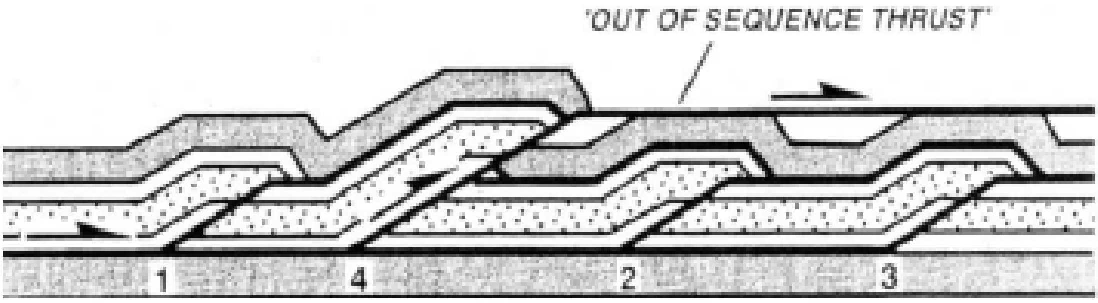

Figure 18: Out-of-Sequence thrust cutting into a foreland-vergent thrust system. Numbers indicate sequence of thrusting (McClay, 1992).

2.12 Thrust Systems

McClay (1992) defines a thrust system as a zone of closely related thrusts that are geometrically, kinematically and mechanically linked. The terminologies for thrust systems stem from Dahlstorm (1970), Boyer & Elliot (1982), and Mitra (1986) and were modified by Woodward et al., (1989). The thrust systems terminologies are significant in this study because McClay (1992) glossary shows a reliable appreciation for these structures. The thrust systems include duplexes and imbricate thrust systems.

2.12.1 Duplexes

McClay (1992) defines duplexes as, an array of thrust horses bounded by a floor thrust (i.e. sole thrust) at the base and by a roof thrust at the top. He explained that the stacking of the horses and hence the duplex shape depends upon the ramp angle, thrust spacing, and displacement on individual link thrusts. These models for duplex formation (Boyer & Elliot 1982; Mitra 1986) generally assume a “forward-breaking” thrust sequence (see thrust sequences above) (McClay, 1992).

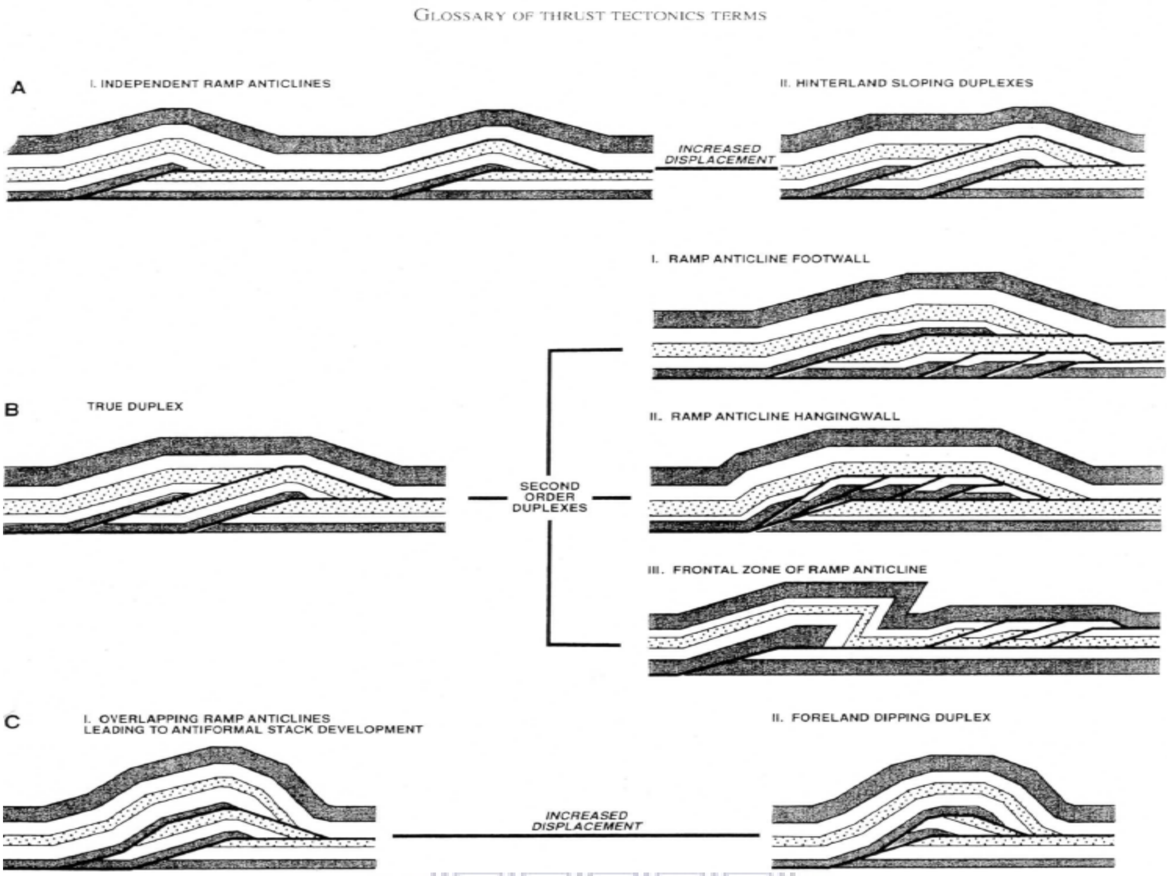

Figure 19: Duplex classification (after Mitra 1986). (a) Independent ramp anticlines and hinterland dipping duplexes. (b) True duplexes with second order duplexes. (c) Overlapping ramp anticlines which produce antiformal stacks and, with increased displacement, foreland dipping duplexes.

Mitra (1986) revised Boyer & Elliott's (1982) classification of duplexes and proposed a threefold classification as illustrated in Fig. 19 above (McClay, 1992). These classifications of duplexes consist of- 1) Independent ramp anticlines and hinterland sloping duplexes (Fig. 19a); 2) True duplexes (Fig. 19b); 3) Overlapping ramp anticlines (Fig. 19c). McClay (1992) states that, for independent ramp anticlines the final spacing between the thrusts is much greater that the displacement on the individual thrusts and the structure formed consists of independent ramp anticlines separated by broad synclines (Fig. 19a). McClay (1992) further states that, hinterland sloping duplexes (Fig.19a) are formed where the initial spacing of thrust faults is small and displacement on individual thrusts is small such that, at the contact between horses, the roof thrust slopes towards the hinterland (Mitra 1986). The formation of true duplexes (such as those modelled by Boyer & Elliot (1982)) is controlled by a particular combination of final thrust spacing, ramp angle and ramp height such that parts of all of the link thrusts and roof thrust are parallel to the frontal ramp of the duplex (Fig.

19b) (McClay, 1992). Overlapping ramp anticlines are formed where the crests of successive ramp anticlines partially or totally overlap (Fig 19c). A system of completely overlapping ramp anticlines in which the trailing branch lines are coincident is termed an antiformal stack (Fig. 19c) (McClay, 1992). McClay (1992) cites Mitra (1986) and further subdivided true duplexes depending upon their position with respect to larger thrusts (Fig. 19b). Duplexes may occur in the footwall to a ramp anticline, in the hanging wall to a ramp anticline and in front of a ramp anticline (Fig. 19b).

2.12.1.1 *Antiformal Stack*

McClay (1992) identifies an antiformal stack as a duplex formed by overlapping ramp anticlines which have coincident trailing branch lines (Fig. 20); this leads to individual horses to stack up on top of each other such that they form an antiform.

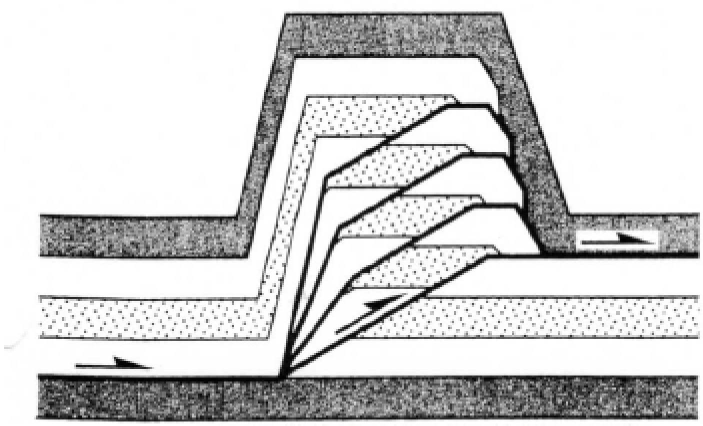

Figure 20: Antiformal stack. (McClay, 1992)

2.12.1.2 *Breached Duplex*

McClay (1992) defines a breached duplex as a duplex in which "out of sequence movement" on the link thrusts have breached or cut through the roof thrust (Fig. 21). McClay (1992) alludes to the fact that Butler (1987) is the one that discusses breaching of duplex structures.

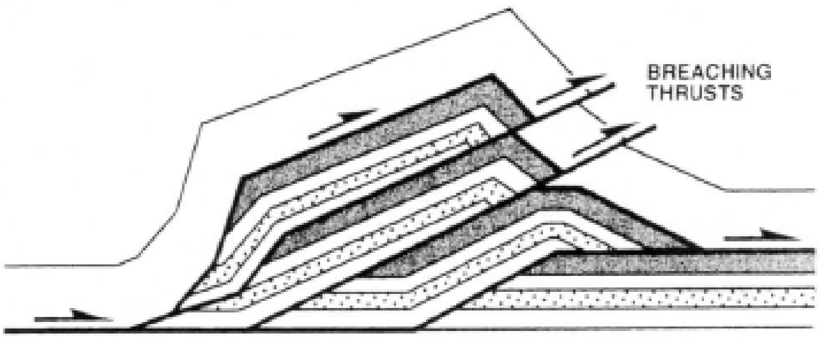

Figure 21: Duplex breached by reactivation of the link thrusts which displace the original duplex roof thrust (McClay, 1992).

2.12.1.3 Corrugated or 'Bump Roof' Duplex

A duplex in which the roof thrust is corrugated or folded (Fig. 22).

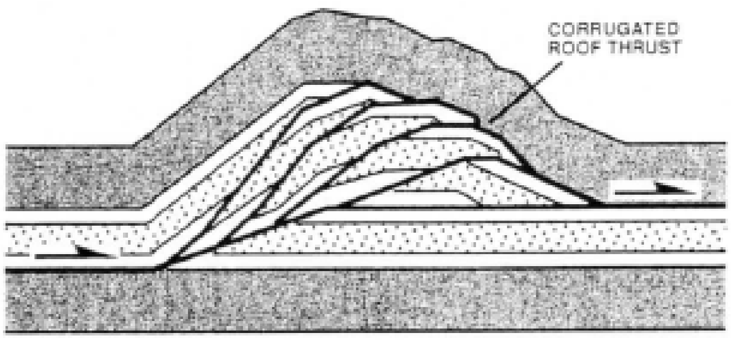

Figure 22: Corrugated duplex (McClay, 1992).

2.12.1.4 Floor Thrust

McClay (1992) defines a floor thrust as the lower thrust surface that bounds a duplex (Fig.19).

2.12.1.5 Foreland Dipping Duplex

Foreland dipping duplex is a duplex in which both the link thrusts and the bedding (or reference datum surface) dip towards the foreland of the thrust belt (Fig. 23) (McClay, 1992).

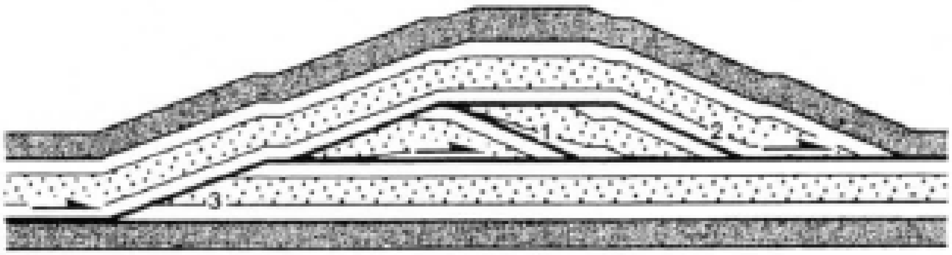

Figure 23: Foreland dipping duplex (McClay, 1992).

2.12.1.6 Hinterland Dipping Duplex

Hinterland dipping duplex are duplexes in which both the linked thrusts and the bedding (or reference datum surface) dip towards the hinterland of the thrust belt (Fig. 24) (McClay, 1992).

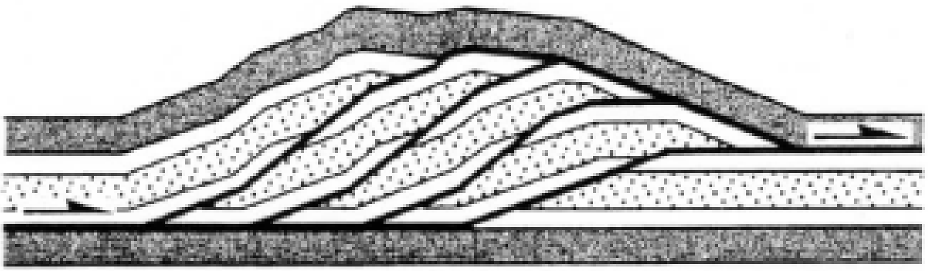

Figure 24: Hinterland dipping duplex (McClay, 1992).

2.12.1.7 Link Thrusts

McClay (1992) defines link thrusts as, imbricate thrusts that link the floor thrust to the roof thrust of the duplex (Fig. 25) and these link thrusts are commonly sigmoidal in shape (McClay &Insley 1986).

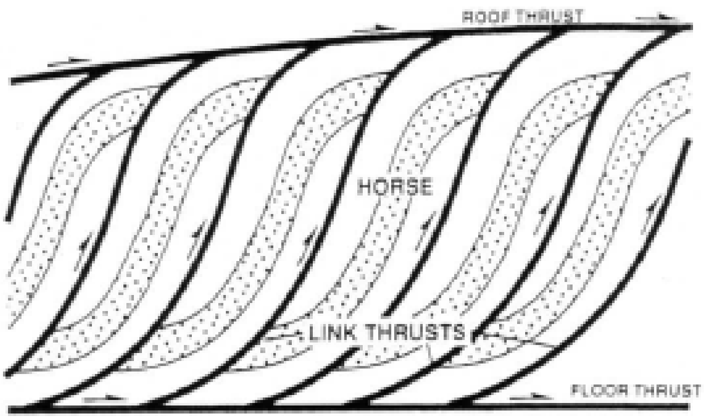

Figure 25: Duplex link thrusts (adapted after McClay & Insley 1986).

2.12.1.8 Passive Roof Duplex

McClay (1992) defines a passive roof duplex as a duplex in which the roof thrust is a passive roof thrust (Fig. 26) such that the roof sequence has not been displaced towards the foreland but has been under thrust by the duplex, cited from Banks & Warburton (1986).

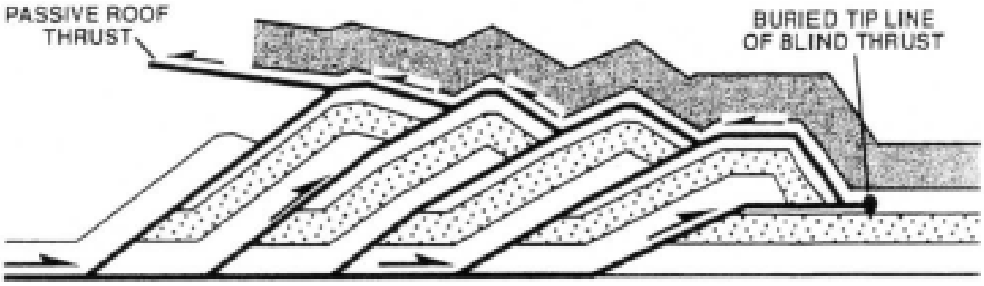

Figure 26: Passive roof duplex (adapted after Bank & Warburton 1986).

2.12.1.9 Passive Roof Thrust

McClay (1992) defines passive roof thrusts as a roof thrust in which the sequence above has not been displaced but has been under thrust (Fig. 26). Passive roof thrusts are commonly developed where tectonic delamination or wedging occurs.

2.12.1.10 Planar Roof Duplex

McClay (1992) defines a planar roof duplex as a duplex in which the roof thrust is planar except where it is folded over the trailing ramp and over the leading ramp (Fig. 27). Groshong & Usdansky (1988) demonstrate that such geometry is a result of a special combination of duplex thrust spacing and displacement.

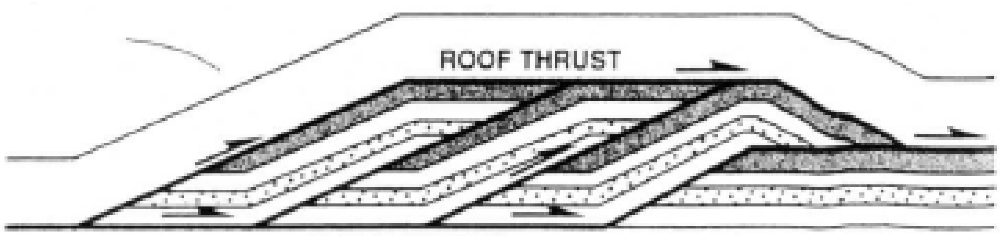

Figure 27: Planar roof duplex (true duplex model of Mitra 1986).

2.12.1.11 Roof Thrust

McClay (1992) defines a roof thrust as the upper thrust surface that bounds a duplex (Fig. 27). Roof thrusts may be smooth or folded by movement on underlying thrusts of the duplex.

2.12.1.12 Smooth Roof Duplex

McClay (1992) defines a smooth roof duplex as a duplex in which the roof thrust varies smoothly (Fig. 28) (McClay & Insley 1986; Tanner 1991). Smoothly varying roof thrust geometry may be interpreted as indicating synchronous thrust movement (McClay & Insley 1986).

Figure 28: Smooth Roof duplex where the roof thrust varies smoothly without folding by the underlying link thrusts (after McClay & Insley 1986).

2.12.1.13 Truncated Duplex

McClay (1992) defines a truncated duplex as a duplex that is beheaded or truncated by an out -of- sequence thrust (Fig. 29).

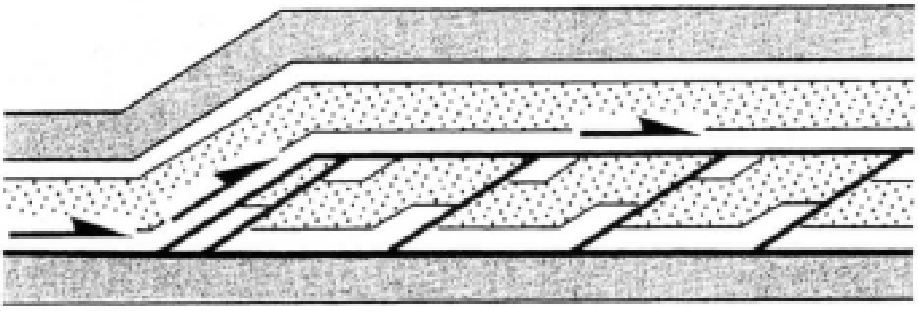

Figure 29: Truncated duplex in which the upper section (leading branch lines) has been removed by an out-of-sequence thrust overriding the duplex (McClay, 1992).

2.13 Imbricate Thrust Systems

McClay (1992) defines imbricate thrust systems as closely related branching array of thrusts such that the thrust sheets overlap like roof tiles (Fig. 30).

McClay (1992) further explains that imbricate thrust systems may be formed by a system of overlapping fault propagation folds (Fig.31). Imbricate fans may also form from duplexes which have the leading branch lines eroded (Fig. 30). Boyer & Elliott (1982) point out the difficulty in distinguishing between imbricate systems formed from duplexes which have had the leading branch lines eroded and those imbricate systems formed from a branching array of thrusts that die out into tip lines and which have been subsequently eroded (Fig. 30), cited in McClay (1992).

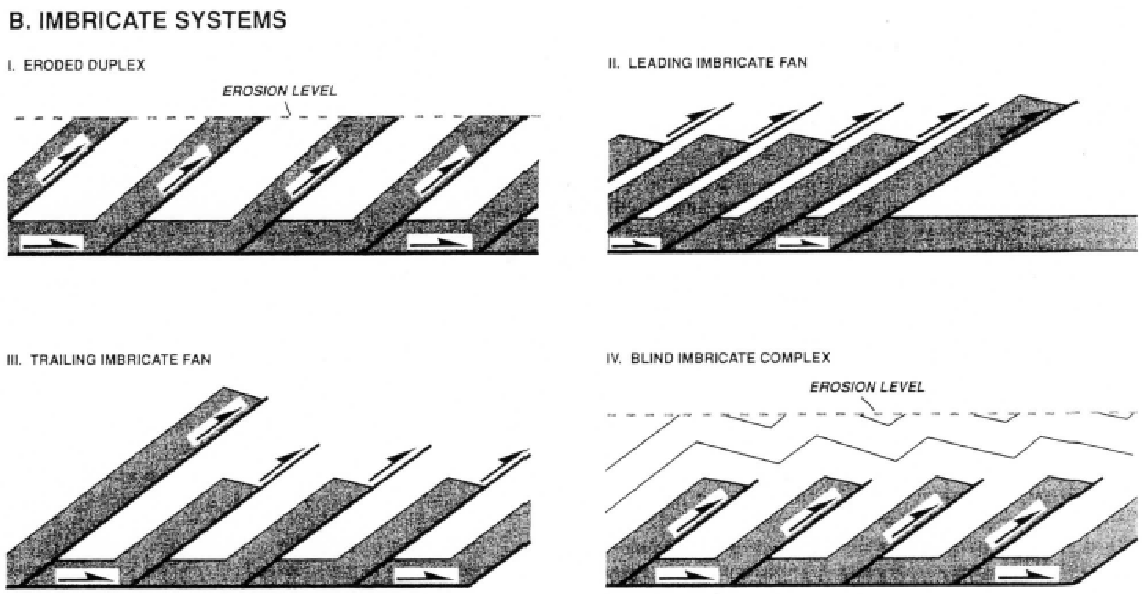

Figure 30: Imbricate systems (schematic) (adapted after Boyer & Elliott 1982; Mitra 1986; and Woodward et al., 1989).

2.13.1 Imbricate Fan

McClay (1992) defines the imbricate fan as a system of linked, emergent thrusts that diverge upwards from a sole thrust (or floor thrust) (Fig.31).

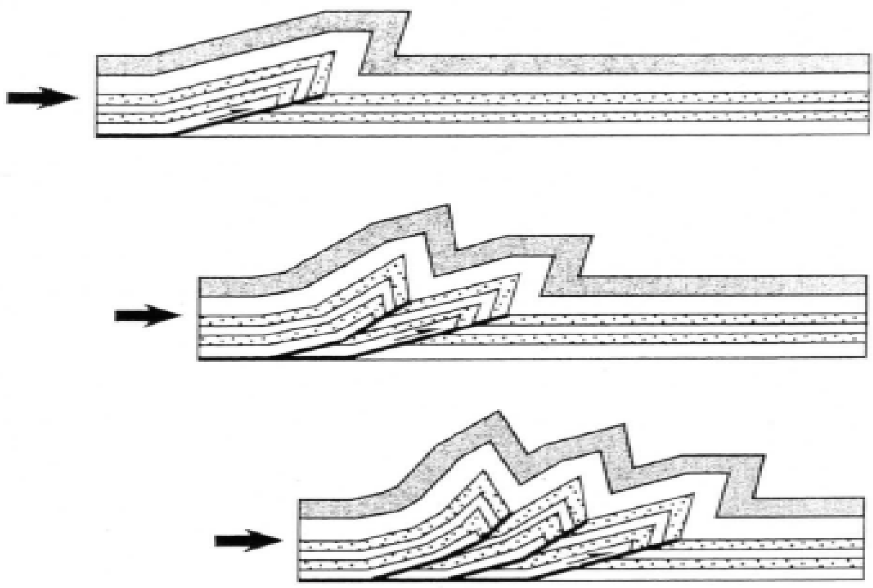

Figure 31: Imbricate fan formed from an array of overlapping fault-propagation folds (adapted after Mitra 1990).

2.14 Neotectonics of Southern Africa – A Review

Thrusting sequence developments in the west-coast are also explained by gravity-driven systems. The major fault developments in the area may be related to the east-west oriented ridge push associated with the Atlantic breakup of Gondwana. This section will explore the interpretation by Andreoli et al., 1996 of the north-south stress field in the "Neotectonics of Southern Africa – A Review". Here the authors interpret the neotectonic faults and other seismogenic structures identified across South Africa.

The neotectonic activity in southern Africa is analyzed in terms of known stress fields and NW-SE trending maximum horizontal compression directions (S_{HMAX}) developed from southern Angola to the offshore Transkei basin were defined as the Wegener stress anomaly (WSA) (Andreoli et al., 1996). Andreoli et al., (1996) further elaborate that the interaction between WSA and the other stress field acting on the African plate (linked to the ridge-push, and to the southern propagation of the African Rift) causes neotectonic faults and intraplate seismicity.

These authors further state that intraplate regions experience spare and scattered seismicity that normally is not associated with any known geological features, these earthquakes appear driven by constrained forces, and affect stable continental (and oceanic) crust well away from the seismic regions at the margins of tectonic plates (Sykes, 1978; Johnston and Kanter, 1990). South Africa is such an intraplate region where damaging earthquakes have taken place in the last two centuries (Femandez and Guzman, 1979 cited in Andreoli et al., 1996).

Andreoli argues that, the data he and his colleagues present provide clear evidence that seismogenic Late Cenozoic tectonic activity in South Africa is more widespread than previously known and that it is associated to several, contrasting stress fields whose origin is not always clearly constrained and that the release of stresses in the region may be influenced by the dynamics of these stress fields. This might be one of the dynamics that lead to how the thrust development formed in the study area (Andreoli et al., 1996).

The review by Andreoli et al., (1996) gives a good illustration of the tectonic activity behind the development of the formations identified in this study. Explaining their methodology, Andreoli et al., 1996 explains that, at the core of their investigation was an attempt to link the tectonic fabric of the southeast Atlantic and southwest Indian Ocean to the tectonic fabric of the African subcontinent.

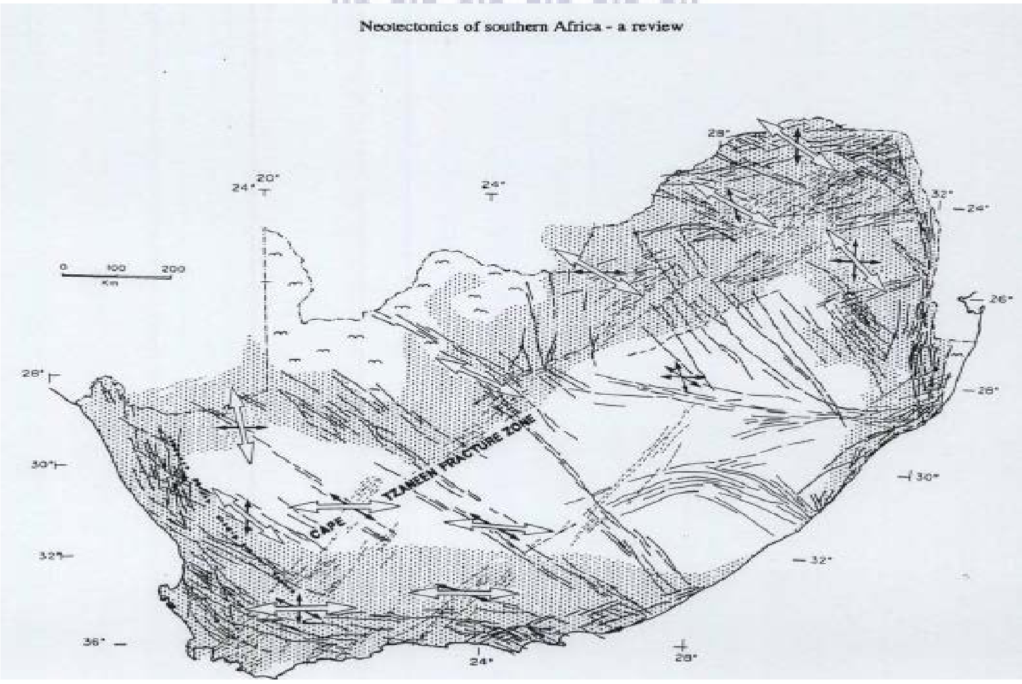

Figure 32: Lineament patterns across South Africa (Modified after HGGA, 1978) in relation to the Cenozoic Kalahari basin (bird wings); subhorizontal rocks of the Karoo Sequence (blank); Pre-Karoo basement, Karoo rocks affected by the Cape Orogeny and/or by Gondwana-age faulting (stippled). Open, broad arrows represent primary free-air gravity trends caused by deep seated structures in selected areas of South Africa (Mushayandebvu and Doucoure, 1994). Shorter, smaller arrows represent secondary, free-air gravity (Mushayandebvu and Doucoure, op.cit.) trends. Note the coincidence between several fracture belt and deep-seated structures in most regions of South Africa; dotted line; possible large scale fracture (Camisani-Calzolari, 1987).

2.14.1 Southwestern Cape Domain

The southwestern Cape domain comprises of the post-Karoo structures which are the onshore Worcester Fault (Ransome and de Wit, 1992), the offshore Aghulas-Falkland fracture zone (FZ) (Cande et al., 1988; Marshall, 1994), and the Cape fracture zone (FZ) (Rabinowitz, 1976). The Cape FZ matches the onshore Cape-Tzaneen FZ (after HGGA, 1978) of similar orientation. The other major structure in the region is, however, the recently proposed, cross-fabric Ceres-Prince Edward Fabric (Andreoli et al., 1993; 1995). Evidence for Late Tertiary to Quaternary neo-tectonic activity in the southwestern Cape is rapidly growing (Andreoli et al., 1996). Seismogenic, mid-crustal left-lateral strike-slip movements along NW-trending faults are induced by easterly-oriented stresses.

Ransome et al. (1993, as cited in Andreoli et al., 1996)) have proposed the existence of a crude, broad seismic zone striking NW-SE from Saldanha Bay to Cape Agulhas, along the Miocene Saldanha-Agulhas axis of uplift (Partridge and Maud, 1987). Structural analysis of the neotectonic fractures and riedel shears between Gansbaai and Quoin Point reveals that the dominant Pleistocene stress field was characterized by extension (S_{hmin}) towards N25^o and a prominent ESE-WNW strike of the faults (Van Bever Donker and Andreoli, 1995). Offshore, “breakout” data from post-rift strata in the Bredasdorp Basin support these findings by showing that extension toward N 045^o- 065^o predominates over a secondary orientation towards N 135^o - 145^o (Fouche, 1995). Offshore, neotectonic activity and recent volcanism in the northeastern Agulhas plateau have been revealed by seismic refraction data (Ben-Avraham et al., 1995).

2.14.2 Seismicity of the Atlantic seaboard (Southwestern and Namaqualand domains)

Current literature dealing with the neotectonic deformation of the western sector of South Africa does not fully explain the processes of seismicity (Ransome et al., 1993; Faurie et al., 1992) and continental margin uplift (Gilchrist and Summerfield, 1990; Gilchrist et al., 1994). Ransome and de Wit (1992) have proposed a microplate hypothesis for neotectonic activity in the region that extends from Saldanha Bay to Cape Agulhas. According to this model, the east-west compression that caused the Ceres earthquake (Green and Bloch, 1974) is related to ridge-push compression from the Mid-Atlantic ridge (Ransome and de Wit, 1992; Ransome et al., 1993).

Andreoli et al., (1996) conclude their findings by describing South Africa as a site of pervasive neotectonic activity which is manifested both along the coastal regions, in the continental interior, and in the ocean floor between the continental margins and the Southwest Indian Ridge. The neotectonic activity was initiated in the Miocene and is largely induced by three major stress fields oriented easterly, north-northeasterly and northwesterly respectively. The northerly to NNE stress field of northern Natal and the easterly stress field near the Zimbabwe-Botswana borders are related to the southern termination of the East African Rift, but the other stress field cannot be satisfactorily interpreted by the available data in terms of “first order” stresses caused by compressional forces applied at the plate boundaries (Zoback, 1992). Andreoli et al., (1996) further state that, most of South Africa, Namibia, and the ocean floor between the Bredasdorp Basin and the Southwest Indian ridge is dominated by a pervasive, NW-trending stress field of deep-seated, undermined origin for which the term Wegener Stress Anomaly is now proposed by Andreoli et al., (1996). The finding that the Witwatersrand gold mines, Cape Town, and Vaalputs fall within the poorly understood Wegener Stress Anomaly imposes the need for further seismological and neotectonic investigations (Andreoli et al., 1996). Therefore the tectonic driving mechanisms of the west coast are not easy to pinpoint however assumptions drawn from limited literature reviewed above have been made.

2.15 Structural analysis of the gravity-driven systems of the Orange Basin

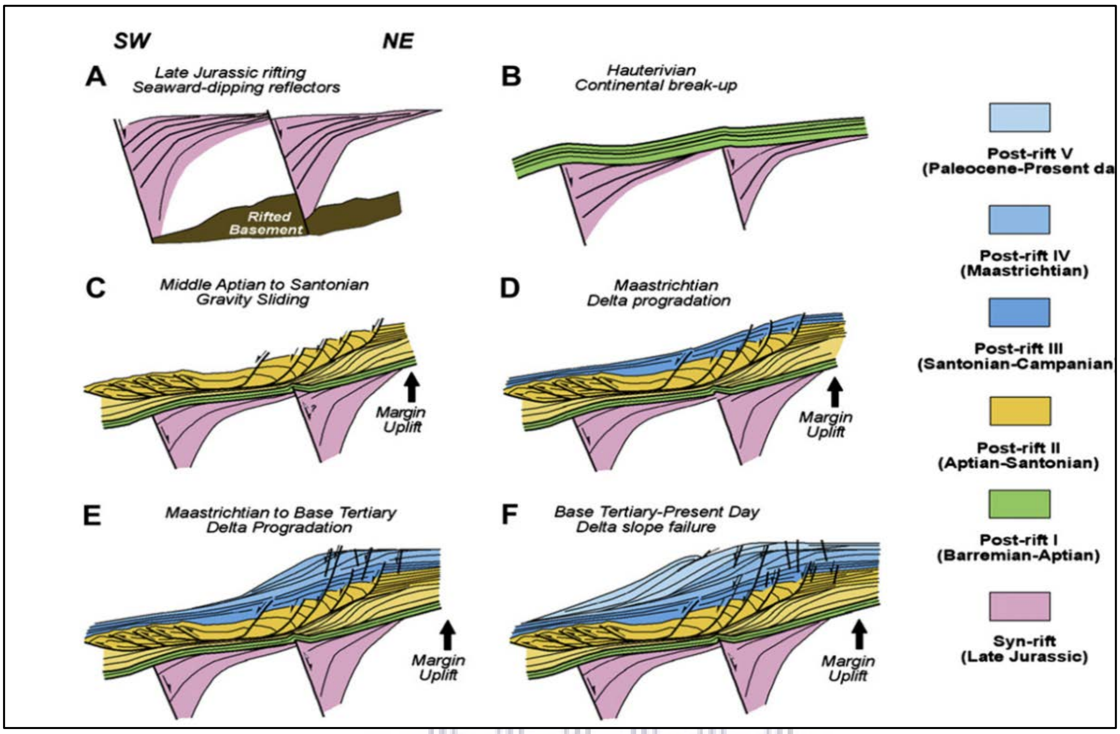

Figure 33: Structural evolution of the Orange Basin gravity-driven system (de Vera et al., 2010).

The episodic gravitational collapse system of the Orange Basin margin characterizes the mid and late Cretaceous deformation. De Vera et al., (2010) suggested that structural evolution of the Orange Basin gravity-driven system is short-lived spanning from the Coniacian (ca. 90 Ma) to the Santonian (ca. 83 Ma). Jungslager, (1999) and Paton et al., (2007) reported that gravity sliding also occurred during the late Cretaceous. Their interpretation of the Orange Basin extends the period for the formation of the gravity collapse system to the Cenomanian and Maastrichtian epochs. Many studies on the Orange Basin attribute the gravity-failure in the late Cretaceous to differential sedimentary loading associated with rapid delta progradation related to high sedimentation rates (Jungslager, 1999; Paton et al., 2007).

Rowan et al., (2004) suggested that gravity failure can also occur as a result of the presence of an efficient, commonly over-pressured detachment layer. The gravitational collapse system of the Orange Basin is estimated by Rowan et al., (2004) to have developed between the Cenomanian (ca. 100 Ma) and the Campanian (ca. 80 Ma) and to a lesser degree during

Maastrichtian (ca. 70 Ma). Orange Basin margin evolution started with rifting during the late Jurassic which is represented by well-imaged wedges of seaward-dipping reflectors (Fig.33A). The post-rift Megasequences were deposited, starting with a deepening-upward succession of continental to deep marine sediments during the Hauterivian (Fig.33B). The combined effect of post-rift thermal subsidence and passive margin uplift 100 to 80 Ma ago initiated gravity failure resulting in stacked gravity slides with complex three-dimensional geometries (Fig.33C). Gravitational spreading and failure of the margin as the result of high sedimentation rates and delta progradational decreased in Campanian times but the margin uplift continued (Fig.33D). Margin uplift is demonstrated by deposition of a series of prograding clastic wedges (Fig.33E) and the development of listric faults (Fig.33F) (de Vera et al., 2010).

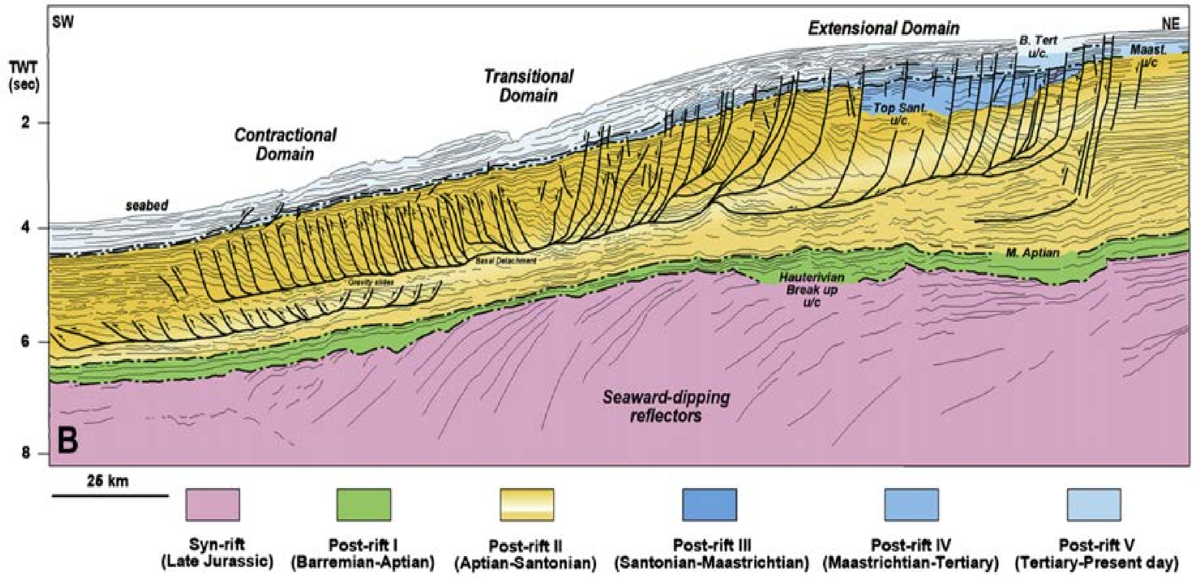

Figure 34: Megasequences and the Late Cretaceous gravity-driven slide system (after Granado et al., 2009).

The gravity-driven system can be divided into three distinct structural domains, based on the across strike variations in structural style (Fig.34). From northeast to southwest these are: an up-dip extensional domain characterized by basin-ward dipping listric faults, a transitional domain with both contractional and extensional features, and a down-dip contractional domain that consists of landward-dipping thrust faults and associated thrust fault-related folds (Rowan et al., 2004) (Fig.34).

3 CHAPTER THREE

3.1 METHODOLOGY

3.1.1 3D SEISMIC INTERPRETATION

The seismic reflection analysis was carried out on Petrel© software. Horizons were picked along continuous reflectors and faults were interpreted in each section at points where seismic reflectors terminate. Correlations of horizons across some faulted blocks are somewhat of an uncertainty as the seismic reflectors are poorly visible. To minimize the degree of uncertainty, analogues from experiments, geological models and geological examples were also used as reference tools to aid the interpretation. Horizon markers provided information on the different depositional units interpreted.

3.1.2 STRUCTURAL INTERPRETATION

For this study, structural interpretation was the most fundamental activity. In order to understand how and when the thrust faults were formed, it was necessary to map a range of marker horizons above and below the target.

3.1.3 FAULT PICKING

Faults were picked in particular as a series of unassigned fault segments and the segments were then assigned to named fault surfaces. The main basal detachment block was digitized first; as the study area was mapped it became clear that the main basal detachment blocks did break into smaller units separated by thrusts. Thrusts were quantified by their amount of shortening to explore their usability as an indicator of deformation. Digitization of the gas-escape structures was carried out and was mapped to draw a relationship between hydrocarbon seeps and the thrusting development in the study area. Although there were only a few gas-escape structures, the structures were digitized so as to show that these structures do appear in the study area although they occur more frequently in the surrounding area. Thrust fault development mapping was achieved through 3-D seismic data interpretation. Thrust faulting in the Study area was interpreted using fault dip and dip azimuth. Fault dip and azimuth were extracted from the seismic cube to analyse thrust faulting and its relationship to the stress field distribution. To perform the interpretation of faults, the following steps were taken. Using the realized seismic cube, an amplitude map was created, and then structural smoothing of the seismic cube was applied. A variance or discontinuity cube was generated which was then used to perform ant-tracking. Ant-tracking traces all the zones of weakness in the seismic data by searching for discontinuities in the seismic data. The automatic fault extraction facility of the software was used to extract fault patches (which are merely fault points with x, y and z coordinates). When digitizing was complete, picking continued on successive vertical displays (inline and cross-line) as required.

It has been explored by Wall, 2008 that all planetary bodies with a solid surface have meteorite impact craters. In order to be comprehensive with my approach in this study, the meteor impact will be considered as a possible mechanism that may have caused the observed structural features.

Based on the morphology, the impact craters are divided into two main groups- i.e. (1) simple crater and (2) complex crater. The characteristics for the simple impact crater include a hemispherical or bowl-shaped depression. The impact craters with down-faulted annular troughs and uplifted central area are called complex craters (Wall, 2008). The general process in both types of impact craters is that they form as the result of gravitational changes during the modification stage of impact crater formation. Most studies on impact craters have been focused on the terrestrial terranes because that is where most impact craters have been discovered. There is limited literature on the main characteristics of the marine impact craters. Crater-like features are found buried at approximately 280 metres below the sea floor in the Orange Basin, within Cretaceous and Cenozoic age marine sediments. The work by de Vera et al. (2010) suggested that the age of the gravity collapse structures for this study area spanned from the Coniacian to the Santonian Epochs. Jungslager (1999) and Paton et al. (2008) on the other hand suggested that gravity collapse systems occurred between the Cenomanian to Maastrichtian Epochs. These deformational periods are both within the Cretaceous and early Cenozoic age marine sediments which is the time where a possible meteorite might have impacted the Orange Basin.

This paper strives to discover the main driving mechanism for the development of these thrust fault developments in the deep-waters of the Orange Basin, being the soft sediment slumping due to gravity tectonics or a probable nearby meteorite impact.

3.1.4 HORIZON PICKING

Having identified these significant stratigraphic surfaces, the next step was to trace them across the survey. Horizon maps of the formation tops were then generated in order to view the structures in three-dimensions. The maps were then gridded to create a complete surface.

3.1.5 GEOLOGICAL INTERPRETATION

For the purposes of this study, the geometrical characteristics of the structures were analyzed through the use of vertical sections, horizontal sections (or time slices), horizon maps and three-dimensional views. Vertical sections, in particular, are adequate to show the geometry of the feature and its position in the subsurface. Time slices can reveal map view geometry but cannot show data referring to a single stratigraphic level (Bacon et al., 2003). For this reason, horizon maps which allowed amplitude changes to be viewed at a single stratigraphic level were used as well.

3.1.6 PROJECT WORKFLOW

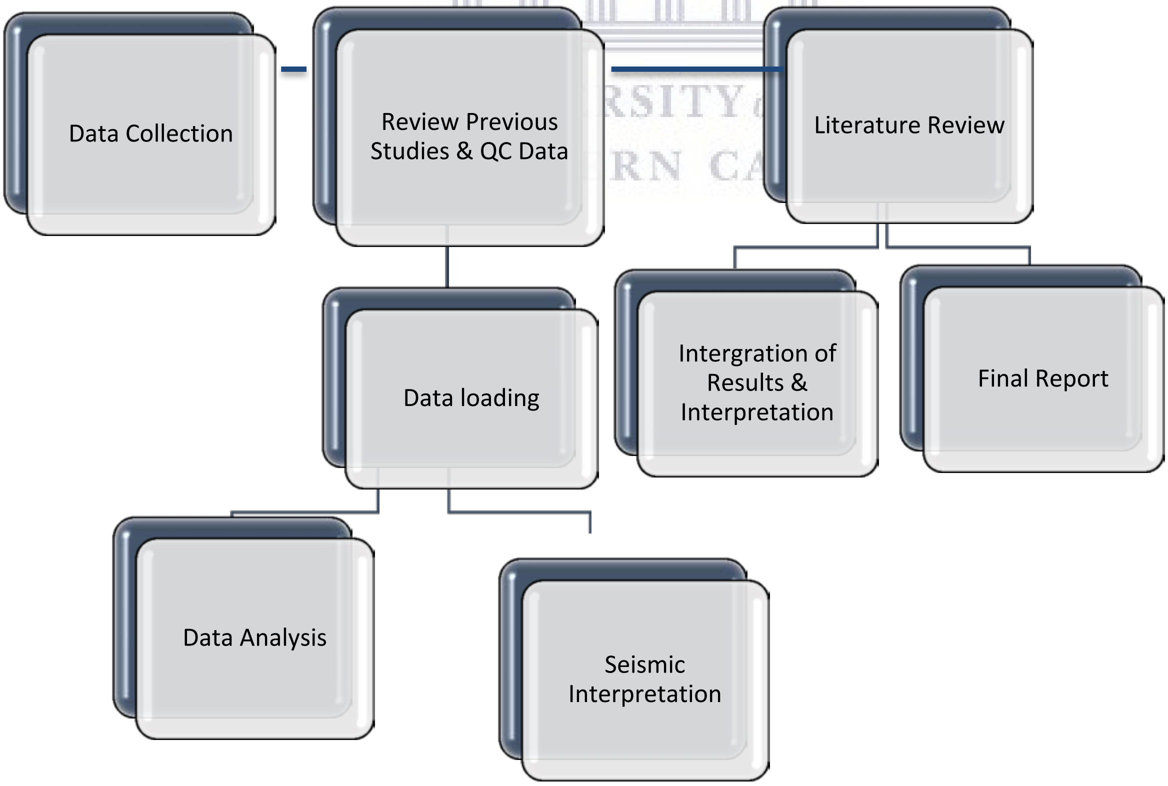

Table 1: Project Workflow chart

3.1.7 SURVEY ACQUISITION

The survey for this study covers 8200 km^2 sparse 3-D seismic data which was acquired in the Orange Basin located along the west coast of South Africa. The survey acquisition and processing information are based on the report by Kramer and Heck (2013) called "Orange Basin 3D™ Pre-processing and PreSDM 2013" courtesy of Shell E&P Company and Dolphin Geophysical. The survey was conducted from the 25th October 2012 to 22nd February 2013 using conventional streamers with sparse geometry. The dataset was acquired along lines running in an approximately North-North-West to South-South-East Orientation. The southern edge is approximately in line with the town of Saldanha Bay (33°S) and the northern edge just south of Kleinzee (30°S). The map projection is UTM zone 33°S, central meridian 15^0 where the survey has an azimuth of 36.6 degrees counter clockwise from the north. The basic paramaters for survey acquisition for the Orange Basin are represented in Table 1.

3.1.8 SEISMIC PROCESSING

The purpose of seismic processing is to augment the interpretable seismic information with respect to noise in the signal. A further purpose is migrating seismic reflectors to their correct spatial locations (Gluyas and Swarbrick, 2004). The 3D data were processed by SIEP-PTI/EP Global Seismic Processing team in Rijswijk, The Netherlands. The processing was done using Shell's in-house software called SIPMAP to provide pre-stack depth migrated data (PreSDM). An improved seismic image for better structural interpretation was provided by PreSDM data for less multiples, less noise and a sharper image, and this was explicitly used below the Aptian unconformity. The original acquisition grid was 6.25m (inline) x 50m (cross line) which was then pre-stack depth migrated resulting in 25m (cross line) by 25m (inline) cell size in the grid. Water velocity profile was obtained to validate the flatness of the water bottom events on the image gathers.

3.1.9 PETREL© WORKFLOW

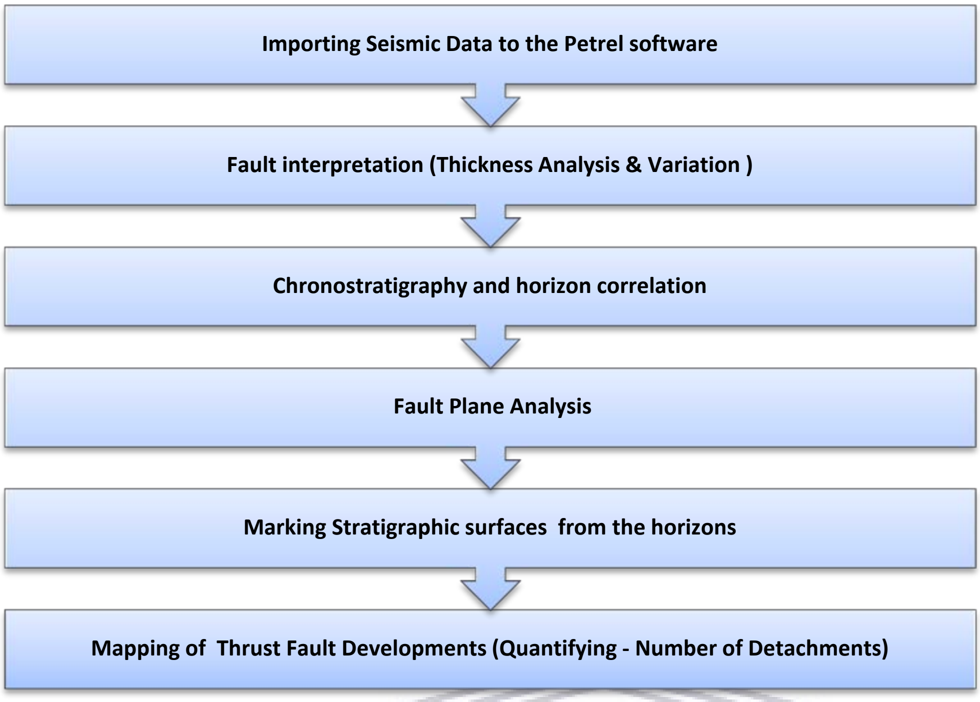

Table 2: Seismic interpretation workflow on Petrel© software

The seismic reflections and structures below the seismic reflector of the break-up unconformity were interpreted to help identify synrift structures such as toe-thrusts, seismic anomalies such as pockmarks, gas chimneys and mud diapirs, seaward dipping reflectors (SDR) and gravity driven features such as syn-sedimentary faults (growth faults) and roll-over anticlines which were reported by Hartwig et al. (2012b) after Bauer et al. (2000). Anomalous seismic features and faults were also mapped for any indication of hydrocarbon seepage features and-processes. The three fault families i.e. listric extensional faults, compressional faults and syn-rift bounding faults were used to help to identify the migration flow paths, determine the seal integrity, and infer the fluid sources and the structural and stratigraphic evolution of the basin. Estimates of the dominant deformational regime can be anticipated. All the seismic interpretations and tectonic features that were mapped on Petrel© will be presented and discussed in Chapter 4 & 5 below.

4 CHAPTER FOUR

4.1 RESULTS

In this chapter, the evolution of the main basal detachment block and associated structures through time is analysed and interpreted. The analysis of seismic data describes the observations made on seismic patterns and structural features to try and understand how the structural mechanisms came about. The analysis of the seismic data in this chapter presents several approaches employed and the outcomes achieved by interpreting the 3-D seismic data. The approach employed in this study to best illustrate the type of thrust sequencing was to identify three sections taken at different locations showing various ranges of shortening.

Furthermore fault morphology, and how these structures break into smaller thrusts during deformation is explored. The study area is flat in the south with little to no deformation; however this changes in the middle of the study area where deformation by thrusting occurs. The main basal detachment block breaks into smaller thrust structures. The main basal detachment block is mapped to illustrate shortening and to quantify how many thrust development occurred in the study area. Does the fault orientation yield any implications on the study area and how does this affect hydrocarbon exploration? Shortening is an indication of deformation of various tectonic regimes that might have impacted the study area. Driving mechanisms such as gravity tectonics, gas escape structures and meteoric impact might answer the question as to how these thrusting sequences came into being. All the results and interpretations were carried out on Petrel© software 2013.

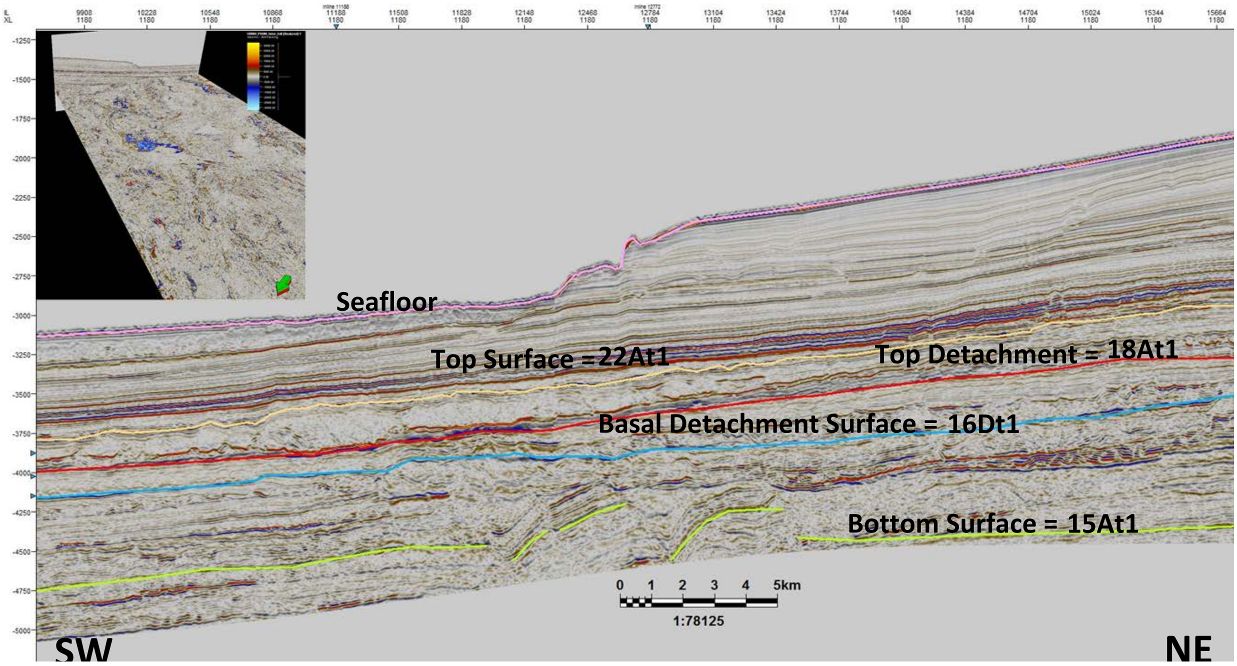

Figure 35: Seismic section of the non-deformed area-southernmost part of the study area. With the Purple line (Seafloor), Top Surface (22At1), Top Detachment (18At1), Basal Detachment (16Dt1) and the Bottom Surface (15At1).

Figure 35 illustrates a seismic section that illustrates an undeformed southern region of the study area. The seismic section is located in the south of the study area of the Orange Basin illustrating seismic facies with little to no deformation. The seismic section is in time.

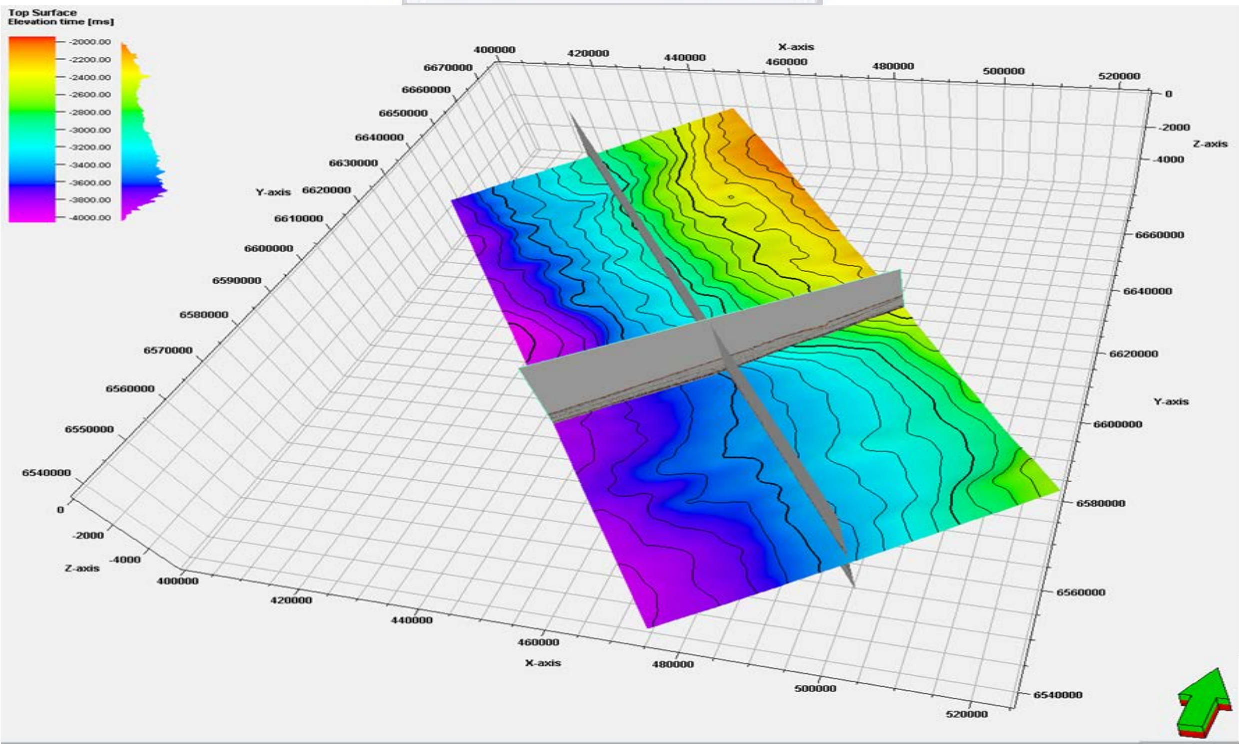

Figure 36: Depiction of the southern part of the study area that is not deformed with inline and crossline forming a nexus at the middle where deformation starts.

Figure 36 depicts the study area with the inline and crossline propagating through it. As stated above, the study area shows an increase in deformation from the south-west to north-east section of the study area.

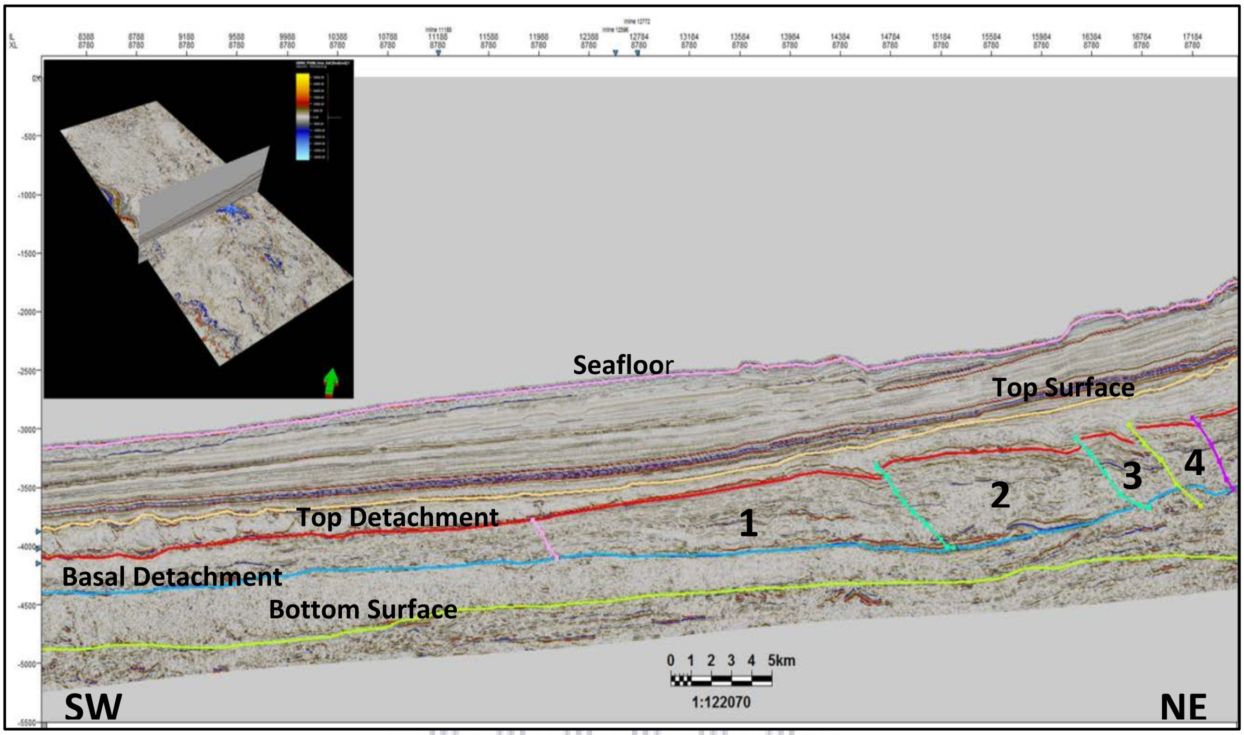

Figure 37: Seismic profile showing all the four main basal detachment blocks that start from the middle of the study area (where deformations begins). (IL-15184 and XL-8780).

Figure 37 illustates a seismic section that depicts the four main basal detachment blocks where thrusting initiated towards the north-east in the study area. Deformation in the study area started from the middle resulting in the number of thrusts in each basal detachment block to break up/shorten into smaller thrust development.

The main basal detachment block 1 is towards the toe of the study area which is towards the deep waters. The basal detachment blocks are located on the contractional domain of the study area where break-back thrust development features are identified. The 3-D data set of this study is mainly on the contractional domain. After presenting the data for the results, the study strives to discuss the illustrations observed and infers findings from examples in the literature.

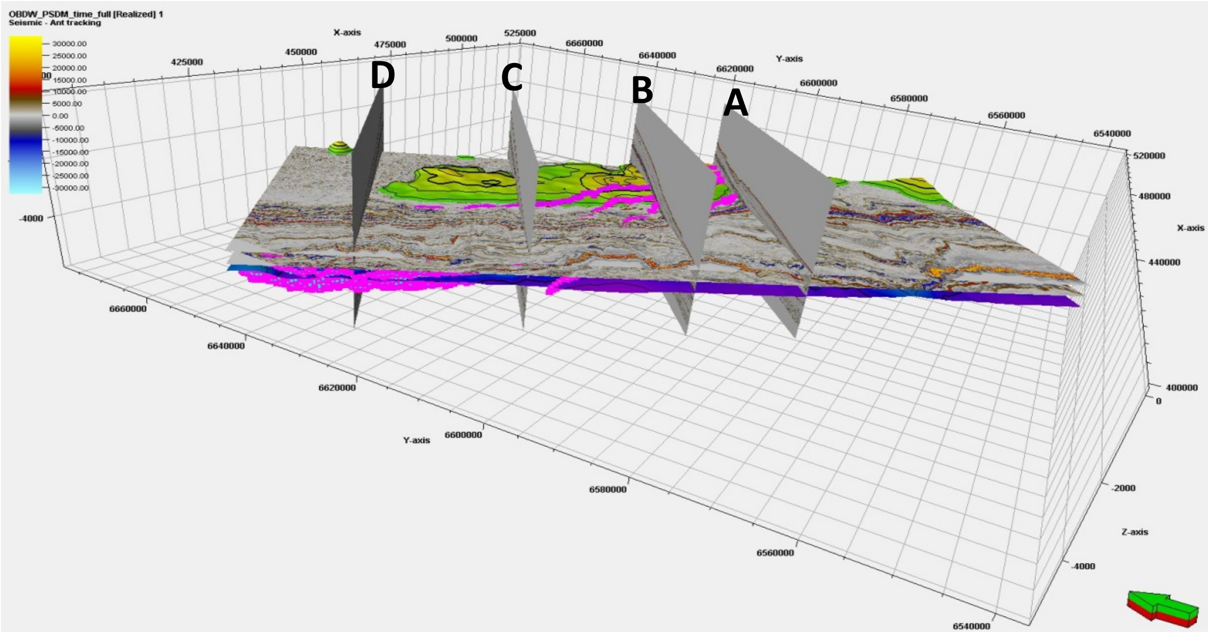

Figure 38: Illustration of the four locations(A,B,C &D) where the sections were chosen from the study area.

Figure 38 illustrates the study area with the four different locations the sections were chosen from, where the amount of thrust sequencing was mapped and quantified as a function of shortening.

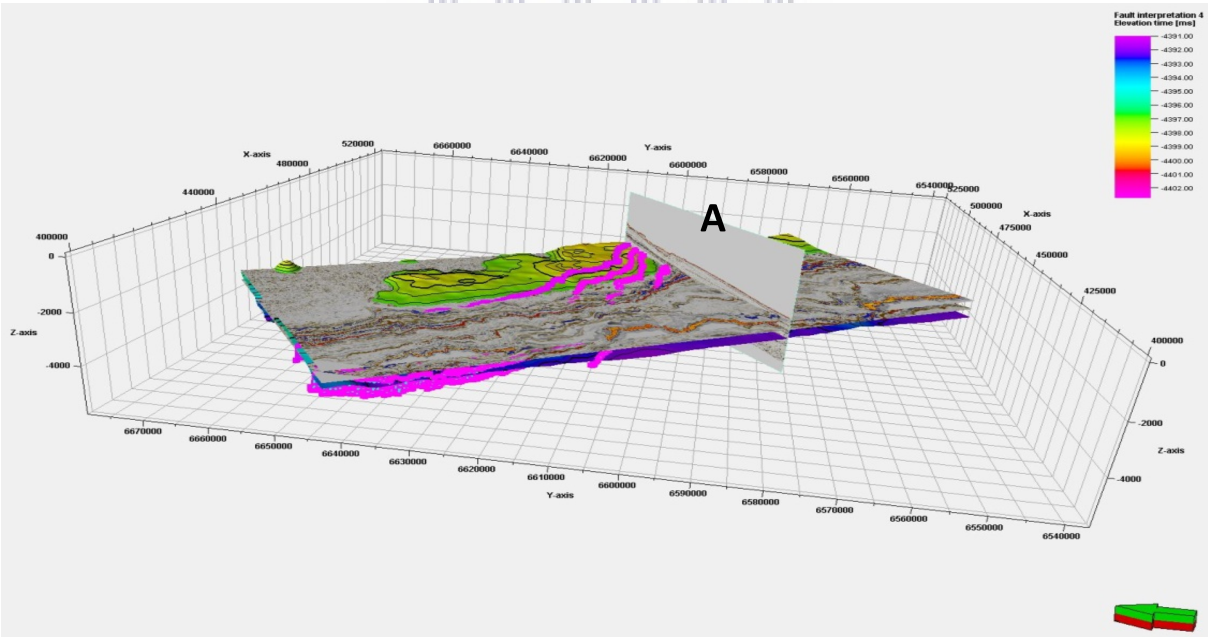

Figure 39: Illustration of location A in the study area.

Figure 39 illustrates location A where the first section was depicted from and the amount of thrust development analysed.

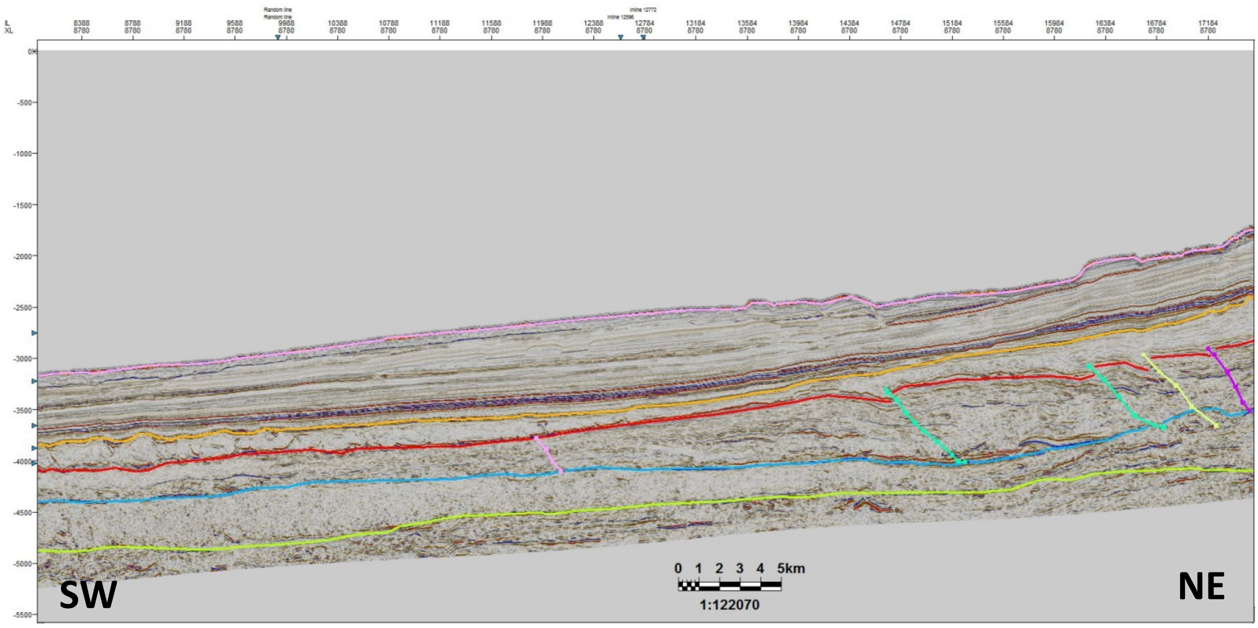

Figure 40: Illustration of the seismic section where thrust sequencing starts at location A.

Figure 40 illustrates the seismic section where the first section is located at A. Thrusting is initiated at this position in the study area and the number of thrust sequences is quantified to indicate the amount of shortening as deformation increases from south-west to north-east in the study area. No amount of shortening is identified at the start of this area.

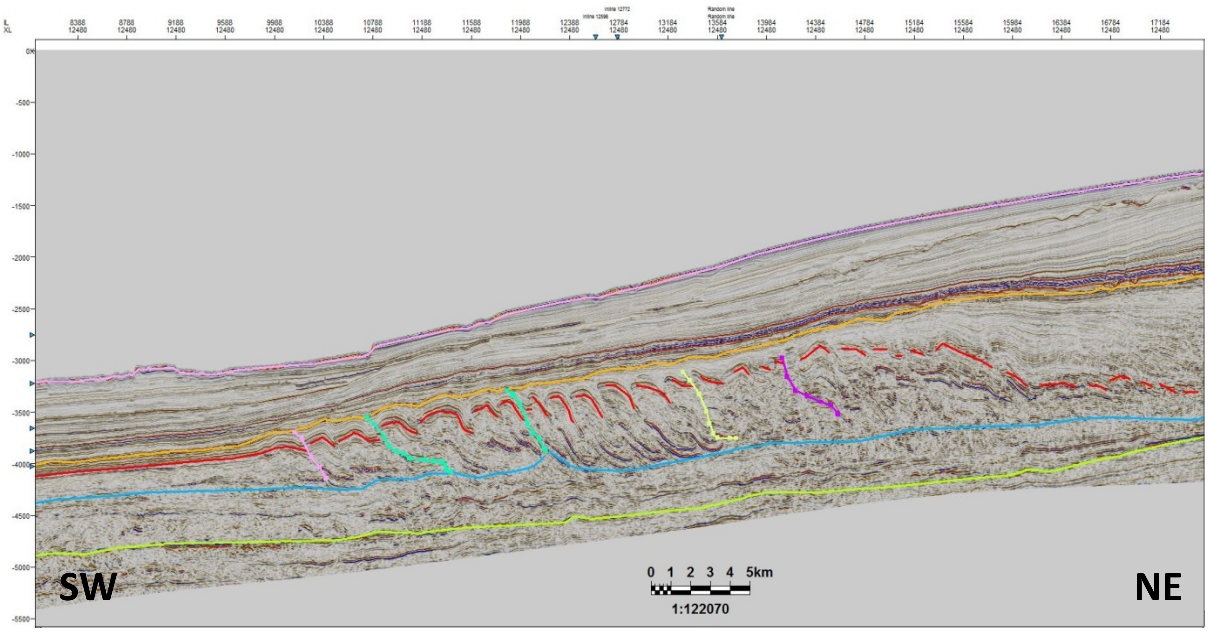

Figure 41: Illustration of thrust sequence development increase as a function of shortening(location A).

Figure 41 illustrates the mapped thrust sequence developments as a function of shortening. Thrust development break basal detachments into multiple thrusts in the section.

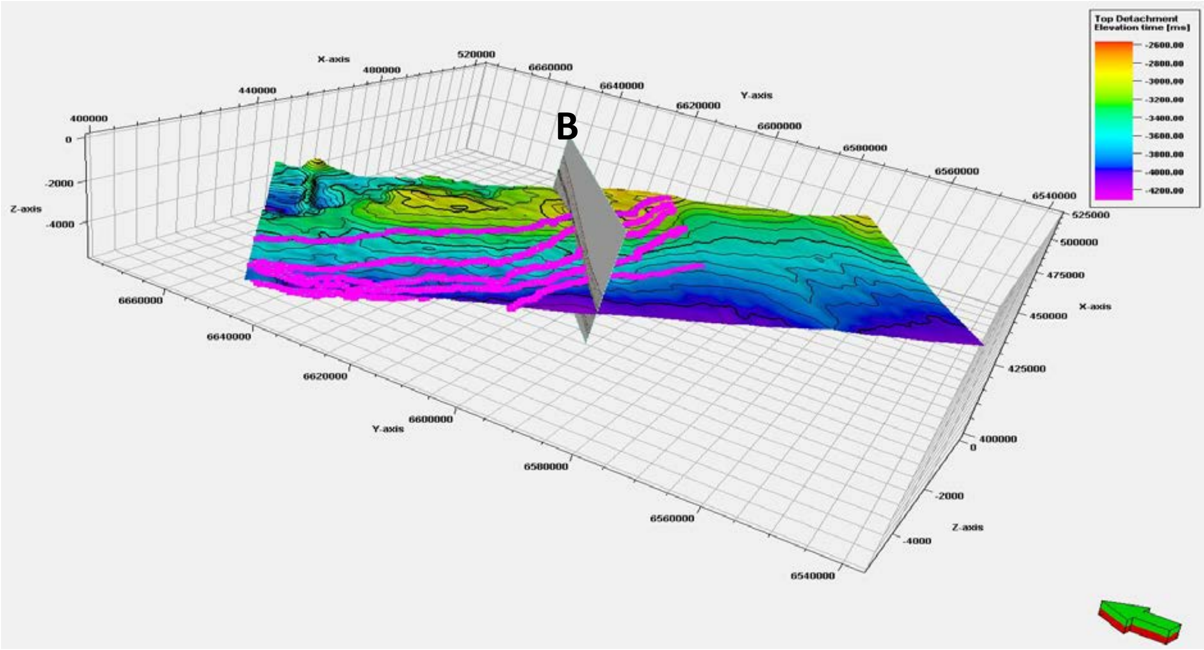

Figure 42: Illustration of location B on the study area.

Figure 42 illustrates the location of B where the seismic section was located, to examine the impact shortening has on thrust sequence development.

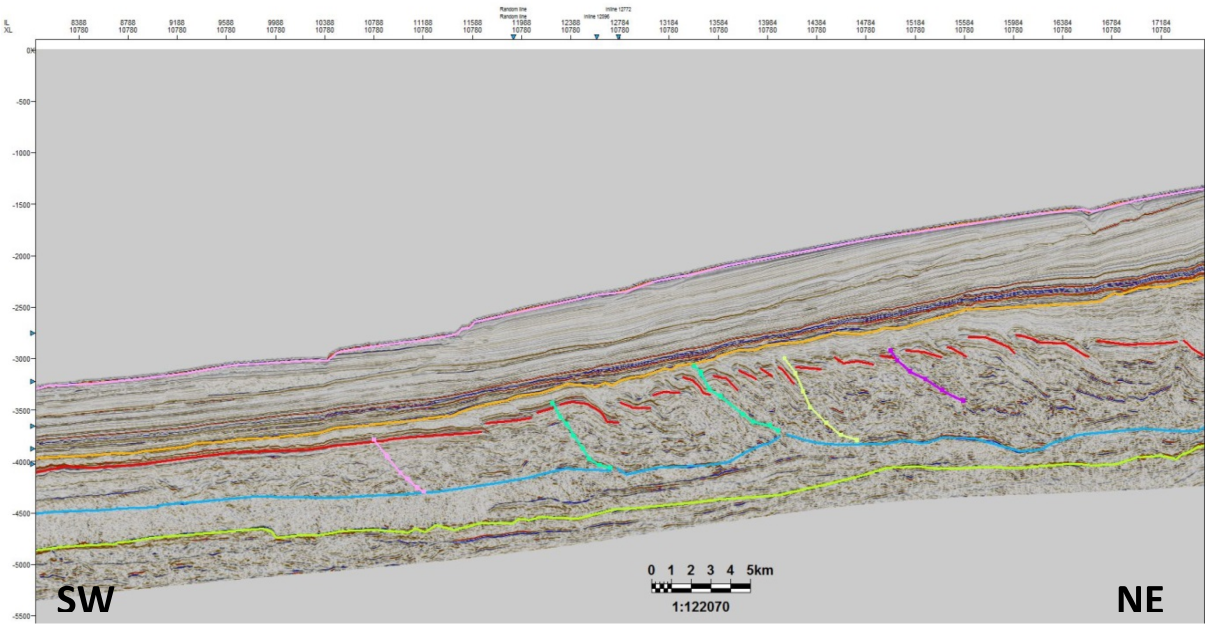

Figure 43: Illustration of seismic section that shows the unfolding of shortening at location B.

Figure 43 illustrates the mapped thrust sequences on seismic section of location B. The thrust development mapped illustrates an increase in thrusts as deformation unfolds. Measuring shortening was a limitation, therefore an increase in thrusts was an indication on shortening.

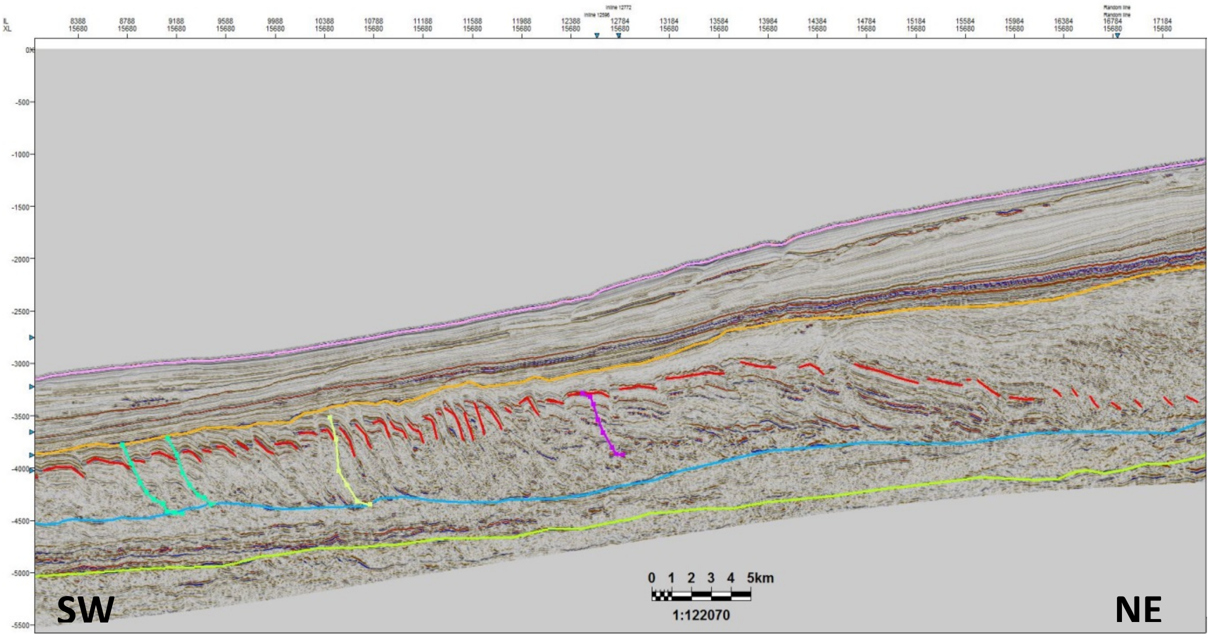

Figure 44: Seismic section of location B as thrusting unfolds towards the north-east from the south-west of the study area.

Figure 44 illustrates the impact shortening has on thrust sequence development in the study area. As thrusting progresses towards the south-west the number of thrusts increases as seen in the seismic section. These features are classified as break-back thrust sequence developments because they tilt backwards as deformation unfolds and they increase in quantity to accommodate more shortening. As stated in literature, Break-back sequence: The sequence of thrusting where new (younger) thrusts nucleate in the hangingwalls of older thrusts and verge in the same direction as the older thrusts (McClay, 1992).

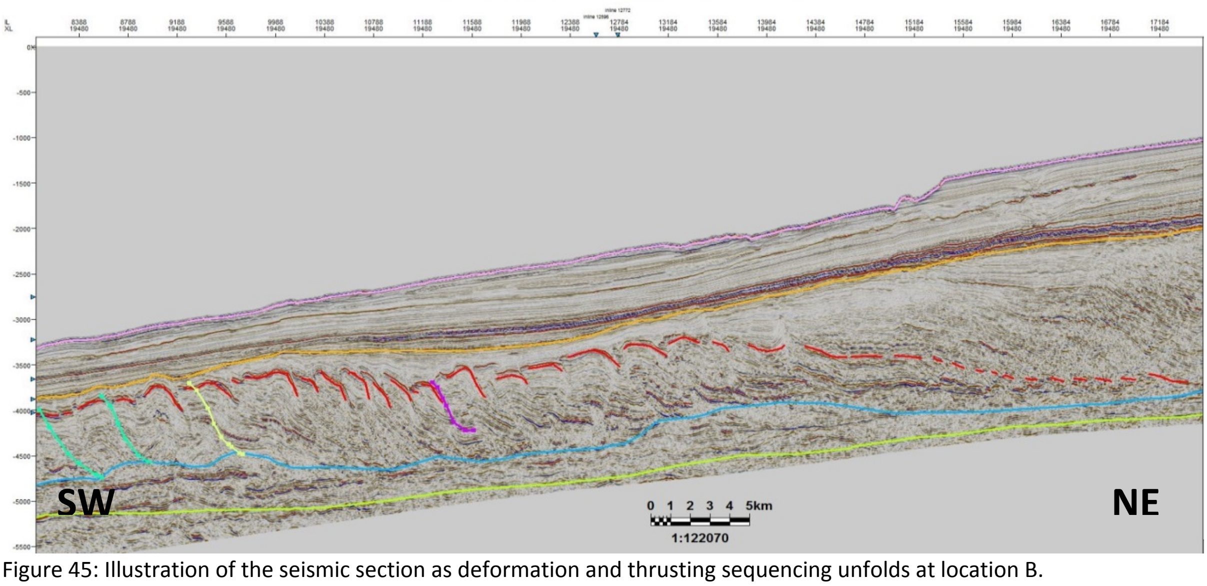

Figure 45: Illustration of the seismic section as deformation and thrusting sequencing unfolds at location B.

Figure 45 illustrates the change in thrusts quantity due to shortening and as deformation increases throughout the study area.

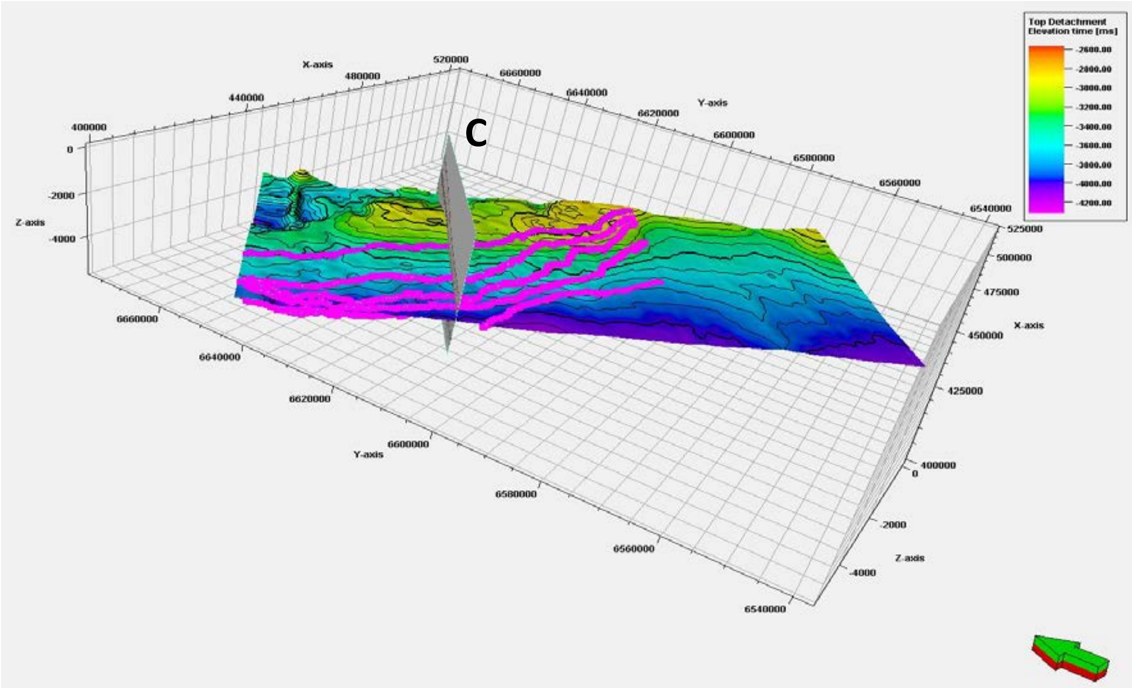

Figure 46: The figure above illustrates location at C where the seismic section was selected to interpret shortening as thrust sequencing unfolds.

We can clearly observe that as deformation propagates from south-west towards the north-east, shortening increases and consequently so does the number of thrust sequences.

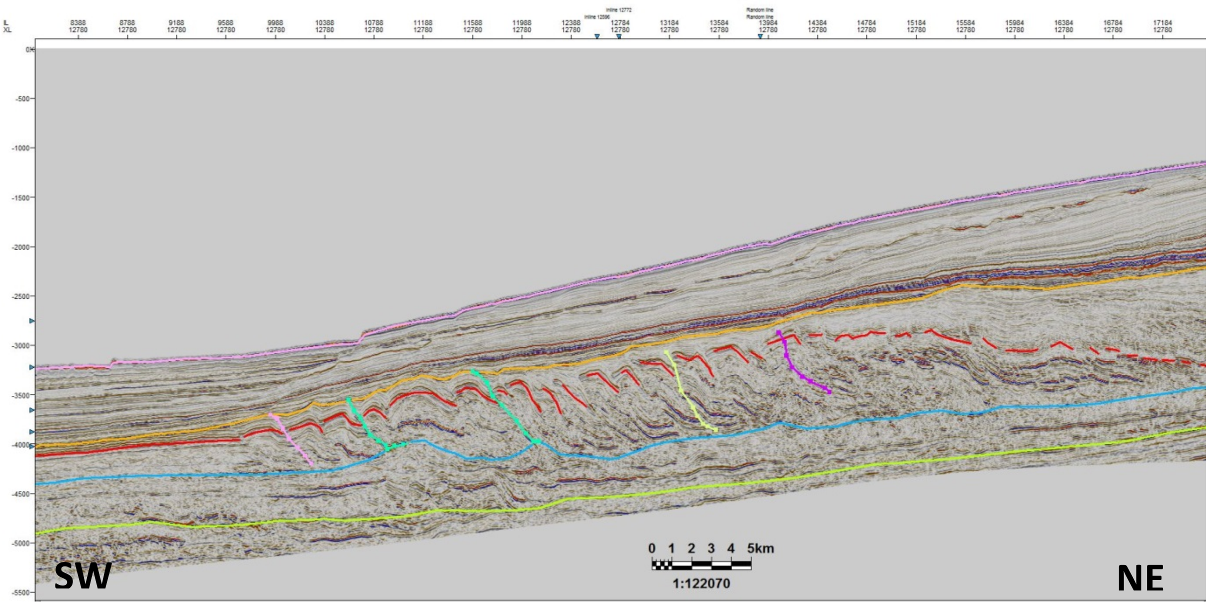

Figure 47: Illustration of deformed basal detachment blocks forming thrust sequences due to shortening at location C.

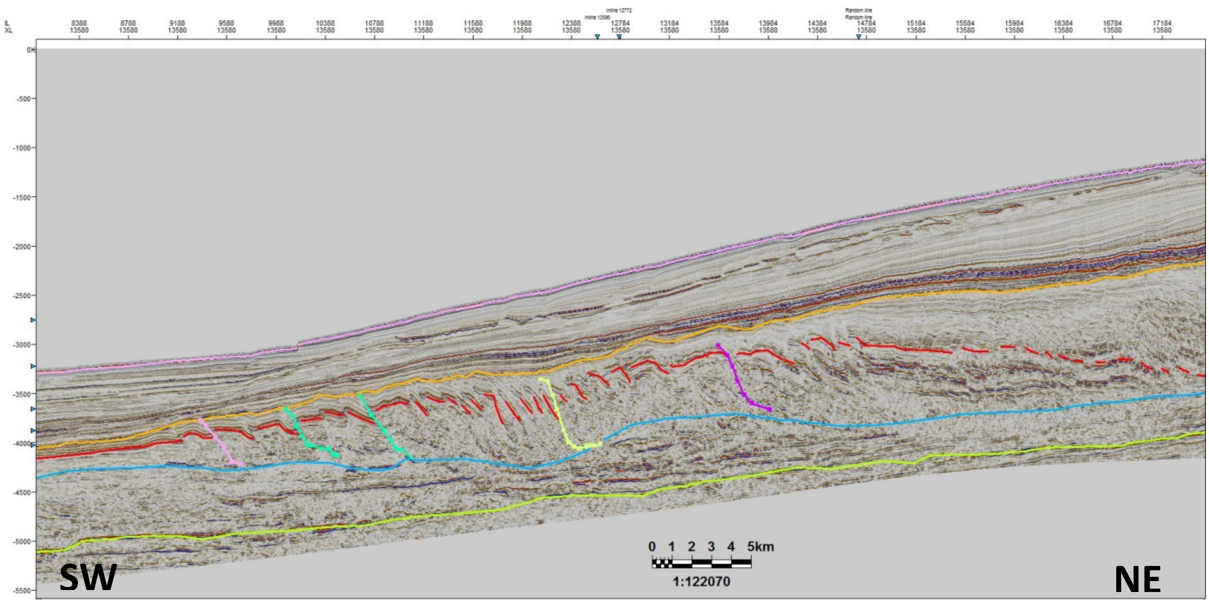

Figure 48: Illustration of mapped thrust sequences, increasing due to shortening at location C.

Moving from section A through to B, C and D, shortening by thrusting is used as a measure for quantifying thrusting. At section A we quantify 6 thrusts, Section B has 8 and with section C having 11 thrusts. It is evident that the number of thrusts increase due to shortening.

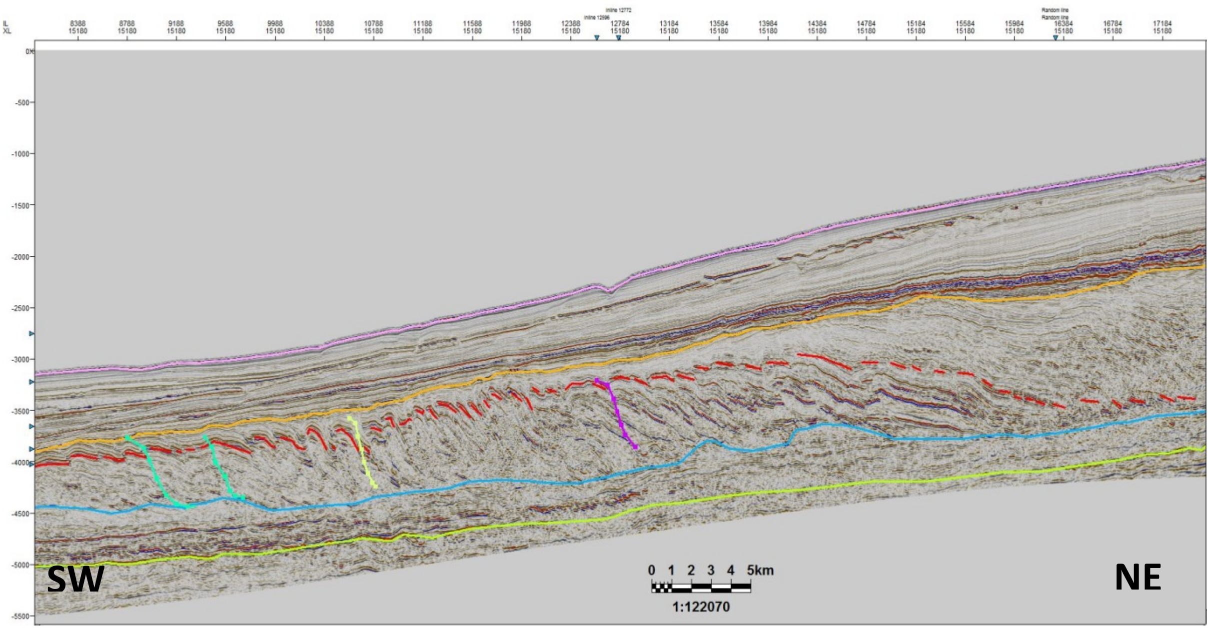

Figure 49: Illustration of thrust developments throughout the study area.

A frequently recognized complexity occurs when a later fault climbs across from the footwall into the hanging wall of an earlier one leading to a breached geometry. This can lead to an overstep geometry where earlier structures are truncated in the footwall of a later fault. The evolution of back-thrusts is considered as identified from section A to D.

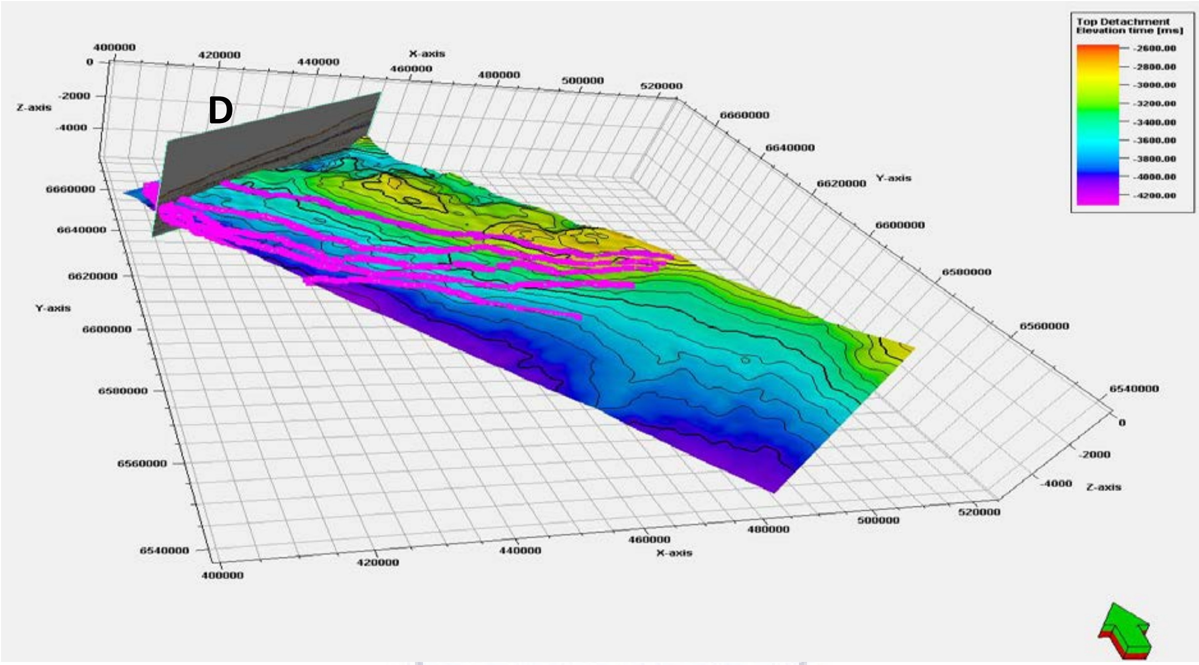

Figure 50: Illustration of the location at D of where the last seicmic section was selected and interpreted towards the toe of the study area at the north.

Figure 50 illustrates the location at D where the last set of thrust sequences were mapped and quantified.

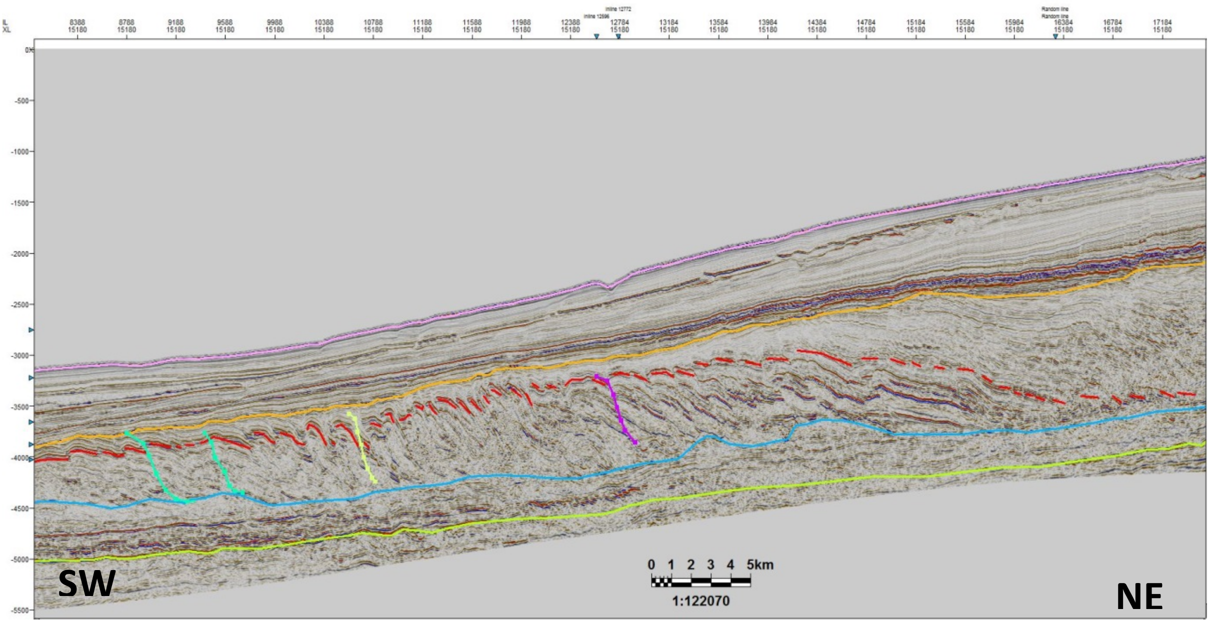

Figure 51: Illustration of the seismic section at location D.

Thrust sequence developments are at the most towards the north of the study area, the thrust sequences have increased to higher quantitities due to shortening. The thrusts at section D reach 13 and further decrease towards the shelf edge.

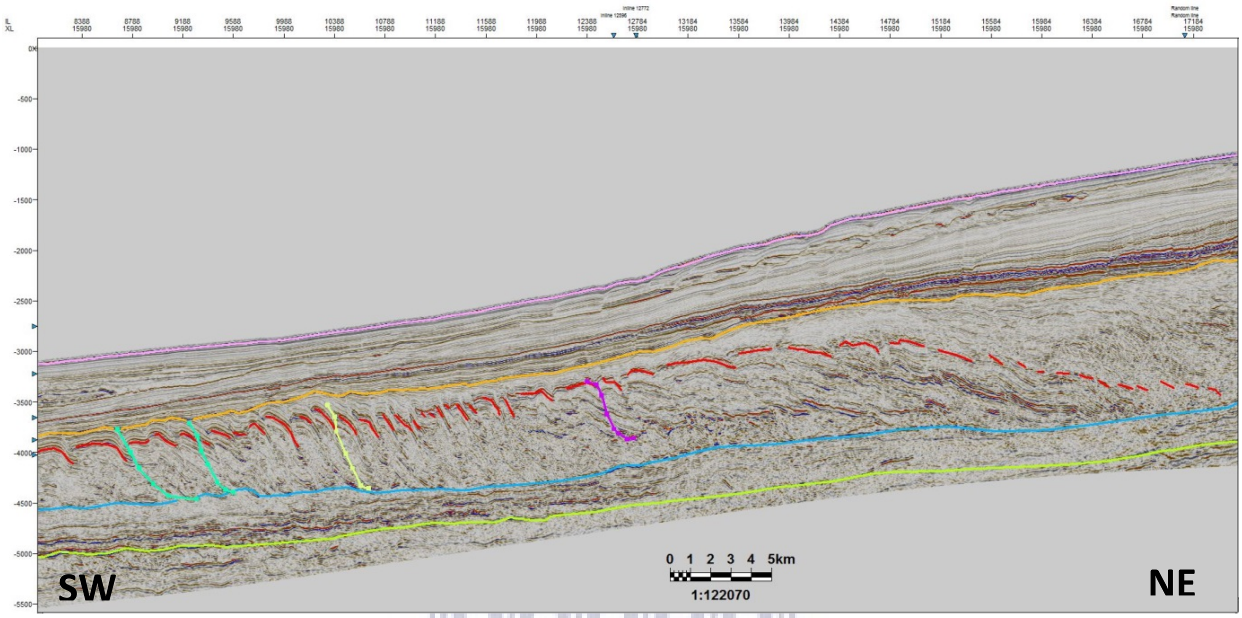

Figure 52: Illustration of increased quantity of thrust sequences at the further most point of the study area.

The Figure 52 above illustrates break-back thrust sequence developments that are of the highest quantity in the study area due to shortening. Deformation towards the north of the study area has resulted in initial basal detachments to break into smaller thrusts that are now of high quantity.

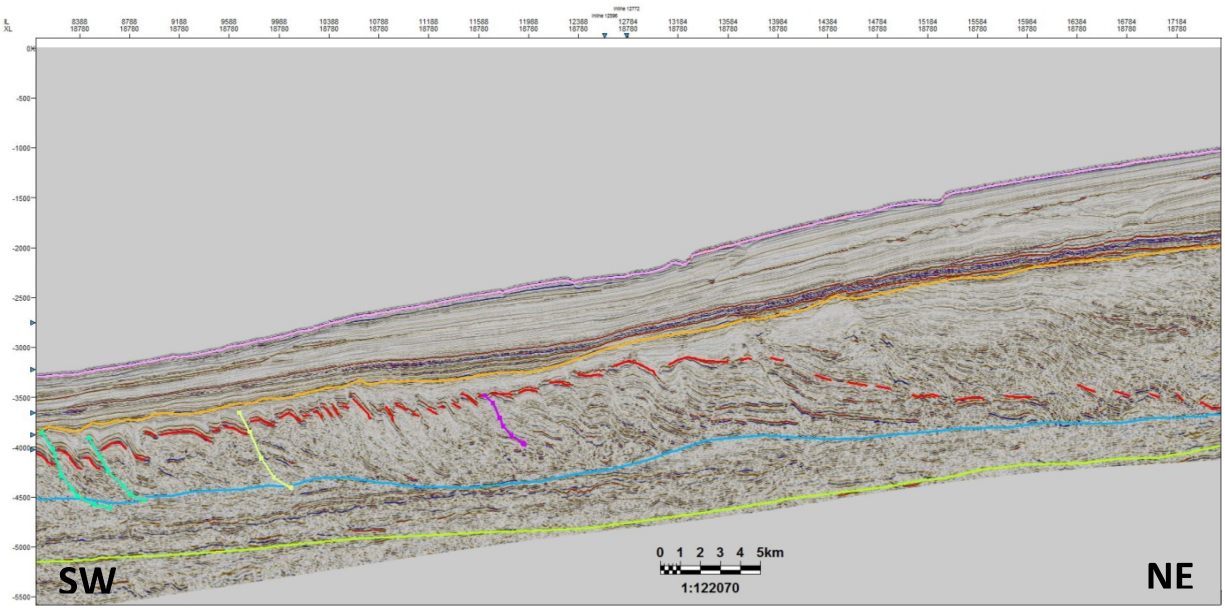

Figure 53: Illustration of the seismic section from the location D in the study area.

The furthest point on the study area is location D and it is illustrated by the seismic section above to have deformed into multiple thrust sequences that have tilted in orientation due to shortening and has increased in quantity aswell. The structural features that are analysed in the above presented results are clasified as break-back thrusts because, the main extensional detachment is the first fault to reactivate, and this is followed by the development of the footwall thrusts. After contractional deformation forward-breaking, hangingwall- vergent back-thrusts develop. The result is a complex development of thrusts that is not simply footwall-nucleating but is governed by the architecure of the pre-existing extensional detachment and by the amount of shortening.

4.2 ISOCHORE MAPS

Isochore maps have been generated between the mapped horizons to interpret structural growth of high and low points of the study area through time and space. Time thickness maps (isochore maps) were extracted to study the basin geometry and topographic relief at different levels of interest. Thickness maps are created from the two seismic surfaces of interest to show the change in thickness throughout the 3D seismic cube. These maps show change in thickness because of topographic contrast which developed as a result of geological events. Since no well and log data are available to perform depth conversions, the thickness maps extracted are in two-way time. (The well and log data provides check-shot data which is important for velocity modelling which is used to perform depth conversion.) Therefore, the thickness discussed in this chapter is a relative thickness represented in two-way time (TWT).

Factors that could affect TWT (among many others) are density and velocity of the material because of poorly consolidated sediments, fluid saturated successions, rock pressure and fluid content (Pandey et al., 2013).Structural uncertainty intrinsic in time is removed through depth conversion to verify the structures from the observed seismic data (Pandey et al., 2013). As stated above, there is no velocity data to perform depth conversion in this research.

Isopach maps have been generated between the mapped horizons to interpret structural growth of high and low points of the study area through time and space. The thickness change between these horizons has been chosen in order to identify the gravity collapse features. High TWT represents an increase in thickness and that there is greater separation between the two seismic horizons. While low TWT represents a lower thickness between the mapped horizons. The change in thickness measured may be a direct result of structural deformation or sedimentological factors such as channel depth, sediment supply, and river velocity. Therefore shortening in intervals is an indication of deformation. Isochore maps thus obtained reveal a thinner sediment package landward of the study area and thicker sediment packages basin-ward due to the removal of sediments during erosion from the landward side of the basin and redeposited deeper in the basin (Jungslager, 1999). The apparent thickness changes between layers and this varies from south to north due to shortening between sedimentary horizons. This results in basin-ward dipping of faults which depict the deep underlying gravity structures that trend sub-parallel to the west coast of Southern Africa (Paton et al., 2008). The thickness change is uniform and progressive.

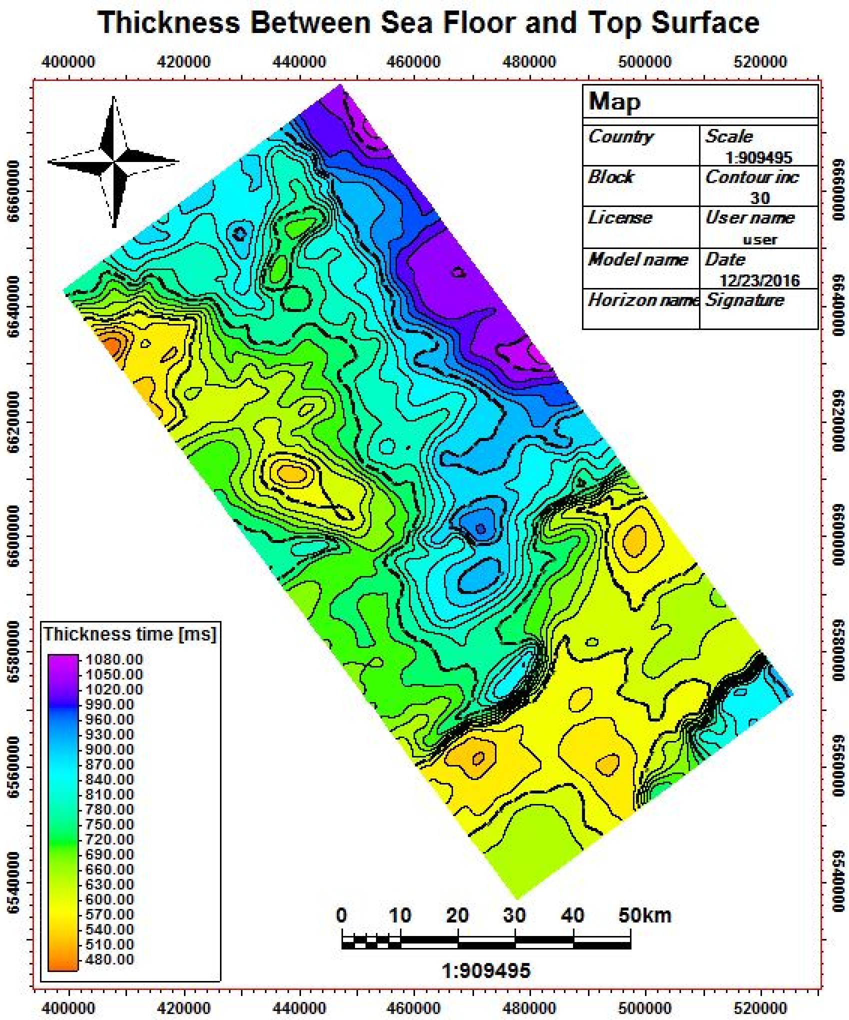

Figure 54: Isochore map displaying thickness between seafloor and top surface.

Surface maps were created in the Petrel© 2013 software package. As stated above, Two Way Time surfaces were not converted to depth because the 3-D data set does not contain well data, therefore could not be calibrated to the stratigraphic tops. Thickness and Isopach maps were generated so as to get the orientation and differences between the unit's base and top. The thickness variations of each unit depend on interactive variables such as the sediment supply, sea level changes and the available accommodation. Figure 54 illustrates the variation in thickness between the seafloor and the top surface. The thickness is measured in time and the thicknesses are indicated by various colours. In the south the thickness is less than in the north leading to interpret that this might be the shelf edge (towards the S). Comparisons between the thickness maps for each seismic unit illustrate the migration of depocentres and the evolution of the sedimentary basin infill through time.

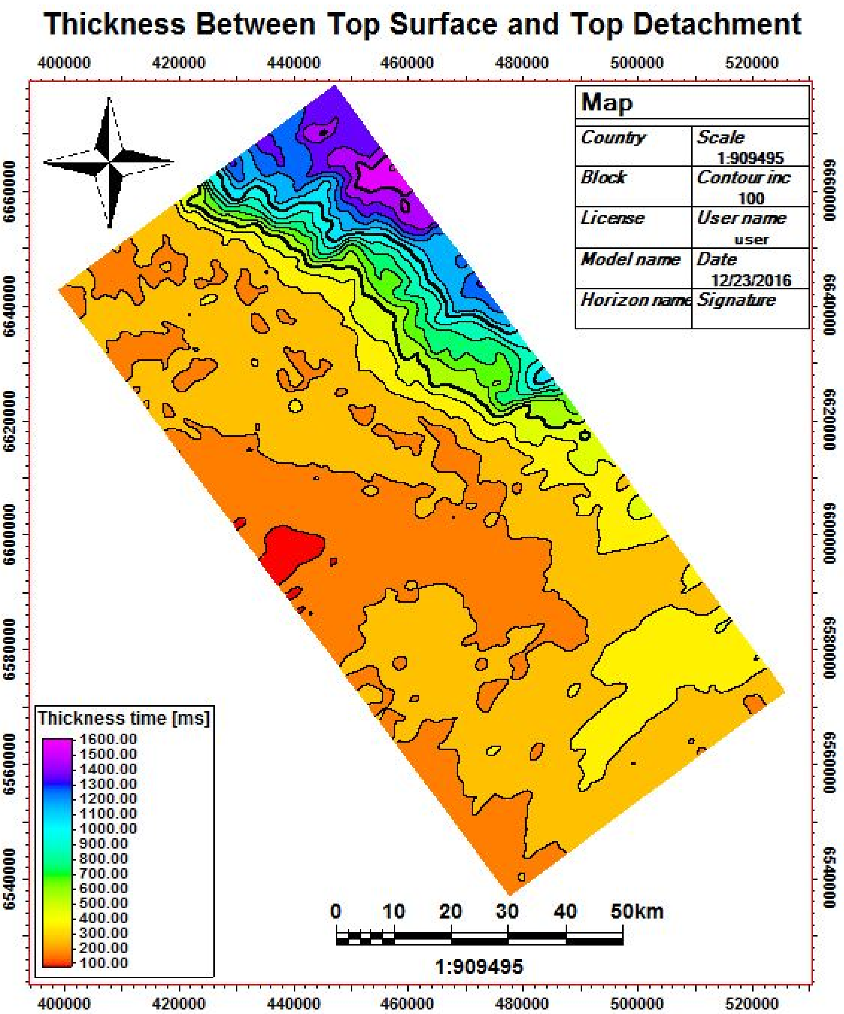

Figure 55: Isochore map showing thickness in two-way-time between top surface and top detachment.

Figure 55 shows the thickness map between the top surface and the top detachment. The thickness between the top surface and the top detachment is thinner in the south and much thicker towards the north-eastern part. The thick part between the top surface and the top detachment might be representing the depo centre, due to increased thrusting observed towards the north. As explained above, these changes in thickness might be driven by the change in stress regimes that occur in the study area. Understanding this phenomenon is very important seeing that it can unravel and better explain why the thrusts in the area change dip and cause a change in thickness as a result of shortening. When stratigraphic layers undergo shortening due to thrusting it results in apparent thickness.

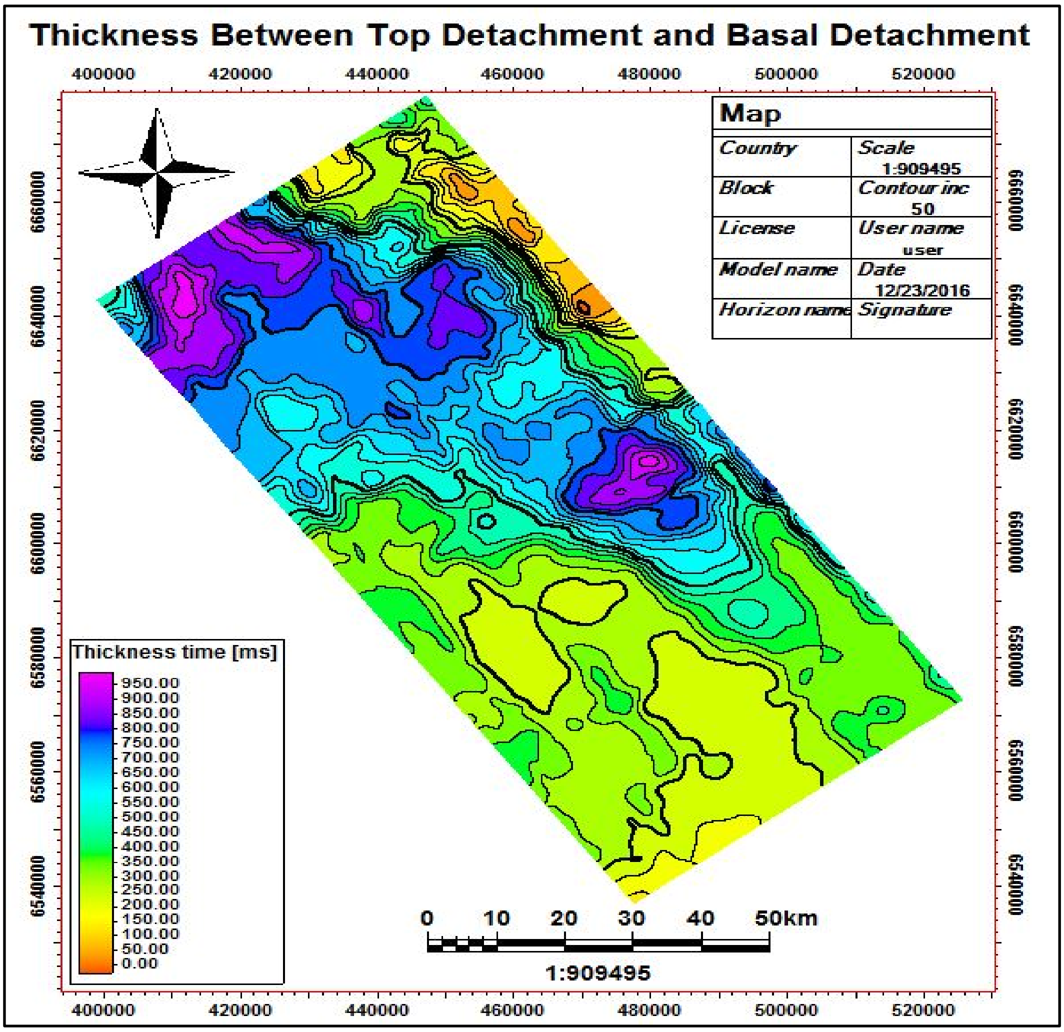

Figure 56: Isochore map displaying thickness between top detachment and basal detachment block surface.

Thickness map between the top detachment surface and basal detachment surface is illustrated above in Figure 56. This thickness map shows how there is variation in thickness from the south to the north, showing some parts to be thicker than others. This shows an inconsistent trend seeing that the south is much thinner and not homogenous compared to the north where it is thick. The thickness variation varies much from middle towards the north where deformation is more intense and may be explained by the observation that the thrusts mapped in this study change dip and hence portray a change in apparent thickness. This map is where the basal detachment blocks are broken down into smaller break-back thrust sequences that might be the reason why the map shows so much variety in thickness.

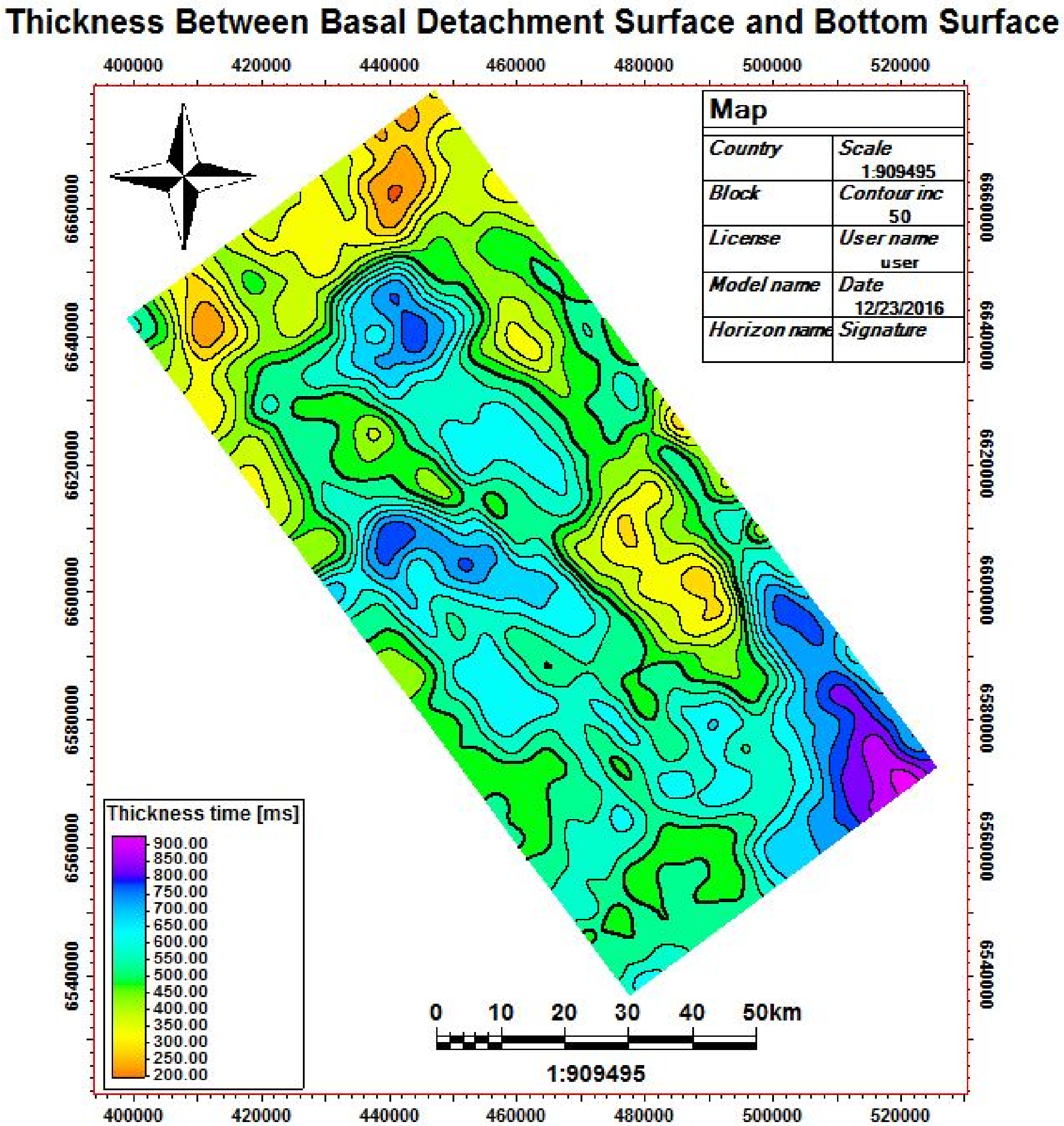

Figure 57: Isochore map displaying thickness between basal detachment block surface and bottom surface.

Figure 57 shows the thickness map between basal detachment bock surface and the bottom surface. Thickness variation in the region is not that much seeing that this surface is the bottom layer and little to no deformation takes place, implying that not much stress impacted the bottom layer.

4.3 STRUCTURE, STRATIGRAPHY AND SEISMIC CHARACTER

For a phenomenon like this to be understood it is vital that there be a clear understanding of the tectonic influence and structures that dominate the area. Stratigraphy also plays a vital role in better understanding the seismic character. Seismic reflections occur as a result of acoustic impedance contrast at the rock boundaries and bedding planes where acoustic impedance is defined by the product between velocity and density (Hartwig et al 2012a).

Stratigraphic boundaries on which seismic energy is reflected are assumed to represent time lines and thus have chronostratigraphic importance. Interpretation is highly depended on the scientist's adequate comprehension of the study area's structural and stratigraphic evolution. An effort by Hartwig to provide a consistent early Cenozoic seismic mapping that is applicable to the entire Orange Basin involved investigating prominent anomalous seismic reflectors and major faults identified in 2-D and 3-D seismic surveys (Hartwig et al 2012a; Hartwig, 2014).

Descriptions of seismic reflection patterns' character and morphology observed within the Cenozoic and upper Cretaceous successions were analysed. Description of the fault morphology throughout different seismic horizons and detailed analyses of the seismic structures were deciphered including their evolution. Relationships between seismic anomalies such as pockmarks on the one hand and structural and stratigraphic framework on the other hand were documented.

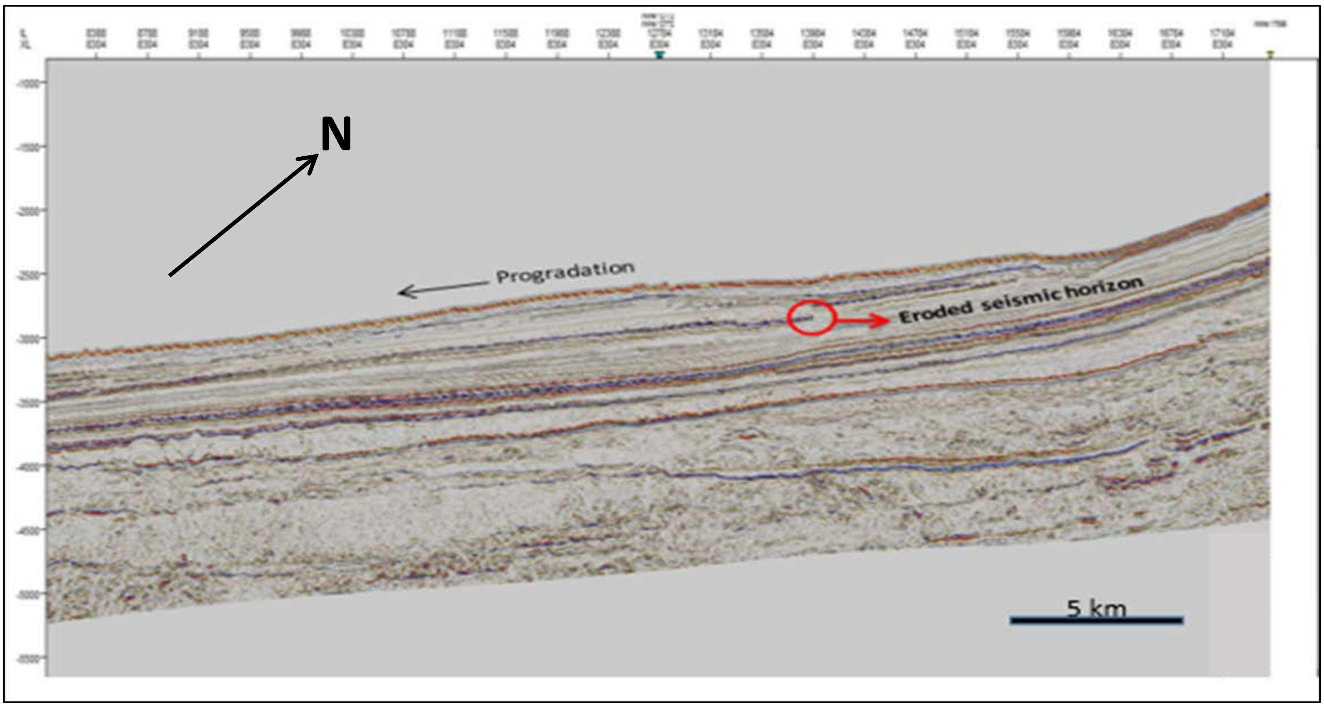

Figure 58: Example of erosional effects in the Tertiary sequence.

Erosional events which have thinned the stratigraphic and structural morphology of the Orange Basin are evident in the above image. Erosional events like this one are evidence of the frequency of sea level change as well as the extent of the drop in sea level. The Cenozoic depositional sequence in the Orange Basin is relatively thin, consequently there are very small seismic sedimentary packages separated by unconformities. This resulted in the depositional history being lost due to the multitude of erosional events affecting these thin sequence boundaries.

4.4 SEISMIC ANOMALIES

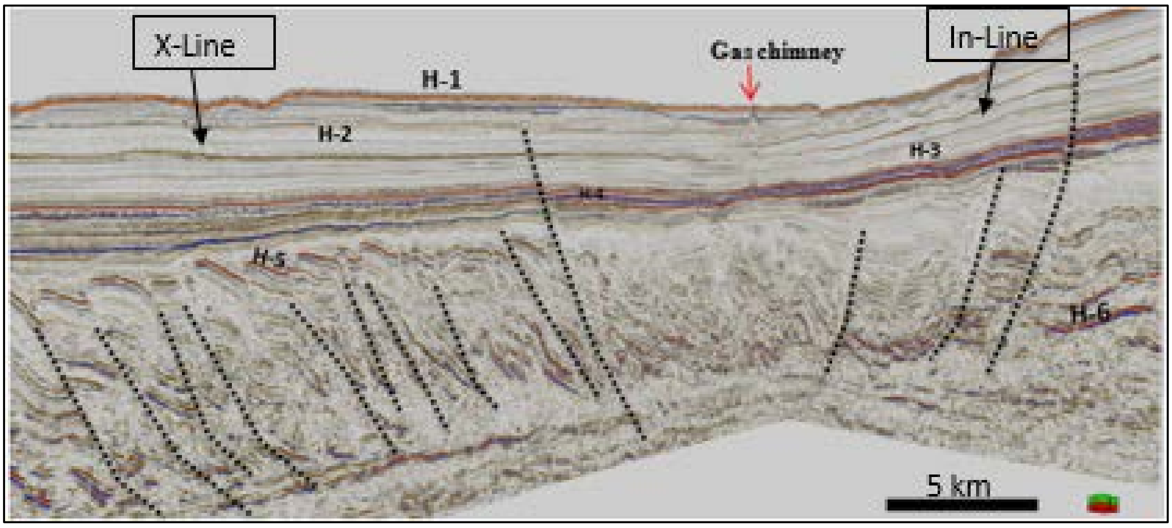

Figure 59: Gas Chimney in both the X-line and Inline.

The seismic image of the study area shows an anomaly that looks like a gas escape structure. Several of these structures have been observed on the seismic data set that was analysed for this study, especially the surrounding area that is just towards the extensional domain hosts a lot of these gases escape structures. This is a cause for concern because there might be a relationship between these structures and the driving mechanism that formed the thrusts seen in this study area. It becomes difficult to reason what was the main reason behind the phenomenon that gave rise to the thrusts that were quantified in this study. There seems to be many schools of thought that suggest a lot of possibilities to the initiation of the break-back thrusts: gravity tectonics (De Vera et al., 2010), gas seepage (Hartwig, 2014), and a meteoric impact (Wall, 2008), mud volcanoes (Hartwig et al., 2012b) to name but a few. We looked at most possible reasons behind the onset of this tectonically rare phenomenon.

The occurrence of gas escape structures in sedimentary basins can be identified on many seafloor features also including mud volcanoes (Milkov 2000), mounds (Hovland & Thomsen., 1997; Naeth et al., 2005), and pockmarks (i.e. Hovland & Judd., 1998; King & MacLean., 1970; Pilcher and Argent, 2007). Natural gas leakage associated with seafloor mounds can be identified by topographically well-defined build-up of organic mounds or mounds formed by inorganic accumulation of mud (Riding 2002). Free gas can be easily identified on seismic data as free gas reduces the acoustic impedance, thereby creating blanking, pull-down of seismic reflections and enhanced reflections such as bright and flat spots (Ben-Avraham et al., 2002).

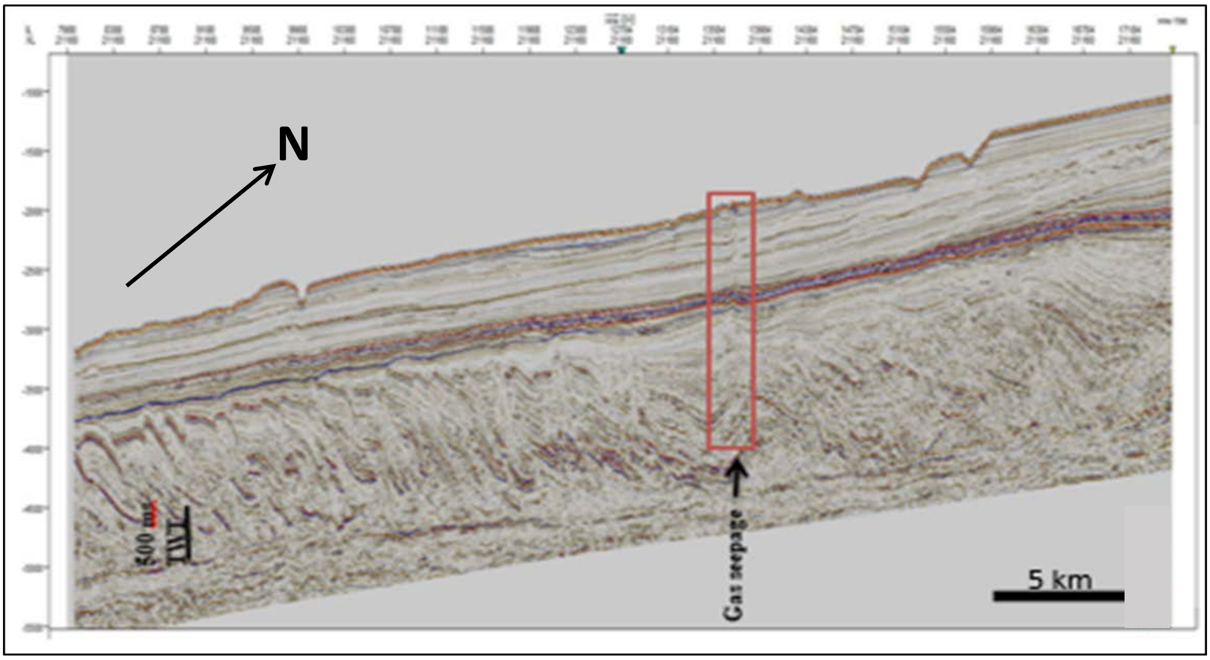

Figure 60: Gas seepage propagating through the sediments up to the seafloor.

The gas chimney penetrates the entire seismic section with its effect mentioned above reaching the sea floor which displays an excess of convex- structures. The seismic record shows significant distortion towards the bottom; this distortion is driven by gravity processes which re-orient and disarrange the sedimentary layers, thus forming a pile of highly faulted sedimentary packages.

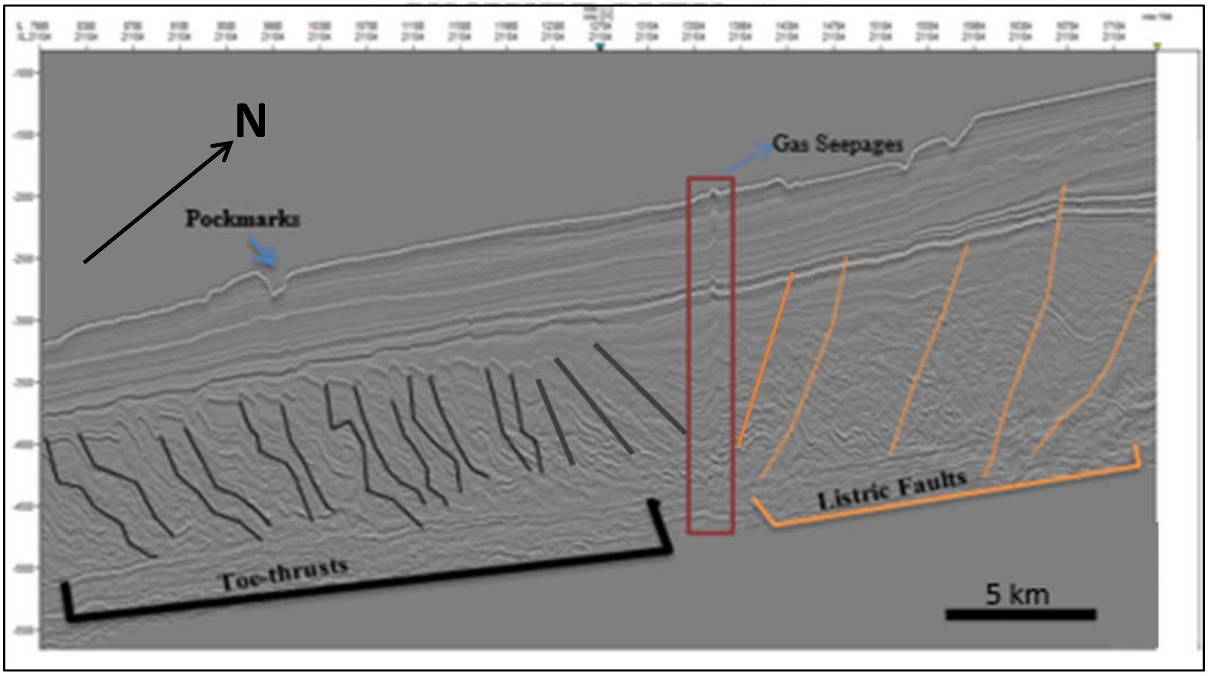

Figure 61: Xline 21104 illustrates the extent of hydrocarbons escape (gas in this instance) as it permeates through different seismic horizons.

Figure 61 presents a grey and black seismic display which shows the most distinct as well as deformational structures as interpreted on Petrel© software. Large depressions observed on the seafloor surface have also been linked to gas escape (Hovland & Judd., 1998; Pilcher and Argent, 2007). These depressions are known as pockmarks and they were first reported on the Scotland Shelf by King and MacLean (1970). Pilcher & Argent (2007) showed that the distribution of the pockmarks is controlled by fluid migration pathways in shallow sediments. The pockmarks normally align with and follow the strike of a subsurface fault. The seismic section shows that the sequence has significantly been truncated by incipient and syn-sedimentary faults which form gravity collapse growth structures. The occurrence of toe-thrusts which have the NW-SE orientation (on the left side of the image) and the listric faults (on the right side of the image) which converge on the gas-chimneys is proof that the gravitational tectonic regime is multifaceted with different structures. The fact that the gas escape indicates that a zone of weakness exists which could be an indication of an extensional regime which opens seals and traps of supposedly trapped hydrocarbons. The movement of such buoyant fluids promotes the formation of hollow-like structures called pockmarks. This may be due to faulting in this particular area. The present-day seafloor fluid escape features in the Orange Basin are marked by a series of seafloor depressions with diameters and depths which range from 75 m to 495 m and 3.6-36 ms TWT (5-2 m) respectively. These hemispherical features are clearly depicted in Figure 54. Figure 54 emphasizes the number of convex hemispherical features that have been promoted by the faults which have provided pathways for gas to permeate and penetrate the seafloor, thus forming pockmarks.

There are two types of seepage structures whose end-members are “active” and “passive” (Abrams 1996). “Active” seepage activity is when there is an ongoing leakage of hydrocarbons in large concentrations within and above the surface sediments. “Passive” seepage activity is when there is low leakage of hydrocarbons from the subsurface to near surface sediments. Research on mud volcanoes is important for petroleum exploration because they indicate evidence of high petroleum potential in the deep sub-surface. Mud volcanoes are topographical features with sub-circular structures up to several kilometres in diameter, elevated above the surrounding seafloor, formed from emission of argillaceous material (Ben-Avraham et al., 2002; Viola et al., 2005). The overflowing mass of mud in mud volcanoes on the surface comprises of a fluid mixture that is methane-enriched mud and mud-breccia (Hartwig, 2014). Mud volcanoes most probably originate in areas with high sedimentation rates of fine-grained sediments, which rise as fluidized mud along faults and fractures, or as a result of rapid overloading of mass mud on the surface due to rapid sedimentation, accretion or over-thrusting (Milkov, 2002) .The driving force that makes fluid rise up to the surface is associated with high pore-fluid pressures that exceed the internal forces or lithostatic pressure (Milkov, 2002).

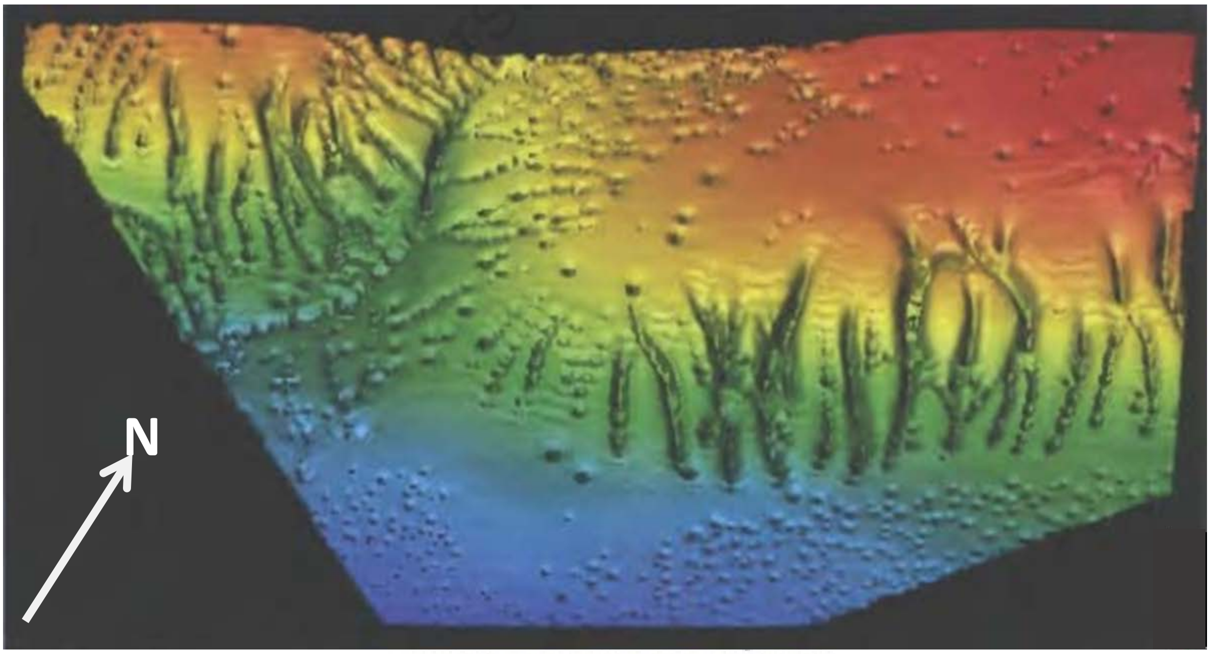

Figure 62: Random and aligned pockmarks on the seafloor, offshore Gabon in water depths ranging from 540m to 1860m over a scale of 5 km (blue colour indicate deep water, red colour indicates shallower) (from Pilcher & Argent,2007).

Gas venting may not always reach the seafloor. Gas migration can be halted by impermeable stratigraphic sequences ("seal") or buried by mass movement deposits as gravity slides (Kaluza & Doyle., 1996). Subsea mounds may also form a bulge in the overlying topography if the fluids continue to accumulate under the seal. This calls for a clear review of the petroleum system, so as to recommend if this region could ever reach production phase for the data presented is used for exploration.

5 CHAPTER FIVE

5.1 DISCUSSION

In this study we seek to understand the origin of tectonic structures mapped on four different locations of the study area, where seismic sections were extracted and interpreted by mapping break-back sequence development. Various authors have proposed different explanations for the features observed as discussed in the literature review. McClay's (1992) glossary of thrust tectonic terms is a 'biblical' terminological reference for thrust development interpreted in this study. Much reference is made on McClay's (1992) review as documented in the literature review. The development of thrusting where new (younger) thrusts nucleate in the hangingwalls of older thrusts and verge in the same direction as the older thrusts were identified and therefore leading us to classify the features in this study as break-back thrusts.

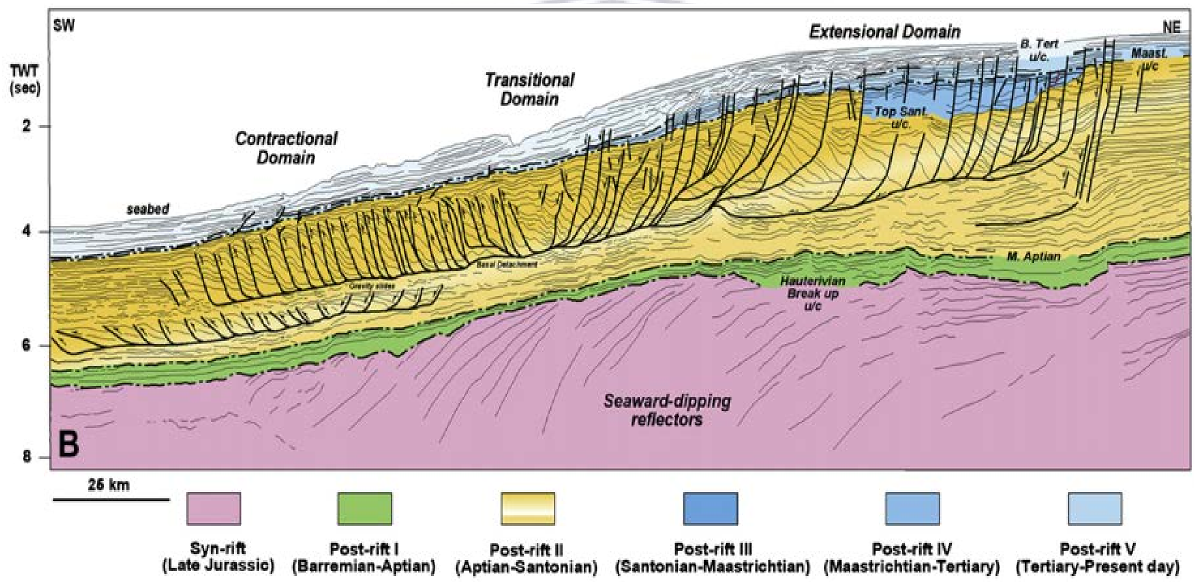

Figure 63: Megasequences and the Late Cretaceous gravity-driven slide system (after Granado et al., 2009).

Figure 63 is a second representation of the same interpretation as in Figure 34 in the literature review section. This interpretation is a reminder of how a gravity-driven system can be divided into three distinct structural domains, based on the across strike variations in structural style (Fig.63). From northeast to southwest these are: an up-dip extensional domain characterized by basin-ward dipping listric faults, a transitional domain with both contractional and extensional features, and a down-dip contractional domain that consists of landward-dipping thrust faults and associated thrust fault-related folds (Rowan et al., 2004) (Fig.63).

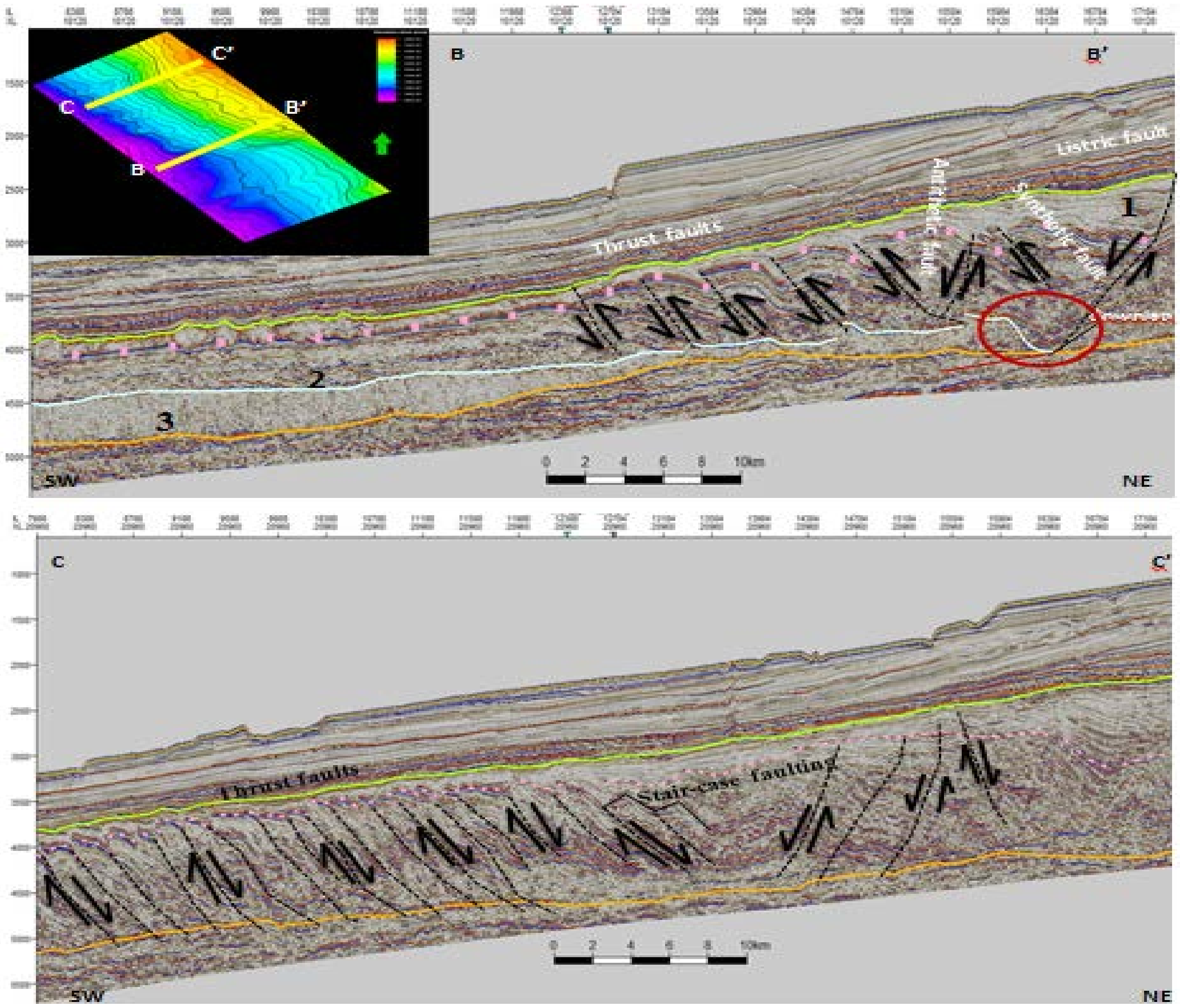

Figure 64: The cross section B-B' displays the start of thrust faults while C-C' has the generational listric faults which are counter directional to the thrust faults.

The thrust faulting creates discontinuities along the interpreted seismic horizons which becomes chaotic as the deformation intensifies. Thrusted seismic horizons are constrained between horizons. Figure 64 shows that deformation starts with three thrust faults (cross section B-B') and increases to eight thrust faults or horses (cross section C-C'). The thrust faults are initiated in the southeast and progressively increase in number towards the north. The number of thrust faults increase laterally forming many horse structures. These horses represent westward verging, rotated and landward dipping thrust faults in deep and shallow regions of the study area.

The listric faults continue parallel along the bottom orange horizon (Fig.64). The transition zone from extensional to compressional faulting shows fault-fold propagation with a wavy reflection pattern indicating an onset of thrust faults (Fig.64, C-C’). The integration between normal and thrust faults forms imbricate structures (cross section B-B’). The average horizontal separation distance from one thrust to the next is ~500m.

Jungslager et al. (1999) suggested that the tectonic processes in the north of the basin initiated rifting which was later followed by flexure subsidence of the shelf and slope which were gravity controlled. Hence, deltaic failure caused by margin uplift was greater in the north as compared to the southern side of the Study area.

5.2 Development of deformation in the study area

The results from the interpreted seismic sections that are used to clarify the implication of the prominent seismic horizons and major faults are presented in chapter four. Despite a significant amount of research in this area there is still confusion on the relationships between gravity-induced structures, the thickness change and development of deformation in the study area.

Isochore maps revealed thinner sediment packages landward of the study area. This thickness difference is the result of the removal of sediments during erosion from the landward side of the basin and redeposition deeper in the basin (Jungslager, 1999). The thickness maps which have been extracted pertaining to the Study area show an increase in apparent thickness towards the north where there is a large number of thrust faults or horse structures. This thicker seismic facies resulted from basin-ward orientation of faults depicting deep underlying grabens and horst structures that trend sub-parallel to the west coast of South Africa (Paton et al., 2008).

Southern areas are partially preserved due to significant slow sedimentation rates and slope processes. The isochore maps show that the main depocentre (indicated by thickening seismic facies) is located in the north western part of the Study area. Steepening and thickening of seismic facies suggests either an increase in sedimentary supply or a stacking of sedimentary layers due to the development of gravity induced faults. Deeper waters created turbidites, channels and associated channel-levee systems due to rapid slope processes and high sedimentation rates which might have resulted in the geometric architecture of the Orange Basin (Kuhlmann et al., 2010).

According to Kuhlmann et al., (2010) the tectonic stress which initiated the opening of the Atlantic Ocean during Gondwana break-up started in the northern side of the area of study and moved the towards the south. The opening or extension of the basin was followed by margin uplift which created a north-east stress field causing gravitational potential energy contrasts which contributed to the development of the observed faulting system.

5.3 The stress and strain distribution in the Orange Basin

Butler and Paton (2010) and de Vera et al. (2010) discovered that there is a mismatch between the minimum estimate of extension (44 km) and slip on thrusts (18–25 km). This mismatch or lack of balance was discovered during structural restorations of the main gravity collapse system between down-dip shortening and up-dip extension. A longitudinal strain component of 18–25 percent is required to compensate for the lack of balance distributed across the system, most reasonably as the result of lateral compaction and volume loss (Butler and Paton, 2010).

According to Granado et al. (2009) lack of balance between structural shortening (16 km) and extension (44 km) can be explained by layer parallel shortening accompanied by volume loss in the thrust belt, and inconsistencies between the acquisition of seismic data, the direction of tectonic movement and location of the seismic line. Widely distributed ductile deformation and substantial amount of the slip required to balance the extensional displacements higher on the slope with compressional displacements on the bottom of the slope must be accommodated by probably volume loss and lateral compaction. This lateral compaction and volume loss presumably predated the localization of thrusts (Butler and Paton, 2010). This is because significant amount of extension has to occur first before any compression can be detected from the seismic data. Lateral strain component external to the deformational system is required to contribute (if not initiated) to the lateral translation during extension. So the deformational features in this study which were proposed to be purely caused by geological processes may have not been the only factor that contributed to the origins of the gravitational tectonics of the Orange Basin.

5.4 The Origins of the gravity collapse systems of the Orange Basin

Even though the controlling factors influencing the gravity collapse structures are poorly understood, the examination of development of deformation from north to south in the

Study area shows that gravity collapse structures are controlled by many factors. Understanding the origins of the gravity collapse systems requires the deep understanding of the following:

1) Passive margin uplift and thermal subsidence

2) Meteorite impact in the Orange Basin

3) Slump sediment deformation

5.5 Passive margin uplift and thermal subsidence

The models by McKenzie (1978) and Wernicke et al. (1985) are widely known and successful models that explain the subsidence and uplift history in the passive margin settings and also in the continental interior. Wernicke et al. (1985) promulgated a simple shear model which predicts the high degree in subsidence and uplift history on either side of the continental basin based on the spatial variation in the mantle thinning and in the changes in the proportions of crust.

The McKenzie model assumes that there is a high degree of symmetry on either side of the rift zone. There are basically three stages for the McKenzie model; (1) Pre-rift phase is the part of the lithosphere which has not been deformed, (2) The stretching phase also known as syn-rift is where continental thinning occurs as the result of the upwelling hot mantle. A lot of horst and graben and subsidence can be observed in this stage. (3) The cooling or post-rift phase is where stretching ceases and cooling starts to achieve thermal equilibrium. The cooling process thickens the oceanic or continental lithosphere which causes further subsidence.

Since the study focuses on the post-tectonic dynamics events which contributed to its evolution through its history, the third stage is more appropriate for this study as it outlines the characteristics which are to be expected during a post-rift phase. Thermal subsidence in the Orange Basin was reported by Jungslager (1999). The thermal subsidence is usually followed by mechanical passive margin uplift and this has not only been observed in the Orange Basin but has also been studied and identified among many areas like South China (Lin et al. 2003) and Western Mediterranean (Watts et al., 1993).

The Orange Basin represents a typical passive margin evolution with syn-rift and post-rift Megasequences. Inadequately imaged transitional zone allows for a down-dip link between extensional and contractional domains. This transitional zone consists of ductile material which absorbed extensional displacement and significant amount of stress external to the deformational system was required to push the transitional zone to initiate thrust faulting. Syn-rift deposition in the Orange Basin is mentioned to have been controlled by extensional faults which occurred as the result of crustal extension and associated mechanical subsidence during the Late Jurassic to Early Cretaceous (160-130 Ma) (Granado et al., 2009). The seaward dipping reflectors (SDRs) in the Orange Basin demonstrate the interaction between crustal extension and thermal subsidence (Séranne and Anka, 2005). Similar to the subsidence of oceanic lithosphere, the post-rift subsidence of extensional basins is mainly governed by thermal relaxation and contraction of the lithosphere, resulting in a gradual increase of its flexural strength, and by its isostatic response to sedimentary loading.

According to Bauer et al. (2000) and Granado et al. (2009) the syn-rift and post rift Megasequences of the Orange Basin were deposited as cooling of the asthenosphere and an underplated igneous material occurred which caused thermal subsidence. This thermal subsidence was succeeded by basin margin cratonic uplift (Gallagher and Brown, 1999) during the Post-rift stage in the early to mid-Cretaceous. Granado et al. (2009) developed a tectonostratigraphic model of the basin which showed that a combination of cratonic uplift and thermal subsidence caused gravity collapse tectonics. Thus gravity tectonics of the Orange Basin according Gallagher and Brown (1999) and Granado et al. (2009) were caused by the south-west African passive margin uplift combined with underplating of igneous material which caused thermal subsidence (Bauer et al., 2000).

5.6 Meteorite impact in the Orange Basin

It has been shown that all planetary bodies with a solid surface have meteorite impact craters. Based on the morphology, the impact craters are divided into two main groups' i.e. (1) simple crater and (2) complex crater. The characteristics for the simple impact crater include hemispherical or bowl-shaped depression (Fig. 65). The impact craters with down-faulted annular troughs and uplifted central area are called complex (Osinski, 2005). The general process in both of the impact crater is that they form as the result of gravitational changes during the modification stage of impact crater formation. Most studies on impact craters have been focused on the terrestrial terranes because that is where most impact craters have been discovered. There is limited literature on the main characteristics of the marine impact craters.

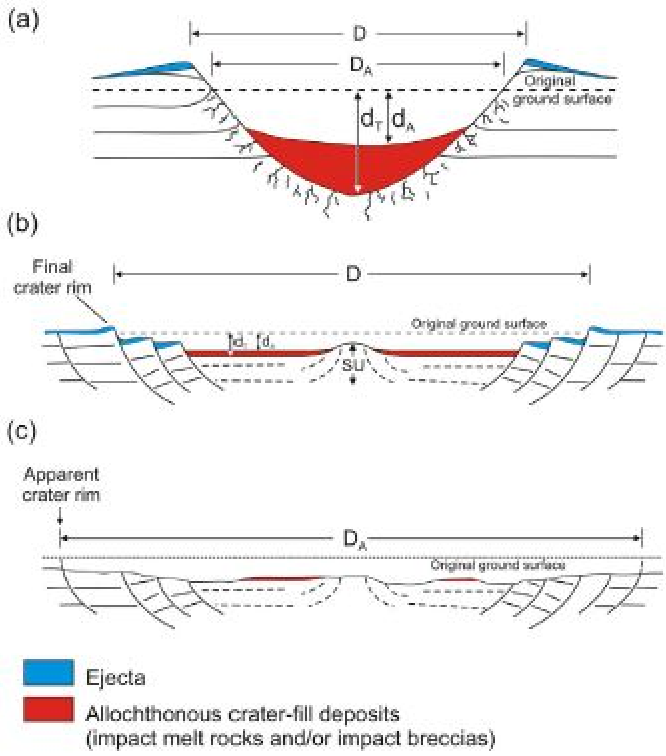

Figure 65: Schematic representation of the simple (a) and complex impact crater (b, c) formations. (After Osinski, 2005)

Wall (2008) noted that the presence of a water column for marine impact craters affects all stages of the meteorite impact which then creates geomorphological features which are different than the terrestrial impact craters. According to Osinski (2005) the kinetic energy of the impact crater transfers shock waves which spread-out as rarefaction or tensional waves which creates compression and subsequent instantaneous melting and/or vaporization of a volume of target material close to the point of impact as the result of the high strain component by the impact.

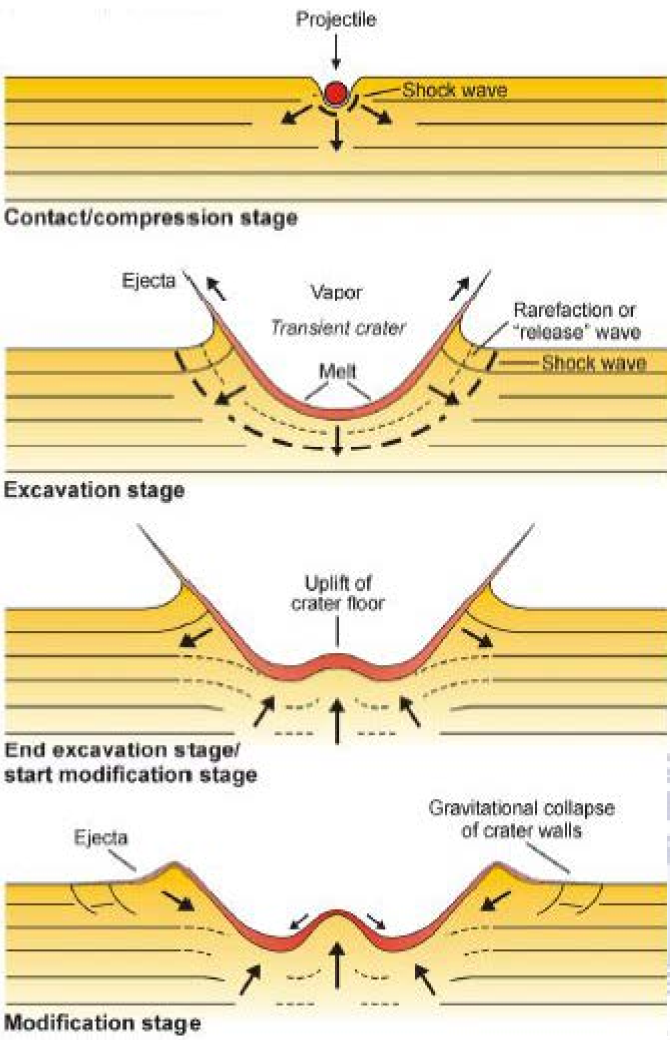

Figure 66: Stages for the formation of the meteorite impact. (After Osinski, 2005)

Geophysical evidence has been used to investigate the impact craters because over the years in has been discovered that geophysical evidence or measurements have played a major role in differentiating depressions which form as the result of volcanoes, salt diapirs and glaciogenic effects (Mhlambi, 2014). Seismic reflection profiles have been used to identify impact craters by looking for typical characteristics like concentric or radial fault distribution, central uplifts and concentric rings of folds and these features are very distinct in the seismic data (Glikson and Uysal,2013; Mhlambi, 2014).

Significant evidence to suggest that the far-field impact of the meteorite impact influenced gravity and toe-thrusting faults is outlined below with reference to the recent work by Mhlambi (2014). Even though seismic interpretation does not provide unequivocal evidence for the impact crater it is however a good start to explain buried structures for offshore environment given the limitation of data in this study.

The thesis presented by Mhlambi (2014) investigated the geometry, morphology, extent and age of the crater-like feature found buried at approximately 280 metres below sea floor in the Orange Basin. The circular crater is buried within Cretaceous and Cenozoic age marine sediments. The work by de Vera et al. (2010) suggested that the age of the gravity collapse structures for this Study area spanned from the Coniacian to the Santonian Epochs. While on the other hand Jungslager (1999) and Paton et al. (2008) suggested that gravity collapse systems occurred between the Cenomanian to Maastrichtian Epochs. These deformational periods are within the Cretaceous and early Cenozoic age marine sediments which is the time where a possible meteorite might have impacted the Orange Basin.

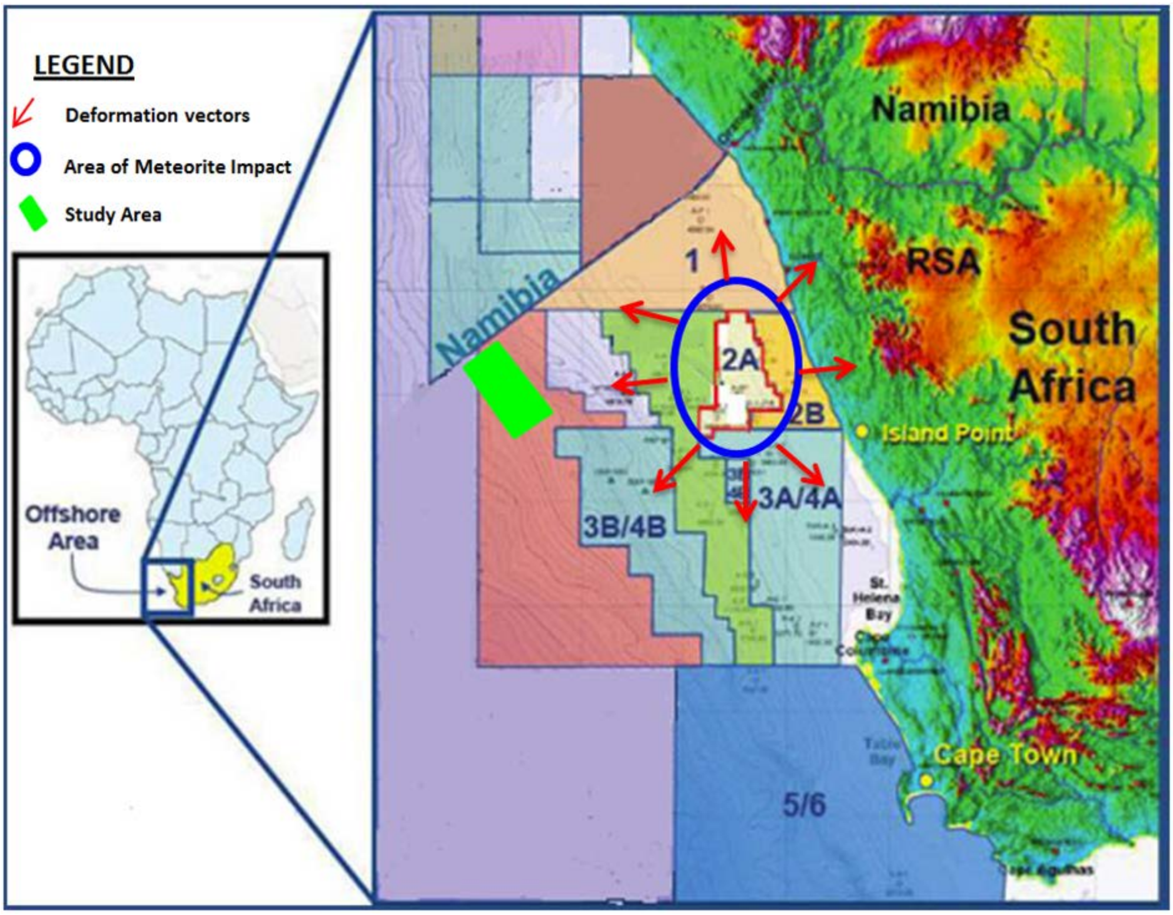

Figure 37: Outward propagation of deformation vectors as the result of a probable bolide impact. Adapted from www.upstreamonline.com and modified after Mhlambi (2014).

Figure 67 above illustrates an exploration area where a probable impact crater was discovered. The deformation vectors might have created gravitational energy contrast which formed concentric folds

(Fig.68 below). The Study area comprises exploration licence Block 2A, which lies approximately 380 kilometres northwest of Cape Town in the northern part of the Orange Basin.

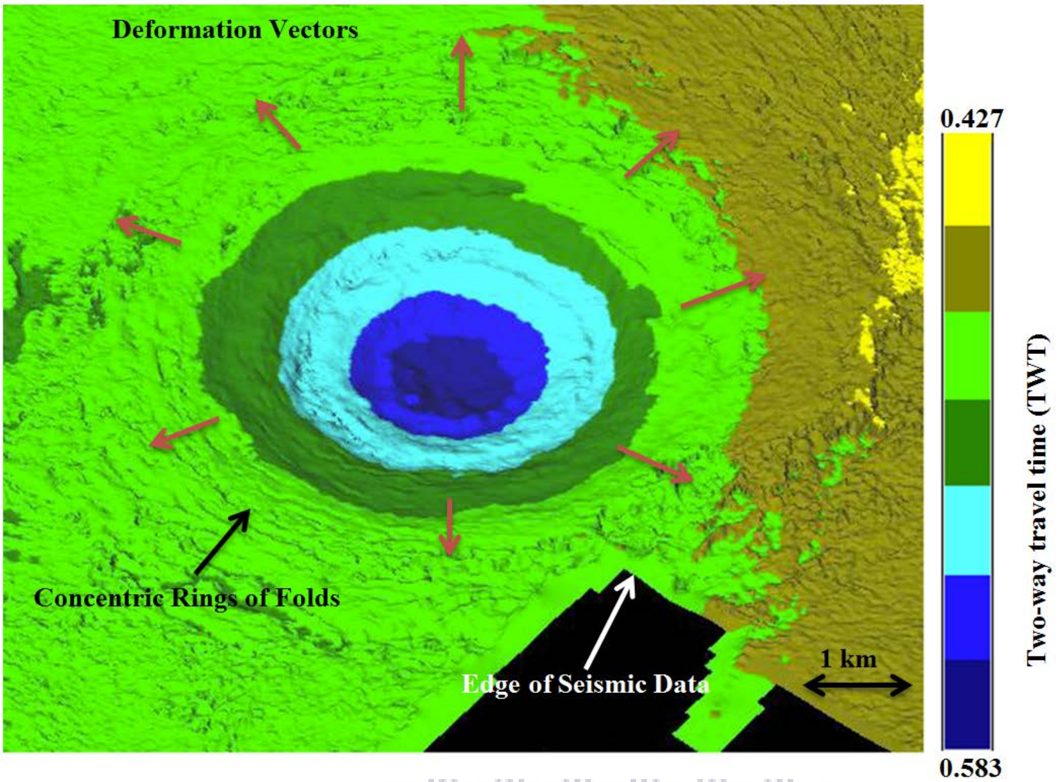

Figure 68: Three-dimensional view of the structure mapped at the base of the Cenozoic strata, adapted and modified from Mhlambi (2014).

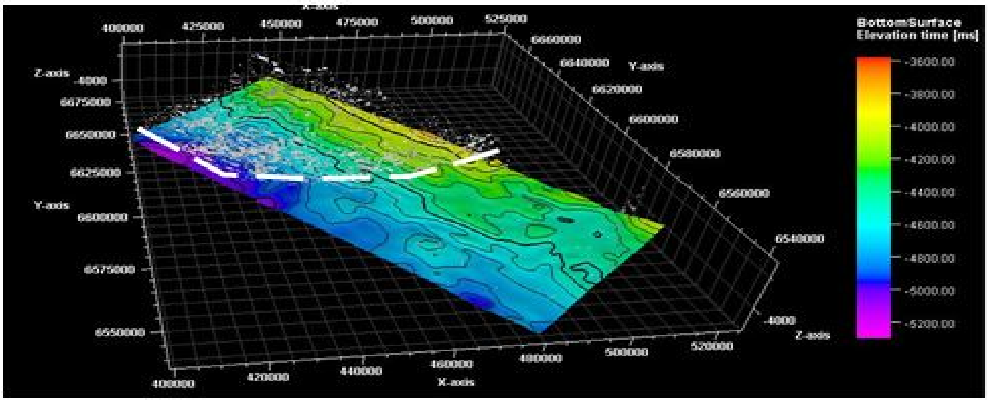

Figure 69: Automatic fault extraction from Petrel© 2014 using 3-D seismic data for this study shows a concentric distribution of faults.

The distribution of these faults shows a hemispherical structure and this is likely the result of the far-field effect of the meteorite impact which is shown in Figure 69. The morphology of the crater (Fig.68) resembles that of meteorite impact craters which can be classified as a probable impact crater (Mhlambi, 2014). Figure 68 shows concentric distribution of faults as the result of outward distribution of deformation vectors. The possible meteorite impact (Fig.69) then created series of *concentric folds extending outward from the central crater. This crater hypothesis by Mhlambi (2014) was proposed instead of the coalescing gas chimneys that define a circular shape which is promulgated by Hartwig et al. (2012). This is because the gas-chimneys do not form perfectly circular geological depressions and the diametres of gas chimneys are typically smaller compared to that of a bolide impact crater.*

5.7 Slump sediment deformation

Huge slope failures have been documented in many parts of the world including the passive continental margins. The presence of the superimposed tectonic structures makes it difficult to recognize slump-sediment deformation. Recognizing the overall kinematic style and the physical state of the structures is very difficult especially where there are superimposed tectonic structures. Addressing the typical characteristics of the slump deformation one should look at the questions required to address the overall kinematic style, the sediment flow rate (high or low), physical state (lithified or unlithified) and the difference in competencies (degree any which the rock resist to deform or erode).

The following section describes the typical slump-sediment deformation features which will be compared to the observed structural features of the seismic data. Deformation structures that formed between horizon one and horizon four are described; this is done with the focus on describing the difference in competencies between the sedimentary layers which has been caused by slump-sediment deformation. The focus here is not dating the deformation, or restoring the deformed structures, the focus here is to logically explain how the geometric architecture of Orange Basin came to be as the result of slump-sediment deformation.

An understanding of slump sediment deformation looks at the reasons why the sediments above the green line are not thrusted but the sediments below are thrusted (Fig.70). The explanation will be the difference in competency of the sediments at the time the slope reached the critical angle of repose.

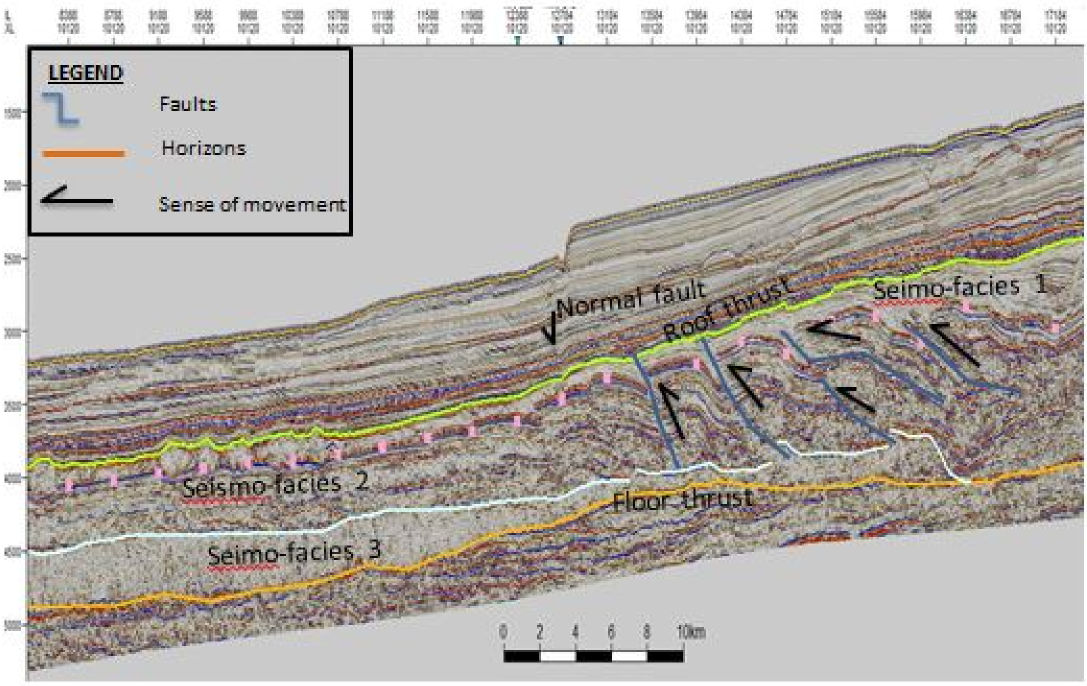

Figure 70: The Figure above shows the interpreted seismic horizons which have been used to understand the geomorphological and structural geometry of the Study area. Seismo-facies 1, 2 and 3 are also depicted.

Below the white line (Fig.70) sediments were too consolidated and had a different angle of repose than the middle package (seimo-facies 1 and 2) which produced horse structures. The greyish white layer which is below the green horizon (seismo-facies 1) could have been an unconsolidated top layer during thrusting or it was a later deposit filling up the gaps formed by the sub-sediment slumping. This greyish white layer produced a new flat surface where the top relatively undeformed package was deposited on top of it (above the roof thrust).

Interpretation of the mechanisms

1. High sedimentation rates associated with rapid delta progradation caused aggradational stacking along a steep depositional margin resulted in the distal regions of the Orange Basin to be relatively unstable. This caused the development of extensional growth faults, large slump structures and associated compressional toe thrusts or horse structures.

2. Then tilting and a layer parallel stress field developed. This layer parallel stress field was too weak to affect the relatively competent top part but it was strong enough to

affect the incompetent middle package (ductile material in the transitional zone) resulting in roof thrust and sole thrust. The roof and floor thrust which formed, constrained the thrust faults or horse structures as the result of the competency difference between the layers above and below the green horizon.

3. There was a high impact crater which as the result of far-field effect, created concentric folds and a hemi-spherical faults distribution, which may have contributed to the movements of thrust faults as seen in seismic section. This impact crater possibly resulted in margin uplift, extensional displacements, ductile deformation and volume loss.

4. The extensive ductile material, lateral compaction and penetrative layer-parallel shortening in poorly lithified rocks could lead to substantial heterogeneity in the permeability and porosity characteristics of the reservoirs; this could have a negative effect on hydrocarbon production.

With the results presented, this study seeks to find the possibilities of origins behind these tectonic features illustrated on the seismic sections presented in the results. We discovered two probabilities to the origin of these tectonic structures, (i) tectonic induced/shortening (gravity tectonics) and (ii) bolide (meteoric impact).

From the extensional domain towards the NE part of the study area, the region is dominated by gas escape features and they surpass the number of gas escape structures on the contractional domain. That is why it was vital to cover the tectonic occurrences and characteristics of the NE geological area (Block 2A-Orange Basin) because there might be a possibility that numerous meteorites have hit the study area and that these structures mapped as gas escape features are in fact impact craters. The distribution, vergence and topography of the area where the thrusts have been mapped confirm the interpretation that gravity tectonics is the most likely mechanism to have formed these structures. The study area vastly shows indications of crater development which supports the notion of a probable meteoric impact that might have struck the Southwest coast of South Africa in the Orange Basin. Impact craters on earth are continually erased by erosion, weathering, re-deposition, volcanic resurfacing and tectonic activity, causing the physical markers to disappear (Pillalamarri, 2008; Wall, 2008). However, certain geological features generated by means other than impact can have comparable circular form, such as volcanoes, salt diapirs and glacigenic features. Hence, a circular geometry alone is not evidence for impact (Pillalamarri, 2008).

In the literature, it is revealed that geophysical measurements have always played a major role in the investigation and study of impact structures (Wall, 2008). In another aspect, geophysical measurements have contributed to the discovery of craters deeply buried in and below older and younger sediments (Ernstson and Claudin, 2013). In most cases, reflection seismology carried out for oil and gas exploration purposes could delineate impact structures by their typical structural features like rings, central uplifts, distinct circular and radial fault patterns, abruptly terminating reflectors and reduced seismic velocities caused by impact brecciation and micro-fracturing (Ernstson and Claudin, 2013; Glikson and Uysal, 2013). Even though the methods of seismic interpretation can aid in the identification of buried impact structures (Mazur, 1999; Wall, 2008), they do not provide unequivocal evidence of impact (Pilkington and Grieve, 1992). Nonetheless, structural features of impact structures that may be imaged on seismic data are often very distinct from structural features associated with salt diapirs, volcanic craters or glacigenic features (Glikson and Uysal, 2013). According to Grajales-Nishimura et al. (2010), once an impact structure has been identified as such, core-log-seismic data integration for high-resolution seismic stratigraphy can reveal information about the timing of impact since an impact can alter subsurface rocks. That is to say that, in theory the position of a crater within strata could be used to constrain its age: sediments that were deposited prior to impact might be strongly deformed by the impact, whereas those that are younger than the impact will not (Stewart and Allen, 2002; Grajales-Nishimura et al., 2010). Wall (2008) noted that the investigation and study of impact craters is based on laboratory experiments, extra-terrestrial examples and evidence from terrestrial impacts (Penfield and Camargo, 1981; Ernstson and Claudin, 2013; Glikson and Uysal, 2013).

The work by de Vera et al. (2010) suggested that the age of the gravity collapse structures for this Study area spanned from the Coniacian to the Santonian Epochs. While on the other hand Jungslager (1999) and Paton et al. (2008) suggested that gravity collapse systems occurred between the Cenomanian to Maastrichtian Epochs. These deformational periods are within the Cretaceous and early Cenozoic age marine sediments which is the time where a possible meteorite might have impacted the Orange Basin. In comparison, very little work has been published regarding marine impact craters (Wall, 2008). Dypvik and Jansa (2003) noted the imbalance and came up with ways of quantifying the geological features that evolve when a meteorite strikes the marine environment. Furthermore, the presence of a water column in the marine environment affects all the stages of crater formation (Wall, 2008). As a result, there are geological and morphological characteristics of impact craters formed at sea which may be different from those formed on land (Dypvik and Jansa, 2003; Wall, 2008). The evidence presented supports gravity-driven collapse structure and not the impact crater. It is therefore decided in this study that gravity tectonics is the main driving mechanism behind the structures interpreted in this study, seeing that, not so much credible literature supports the ''extra-terrestrial theory''.

6 CHAPTER SIX

6.1 CONCLUSION

In the present study the tectonic features analysed on seismic sections were classified as break-back thrust developments as per definition by McClay 1992 of the deep-waters in the Orange Basin. These tectonic features were mapped and quantified by shortening, demonstrating an increase in thrust abundance towards the North of the study area. Ultimately the stress field distribution and fault detachments in the study area yields a distribution of thrusts that increases towards the north with different shortening variations. Shortening variation illustrates that the stress in the study area is not uniform and served as a metric for the quantification of the thrusts sequences in the study area. The study area was divided into three domains namely the contractional domain (study area), transitional domain and the extensional domain.

The gas escape structures on the contractional domain (study area) were not as many as on the extensional domain. This implies that normal faults in extensional regimes are likely to be more conduits for migration than faults in compressional regime. Thus a lot of suggestions arise when trying to better understand the tectonic framework that lead to these structures and tectonic features that are seen in the deep-waters of the Orange Basin. Numerous pieces of evidence surface when trying to unravel the mechanisms that influenced the orientation and change in direction of the thrusts that are on the contractional domain. It is well documented that gravity tectonics is the main driving mechanism behind the features in the study area. However crater development also rose as a probability in the tectonic characteristics in the study area, for which there is no published evidence. Wall, 2008 proposed that a meteoric impact might have caused the deformation in the study area. For this reason, it can be classified as a complex "wet" impact crater as it is formed in the marine environment. The tectonic driving mechanism that formed the thrusts was caused by a combination of gravity tectonics and crater developments and is signalled by the presence of a large number of gas chimneys.

Gravity collapse structures in this study show uniform deformation thrust fault sequencing which supports the notion of gravity tectonism in the study area. The possible reason for gravity induced deformation to have been formed uniformly and not chaotically could be that gravity faulting was caused by slow margin uplift, followed by extensive lateral erosional events which formed continuous unconformable layers. There is no evidence of erosional events which have created flat surfaces for the gravity induced structures constrained within a very short period of the Basin's geological history.

There is less evidence on the possible reasons on what influenced the homogeneity and continuity of the thrust faults of the basin. The contention will be that the basin either underwent an erosional period during Maastrichtian era causing erosion of the upper horizon of the gravity collapse structures causing them to be constrained within this horizon. The other possible explanation will be the far-field effect of the bolide impact to the south of the study area. The Orange Basin might have been influenced by the far field energy effects of this bolide impact which occurred during the Cenozoic era. The stress field distribution of the impact is circular and a northward directed component may have affected the distribution of gravity induced faults. The gravity induced faults are late tectonic and are the reflection of geological events which occurred to influence the geometry. It is therefore convincing that gravity collapse systems of the Orange basin were the main driving mechanism behind the thrusting sequences that lead to break-back thrusts that are mapped in this study. Another possibility of the fault developments might be related to the Atlantic breakup of Gondwana. The findings in the study are also related to the north-south stress field interpretation by Andreoli et al., 1996 as presented in the literature review chapter.

6.2 RECOMMENDATION

It is recommended that more seismic surveys be done on the study area and deeper structures be analysed because with the current data there is no proper understanding of the mechanism of shortening. It is also not definite what tectonic activity defines the development of the structures in the Orange Basin. A better understanding of the tectonic genesis of the Orange Basin is required especially for the deep-water seeing that not only one theory can explain the tectonic genesis in the study area. The crater development reasoning also lacks seismic imaging and extensive literature documentation. The petroleum system needs to be carefully reviewed with a complete set of geological and petro-physical data such as wire line logs and drill cores for the area before considering any production, due to the leakage features identified. Therefore the logical reasoning that is supported by the literature and results analysed is that there was a combination of tectonic activities that lead to the development of the Orange basin's thrust development. We should look at the origins of the gravity induced collapse structures using seismic data with well data to perform depth conversion and to ascertain the depositional period for the interpreted horizons in this study. Understanding gravitational systems lies in the kinematic evolution of the basin's deformational domains. Local and regional stress field distribution studies are required to understand the geodynamic evolution and the lack of structural balance in the basin. The detailed studies for compressional and extensional systems have to be tested against the deformation requirements for the whole gravitational system in its regional context. 3-D Geological modelling with computerized simulation of the possible formation or origins of the gravity collapse of the study area is required.

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